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CHARLES D. WALCOTT, DIRECTOR

THE

MARQUETTE IRON-BEARING DISTRICT OF MICHIGAN

WITH

ATLAS

BY

CHARLES RICHARD VAN HISE and WILLIAM SHIRLEY BAYLEY

INCLUDING

A CHAPTER ON THE REPUBLIC TROUGH

BY

HENRY LLOYD SMYTH

WASHINGTON
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LETTER OF TRANSMITTAL.

Department of the Interior,
United States Geological Survey,
Washington, D. C., January 31, 1896.

Sir: I transmit herewith the manuscript and illustrations of a memoir and the plates for an accompanying atlas upon the Marquette Iron-bearing District of Michigan, by W. S. Bayley and myself.

The field work upon which the present report is based began more than five years ago. This work was by W. N. Merriam, W. S. Bayley, H. L. Smyth, J. Morgan Clements, James R. Thompson, and C. R. Van Hise, although Mr. Bayley mapped a larger area than anyone else. Several others have rendered subordinate assistance. The mapping of the area from west of the center of R. 28 W. to Michigamme was mainly the work of Mr. Merriam. He also studied the Republic tongue, but his work in this part of the area was supplemented by a much more detailed study by Mr. Smyth. From the center of R. 28 W. to the center of R. 27 W., the mapping was partly the work of Mr. Merriam and partly that of Mr. Bayley. East of the center of R. 27 W. to Lake Superior the mapping was mainly by Mr. Bayley, although Mr. Clements assisted one field season. Mr. Smyth mapped the Republic tongue and the area to the west. All the underground work in connection with the mines was done by Mr. Thompson. My own part of the task was the structural study of the whole district, to which I gave one entire field season and large parts of several others.

The field work on the western part of the district by Mr. Merriam and Mr. Smyth was for private parties. The original specimens, notes, and maps were placed at our disposal for the preparation of this report. To the gentlemen furnishing this material we are very greatly indebted. To Mr. James R. Thompson our especial thanks are due for a large amount of gratuitous work, and especially for plats and sections of the majority of the mines of the district, showing the relations of the iron-ore deposits to the surrounding rocks. To the agents, superintendents, and engineers of the mines of the district we are indebted for numberless courtesies.

Of the manuscript, Chapter I, upon the literature; Chapter II, upon the Basement Complex; Section III of Chapter IV, upon the Clarksburg formation, and Chapter V, upon the igneous rocks, were prepared by W. S. Bayley. Chapter VI, upon the Republic trough, was prepared by H. L. Smyth. Chapters III and IV, with the exception of Section III of the latter chapter, upon the Algonkian, were prepared by C. R. Van Hise, as was also Chapter VII, upon the general geology.

The drawing for the atlas was done by E. R. Maurer and F. E. Morrow. The beautiful originals for the colored plates were prepared by Mr. J. L. Ridgway, from polished specimens furnished him. They are photographic in their accuracy.

Very respectfully, your obedient servant,

C. R. Van Hise,

Geologist in Charge.

Hon. Charles D. Walcott,

Director United States Geological Survey.

OUTLINE OF THIS MONOGRAPH.

The Marquette district occupies an area extending from Marquette on Lake Superior west to Michigamme, a distance of something less than 40 miles. The breadth of the area of the Marquette series proper varies from about 1 mile to more than 6 miles. From the western part of the main area two arms project for several miles, one to the southeast, the Republic trough, and one to the south, the Western trough.

The rocks in the district comprise three series, separated by unconformities. These are the Basement Complex or Archean, the Lower Marquette, and the Upper Marquette, the two latter constituting the Algonkian for this district. The Basement Complex gives no evidence of water deposition. The Lower Marquette and Upper Marquette series are mainly sedimentary, although large masses of igneous rocks are included. Each of the series of the district consists of several formations. The transgression of the Lower Marquette sea took place slowly, so that in parts of the district the Lower Marquette succession is incomplete. In other parts the succession is incomplete because of inter-Marquette erosion. After the Upper Marquette series was deposited the district was folded, faulted, and fractured in a complex fashion, with resultant profound metamorphism.

Chapter I gives a history of geological explorations in the Marquette district, and a full summary of previous literature.

Chapter II treats of the Basement Complex. This occurs in two main areas, one north of the Marquette series, called the Northern Complex, and one south of the Marquette series, called the Southern Complex. There are also isolated areas within the Algonkian. The Basement Complex is composed of schistose and massive phases of crystalline and pyroclastic rocks, so different from the Algonkian sediments that there is rarely any difficulty in distinguishing between them. The schistose phases are acid, intermediate, and basic. They are cut by a variety of massive igneous rocks, basic, acid, and intermediate, in the forms of bosses and dikes. The rocks are undoubtedly of widely different ages, but we are unable to separate them into sharply defined series upon the basis of age.

The Northern Complex is treated under the divisions Mona schists, Kitchi schists, gneissoid granites, hornblende-syenites, basic dikes, acid dikes, peridotite, and ferruginous veins. The Mona and Kitchi rocks are greenstone schists, which are believed to be largely recrystallized volcanic materials. Their original forms included both tuffs and lavas. Basic schists are predominant, but acid schists are found. The Mona schists are nonconglomeratic green schists. The Kitchi schists contain numerous pebble-like bodies, which give them in many places a conglomeratic appearance. The gneissoid granites and syenites are plutonic intrusive rocks within the greenstone schists. The basic dikes are mainly diabase. The majority of these are schistose, and earlier than the upper beds of the Marquette series. A few are fresh, and these are probably of Keweenawan age. The peridotite is older than the Cambrian sandstone, and younger than the greenstone schists of the Basement Complex. The ferruginous veins are believed to be water-deposited, and were formed previous to the deposition of the Lower Marquette series.

The Southern Complex is treated under the divisions micaceous schists, amphibole-schists, gneissoid granites, Palmer gneiss, and intrusives. The micaceous schists include muscovite-schists, biotite-schists, feldspathic biotite-schists, and hornblendic biotite-schists. The amphibole-schists include greenstone schists, hornblende-schists, and micaceous hornblende-schists. The intrusives are mainly basic and acid dikes. The greenstone schists, the granites, and the dike materials are similar to the corresponding rocks of the Northern Complex. The granites are intrusive in the schists. The isolated areas within the Algonkian are gneissoid granite and schistose greenstones, that differ in no essential respect from the corresponding rocks of the Northern Complex and Southern Complex. The Basement Complex was deeply denuded before Lower Marquette time, as is shown by the fact that the plutonic rocks yielded their detritus to the basal formation of the sedimentary series.

CHAPTER III treats of the Lower Marquette series. The Lower Marquette series is composed of the following formations, from the base upward: The Mesnard quartzite, the Kona dolomite, the Wewe slate, the Ajibik quartzite, the Siamo slate, and the Negaunee iron formation. For each of these formations the distribution, exposures, topography, folding, petrographical character, relations to adjacent formations, thickness, and interesting localities are discussed. In treating the Negaunee iron formation, the iron-ore deposits and prospecting are also considered.

The Mesnard quartzite formation, from 110 to 670 feet thick, is, as the name indicates, chiefly a metamorphosed sandstone. However, in this formation are other varieties of rock. At the bottom is a conglomerate, which at most places, in grading into the quartzite, passes through slate and graywacke. The conglomerate is basal, in any particular locality being composed of coarse and fine detritus from the immediately adjacent rocks of the Basement Complex. At the top of the formation is a thin belt of slate. The Mesnard quartzite is the first deposit of the transgressing Lower Marquette sea. By the time the sea had transgressed a short distance upon the Marquette district the Kona dolomite began to be formed, and hence the Mesnard formation is confined to the eastern part of the district. In a large way the Mesnard formation is folded into an east-west syncline with a westward pitch. The two limbs unite south of Marquette and complete a U. Superimposed upon this fold of the first order are close folds of higher orders, running in various directions, but more continuously east-west. The rocks of the formation vary from those which have been indurated mainly by siliceous cementation to those which have been completely metamorphosed. At various places along the contact horizon of the Marquette series and the Basement Complex the mashing and shearing have been so profound as to transform both into crystalline schists, which appear to grade into each other. The coarser-grained kinds of the dynamically metamorphosed rocks are extensively fractured, while the finer-grained kinds are mashed without macroscopical fractures. Microscopically, every original particle, small or large, shows strain effects.

The Kona dolomite, from 425 to 1,375 feet thick, is largely an altered limestone. The formation, however, includes interstratified layers of slate, graywacke, and quartzite, with gradation phases between these and the pure dolomite. The Kona dolomite, like the Mesnard quartzite, is confined to the eastern part of the district. The formation has been folded in a complex manner, the folds running east-west and north-south. Consequent upon the folding and the different resisting powers of its layers, the topography of the formation is exceedingly rough. When deformed the dolomite yielded in most places without prominent fractures or cleavage, but in the interstratified slates cleavage was developed in many places, and the graywackes and quartzites were fractured or brecciated. The dolomite varies through a slate into the Mesnard quartzite below, and by a lessening of the calcareous constituent gradually passes into the Wewe slate above.

The Wewe slate, 550 to 1,050 feet thick, is chiefly a metamorphosed mudstone. With the slates are, however, conglomerates, quartzites, graywackes, mica-slates, and mica-schists. The Wewe slate, like the two previous formations, is confined to the eastern part of the district. The formation in a large way is folded into a great westward-plunging syncline, and upon this major fold are superimposed folds of a higher order. The western boundary of the Wewe formation was the western limit of the seashore at the time of the deposition of this formation, and thus basal conglomerates are here found, which in all respects are similar to those of the Mesnard formation, being composed chiefly in each case of detritus derived from the immediately subjacent rocks of the Archean. As the result of the folding, the slates show very generally a cleavage or fissility, but in many places where they are coarse or brittle they are fractured through and through, or even transformed into reibungsbreccias. The formation grades into the Kona dolomite below and into the Ajibik quartzite above.

The Ajibik quartzite, from 700 to 900 feet thick, is mainly a metamorphosed sandstone. The time of the Ajibik quartzite marks a rapid advance of the Lower Marquette sea, and therefore the formation extends to the western end of the district. In the eastern part of the area the Ajibik quartzite grades down into the Wewe slate, but for the major portion of the district it rests unconformably upon the Basement Complex. At many localities contacts and basal conglomerates are known. In some places the metamorphism has been so severe as to transform the Basement Complex and the Ajibik quartzite into crystalline schists, with parallel structures. The quartzite grades above either into the Siamo slate or into the Negaunee iron formation. In different parts of the district, depending upon various conditions, the original sandstone has been transformed into quartzite, cherty quartzite, ferruginous quartzite, ferruginous cherty quartzite, quartz-rock, and quartzite-breccia. Some of the dynamic breccias so closely resemble ordinary conglomerate as to deserve the name pseudo-conglomerate.

The Siamo slate, from 600 to 1,200 feet thick, is chiefly an altered mudstone, although locally it was a grit or sand-rock, which has subsequently been changed to graywacke or quartzite. The larger area of the formation is confined to the eastern part of the district, although a belt runs near the north side of the Marquette series to the west end of the district. The major folding is similar to that of the other formations. Superimposed upon the larger folds are secondary folds, and these at various places are monoclinal. The formation is very generally affected by a cleavage or fissility, and in the case of the monoclinal folds the cleavage is inclined in the same direction as the axial planes of the folds. The Siamo slate grades into the Ajibik quartzite below and into the Negaunee iron formation above.

The Negaunee formation, from 1,000 to 1,500 feet thick, is nonfragmental, heavily ferruginous throughout, and contains the greater iron-ore deposits of the district. It is therefore called the iron-bearing formation. Large quantities of intrusive greenstones are associated with the formation, the masses of which vary in magnitude from great bosses 2 miles or more long and a half mile wide to small dikes. The largest area of the Negaunee formation is in the east-central part of the district. From this area two belts extend west to the western end of the district. Upon the whole, the formation is soft, and occupies lowlands between the more resistant greenstones and the Ajibik quartzite. The formation is underlain by the Siamo slate or Ajibik quartzite, into which it grades, and is overlain uncomformably by the Upper Marquette series. Petrographically the formation comprises sideritic slate, which may be grünerític, magnetitic, hematitic, or limonitic; grünerite-magnetite-schist; ferruginous slate; ferruginous chert; jaspilite; and iron ore. The ferruginous chert and jaspilite are frequently brecciated; the other kinds less frequently. The sideritic slate is the original form from which the other varieties of rock have developed. The grünerite-magnetite-schists were formed by partial recrystallization of the silica, by oxidation of the iron oxide in part to magnetite, by the union of a part of the silica and iron protoxide, producing grünerite, and with the loss of carbon dioxide. The ferruginous slates are the direct result of the decomposition of the iron carbonate and the peroxidation of the iron with partial or complete recrystallization of the silica. The ferruginous cherts differ from the ferruginous slates in that the iron oxide and the chert are largely concentrated into alternate bands. The jaspilites differ from the ferruginous cherts in that each of the quartz grains of the chert bands is stained red by included hematite. The iron ores resulted from the concentration of the iron oxides through the agency of downward-percolating waters. These concentration-bodies usually occur upon impervious basements in pitching troughs. The pitching troughs are formed by the Siamo slate, the Ajibik quartzite, a mass or dike of greenstone, or by some combination of these. The ore deposits are likely to be of large size where as a result of the folding the iron-bearing formation is much fractured, thus permitting the ready action of percolating waters. The ore deposits occur at the bottom of the Negaunee formation, within the Negaunee formation, and at the junction plane between the Negaunee formation and the overlying Ishpeming formation. From the position of the ore deposits above the impervious formations it is concluded that their concentration occurred during or subsequent to the folding which took place later than Upper Marquette time.

CHAPTER IV treats of the Upper Marquette series. This series is composed of the following formations, from the base upward: The Ishpeming formation, the Michigamme formation, the Clarksburg formation. As in the case of the Lower Marquette series, for each formation the distribution, exposures, topography, folding, relations to adjacent formations, petrographical character, thickness, and interesting localities are discussed.

The Ishpeming formation includes two classes of rock, which are called the Goodrich quartzite and the Bijiki schist. These rocks are sufficiently different to have different formation names, but the Bijiki schist for the west end of the district occupies a part of the horizon of the Goodrich quartzite in the central part. The quartzite, from 600 to 1,550 feet thick, is confined to the central and western parts of the district. The main area of the formation is folded into a synclinorium, which, as a result of a western pitch, terminates to the east at Ishpeming. On account of the resistant character of the formation, for much of the district it constitutes a ridge separating the less resistant Negaunee formation below and Michigamme formation above. The Goodrich quartzite rests unconformably upon the Negaunee formation. For the greater part of its area it grades up into the Michigamme or Clarksburg formations, but in the northwestern part of the district it passes into the Bijiki schist. The least metamorphosed rocks are quartzites and quartzite-conglomerates, the grains of which show pressure effects. The more metamorphosed rocks have been so mashed as to have become schist-conglomerates and micaceous quartz-schists. Where the formation rests upon the Archean the mica-schists and mica-gneisses also occur. Between the various kinds there are all gradations. At the base of the Goodrich quartzite is a basal conglomerate. For the major part of the district this conglomerate rests upon the Negaunee formation. Its detritus is therefore derived mainly from that formation, and the rock is an ore, chert, jasper, and quartz conglomerate. At a few places the Archean rocks are subjacent, and their materials predominate in the conglomerate. The Bijiki schist, from 0 to 520 feet thick, is confined to the western part of the district. The rock is a banded grünerite-magnetite-schist, which has been derived by metasomatic and dynamic processes from an impure siderite.

The Bijiki schist grades into the Goodrich quartzite below and into the Michigamme formation above.

The Michigamme formation occurs in a single large belt, stretching from the center to the western end of the district. It is folded into a great composite syncline at the center of the Marquette synclinorium. The rocks were originally ferruginous and nonferruginous muds and grits. These have been altered to slates, graywackes, mica-schists, and mica-gneisses. In this transformation the feldspars have decomposed to quartz and mica, the fragmental quartz has been granulated, and the most metamorphosed of the resultant rocks are foliated, completely crystalline schists. The formation grades below into the Goodrich quartzite, Bijiki schist, or Clarksburg formation. Its thickness is very considerable, probably 2,000 feet or more, but no accurate estimate can be given.

The Clarksburg formation differs from the other formations of the Marquette series in that its predominant rocks are composed of volcanic materials. The formation embraces basic lava flows, tuffs, ashes, and breccias, which locally are interleaved with or grade into graywacke, slate, or conglomerate. Much of the material has been profoundly metamorphosed, and schist-conglomerates, mica-schists, and hornblende-schists have resulted. All of the foregoing rocks are cut by dikes and masses of greenstone. The formation is confined to the south-central part of the district. It grades into the Ishpeming formation or the Michigamme formation below and into the Michigamme formation above. No accurate estimate of the thickness of the formation can be given. The volcanic material was poured out from a number of vents, the more important ones which have been recognized being located near Clarksburg, Greenwood, and Champion.

Chapter V treats of the igneous rocks of the Marquette series not belonging to the Clarksburg formation. These rocks are all basic, having the composition of altered diabases. As to age, they are divided into pre-Clarksburg greenstones and post-Clarksburg greenstones. The older rocks occur as dikes, bosses, sheets, and tuff beds, although the latter two are subordinate. They vary from rather fresh diabases to schistose rocks which are micaceous hornblende-schists, chlorite-schists, or talc-schists. The more metamorphosed forms are most abundant on the peripheries of the masses, and especially close to the rocks of the Negaunee formation, and such rocks are often heavily ferruginous. The post-Clarksburg greenstones comprise only dikes and bosses. They are much fresher than the older greenstones, being mainly nonfoliated. Their alterations are chiefly metasomatic. They comprise olivine-diabases, quartz-diabases, porphyrites, and basalts. It is conjectured that these rocks are correlative with the eruptives of the Keweenawan series.

Chapter VI treats of the Republic trough. This is an isoclinal syncline, extending southeast from the western end of the district. The rocks of the Republic area belong to the Archean, Lower Marquette, and Upper Marquette series. The Archean rocks comprise granites, gneisses, and crystalline schists. The schistose structure is especially developed adjacent to the Algonkian rocks. The Lower Marquette series includes the Ajibik quartzite and the Negaunee formation. The Ajibik quartzite, probably not exceeding 100 feet in thickness, rests unconformably upon the Archean. At one place a coarse basal conglomerate is found in direct contact with the rocks of the underlying series. For the most part the formation has been transformed to a micaceous vitreous quartzite or into a mica-schist. The Negaunee formation consists of two horizons, a grünerite-magnetite-schist below, and a specular jasper above. The Upper Marquette series consists of the Goodrich quartzite and the Michigamme mica-schist. The Goodrich rock has been transformed to a quartz-schist or to a micaceous quartz-schist. In the southeastern part of the trough, at the bottom of the Goodrich quartzite, is a great conglomerate, the detritus of which is derived mainly from the underlying Negaunee formation; also there is a difference in dip between the Goodrich quartzite and the Negaunee formation. From these facts it is certain that the two are unconformable. The Michigamme mica-schist occupies the center of the tongue. This grades down into the Goodrich quartzite. Basic intrusives occur in both the Upper and the Lower Marquette series, the same as in the remainder of the district. A fault with hade nearly but not quite parallel to the bedding occurs on the eastern side of the trough near Republic. The iron-ore deposits are at the contact of the Ishpeming and Negaunee formations or within the Negaunee formation. The important deposits are at the end of the trough, and especially at the bottom of subordinate plunging synclines. They are secondary concentrations, produced by downward-percolating waters.

Chapter VII treats of the general geology, and involves a consideration of the Basement Complex, the Lower Marquette, and the Upper Marquette series. The Lower Marquette has a possible maximum thickness of 6,120 feet, but it is not probable that any single section will give as great a thickness as 5,000 feet. The Upper Marquette series, excluding the volcanics, is probably less than 5,000 feet thick; including the volcanics it is probably more than 5,000 feet thick. Before the beginning of the deposition of the Lower Marquette series the Basement Complex had been deeply eroded. The transgression horizon of the Lower Marquette series is a conglomerate, which quickly passes upward into a quartzite. As the sea occupied a considerable time in advancing over the land area, and as the advance was from the east, several formations were deposited in the eastern part of the district before the entire area was submerged. These formations are the Mesnard quartzite, the Kona dolomite, and the Wewe slate. Thus we have these formations and the overlying Ajibik quartzite overlapping one another to the west. It follows that the transgression horizon is somewhat arbitrarily divided between four formations.

The Lower Marquette series rests unconformably upon the Archean. This is shown at many localities by numerous unconformable contacts and great basal conglomerates, the main part of the detritus being in each case identical with the rocks of the Basement Complex at that locality. Within the sediments of the Lower Marquette series are a few thin lava beds, showing volcanic activity in Lower Marquette time. After the deposition of the Lower Marquette series the land was raised above the sea, and erosion set in and continued for a long time. The denudation was deep enough in some places to remove the entire Lower Marquette series. The Upper Marquette series was therefore deposited unconformably upon the Lower Marquette series and the Archean. For the major part of the district the immediately subjacent rocks belong to the Negauneee formation, and the basal conglomerate for this area consists mainly of detritus derived from that formation. For smaller areas other formations of the Lower Marquette series or the rocks of the Basement Complex underlie the Upper Marquette rocks, in which cases the detritus is derived mainly from them. Above the conglomerate, the first deposit of the advancing Upper Marquette sea, a sandstone was piled up, which was later transformed to the Goodrich quartzite. In the western part of the district, above this came a sideritic slate, which has been changed to a grünerite-magnetite-schist—the Bijiki schist. Above the Bijiki schist followed the muds and volcanics which have been transformed respectively to the rocks of the Michigamme and Clarksburg formations. Within the Lower and Upper Marquette series are abundant intrusives.

After the deposition of the Upper Marquette series the three series of the district were folded together. The folding is of a complex character. The largest but least conspicuous folds have an east-west direction. The major east-west fold is a great synclinorium, which in the central part of the area is of the abnormal type. Upon the primary folds are secondary ones, upon these tertiary ones, and so on to microscopic plications in the case of the finer-grained rocks. The more plastic formations yielded mainly by flowage; the less plastic formations yielded partly by fracturing, although in a large way obeying the general folding of the district. At many places the fracturing was so complete as to produce reibungsbreccias, or even pseudo-conglomerates. A microscopical study shows that not a cubic inch of material has escaped dynamic action. Every original grain of fair size gives evidence of interior movement. The rocks have been kneaded throughout. As a result of the dynamic action, there has also been faulting, but with two or three exceptions the faults are so small as to be unimportant. The manner in which the rocks have responded to deformation shows that when folded they were in the zone of combined fracture and flowage. It is believed that they were buried under a thickness of several thousand feet of sediments, perhaps as much as 10,000 feet.

The various formations of the Marquette series, as a result of the dynamic and other processes, were metamorphosed in different ways, dependent upon their composition and position. In the softer rocks cleavage and fissility were generally developed, and the rocks were extensively transformed to slates or schists. In the harder rocks these structures are less prevalent, although at many places along the major planes of accommodation, and especially at the contacts between the Basement Complex or Archean and the Marquette series between the Lower Marquette and Upper Marquette series, they also have been transformed into crystalline schists. At the former place the Archean rocks have been transformed into similar crystalline schists. The rocks upon opposite sides of a contact have parallel schistosity, and therefore there are here apparent gradations between the unconformable Lower

Marquette and Upper Marquette series, and between the unconformable Lower Marquette series and the Archean. After the last period of dynamic metamorphism it is believed that the crystals of hornblende, garnet, staurolite, andalusite, and chloritoid, which are now unstrained, developed, under quiescent conditions. The metamorphism is much more profound in the western part of the district than in the eastern and central parts. This variation in metamorphism corresponds with the closeness of folding.

During and subsequent to the later folding of the district the area has undergone vast denudation. The character of the folding shows that great mountain masses must have been produced, which have been now reduced to approximate plains, so that the district is merely bluffy.

The Lower Marquette and Upper Marquette series are correlated with the Lower Huronian and Upper Huronian series of the north shore of Lake Superior. They are also correlated with the Lower Menominee and Upper Menominee series. The correspondence of the formations of the Marquette series to those of the Menominee series is only approximate.

THE MARQUETTE IRON-BEARING DISTRICT OF MICHIGAN.

By C. R. Van Hise and W. S. Bayley.

INTRODUCTION.

This report is a final account of the Marquette district, the oldest important iron-producing area of the Lake Superior region. Already two detailed reports have been issued upon it by the Michigan State survey. The first, by Maj. T. B. Brooks, published in 1873, was a faithful account of the structural and economic geology of the part of the district producing iron ore at that time, no attempt being made to completely map the area. The intrusive character of most of the greenstones and the physical break existing between the Upper Marquette and Lower Marquette series were not recognized. While for closely studied localities Major Brooks's mapping is remarkably accurate, it was not possible under the circumstances to fully determine the general succession. The second report, by Dr. Carl Rominger, was published in 1881. This report is accompanied by an areal map of the district from Lake Superior to 1 mile into R. 28 W. The topography is carefully indicated by hachures, and the areal distribution of the more important formations is delineated with a fair degree of accuracy, showing that the district had been traversed with great patience. However, all quartzites are placed together, without reference to their age, and the same is true of the slates. The map is not accompanied by any sections. It is therefore to be considered as a lithological rather than a structural map. Many other papers upon the Marquette district, of greater or less importance, have been published by Wadsworth, Irving, Pumpelly, and others.

A preliminary report has been published by us in the Fifteenth Annual Report of the United States Geological Survey.

The present report is based upon a detailed examination of the entire Algonkian area from Lake Superior to Lake Michigamme. Topographic maps of a part of the district, made by the United States Geological Survey, have been supplemented in critical areas by large-scale plane-table sheets. Practically all outcrops have been accurately mapped on a large scale. In the mining part of the area advantage has been taken of underground workings and borings. Owing to the detailed character of this work, combined with the advance of geological knowledge in the past twenty years, it is now possible to present a much more satisfactory account of the structure of the district than has yet been given.

Notwithstanding the fact that mining has been done for many years in the district, it is little traveled away from the roads. The timber has been cut off for iron smelting. Where the cut has been comparatively recent the fires have run, and there is now a tangle of fallen timber and briars and bushes. Where the cut is older there is a thick second growth, 20 to 50 feet high. The area is therefore much more difficult to penetrate than was the primeval forest. Moreover, the bushes are an effectual bar to extended vision, except from high, rocky points. While the district is not mountainous, in detail much of it is exceedingly rough, so that in traversing parts of it one is nearly always ascending or descending a steep slope. Other parts are covered by a mantle of glacial deposits, through which the rocks rarely protrude. Because of the irregularity of the topography and the difficulty of seeing, it has been impossible to base locations on the ordinary topographic maps. For the larger part of the district locating was done either with the aid of the plane-table or by pacing from section corners and quarter posts.

The rocks of the district comprise three series, separated by unconformities. Each of these series consists of several formations. The transgression of the sea did not occur over the entire district even approximately at the same time, so that in parts of it the succession is not complete, and in other parts the succession is incomplete because of intervening erosion. Finally, the district has been folded in a complicated fashion in two directions, with resulting profound metamorphism.

It is plain from the foregoing that the district is one of exceeding difficulty, and that it has been possible to unravel its intricacies only by patient and laborious work.

The Algonkian of the Marquette district is divisible into two series, presumably the equivalents of the Lower Huronian and the Upper Huronian of other districts of the Lake Superior region and of the Original Huronian of Canada. These two divisions are separated by an unconformity. In this paper the lower clastic series of the Marquette area will be called the Lower Marquette series, and the upper the Upper Marquette series. The Algonkian rocks are bounded on the north and on the south by the Basement Complex, or Archean. The Archean consists of an intricate mixture of granite, gneisses, schists, and surface volcanics. All are thoroughly crystalline.

The Lower Marquette series covers the larger part of the area of Algonkian rocks east of Ishpeming, and forms belts on the north and south sides of the Algonkian area west of Ishpeming. The easternmost Upper Marquette rocks appear at Negaunee and at Palmer. Here, however, they are in patches, the east end of the main area appearing at Ishpeming. From this place west the Upper Marquette rapidly widens. At Lake Michigamme the Algonkian expands into a broad area, from which several arms extend. In each of these arms the lower series occupies the outer borders of the Algonkian belts, the upper series appearing in the centers.

The area discussed in the present paper is limited on the west by the east mile of R. 31 W., and on the south by T. 46 N., with the exception that the southern extremity of the Republic tongue extends into T. 45 N. The Algonkian rocks of this area, speaking broadly, are in a great synclinorium. This synclinorium is of a peculiar and complicated character, which will be fully considered later. It is sufficient here to say that in the middle of the district the rocks in the outer borders of the Algonkian belt are in a series of sharply overturned folds. The Algonkian rocks on either side of the trough have moved over the more rigid Archean granite, and, as a consequence, on each side of the Algonkian trough a series of overfolds plunge steeply toward its center, producing a structure resembling in this respect the composed fan structure of the Alps. There is, however, this great difference between the Marquette structure and that of the Alps, that in passing from the sides of the trough toward the center newer rock appear rather than older ones, so that in the center of the synclinorium the youngest rocks are found. It is as if the composed fan folds of the Alps were sagged downward, so that the structure as a whole is a synclinorium rather than an anticlinorium. The structure thus differs from the composed fan structure of the Alps and from the inverted intermont trough of Lapworth, and may be called an abnormal synclinorium[1] (fig. 1). This structure prevails in the central part of the area from Ishpeming and Negaunee westward to Clarksburg, but it does not extend to Lake Superior on the east nor to Lake Michigamme on the west.

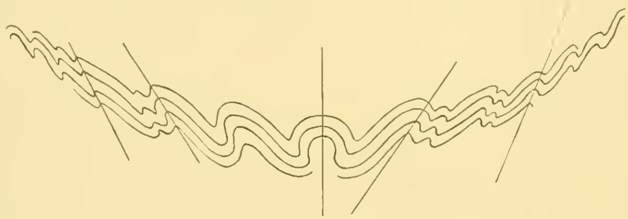


Fig. 1.—Generalized cross-section of Marquette synclinorium, showing the Marquette type of fold.

While the more conspicuous folds have in general an east-west direction, the rocks have also been under strong east-west compression, as a consequence of which the folds are buckled so that they often show a steep pitch. In places the north-south folds become more prominent than the east-west folds, and control the prevalent strikes and dips. In an intermediate area the two series of folds are about equally important, thus producing most irregular strikes and dips. These north-south folds are of two orders: the first of great magnitude, but small dip; the second, superimposed on the first, of less length of wave, but with steeper dip.

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part 1, 1896, pp. 612, 616-620.

CHAPTER I.

By W. S. Bayley.

GEOLOGICAL EXPLORATIONS AND LITERATURE.

That portion of the Lake Superior region known as the Marquette iron range was brought to the notice of geologists by the early navigators of the lakes during the first quarter of the present century, and to the industrial community in the year 1850, when the surveyors of the Chippewa land district announced the discovery of great masses of iron ore in the valley of the Carp River. The literature which deals with the geology of the district far exceeds in volume that devoted to all the other iron-ore-producing areas in Michigan, Minnesota, and Wisconsin taken together. This is due to the early discovery of the district, to its importance as an ore producer, to its comparatively easy accessibility, and to the fact that its geology is so complicated as to have afforded data for many different theories concerning it. These theories have given rise to frequent and sometimes violent discussions, and though many have been proved untenable, they have done much toward the development of correct notions of the origin and the geological relationships of the various rocks occurring in the district.

The history of the literature on the Marquette district may be divided into four periods, as follows: The first extending from the year 1820 to 1850, the date of the appearance of Foster and Whitney's joint report; the second beginning in 1850 and ending with the establishment of the Michigan survey in 1870; the third beginning in 1870 and ending with the publication of Rominger's report in 1881; and the fourth embracing the time that has elapsed since 1881.

The work of the first period was mainly preliminary. It began with the general notes of the early navigators and explorers, and ended with the statement of the general features of the Marquette geology as given in Foster and Whitney's report. This was a period of great activity. It included the writings of the navigators or explorers, Schoolcraft and Bayfield, of the first State geologist of Michigan, Dr. Houghton, and of the United States surveyors and geologists, Cunningham, Gray, Locke, Channing, Burt, Hubbard, Jackson, Foster, and Whitney. The various reports made were devoted to a general discussion of the geology of the district and to the classification of the rocks found.

The second period was not so fruitful of results. The only notable paper published during this time was that of Kimball, which appeared in 1865. Whitney, Rivot, Whittlesey, Hunt, Bigsby, and Credner also contributed to the discussion. Very little that was new was added to the knowledge of the region, the principal articles, with the exception of the one by Kimball, being in confirmation or in contradiction of the various points raised by Messrs. Foster and Whitney—mainly with respect to the divisibility of the "Azoic" series. In Kimball's article the sequence of the rock beds in several portions of the iron range is noted, and a theory of the origin of the iron ores, in opposition to that advanced by Foster and Whitney, is advanced.

The third period was again a time of activity, made so through the efforts of the Michigan and Wisconsin surveys. Alexander Winchell, Brooks, Julien, Wright, Wichmann, and Rominger contributed to the State reports, while Wadsworth, Crosby, and others published in the various journals. In this period the publications took a much wider range than in preceding periods. Brooks and Rominger each published lengthy reports dealing with the general geology of the entire district. Detailed descriptions of observations are the rule in all the papers written, and the conclusions are based on these. In this period also the first detailed maps of the mining region were made. In general the principal work done was the recording of accurate observations. This period is also noted for the vigorous controversy that arose between the advocates of the theory which ascribed to the jaspers and ores of the region an eruptive origin and the adherents of the theory which regarded them as of sedimentary origin. The controversy continued to be waged violently through the greater portion of the fourth period, until finally, near its close, it was settled to the satisfaction of both sides.

The fourth period is noted especially for the writings of the geologists of the United States Geological Survey, more particularly those of Irving, Pumpelly, Van Hise, Williams, and Smyth, although the work of the newly reorganized Michigan survey was an important element in settling several of the questions that had been raised in the earlier discussion. Wadsworth, Patton, Lane, and Rominger contributed to the Michigan reports. Among the other geologists who published during this period are Alexander Winchell, N. H. Winchell, Hunt, Reyer, Birkinbine, and Putnam. The principal problems attacked were the classification of the Marquette formations into series, the definition of the series, and their correlation with the series existing elsewhere in the Lake Superior region. During this period also a number of the doubtful questions as to the origin of certain members of the various formations were settled, so that at its close nearly all the geologists with a personal knowledge of the region came nearer to agreement than at any earlier time.

With this brief outline of the general direction taken by the geological literature of the district, we pass at once to the consideration of the literature itself, discussing the several articles in the order of their publication. A synopsis of each article is given, and this is accompanied by a commentary intended to explain the circumstances under which the different papers were written. Where possible the authors' own words have been quoted freely in the abstracts, since it is thought better to allow them to explain their own views than to make the explanations for them. Now and then a critical comment has been introduced, but the comment is in criticism of some statement of fact by an author, and not of his views.

1821.

SCHOOLCRAFT, HENRY R. Narrative journal of travels from Detroit northwest through the great chain of American lakes to the sources of the Mississippi River, in the year 1820. Albany, 1821. Pages 157–160. With map and plates.

The first reference to the geology of the Marquette district is found in a volume by Schoolcraft, who, in the course of his travels along the south shore of Lake Superior, as a member of the exploring party under Governor Cass, of Michigan, observed the existence of granite at the point now known as Granite Point, some 9 or 10 miles north of the present city of Marquette, and the unconformity between it and the sandstone immediately overlying it. The granite, "rising out of the lake to a height of 200 feet, is connected with the shore by a neck of land consisting of red and gray sandstone in horizontal layers." Greenstone veins, varying in width from 2 to 30 feet, were noticed cutting the granite. "The sandstone laps upon the granite, and fits into its irregular indentations in a manner that shows it to have assumed that position subsequently to the upheaving of the granite. Its horizontality is perfectly preserved, even to the immediate point of contact, which is laid bare to the view." A geological section is published, showing the unconformity of the sandstone on the granite. The author does not pretend to know the age of the sandstone, but he thinks "its position would indicate a near alliance to the 'Old Red sandstone.'" The country back of the lake appeared to Schoolcraft to consist largely of granite.

Thus the existence of granite cut by trap dikes in the Marquette region, and of sandstone much younger than the granite, was first made known by Schoolcraft, who also pictured and made classical one of the best-known unconformities on Lake Superior.

1829.

BAYFIELD, H. W. Outlines of the geology of Lake Superior. Trans. of the Lit. and Hist. Soc. of Quebec, Vol. I, 1829, pages 1–43.

Commander Bayfield, in 1829, on his tour around the lake, made a number of observations concerning the geology of its coasts. He confirms Schoolcraft's discovery of the existence of granite at Granite Point and of horizontal sandstone resting immediately upon it. He finds this same sandstone with similar relations to the granite all along the south coast of the lake from this point as far west as the east side of Keweenaw Bay. Like Schoolcraft, he regards it as probably the "Old Red." The granite and certain greenstones associated with it are cut by "veins of hornblende," which, however, never pass upward into the sandstone.

1841.

Houghton, Douglass. Fourth annual report of the State Geologist, Douglass Houghton. State of Michigan, House of Representatives, No. 27. Reprinted in "Memoirs of Douglass Houghton, first State Geologist of Michigan," by Alvah Bradish. Detroit, 1889. 302 pages.

The first general statements made with respect to the relations of the Lake Superior rocks to one another are to be found in the reports of Dr. Houghton, first State geologist of Michigan. The fourth report, published in 1841, deals principally with the geology of the copper region, although the general geological relations of the different portions of the Lake Superior region to one another are discussed, and the boundaries of the present Marquette district are outlined. The presence of "Primary" and "Metamorphic" rocks in the vicinity of the present city of Marquette was known to the author, though he refers to this locality only in a general way as the region north of the Chocolate River. At Presque Isle, moreover, he recognized the presence of a serpentinous trap rock, which he thought had been raised up through the sandstones now lying upon it, for the original horizontal stratification of the sedimentary rock has been so disturbed that its strata now dip away from the trap in all directions. At the junction of the two rocks the sandstone has been shattered and impregnated with calcareous matter, and both rocks have lost their characteristic features (pp. 180–181).[1]

The main features of the geology of the Upper Peninsula of Michigan are here for the first time approximately outlined. The primary rocks are reported as extending northwestward from Little Presque Isle, a small point jutting into Lake Superior, a little southeast from River des Morts, now known as Dead River. Along the lake shore they are known as far west

[1] All references by page number in this review are to the report as reprinted in the Memoir of Douglass Houghton.

as the Huron Islands, while inland they stretch westward as far as the source of the Wisconsin River (p. 166). The larger portion of the Primary series consists of granite or syenite (hornblende-granite). In its southeastern portions granite is the predominant rock. Toward the northwest the character of the series changes almost imperceptibly. Quartz becomes less and less abundant in the granite, and hornblende more abundant, until finally the rock passes into a granular compound of feldspar and hornblende, or into a greenstone. The granitic members of the series (which are those included within the present Marquette district) are traversed in all directions by greenstone dikes of various magnitudes that have produced contact effects in the granite on both sides of them. These dikes are connected with the great greenstone masses to the northwest. They are not only of the same composition as the greenstone, but as the large areas of the greenstone are approached the dikes become more and more abundant in the granite, "until at length it becomes difficult to determine which of the rocks predominates in quantity." Occasionally veins of other rocks than greenstone are to be found cutting the granite, and "in a single instance what was regarded as a true vein of porphyry, having a width of nearly 3 feet, was noticed, which vein is crossed at angles of 53° and 107° by a vein of greenstone, having a width somewhat less than that of the porphyry. In this instance the greenstone is clearly the most recent vein" (p. 176).

It is evident that Houghton did not discriminate between the younger greenstone dikes in the granite and the greenstone-schist comprising the large areas of greenstone to which he makes reference. The latter do not send apophyses into the granite, but, on the contrary, the granite sends dikes into the greenstone-schists. There is a gradation such as Houghton describes, but the granite, and not the greenstone-schist, is the invading rock. The small dikes in the granite are as described in the report, but they are not genetically connected with the greenstone-schists.

"Flanking the primary rocks on the south," writes Houghton, "is a series of stratified rocks consisting of talcose, mica, and clay slates, slaty hornblende rock, and quartz rock, the latter rock constituting by far the largest proportion of the whole group." Passing from the granite southward near the lake shore, the series consists of a serpentine rock into which the granite insensibly grades, hornblende-slates, talcose and micaceous slates and clay-slates, and finally quartzites. The series dips irregularly to the south and southeast, while the cleavage of the slates is very uniform to the north (p. 168). These "metamorphic" rocks are confined exclusively to the range of hills lying upon the southeast side of the granitic rocks. They occupy a belt of country having an average width not exceeding 6 to 8 miles. The precise limit of the series to the southwest is unknown. The southeastern boundary is the Chocolate River. The alternations of the different members of the series are so complicated that the author does not attempt to describe them. He contents himself with a description of the quartzite, which he finds to be granular and compact, and a statement with regard to the serpentinous rock lying immediately south of the granite. This rock has a regular-jointed structure resembling stratification. In composition it is very close to greenstone, since it consists essentially "of granular feldspar and hornblende, with which serpentine is intimately blended. This rock only occurs in the talcose slate as we approach the granitic region, and possibly a more close examination may show it to be a simple series of dikes lying parallel to the line of cleavage of the slate rocks" (pp. 182–183). Like the primary rocks, the metamorphic ones are traversed by trap dikes.

The serpentinous rocks to which the reference is made are the greenstone-schists which were so long regarded as part of the sedimentary series, and whose origin was a matter of doubt until G. H. Williams proved them to be altered basic tuffs. The mica-slates and clay-slates and the quartzites are members of the Marquette series.

In the economic portion of the report the State geologist refers to the value of the granite and the greenstones as building materials, and gives a list of the minerals found in the primary and metamorphic series. Among those in the metamorphic series novaculite and hematite are mentioned, but the latter is not thought to be of much value. "Although the hematite is abundantly disseminated through all the rocks of the metamorphic group, it does not appear in sufficient quantity at any one point that has been examined to be of practical importance" (pp. 196–197).

1845.

Cunningham, Walter. A copy of a report of Walter Cunningham, late mineral agent on Lake Superior. Dated January 8, 1845. Communicated by Hon. William Wilkins, Secretary of War, February 11, 1845. 28th Congress, 2d session, 1844–45. Senate Documents, Vol. VII, No. 98. 5 pages.

After Dr. Houghton's unfortunate death, the first information that comes to us concerning the geology of the Marquette district is through the reports of the commissioners appointed to examine the country ceded to the United States Government by the Chippewa Indians, a large tract, including all of the area embraced in the iron and copper districts of the south shore of Lake Superior, in addition to much other land. Gen. W. Cunningham had been sent by the War Department into the "Chippewa land district" to examine the country and to gather information with respect to the extent of the mineral lands on the south shore of the lake, that these lands might be designated "mineral lands" by the proper authorities, and so treated.

General Cunningham submitted his report in 1845. In it the Chocolate River was fixed upon as defining the southern boundary of the mineral tract, not because iron ores had been discovered near it, but presumably because "in the vicinity of Death River important discoveries of lead ore have been made." Very little was afterward heard of these discoveries, but, at the time he wrote, Cunningham believed these occurrences of galena marked the northeastern end of the lead range whose southwestern extension formed the great lead region of Iowa, Illinois, and Wisconsin.

Stockton, John. A report of John Stockton, superintendent of the mineral lands on Lake Superior, with maps, etc. Dated February 24, 1845. Transmitted to the Senate March 17, 1845. 28th Congress, 2d session, 1844–45. Senate Documents, Vol. XI, No. 175, pages 2–22.

Upon the designation of the "mineral lands" by General Cunningham they were placed under the charge of General Stockton as superintendent, with headquarters at Copper Harbor, on Keweenaw Point.

In his own report Stockton deals almost exclusively with that portion of the mineral lands in which copper was known to occur.

Gray, A. B. Report by A. B. Gray. Ibid., pages 15–22. With map.

Accompanying Stockton's report are the reports of his several assistants, among whom was A. B. Gray, who refers incidentally to the rocks between Granite Point and the Chocolate River as "trap and granite, bearing the strongest indication of a metalliferous nature" (p. 18). They contain veins of galena, chalcopyrite, and pyrite. The traps and granites appear as knobs, some of which "are based on the south by metamorphic and sandstone rocks." With Gray's report is published a map of the west half of Lake Superior, showing very well the main features of the topography of the district lying between the Montreal and Chocolate rivers, but containing no geology.

1846.

Gray, A. B. Report of A. B. Gray relative to the mineral lands on Lake Superior. Dated March 10, 1846. Transmitted to the House of Representatives June 16, 1846. 29th Congress, 1st session, 1845–46. Executive Documents, Vol. VII, No. 211. 23 pages. With map.

In a second report, written about a year after that last referred to, Gray, who in the meanwhile had been appointed assistant superintendent, reports the progress of his surveys of the Lake Superior mineral district, and gives on a large-scale map the location of claims filed by mineral prospectors. It is interesting to note that a large number of claims had been leased in the district with which we are concerned at present, especially in T. 47 N., R. 26 W., and T. 47 N., R. 27 W., the two most important iron-producing townships in Michigan, and that they had been taken up, not with a view to prospect for iron ore, but, in all probability, in the hope that galena, copper, or an ore of copper might be discovered on them. It is true that Samuel Peck reported the existence of large exposures of specular iron ore in the range of hills south of Dead River and about 10 or 12 miles inland, but it is plain that a great deal less interest was taken in this discovery than in that of galena on Dead River and near the Carp, of gold in the "iron range," and of black oxide of copper at Presque Isle and near the mouth of the Carp.

Rogers, H. D. Verbal communication to the Boston Society of Natural History, April 1, 1846. Proc. Boston Soc. Nat. Hist., Vol. II, pages 124–125.

In the same year in which Gray wrote, Professor Rogers, in a verbal communication to the Boston Society of Natural History, gave an account of the mode of occurrence of copper at Keweenaw Point, and discussed the age of the sandstones and conglomerates of the Lake Superior region. In the course of his remarks he announced the discovery of a contact between a red sandstone and an underlying series of sandstones which he thought to be the equivalent of the Primal sandstone and slate of the Appalachian series, known in the reports of the New York survey as the Potsdam sandstone. The location of the contact is in the neighborhood of the Chocolate and Carp rivers. The underlying sandstone is highly inclined and is "traversed by parallel east and west axes." On the uplifted edges of this sandstone rest unconformably beds of the conglomerates and sandstones of the red sandstone series, with very gentle northern dips. If the underlying sandstone is Potsdam, then the red sandstones and conglomerates of Lake Superior are post-Paleozoic. The author concludes, "from various points of analogy between the red sandstone itself, its trappean dikes, and their mineral associations with the similar components of the Mesozoic or New Red sandstone of the Atlantic States, that the formation in question is of equivalent age and origin with this last-named interesting group of rocks."

This contact was later described and pictured by Irving and other geologists. Professor Rogers described its essential features well, but his conclusion with regard to the age of the overlying rock is of course valueless, since the underlying sandstones are Algonkian, and not Cambrian. Moreover, the overlying sandstones are not cut by trappean dikes.

1848.

Locke, John. Report of John Locke to Dr. C. T. Jackson, describing the observations made on the geology of the mineral lands in Michigan. Dated October 27, 1847. 30th Congress, 1st session, 1847–48. Senate Documents, Vol. II, No. 2, pages 183–199.

By acts of March 1 and March 3, 1846, the mineral lands of Lake Superior were taken from the jurisdiction of the War Department and placed under control of the General Land Office, at that time a branch of the Treasury Department. Thereupon Dr. C. T. Jackson was appointed by the Acting Secretary of the Treasury "to make a geological survey of the Lake Superior district, in Michigan." Dr. Locke was selected by Dr. Jackson to be assistant geologist to take charge of one of the exploring parties, whose duty was to examine that portion of the south shore of the lake east of Keweenaw Point His report was published in 1848, although the reports of Jackson's other assistants did not appear until the records of the following Congress were printed, and not until after the appearance of the reports of the linear surveyors, whose work was concluded and whose results were probably known to Dr. Locke before he took the field. These latter reports take precedence in point of time, although they were not given to the public until after Locke's report.

In his report Locke mentioned pure iron ore as occurring on Presque Isle. He further remarks (p. 187):

> The region drained by Dead and Carp rivers is full of interest, and, geologically, is a "compact country," presenting a great variety in small distances. * * * [It consists of] knobs of greenstone and augitic trap, surrounded by altered sandstone and slates. Perhaps not so much "knobs" as ridges. The sandstone is changed almost into quartz, and the slates occur so much transformed that at some points it is difficult to distinguish them from trap. * * * This region has been called the "Cornwall of America," in reference to its general geology. It has been said that there are rocks there suitable to contain gold, silver, copper, lead, &c. So far as I have observed, it is a gold region "all but the gold," a silver region without silver, and a copper region with veins and bunches of ore so thin and scattered as to be unprofitable for working.

The author of the report refers to the ore of the Jackson Iron Company as similar to that of Missouri, and announces the discovery of some very pure iron ore along the western edges of Ts. 47 and 48 N., R. 26 W., and in the contiguous towns. He also identifies the "granite" of the Michigan map (probably referring to the map afterward published by the linear surveyors) as a porphyritic syenite.

Channing, Wm. F. Dr. Channing's synopsis of the survey in charge of Dr. John Locke. (Second section.) 30th Congress, 1st session, 1847–48. Senate Documents, Vol. II, No. 2, pages 207–208.

Locke's report is so badly written that it is fortunate for its author's reputation as a geologist that he had with him as "first subagent" Dr.

Channing, who has given us a synopsis of the geological results reached by Locke's party.

After referring to the point of Presque Isle as consisting of "trap much modified by the neighboring sandstone, with which it has a junction a short distance inland," and to the character of the ores ("sulphuret of copper and iron") mined there, Channing briefly outlines the results of a trip made inland from the Carp River "through the metamorphic region and the iron region to the syenite on the Escanawby River," as follows:

> On Carp River the principal rocks are the metamorphic slates and sandstone quartz. In the former, in T. 48, R. 26, two veins of quartz were observed containing copper pyrites. * * * In sec. 30, T. 48, R. 26, a quarry of hornstone occurs, adjoining the quartz, which furnishes oilstones of the finest quality.
>
> The location of the Jackson Iron Company is in R. 27, T. 47, sec. 1. The iron region, which has its northern limit here, was observed for many miles. It consists of magnetic and unmagnetic oxides of iron, occasionally associated with metamorphic slate or chlorite slate. * * *
>
> South of the metamorphic region the slates and sandstone quartz gradually pass into quartz and feldspar rock and fine-grained syenite.
>
> Still farther south the coarse and porphyritic syenite on the Escanawby River comes in. These rocks were rarely found to contain mica.

The published documents of the first session of the Thirty-first Congress (1849–50) contain the reports of the linear surveyors, those of Dr. Jackson and his assistants, and of Messrs. Foster and Whitney, who succeeded Jackson as United States geologists. Although all these bear the same date of publication, the reports of the linear surveyors had been submitted to the authorities several years before their publication, even before the date of publication of Locke's first report already referred to, and copies of them had evidently been furnished to Jackson and to Foster and Whitney before they entered upon their surveys; so that the reports bearing date of 1849–50 must not be looked upon as contemporaneous. The work of the linear surveyors was prior to that of Jackson and his assistants, while the work of Foster and Whitney was undertaken, at least in part, after Jackson's work. The value and importance of the different reports published in this year must be judged in the light of this knowledge.

The Chippewa land district was subdivided into townships and sections by William A. Burt, Bela Hubbard, and others, under the direction of Douglass Houghton, during the years 1845 and 1846. Houghton instructed his assistants to observe the ledges on their lines of traverse, 1 mile apart, running east and west and north and south, to report their character, and to collect specimens from them. The reports of Messrs. Burt and Hubbard are based on these observations. Geology, of course, was of secondary interest to these surveyors, and yet their geological work has been of great value to all later geologists who have made excursions into the district surveyed. Foster and Whitney used the linear surveys to great advantage in prosecuting their explorations, and all geologists who have followed these two have been guided to important outcrops by the notes of the surveyors. These notes, as has already been mentioned, are printed in the same volume of the Government records as the reports of Jackson and of Foster and Whitney, but since the latter gentlemen made use of them, it is but right that Messrs. Burt and Hubbard should be given priority in a discussion of the literature of the region. Consequently, in this chapter their reports are given precedence of the reports of Jackson and Whitney, although appearing later in the same volume that contains the reports of these latter gentlemen.

1850.

Burt, Wm. A. Topography and geology of the survey, with reference to mines and minerals, of a district of township lines south of Lake Superior. 31st Congress, 1st session, 1849–50. Senate Documents, Vol. III, No. 1, pages 811–832. With map, opposite page 880.

Burt, as the result of his first year's survey, divided the rocks seen by him during his journeys along the section lines into five principal groups: the primary rocks, the traps, the conglomerates, the sandstones, and the slates. The primary rocks, including the metamorphic ones, he found generally a little inland, with the metamorphic rocks flanking the other members of the primary series on the south. The rock to the north is "sienite," or "sienite granite." Hornblende is a more frequent constituent than mica, hence "sienite" is the predominant rock type. Greenstone intrusives and veins of quartz and feldspar cut the primary rocks in all directions. In the metamorphic series south of the primary granite and syenite, "quartz, compact and granular; imperfect talcose slates, which are in some instances slightly argillaceous, and slaty hornblende" are the predominant types. The rocks are more or less stratified, and are imperfectly jointed. Within the area of the metamorphic rocks the surveyors saw several knobs of syenitic granite and some dikes of greenstone. On the sketch-map accompanying the report (opposite p. 880) are given the outlines of the areas occupied by granite, metamorphic rocks, and clay-slates in T. 48 N., R. 26 W.; T. 49 N., R. 25 W., and T. 47 N., R. 26 W. (See Pl. I.)

Hubbard, Bela. General observations upon the geology and topography of the district south of Lake Superior, subdivided in 1845 under direction of Douglass Houghton, deputy surveyor. 31st Congress, 1st session, 1849–50. Senate Documents, Vol. III, No. 1, pages 833–842.

Hubbard's report is upon the same district as is that of Burt, referred to above. The author divides the townships surveyed in 1845 into two classes, in one of which he places Ts. 46 N., 47 N., and 48 N., Rs. 24 W., 25 W., and 26 W., all in the Marquette district. He then proceeds to describe the geology of these towns. He adds little new to Burt's description, but his treatment of the subject is more satisfactory, as it is more comprehensive. T. 46 N., Rs. 24 W., 25 W., and 26 W., and the lower tier of sections in the towns north, are occupied by granites. These rocks appear in a succession of rounded knobs, having a general direction a little south of west. They "vary much in character and composition, being sometimes hornblendic and approaching a perfect sienite, but more commonly feldspathic, or composed of quartz and feldspar." In the more southerly portion of the district the feldspar is red, and the granite of a corresponding tint. Some portions of the rock are massively stratified. A second area of granite begins on the coast a little south of Presque Isle and runs westerly inland. It occupies the portion of T. 48 N., R. 25 W., lying north of "Rio des Morts" (Dead River). "The granite of this portion of the country is traversed by large and irregular dikes of greenstone trap, and the granite itself puts on a trappean character, the two rocks being sometimes with difficulty distinguished from each other. This is the commencement of an apparently very large extent of granitic country extending westerly into the region not yet surveyed by section lines"

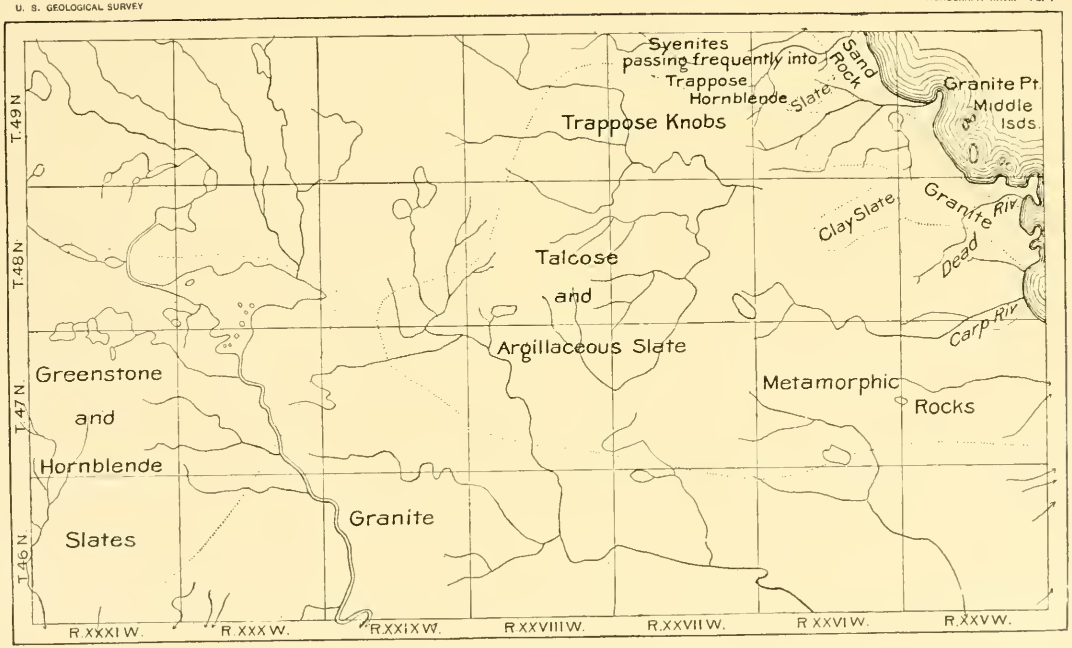
(p. 834). Between the northern and southern granite areas lies the region of metamorphic rocks. This region is divided into two parts—the southern or quartzite portion, and the northern or trappean portion, corresponding to our present division into the fragmentals and greenstone-schists. In the southern area are found white and brown quartz rocks, talcose and augitic slates and clay-slates, slaty hornblende, and specular and micaceous oxides of iron. These rocks cover a tract of country lying "between the granites on the south and a line bearing north of west from the mouth of Carp River to the center of the west line of township 48, range 26." This tract is described as rolling, with numerous ridges trending nearly east and west. The central portions of many of the ridges seem to be trap, which is capped and flanked by the metamorphosed rocks. No outcrops of this trap were seen, however. Its presence was inferred from the character of the metamorphic rocks and their dips, which were thought to be in all directions away from a central axis. All the metamorphic rocks are pervaded by "the oxides of iron, sometimes intimately disseminated, and sometimes in beds or veins," which are frequently of such "great extent as almost to entitle them to be considered as rocks." The ores are described, and the positions of some of these outcrops are noted. The northern portion of the metamorphic area embraces all the country between the quartzite group just described and the granites to the north, with the exception of about 5 square miles in the northeast part of T. 48 N., R. 26 W., where clay-slates occur. "This division of the metamorphic region is characterized by the frequent occurrence of knobs or uplifts of greenstone and augitic trap, making their appearance rather irregularly over the country, and surrounded by altered sandstones and slates." The greenstone is igneous in origin.

This report of Hubbard's is by far the most satisfactory one published up to this time. It supplements Houghton's general report of 1841, and for the first time gives a fair idea of the character of the country now included in the Marquette area, the distribution of the rocks occupying the district, and their relations to one another. Of course the report is fragmentary. The author regarded it as such, and yet it contains in shadowy outline many of the conclusions of later geologists.

Burt, Wm. A. Geological report of the survey, "with reference to mines and minerals," of a district of township lines in the State of Michigan, in the year 1846, and tabular statement of specimens collected. Dated March 20, 1847. 31st Congress, 1st session, 1849–50. Senate Documents Vol. III, No. 1, pages 842–875. With maps, opposite page 880.

The experiences of a second season in the Upper Peninsula of Michigan resulted in Burt's second report. In this the author generalized to a greater extent than was possible in his earlier report. The territory surveyed during this second season embraced all of the "Marquette district," in addition to the country north and south of it for a number of miles. The general geology of all this area is briefly outlined, and the results of the year's work are indicated on a map.

The granites of the region are said by the author to pass in some instances into syenitic greenstones. They are cut by trap and are very often gneissic in structure. In Ts. 47 N. and 48 N., Rs. 27 W., 28 W., and 29 W., are argillaceous slates that are the extension westward of the slates observed in 1845. These slates dip "at a high angle, generally conforming to the surrounding granites, or flanking the numerous protrusions of greenstone within their boundary. They appear like the remnants of overlying rocks among the greenstones, which have escaped the denuding effects of causes that partially stripped this region of similar rocks previous to the completion of its present elevation" (p. 546). "The talcose slates are of many varieties, such as would result from their passing into argillitic and into hornblende slates." The greenstone and hornblende-slates occupy only a small portion of the area mapped in Pl. I, though they formed the largest portion of the area surveyed. The greenstones are described as more or less granular and syenitic rocks, with a dark color when moist. Their composition is hornblende, feldspar, and quartz, with the hornblende largely predominating, sometimes almost to the exclusion of the other constituents. The hornblende-slates are fine-grained and compact varieties of the greenstone, possessing a "laminated or slaty structure." The slates are cut by quartz veins and by later trap dikes which are supposed to unite with the trap range of Keweenaw Point to the west.



PORTIONS OF BURT'S, HUBBARD'S, AND IVES'S MAPS OF THE UPPER PENINSULA OF MICHIGAN.

The author concludes his remarks on the general geology of the region by mentioning the locations of fourteen exposures of iron ore met with along the traversed lines. He infers from his observations that the region is an exceedingly rich one, far excelling any other portion of the United States in the abundance and good quality of its ores (p. 852). It is to Burt's energy and to his discovery of ore that later developments of the iron district are due, although, as we have seen, Locke's report referred to the ores of the region two years before that of their discoverer was given to the public.

Lists of specimens collected along the township lines are appended to the reports, and it is these that have afforded such great aid to later geologists.

JACKSON, CHARLES T. Report on the geological and mineralogical survey of the mineral lands of the United States in the State of Michigan, etc. Dated November 10, 1849. 31st Congress, 1st session, 1849–50. Senate Documents, Vol. III, No. 1, pages 371–502. With maps. Also House Documents, Vol. III, No. 5, pages 371–502.

Reference has already been made to the appointment of Dr. Jackson, in 1847, as geologist for the survey of the mineral lands of the State of Michigan. The reports of Locke and Channing, which appeared in 1848, were the first fruits of the survey. In 1850 the reports of Jackson himself and of several of his assistants were submitted to the Secretary of the Interior, concluding the survey under Jackson's charge.

In his own report Jackson gives a minute and detailed account of his explorations and their results. Most of Jackson's personal observations were made in the copper region. In the report, however, he notes that in 1845 Mr. Joseph Stacy explored the region "between the mouth of Dead River and Lake Michigan, and established the fact that there was an inexhaustible amount of compact and micaceous specular iron ore in that district." Its analysis gave: Silica, 3.88; lime, 0.17; peroxide of iron, 96.11. A small portion of the ore is in the state of magnetic oxide. The localities were examined more carefully in 1847 by Assistant Geologist Locke and Subagent Channing, whose report is referred to below. In 1848

Jackson received a specimen of pure hematite from near the Carp River (pp. 478–479). The maps that accompany the report are mainly of the copper regions.

LOCKE, J. United States geological survey of public lands in Michigan. Field notes of 1847. Accompanying report of Dr. Jackson. 31st Congress, 1st session, 1849–50. Senate Documents, Vol. III, No. 1, pages 572–586.

Although Locke's report, which accompanies that of Dr. Jackson, is but a copy of the author's field notes, it contains a few points of interest concerning the iron region. Locke and his assistants coasted along the shore of Lake Superior from L'Anse to beyond the Chocolate River. At Presque Isle the junction of the trap and sandstone on the east side of the point was observed, and fresher trap dikes in the main "trap mass" were noted. In the vein mined by the New York and Lake Superior Mining Company is a mixture of galena, asbestos, pyrite, and arsenopyrite. Inland from the mouth of the Carp River a large number of veins of quartz containing copper pyrites were seen cutting metamorphic slates. At the Jackson location (sec. 1, T. 47 N., R. 27 W.) the direction of the iron range is about east and west. Much ore lies in loose pieces on the surface of the ledges. The best of it is of a loose crystalline structure, but about one-half consists of "ribbon" ore, striated with red veins, which deserve examination to ascertain their character, while a third variety is a slaty ore, compact and pure. Along the west lines of secs. 6 and 7, T. 47 N., R. 26 W., exposures of ore, metamorphic sandstone, and ferruginous quartz were seen. Continuing farther south, the explorers found ores of various qualities, and at the southwest corner of section 18 an "augitic rock." On the east branch of the Escanaba River they ran into "red sienite." About a mile north of the Carp River, near the coast, there occurs a clay-slate, which farther north is "highly metamorphic, and a trappean rock occurs, apparently blending with the slate." Trap rocks "seem to be frequently interfused with the metamorphic rocks in this region, and sometimes to receive even a stratified structure, when slightly changed from their original type." "With regard to the metamorphosed character of the region to which these notes * * * refer, there can be no doubt in placing the coarsely crystalline sienite of the Escanawby and southern part of the primitive district apart from the trap and copper-bearing rocks of Lake Superior."

At the mouth of Dead River syenite was observed, and at the first falls, 1 mile upstream, a talcose slate. Syenites and various slates were noted at other places in the vicinity of Dead River, and the syenite was seen to be cut very frequently by trap dikes. At "Point No. 2, west of Presque Isle," a junction of red sandstone with syenite is said to occur, but it seems to have had very little significance to the writer, as he does not describe it, but merely asserts its existence. The contact is probably the unconformity at Granite Point.

Foster, J. W. Notes on the geology and topography of portions of the country adjacent to Lakes Superior and Michigan, in the Chippewa land district. Dated May 26, 1849. 31st Congress, 1st session, 1849–50. Senate Documents, Vol. III, No. 1, pages 773–801.

J. W. Foster, another of Jackson's assistants, reports the results of his explorations along the Michigamme and Menominee rivers to Green Bay. Only one or two observations are of interest to us in the present discussion. Indications of the presence of iron ore on the north side of Lake Michigamme are plentiful. Hornblendic and argillaceous slates form a range bounding the lake on the north, and within the hornblende rocks are beds of quartz. In sec. 1, T. 46 N., R. 30 W., where Republic was afterward located, Foster and his associates crossed an almost perpendicular cliff, composed of such pure specular oxide of iron that its mineral associates were difficult to determine. This pure ore forms the brow of the cliff. Beyond it succeeds a bed of quartzite, containing small specks of ore and large rounded masses of the same material, forming with the quartzite a conglomerate. This is the first mention of a conglomerate associated with the iron rocks, and, strange to relate, this first conglomerate observed was the last one whose significance in the geological history of the region was realized.

The ore was regarded by Foster as continuous with that of Carp River, because the mineralogical and geological associations of the ore in both localities are the same. Other beds of the same ore were observed farther south along the Menominee River. Foster writes (p. 776):

These beds, so far as I have observed, present a marked similarity in mineralogical characters, and derive their origin from common causes, and these were *aqueous*. The jointed structure and waved stratification of some of the beds prove that *igneous* causes have operated, since their deposit, to modify and change their character.

WHITNEY, J. D. Verbal communication to the Boston Society of Natural History. December 19, 1849. Proc. Boston Soc. Nat. Hist., Vol. III, pages 210–213.

J. D. Whitney, who was also associated with Jackson, gave the main results of his work in an address to the Boston Society of Natural History, delivered in December, 1849, anticipating, to some extent, his official reports. As in the case of most other accounts of Lake Superior geology, this one is devoted principally to the copper region. Reference, however, is made to immense deposits of iron ore, existing mainly as a fine-grained, almost chemically pure peroxide of iron. "It occupies about eighty quarter sections of the mineral country, and, at the nearest point, is about 12 miles from the lake." The quantity of the ore is reported to be beyond calculation. "It appears in the form of solid ridges and knobs, evidently of igneous origin, the highest being about 1,100 feet above the level of the lake, and some of them being half a mile long." The speaker exhibited to the society a specimen of banded jasper and ore. In reply to questions, Whitney declared that no New Red sandstone occurs in any of the region examined by him. Since he had examined the coast of the lake near the Carp and Chocolate rivers, it is evident that he disagreed with Rogers as to the age of the Lake Superior sandstones and conglomerates.

FOSTER, J. W., AND WHITNEY, J. D. Synopsis of the explorations of the geological corps in the Lake Superior land district in the Northern Peninsula of Michigan, under the direction of J. W. Foster and J. D. Whitney, U. S. Geologists. Dated November 5, 1849. 31st Congress, 1st session, 1849–50. Senate Documents, Vol. III, No. 1, pages 605–625. With maps.

After the resignation of Dr. Jackson from the position he held on the Lake Superior Survey, J. W. Foster and J. D. Whitney, his principal assistants, were appointed to succeed him. They were furnished with copies of the field notes of the linear surveyors, in which many ledges of iron-bearing rocks had been located. With the aid of these and their own observations they presented in their first joint report a fairly good general view of the iron district. They also constructed a map which gave the first information we possess of the distribution of the ore-bearing rocks. The report is simply a synopsis; so it is limited to general statements. With reference to the iron region, we quote (pp. 609–610):

> On referring to the map which accompanies this synopsis it will be seen that the iron occurs in a metamorphic formation, bounded by two granite belts—one on the north and the other on the south—and that it is prolonged westerly beyond the Machigämig River. This formation consists of hornblende, talcose, and chlorite slates, with associated beds of hornblende and felspar rocks, evidently trappean in their origin. In that portion of the region drained by Carp and Dead rivers, and even in the head waters of the Escanaba, the trappean rocks rise in irregular knobs and ridges from 100 to 200 feet above the general level of the country, and from 800 to 1,000 feet above the lake level. To the west and south of Machi-gummi (or Big Lake) the ridges are less abrupt, and there are some townships where there is scarcely a single exposure of the rock in place.

A description of the ores is given, their banded character is noted, and the great abundance of good ore in the region is emphasized. Nothing else of interest concerning the iron region is given in the synopsis.

On the map the color for the metamorphic rocks of the Azoic system is made to cover a large area of country which we now know to be underlain by older rocks. The metamorphic series included the iron-bearing rocks, but besides these it embraced also the "green-schists" north of the iron belt proper, and many hornblende-schists and mica-schists southeast of Lake Michigamme. In the metamorphic area four colors are used to distinguish the four rocks, quartz, saccharoidal limestone, trappean rocks, and the undifferentiated schistose series. At the mouth of the Carp River there is mapped a small area of sandstone, belonging at the base of the Silurian system. The quartz is in ranges, beginning as two ridges at the lake shore on both sides of the Carp River, uniting into one about 5 miles inland, and continuing as a single ridge to Teal Lake and 2 miles beyond. The saccharoidal limestone is represented as several narrow bands occurring along the north sides of the eastern quartz ridges. Presque Isle is colored for basalt, which.

like the granite north and south of the metamorphic belt, is regarded as younger than the metamorphic rocks.

This map, which from the necessities of the case was very general, served as a good basis for the more detailed maps published later.

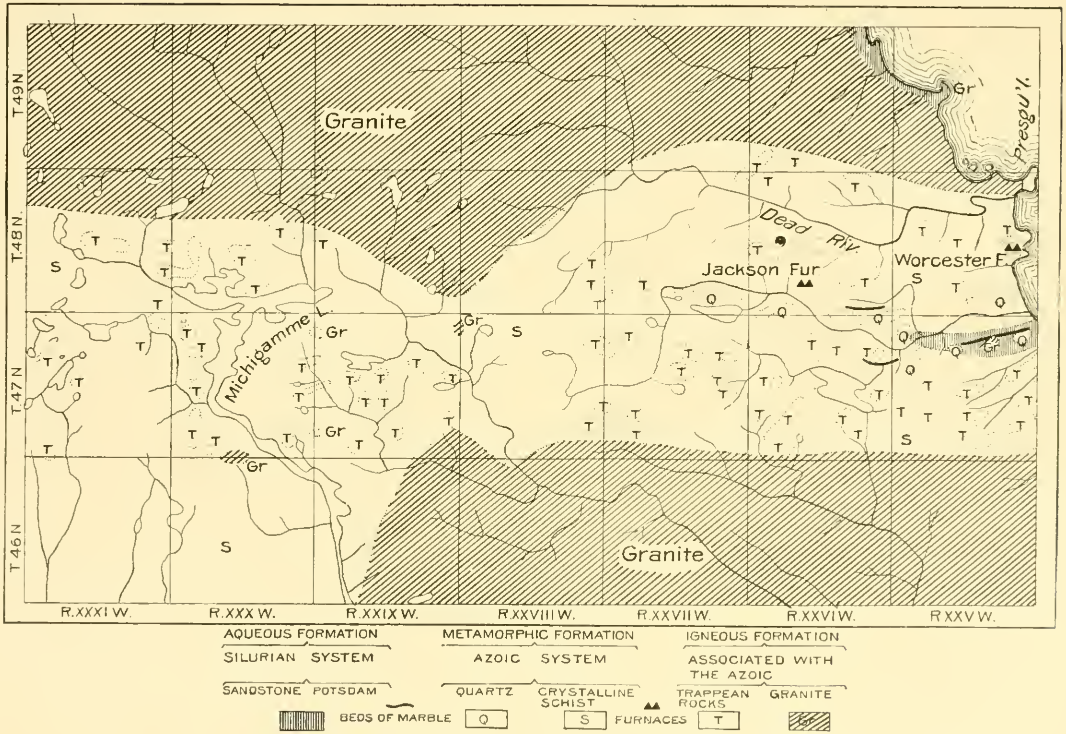
1851.

FOSTER, J. W., AND WHITNEY, J. D. On the different systems of elevation which have given configuration to North America, with an attempt to identify them with those of Europe. Proc. Am. Ass. Adv. Sci., Vol. V, 1851, pages 136–138.

In the following year the same authors published a general paper, in which three "grand systems of elevation" are described as having determined the outlines of North America. The first of these is the "Lake Superior system," which ended immediately before the deposition of the Potsdam sandstone. The culminating points of this pre-Potsdam continent were in the Lake Superior district. It "stretched out in a long and narrow belt of land, with here and there a detached island, like that of the iron region of Missouri or that of Carp River." Its longest direction was east and west.

FOSTER, J. W., AND WHITNEY, J. D. On the Azoic system as developed in the Lake Superior land district. (Abstract.) Proc. Am. Ass. Adv. Sci., Vol. V, 1851, pages 4–7.

This paper is an abstract of the well-known report referred to below. In it the authors refer to the existence in the Lake Superior region of a series of gneisses, schists, quartzites, marbles, and iron ores, lying unconformably below the Potsdam sandstone. Most of the rocks are regarded as metamorphosed sediments that have been changed from the original sandstone into subcrystalline masses that have lost nearly all traces of their stratification. They have been subjected to the most violent dislocations, appearing now as vertical beds or in the form of folds, compressed and in some cases overturned. With these are associated flows, dikes, and bosses of eruptive rocks, to whose existence the metamorphism of the sediments is ascribed. Between this system of rocks and the overlying Potsdam sandstone there is a clear and well-defined line of demarcation. In the



PORTION OF FOSTER AND WHITNEY'S MAP OF THE LAKE SUPERIOR LAND DISTRICT.

rocks below this line are evidences of intense and long-continued igneous agency, and in those above it proofs of comparative tranquillity and repose. These pre-Potsdam rocks occupy an almost continuous belt along the north shore of Lake Superior, and are extensively developed in the southern shore, forming the watershed between the respective river systems of Lake Superior, Lake Michigan, and the Mississippi. The unconformable superposition of the Potsdam sandstone of the Silurian system upon the quartzites of the Azoic system was seen near Carp River, where the last-named rocks occur in ripple-marked beds standing nearly vertical, while the sandstone lies around it in nearly horizontal beds.

The Azoic series was characterized by immense deposits of iron ore, and the Silurian strata by deposits of copper. Near Teal Lake is a high hill composed of alternating layers of jasper and iron ore that are curiously contorted and plicated.

It is impossible to form a correct notion of the thickness of the Azoic series. If measured across the edges of the strata, we should have a thickness greater than that of the whole fossiliferous series. The strata, however, are plicated and folded, so that in measuring across their edges the observer is passing over a repetition rather than a succession of beds.

Foster, J. W., and Whitney, J. D. Report on the geology and topography of the Lake Superior land district. Part II. The iron region, together with the general geology. Dated November 12, 1851. 32d Congress, special session, 1851. Senate Documents, Vol. III, No. 4. 406 pages. With plates and maps. Abstract in Bull. Soc. Géol. France, 1850, pages 89–100.

A little later in the same year Foster and Whitney published the report which sums up all the information concerning the geology of the Lake Superior region gathered by the authors during their four years' connection with the survey of the Chippewa land district, first as assistants of Dr. Jackson, and during the last two years as the geologists in charge of the survey. In this report the authors present an account of the geology of the entire Upper Peninsula of Michigan. For the first time we here learn of the general relations to one another of the various rock systems in this region, and obtain the first definite information with respect to the detailed geology of the iron-producing district. Although imprinted with "The Iron Region" on its title-page, the description of the iron region proper occupies only about 95 pages of the report.

The map accompanying the report is in general like that published with the authors' earlier report (Pl. II), though the colors have been changed. Presque Isle has for some reason been colored as granite, and "basalt" has been left out of the scheme of colors. There are a few other differences in the two maps, but in the main they are identical.

The report is introduced by a tabular statement of the order of succession of the rocks existing within the limits of the district studied. This table as given by the authors (p. 2) is as follows:

Classification of the rocks.

Formations	Igneous	Of various ages	Plutonic rocks	Granite.
				Syenite.
				Feldspar and quartz rock.
			Trappean or volcanic rocks	Greenstone, or dolerite, porphyry.
				Basalt, amygdaloid.
				Hornblende and serpentine rocks.
				Masses of specular and magnetic oxide of iron.
	Metamorphic	Azoic system	Gneiss, mica, and hornblende slate.	
			Chlorite, talcose, and argillaceous slate.	
			Beds of quartz and saccharoidal marble.	
	Aqueous	Silurian system	Lower	Potsdam sandstone.
				Calciferous sandstone.
				Chazy limestone.
				Bird's-eye limestone.
				Black River limestone.
				Trenton limestone.
				Galena limestone.
				Hudson River group.
			Upper	Clinton group.
				Niagara group.
				Onondaga salt group.
		Devonian system	Upper Helderberg series.	
		Drift system	Beds of sand, clay, and gravel, rudely stratified.	
			Transported blocks of granite, greenstone, etc.	
		Alluvial deposits	Sand and pebble beaches, marshes, flats, hooks, spits, dunes, etc.	

Of these various divisions of rocks there are present in the region with which we are now concerned the following: the Potsdam sandstone of

Silurian age, all the members of the Azoic system, all the members of the Volcanic series except the basalts and amygdaloids, and representatives of all the Plutonic rocks.

The oldest class of igneous products consists of hornblende and feldspar rocks and serpentine rocks, and may be regarded as contemporary with the Azoic system. Next in order are the granites and syenites, which are intermediate in age between the Azoic and Silurian systems. These are traversed by at least two systems of greenstone dikes, which are anterior to the purely sedimentary deposits. * * *

Below all the fossiliferous groups of this region there is a class of rocks consisting of various crystalline schists, beds of quartz, and saccharoidal marble, more or less metamorphosed, which we denominate the Azoic system. This term was first applied by Murchison and De Verneuil to designate those crystalline masses which preceded the Paleozoic strata. In it they include not only gneiss but the granitic and plutonic rocks by which it has been invaded. We adopt the term, but limit its significance to those rocks which were detrital in their origin, and which were supposed to have been formed before the dawn of organized existence. (P. 3.)

The rocks described by the authors as comprising the Azoic system include "gneiss, hornblende, chlorite, talcose, and argillaceous slates, interstratified with beds of quartz, saccharoidal marble, and immense deposits of specular and magnetic oxide of iron." Most of these rocks are regarded as metamorphosed sediments that have been altered by intrusions of trap, basalt, and serpentine, which occur cutting through the sediments as dikes, interleaved with them as sheets, or protruding through them as bosses. The rocks are contorted. They rarely exhibit the characteristics of sediments, but the evidences of their metamorphic origin are plain, since they become more and more crystalline as the great "lines of igneous outburst" are approached. "Gneiss generally flanks the granite, succeeded by dark masses of hornblende with numerous joints, but obscure lines of bedding, which often graduates into hornblende slate or chlorite slate as we recede from the purely igneous products" (p. 14). In the vicinity of the settlement of Marquette "an epitome of nearly the whole geology of the district" may be observed. Here the authors noted the existence of two quartzite ridges, one on each side of the Carp River. These unite farther westward and form a single ridge that extends beyond Teal Lake. The horizontal Potsdam sandstone is described as abutting against the quartzite, and the latter rock is mentioned as containing fragments of slate and jasper, and hence as being younger than these rocks. Granite is said to have intruded the quartzite of the southern ridge, causing great dislocations in its beds, and metamorphosing it to such an extent as to destroy its bedding planes. Siliceous slates and marbles are interstratified with the quartzites near the lake. North of the quartzite range the country as far north as the Dead River is underlain by chlorite-slates and talcose slates, intersected by three east-and-west belts of igneous rocks, many of which are thought to occur as sheets. "Many of the slates appear to be composed of pulverulent greenstone, as though they might originally have been ejected as an ash and subsequently deposited as a sediment, and pass by imperceptible gradations from a highly fissile to a highly compact state" (p. 16). This is the first expression of the view that some of the greenstone-schists of the region were originally volcanic ashes, although the illustrations offered are not always of the rocks which were later shown to be tuffs, and the processes by which the ashes were made were not conceived as the same in nature as we now regard them.

Where the Azoic slates and the overlying Potsdam sandstone are in contact, the latter may plainly be seen to be the younger rock. At L'Anse (which is at the head of Keweenaw Bay and outside of our district) there is an unconformable superposition of the sandstones and the slates. The authors picture this and describe it in some detail as of great importance.

This section is exceedingly instructive, inasmuch as it enables us to draw a line of demarcation between two formations, different in age and external characters. While the newer formation—the Potsdam sandstone—is but slightly if at all disturbed, and little changed by metamorphism, the older or Azoic slates are contorted and folded into numerous arches, and in several places invaded by igneous rocks. Their structure has been changed from granular to subcrystalline, and the whole mass is intersected by numerous planes of lamination. (P. 19.)

The granite of the Azoic was found to form many of the points of the lake north of Little Presque Isle, and to occur inland in rounded, dome-like hills. Everywhere this granite is cut by "powerful" dikes of greenstone and veins of quartz.

In describing a section from the shore of Lake Superior across Teal Lake to the mouth of the Escanaba River, the authors give many details as to the occurrence of beds of conglomerate, slates, etc. On the line between secs. 29 and 32, T. 47 N., R. 26 W., near where the village of Palmer is now situated, a large exposure of conglomerate was found which "is made up of coarse blocks of various sorts which belong to the neighboring trappean and slaty beds, and are of very considerable dimensions. Among them we recognized not only fragments of the rock associated with the iron, but masses of the iron itself, and of the banded and jaspery varieties." This is evidently the description of an exposure of Upper Marquette basal conglomerate. The authors regard it, however, as a friction conglomerate, whose origin is connected with the "eruption" of the adjacent granite, i. e., the granite to the south. The ore deposits are older than the conglomerate, because they yielded fragments to the latter. But, since these and other fragments were cemented by ferruginous material, it was presumed that "emanations of metallic matter must still have been issuing from beneath" when the conglomerate was formed (p. 41). The relations existing between the granite and the Azoic slates are thought to be those of an intrusive rock to an intruded series. The hornblende-slates near the southeast corner of sec. 25, T. 47 N., R. 27 W., for instance, are penetrated by a wedge of granite, "shooting out in ramifying branches." Such are, indeed, the relations of the granite to these hornblende-slates. The authors did not realize, however, that these hornblende-slates are older than many of the other members of their Azoic series.

From the quotations that have been given it is seen that Foster and Whitney regarded as present in this region two series of sedimentary rocks, the Potsdam representing the Silurian, and the Azoic a pre-Silurian series. The former were shown to be much younger than the Azoic rocks, which are much metamorphosed. The Azoic series alone is cut by dikes of greenstone and by granite; hence both these rocks are younger than the Azoic, but not so young as the Potsdam. In the Azoic occur the ore beds.

These ore beds were found principally in a belt of crystalline schists and intercalated trappean rocks, bounded on each side by a belt of granite. Many occurrences of the ore were located in the present Marquette district, and a large number of the occurrences are described at some length. In some of these exposures dark quartzites are associated with the ores, and the fragmental rock is impregnated with the oxide. This observation leads the authors to conclude that the diffusion of ore through the rocks must be ascribed to some general cause quite independent of the nature of the rock itself. Many descriptions of now famous ore bodies are given. It is frequently asserted that the ore beds are associated with the greenstone dikes, and that the other rocks associated with the ores are saturated with emanations of iron oxide. In secs. 10 and 11, T. 47 N., R. 27 W., in the vicinity of the present city of Ishpeming, large deposits of almost pure ore were discovered. Here the ore "exhibits many of the characters of an igneous eruptive rock, and can not be regarded in any other light than as a huge lenticular mass, which has been elevated to its present position from beneath while in a semifluid state, exactly in the same way as the trappean ridges which accompany it and which it so strikingly resembles in general outline and position." After discussing the various theories that might be offered to explain the existence of ore and jasper in the forms noted in the region, the authors conclude with a résumé of their opinions with respect to the origin of the Azoic rocks in general and the ore beds in particular. We quote the résumé entire (p. 69):

We may conceive that the various rocks of the Azoic series were originally deposited in a nearly horizontal position, at a period prior to the appearance of organic life upon the earth; that these stratified deposits were composed, for the most part, of finely comminuted materials, principally siliceous and argillaceous, in some cases consisting of almost pure silex, like the purest portion of the Potsdam sandstone which was afterwards deposited upon these strata.

During the deposition of these strata, at various intervals, sheets of plastic mineral matter were poured forth from below and spread out upon the surface of the preexisting strata. These igneous rocks are exceedingly compact and uniform in their texture, which would seem to indicate that they were under heavy pressure, probably at the bottom of a deep ocean. The same depth of water is also inferred from the comparative absence of ripple-marked surfaces throughout the whole series.

During this period the interior of the earth was the source of constant emanations of iron which appeared at the surface in the form of a plastic mass, in combination with oxygen, or rose in metallic vapors, or as a sublimate, perhaps as a chloride; in the one case it covered over the surface like a lava sheet: in the other it was absorbed into the adjacent rocks or diffused through the strata in process of formation. Besides, a large amount of iron entered into the composition of the igneous rocks of this period, chiefly in combination with silica, as a silicate of the protoxide. Portions of the eruptive masses were occasionally subjected to denudation, and the ferruginous particles were, under the action of violent currents, spread out in thin beds, or swept into some depression of the surface, forming a lenticular mass, upon which the strata were afterwards accumulated.

When the siliceous materials had become impregnated with metallic matter, which may have been scattered more or less uniformly through it, a rearrangement of the siliceous and ferruginous particles in some instances took place, under the action of segregating forces, by which the whole mass assumed a banded structure.

Subsequently, the whole series of beds, slaty, quartzose, ferruginous, and trappean, were elevated and in all probability folded, perhaps at the epoch of the elevation of the granite ranges on the north and south of the ferriferous belt of the Azoic system.

From this quotation we see that while the authors regarded the ore material as igneous, they nevertheless, in order to explain the banded nature of some of the jasper ores, found it necessary to admit the action of segregating forces, and in order to account for the lenticular forms of some of the deposits they made use of the ideas of denudation and deposition. The reason for refusing to accept the theory of a sedimentary origin for the banded ores and jaspers in general is apparent from the following quotation (pp. 67–68):

At first glance this banded structure might be regarded by some as the result of aqueous deposition, by which alternate seams of quartzose and ferruginous matter were spread over each other, and the whole subsequently solidified and welded together by heat; but if we examine the circumstances more closely it will be found more difficult to account for all of the facts under this hypothesis than might at first appear. The extreme tenuity of these bands, which are often no thicker than a sheet of paper, renders the supposition of their analogy to strata highly improbable. In fact, this banded structure in many of the Lake Superior ores—for example, at the Cleveland iron knob—will be hardly apparent to the eye on fresh fracture of a specimen, the weathered surface of which may present a beautiful series of intricate convolutions of alternate bands of bright-red and steel-grey. Besides, on examining this mountain mass we find every portion exhibiting equally fine and equally contorted series of convolutions. If these were really the result of aqueous deposition we should expect from analogy with other deposits of a similar character that some of the layers would be of more considerable thickness than others, and that, supposing the contortions to have been caused by lateral pressure of the plastic mass, in some cases at least the foldings would exhibit a considerable radius of curvature, which is not the case here.

Reference has already been made to the discovery by the authors of great numbers of greenstone dikes in the Azoic schists, and of knobs of greenstone scattered among those of the ores. They find great difficulty in distinguishing between the greenstones of igneous and those of metamorphic origin. "The passage of one into the other, especially in the southern portion of the district, seems in many cases to be gradual, and their general appearance and structure is so much alike that it is often difficult to say where one begins and the other ends." Evidently the authors regard many of these greenstones as forming portions of volcanic flows. They class them with the diorites.

The unconformity at Granite Point between the granite and the sandstone, and that at the Carp River between the latter rock and vertical quartzite, were observed and correctly interpreted.

From 1850 to the appearance of Brooks's report in the Geology of Michigan in 1873 very little additional information was published concerning the relation of ore deposits to their associated rocks in the Marquette district. A number of short papers appeared in this interval, but they treated only of small points in the geology of the region, and none dealt with the relations of the rocks to one another.

1852.

Bigsby, John J. On the physical geography, geology, and commercial resources of Lake Superior. Edinburgh New Philos. Journ., No. 105, July, 1852, pages 55–62.

Bigsby gives a general account of the geology of the Lake Superior region, which is based largely on the reports of the earlier investigators. It contains nothing that had not already been commented upon by others.

1854.

Whitney, J. D. The metallic wealth of the United States. Philadelphia, 1854. H. R. Schoolcraft. 510 pages.

Whitney, in 1854, published a volume containing a few references to the iron ores of Michigan, repeating the statements made in Foster and Whitney's report on the Iron Region. The ores are described as occurring "at intervals in a belt of slates from 6 to 25 miles wide, extending for a distance of 150 miles or more westward into the State of Wisconsin."

1855.

SCHOOLCRAFT, HENRY R. **Observations on the mineralogy and geology of the country embracing the sources of the Mississippi River and the Great Lake basins. Summary narrative of an exploring expedition to the sources of the Mississippi River in 1820. Philadelphia, 1855. Pages 303–362.**

Henry R. Schoolcraft, as geologist to the expedition of 1820 to the sources of the Mississippi, made a report to the Hon. John C. Calhoun, then Secretary of War, giving a brief account of the geology of the region traversed by the exploring party thirty-five years before. In this we find several references to the country with which we are now concerned. The sandstone near Presque Isle and at Granite Point is described as horizontal. The first-named point was recognized as "a headland of serpentine, resting against which is a curious formation of magnesian breccia" (pp. 321–322). Magnetic oxide of iron is reported as occurring in mountain masses in the valley of the Carp River.

1856.

WHITNEY, J. D. **On the occurrence of the ores of iron in the Azoic system. Proc. Am. Ass. Adv. Sci., Vol. IX, 1856, pages 209–216.**

After the publication of the "Report," Whitney spent portions of two seasons in the Lake Superior region, and visited the iron districts of Missouri and northern New York. The author finds a strong analogy existing between the relations of the ores with the rocks associated with them in these two districts and in Scandinavia and the relations of the Marquette ores with their associated rocks. All the facts observed confirm him in the belief that the Lake Superior ores are Azoic. They occur in large quantities, and consist almost uniformly of specular and magnetic oxides. Hydrous ores, carbonates, etc., were not seen in the district, though it is thought possible that they may exist on the borders of the ore deposits, where they may have been affected by the adjacent rocks. The larger deposits are described as lacking the characteristics of veins.

Some of the smaller ones "approach much nearer to segregated veins, and might be classed with them, were they not developed on so large a scale as to render it difficult to conceive of segregation as a sufficient cause for their production" (p. 212). Hence the author declares that there is only one hypothesis that will explain their occurrence. We quote as follows (pp. 212, 213–215):

They are simply parts of the rocky crust of the earth, and, like other igneous rocks, have been poured forth from the interior in the molten or plastic state. No other origin can be assigned to the dome-shaped and conical masses of Lake Superior and Missouri, or to the elongated ridges of the first-named region.

The eruptive origin of the great Lake Superior ore-masses seems also well sustained by the phenomena which they exhibit. They alternate with trappean ridges whose eruptive origin can not be doubted, and which themselves contain so much magnetic oxide disseminated through their mass, as one of their essential ingredients, that they might almost be called ores. These eruptive masses include the largest and purest deposits of ore which are known in the Lake Superior or the Missouri iron regions; but there are other localities in both these districts where the mode of occurrence of the ore is somewhat different and where the evidences of a direct igneous origin are less marked. This class comprehends those lenticular masses of ore which are usually included within gneissoidal rocks, and whose dip and strike coincide with that of the gneiss itself, but whose dimensions are limited. * * * Such beds of ore as these may in some cases be the result of segregating action; but the facts seem rather to indicate that they are made up of the ruins of preexisting igneous masses which have been broken and worn down during the turbulent action which we may suppose to have been preeminently manifested during the Azoic epoch, and then swept away by currents and deposited in the depressions of the sedimentary strata then in process of formation. In confirmation of this hypothesis * * * it may be noticed that the ores occurring in this form and position are less pure than those of decidedly igneous origin, as if they had become more or less mixed with sand during the process of reconstruction, so that they not unfrequently require to be separated from their earthy impurities by washing before they can be advantageously used. Again, it may be observed in the case of some of the ore beds of this class that the bed rock or foot wall is considerably rougher or more irregular in its outline than the hanging wall or roof, as if depositions had taken place upon a surface originally rough and uneven, the upper surface of the ore being considerably smoother and more regular than the lower one, and sometimes separated from the rock by a thin seam of calcareous matter.

There is still another form of deposit which is not unfrequently met with in the Lake Superior region. * * * This consists of a series of quartzose beds of great thickness, and passing gradually into specular iron, which frequently forms bands of nearly pure ore, alternating with bands of quartz more or less mixed with the same substance. * * * Deposits of this character are usually very distinctly bedded. * * * These deposits seem to have been of sedimentary origin, having been originally strata of siliceous sand, which has since been metamorphosed. The iron ore may have been introduced either by the sublimation of metalliferous vapors from below during the deposition of the siliceous particles or by precipitation from a ferriferous solution, in which the stratified rocks were in process of formation.

Rivot, L. E. Voyage au Lac Supérieur. Ann. des Mines, Sér. V, Tome VII, 1855, pages 173–328; Tome X, 1856, pages 365–474.

Rivot, of the École des Mines, Paris, made two visits to the Lake Superior region in the years 1854 and 1855, respectively, with the purpose of studying the geology of the copper rocks, more particularly on Keweenaw Point. In connection with his study he made a general survey of the granitic and the iron-bearing rocks. According to this author, granites associated with gneiss and various schists, quartzite, limestones, slates, and trap form a belt stretching from a point on the lake north of Marquette as far west as the State of Wisconsin. They constitute a metamorphic series, and in them are great beds of iron ore, associated with amphibole-schists. At the Jackson mine the ores are accompanied by trap and by talc-schists and amphibole-schists, in which the "primitive stratification" can still be detected. To the north and south the iron-bearing beds are limited by conglomerates composed of portions of all the rocks noticed in the region, cemented by a ferruginous matrix. The traps associated with the ores are said to be similar to those in the Keweenawan region. They pass into the amphibole-schists, and like these latter are believed to be metamorphic and "not igneous rocks" (p. 413).

All the "metamorphic" rocks are believed to have been sediments which have since their deposition been metamorphosed into crystalline schists and granites, the latter of which in their present position are younger than the traps and sandstone lying upon them. In other words, the granite was apparently regarded as the fused basal portion of a sedimentary series, which, after fusion, intruded the upper beds of the series (p. 231). The granites, schists, traps, and sandstones are, seemingly, all believed to be of

Cambrian age, the discordance between them being explained as due to dislocations caused by the granite. Even the sandstone near Marquette is supposed to have suffered fracturing, etc., through the action of the granite. The unconformity at Granite Point is not referred to specifically.

Later observations have shown that nearly all of Rivot's generalizations regarding the origin of the metamorphic rocks and their relations to one another are erroneous.

1857.

WHITNEY, J. D. Remarks on the Huronian and Laurentian systems of the Canada Geological Survey. Am. Jour. Sci. (2), Vol. XXIII, 1857, pages 305–314.

Whitney, in 1857, published an article which, while it does not treat directly of the Marquette rocks, does so indirectly. The Canadian geologists, as a result of their studies, had come to the conclusion that under the Potsdam of the western Great Lakes there are two great unconformable series of rocks, called by them the Laurentian and the Huronian series. The purpose of Whitney's article is the denial of the existence of two series beneath the Potsdam of the south shore of Lake Superior.

1859.

LESLIE, J. P. The iron manufacturer's guide to the furnaces, forges, and rolling mills of the United States, etc. New York, 1859. Pages 480–489.

This author gives a very generalized account of the ores of Marquette, the descriptions of their geology being taken mainly from the reports of Foster and Whitney and of Rivot. The ores are said to be in a gangue rock, consisting of a mixture of quartz and a silicate of iron, alumina, and lime.

WHITTLESEY, CHARLES. On the origin of the Azoic rocks of Michigan and Wisconsin. Proc. Am. Ass. Adv. Sci., Vol. XIII, 1859, pages 301–308.

Charles Whittlesey, in this article, deals with the Marquette district only as a portion of a larger Azoic area. From the results of chemical analyses of many rock specimens collected from northern Wisconsin and Upper Michigan he concludes that there are two metamorphic series in the Azoic, both older than the Potsdam, one characterized by the presence of the alkalis, sodium and potassium, and the other destitute of these elements. From a careful reading of Whittlesey's article it appears that the author is inclined to doubt the sedimentary and metamorphic origin of the Huronian ores and to advocate an eruptive origin for them, as well as for the schists associated with them.

1861.

HUNT, T. S. On some points in American geology. Am. Jour. Sci. (2), Vol. XXXI, 1861, pages 393–414.

Hunt reviews the conclusions reached by studies in the older rock formations of America, and announces that Mr. Alexander Murray, after an examination of the south shore of Lake Superior, had found that the Marquette ores, together with the quartzites, conglomerates, limestones, slates, and the "great beds of diorite which we are disposed to regard as altered sediments," all belong to the Huronian series as defined by the Canadian survey, and to that portion of it which is equivalent to Murchison's Cambrian in Scotland (p. 394).

WINCHELL, ALEXANDER. First biennial report of the progress of the geological survey of Michigan. Lansing, 1861. 339 pages.

By an act approved February 15, 1859, the State of Michigan decided to finish its geological survey begun under Dr. Houghton. Alexander Winchell was appointed State geologist. He published one report, which is devoted almost exclusively to the geology of the Lower Peninsula. In a few sentences the geology of the Upper Peninsula, as outlined by Foster and Whitney, is described.

This report constitutes about all of the results of the revivified survey. It was evidently abandoned at the opening of the war, and nothing else was done by the State in the way of geological work in the Upper Peninsula until the second survey was established in 1869.

1863.

BIGSBY, J. J. On the Cambrian and Huronian formations. Quart. Jour. Geol. Soc., Vol. XIX, 1863, pages 36–52.

Bigsby correlates the Azoic rocks of the south shore of Lake Superior with the Huronian of Canada. He places in this group not only the schists, slates, quartzites, and limestones, but also "the extraordinary and extensive intermixture of the beds of greenstone and granite which defy description and classification."

1865.

KIMBALL, J. P. On the iron ores of Marquette, Michigan. Am. Jour. Sci. (2), Vol. XXXIX, 1865, pages 290–303.

In the year 1865 Kimball published the most important article on the iron district of Marquette that appeared between the report of Foster and Whitney and that of Brooks. In it the author contradicts Whitney's notion that the Azoic of the Marquette region is nondivisible. Following Hunt, he divides the rocks underlying the Lake Superior sandstone into two series, the Laurentian and the Huronian. He calls attention to the fact that the granites are separated from the Azoic schists by Foster and Whitney on lithological rather than structural grounds, and therefore that the relations of the schists to the granite have not been established upon sufficient data. From his own observations made in the Huron Mountains and elsewhere he concludes that the granites and the associated rocks are metamorphic and indigenous (were formed in their present positions), and are not exogenous (intrusive), as Foster and Whitney declared the granite to be. It is true that Mr. S. W. Hill, working with Foster and Whitney, discovered a granite dike intrusive in slates, and therefore younger than the latter; but Kimball explains this as an independent dike, not in any way connected with the greater masses of granite. On account of the lithological similarity of this rock with the Laurentian granites of Canada, and in accordance with the author's notion as to its origin, the granites and gneisses of the Marquette district are placed in the Laurentian series, which is older than the Huronian.

This conclusion is correct, but the granite is nevertheless intrusive, as Foster and Whitney supposed.

South of the granite and its associated gneisses lie the great greenstone-schist areas of later authors. These are described by Kimball as dark-colored hornblende-schists, which represent the "base of the Azoic or Huronian series." They are separated from the gneisses, so far as we can learn, simply because of the great lithological differences between the two sets of rocks. Following these schists to the south is—

a series of augitic rocks and schists, interstratified with magnesian hydrous rocks and slates, the two kinds of rocks being represented on the one hand by hypersthene, pyroxene, and bedded diorite passing into diorite-slates, and on the other by talcose and chloritic schists. The former character of the rocks prevails to such an extent as to impart to the lower members of the Huronian series a distinctively augitic aspect. The several rocks composing this augitic zone are commonly of a greenish color, and vary in this respect chiefly as to shade, resembling in this particular the lower slate-conglomerate which marks the base of the series in Canada, and from which they seem to differ only in the absence of pebbles and bowlders from the subjacent Laurentian rocks, which there form a distinguishing feature. (P. 294.)

From this quotation it is plain that the author regards these green schists as of sedimentary origin, and as forming the lower division of the Huronian series. South of these are the quartzites, slates, and other plainly fragmental rocks, which "are associated with greenish hornblendic slates and more or less crystalline diorite, and at their base with bands of dolomite, somewhat siliceous and highly altered." Overlying the quartz zone are the ores of the region, associated with talcose, argillaceous, and siliceous schists. These are thought to be the equivalents of the upper slate-conglomerate of the north shore, which is Upper Huronian. The ores are specular schists and conglomerates and earthy red hematites. The conglomerates are described as resting upon diorites and chlorite-schists in some cases, and upon dark quartzites in others. The crystalline rocks of the Huronian are regarded as metamorphic as well as the schists. No "trappean overflows" were observed, as were reported by Foster and Whitney. Thus Kimball seems to place himself alongside Rivot in denying the igneous origin of any of the larger masses of greenstone in the region, while at the same time he acknowledges the igneous nature of the smaller dikes.

In addition to his discussion of the general relations of the Marquette rocks, the author attacks the problem of the genesis of the ores, and declares very strongly in favor of their sedimentary origin. This is the first time any definite statement had been made in contradiction to Foster and Whitney's declaration that the greater portion of the specular jasper is eruptive.

The author describes the entire series of the iron-bearing rocks as occurring in great flexures, with a uniform trend east and west.

The position of the beds of specular iron ore [is] * * * at the top of the Huronian series as developed in the Marquette region, and * * * they are interstratified with talcose and argillaceous schists. Sharing the plications of the entire series, these specular schists, as they may properly be called, are accordingly folded into synclinal basins and anticlinal crests, of which the axes in the case of the former lie below drainage, in the bottoms of the valleys, and in the case of the latter are commonly obliterated through the erosion of elevated outcrops. * * *

The bosses of specular iron, the iron knobs, * * * are the most striking examples of exception to the general effects of denudation already noticed. They are instances of the preservation of the anticlinal crest. * * * (P. 299.)

The ores were observed to be associated with the schists in these folds, and hence they must have been "under the same conditions of deposit and secondary modification" as these latter, which, it is believed, are metamorphosed sediments.

The hard ores of the region are shown to be genuine sediments. We quote the author's own words (pp. 301–302):

Beds of specular conglomerate are of frequent occurrence throughout the iron region of northern Michigan, consisting of a paste of specular peroxyd of iron, through which are disseminated fragments of jasper and rounded pebbles of specular iron ore, which usually differ from the paste in texture, a difference very perceptible among ores of any one class, even within narrow limits of distribution. These conglomerates not unfrequently resemble breccia in the angularity of the jasper fragments which they contain; but the pebbles of specular peroxyd, although sometimes obscure in a matrix of the same material, commonly serve to indicate the detrital origin of these beds. That they are derived from local detritus is evident from the fact that the jasper fragments are not rounded, while the particles of softer specular iron ore are worn but slightly. They seem to be of littoral formation and to have been derived from dismembered and crumbled deposits of successive laminæ of jasper and iron ore, similar to those deposits distinguishable in the bosses of the region. The specular conglomerate invariably exists under circumstances of true bedding, and is traversed by parallel joints splitting the imbedded pebbles. It occurs interstratified with talcose and argillaceous schists quite as regularly as the homogeneous ores. * * * A specular conglomerate, uncontaminated with any considerable portion of jasper, forms the bulk of the schists at present wrought by the Lake Superior mine.

The author concludes his discussion of the origin of the ores by the statement that—

the iron ores of the Huronian series in Michigan are essentially schists and heavy bedded strata, in which none of the phenomena of aqueous deposits formed by precipitation from water on the one hand, or by detrital accumulation on the other, are wanting. They exhibit not only stratification, anticlinal and synclinal folds, but are invariably traversed by systems of joints, and at many points exhibit a perfect slaty cleavage. (P. 302.)

As for the greenstone-schists and greenstone-slates, he declares that they—

are intermediate in composition between clay-slate and hornblende-slate, and together with the talcose and chloritic slates, with which they are interstratified, are probably products of such a decomposition in the wet way of the same crystalline sediments which, entirely or less undecomposed, have gone to form those greenstones which constitute members of the same series. (P. 303.)

This means, we suppose, that the greenstone-schists were deposited as crystallized sediments, and were afterward metamorphosed in the presence of water. The paper concludes (p. 303):

From a stratigraphical point of view, while evidence is elsewhere often obscure, the Huronian greenstone, schists, and iron ores of Northern Michigan, in the absence of close attention to their special chemical conditions, exhibit sedimentary and metamorphic phenomena adequate to render quite untenable, it is believed, the theory of the exotic character of any portion of them.

1866.

Daddow, S. H., and Bannan, Benj. Coal, iron, and oil; or the practical American miner. Pottsville, Pa., 1866, pages 546–550.

In connection with a discussion of the iron ores of the United States, Daddow and Bannan describe those of the Marquette region at some length. The productive magnetic masses of the district are believed to be the result of precipitation. They are said to be uniformly stratified.

The rocks which are intercalated with the ores are of volcanic origin, and though not now reposing in the form of dikes, they are true volcanic rocks, disintegrated by coming in contact with water while in a molten state.

The authors quote a private report by Foster to the Iron Cliffs Mining Company, in which, however, there is nothing recorded new to the literature of the subject. The ores are divided into the magnetites, red hematites, and brown hematites, all of which seem to be regarded as sedimentary in manner of deposition, but as volcanic in origin. Even the conglomerates of the region are explained as volcanic:

> Much of the specular ore contains fragments of angular jasper in the shape of breccia, evidently the disintegrated portions of trappean rocks which were precipitated with the ores when the molten mass was thrown into the surrounding waters, proving that these accumulations of ore-beds and intercalated schist owe their origin to local causes, or that they are not the results of distant formations, but that they are true beds formed by the flow of molten lava, highly impregnated with iron, into the waters that existed around and perhaps over the volcanic vents. (P. 548.)

1868.

Credner, Hermann. Die Gliederung der eozoischen (vorsilurischen) Formationsgruppe Nord-Amerikas. Zeits. gesammt. Naturw., Giebel, Vol. XXXII. 1868, pages 353–405.

Hermann Credner, during his visit to North America, made a rapid examination of the pre-Silurian rocks of Michigan and Minnesota, and announced his conclusions regarding them in two articles, of which the first deals with the general relations of the pre-Silurian formations to one another and to the younger rock series for all the explored parts of the United States and of Canada.

The author agrees with Kimball in dividing the pre-Cambrian rocks of the Marquette district into two divisions. The basal rocks all over upper Michigan he declares to consist of a series of gneisses, mica-schists and hornblende-schists, granites, and syenites, which are included together as the Laurentian series. Above these unconformably are the Huronian beds. The principal rocks of the Laurentian are mica-schists. These are interbedded with granites, syenites, hornblende-schists, and gneisses, the whole forming a conformable series 20,000 feet in thickness. Details are given and localities are described in which the relations between the Laurentian and the overlying Huronian series were made out, but these localities are without the limits of the Marquette area, so they do not directly concern us at the present time. It may be mentioned, however, that at Sturgeon River, in the Menominee district, the author observed a great layer of conglomerate, which he thought was embedded in the gneisses. Largely because of this observation, he concludes that the whole Laurentian series is a bedded one of metamorphosed fragmental sediments.

In the Marquette area the oldest member of the Huronian series is a quartzite impregnated with iron oxide. In the northern portion of the district siliceous hematite replaces the quartzite, and in both portions of the region limestone is the next succeeding rock. Serpentines, chlorite-schists, talc-schists, and diorites are interbedded with the quartzites. This series of rocks, according to the author, was deposited close to the shore-lines, whereas the Menominee series to the south was a deep-sea deposit. The ores of the Marquette district were examined quite closely. They are described as consisting of magnetite, martite, and hematite.

Structurally the Marquette Huronian forms a great synclinal basin made up of minor synclinal and anticlinal folds, of which there are six in the neighborhood of Marquette. Underlying this folded series unconformably is the Laurentian, and above it unconformably is the Lake Superior sandstone.

1869.

CREDNER, HERMANN. Die vorsilurischen Gebilde der "oberen Halbinsel von Michigan" in Nord-Amerika. Zeits. der deutschen geol. Gesellschaft, Vol. XXI, 1869, pages 516–568. With map and three plates of sections.

In the second article Credner gives more specific details concerning the geology of the Upper Peninsula of Michigan. The geology of Smiths Mountain (now Republic Mountain) and of the Negaunee region is fully described. The sequence of rocks in both districts is given as the author saw them, and inferences are drawn from the observations. The schistose greenstones associated with the quartzites and ores are regarded as interbedded chlorite-schists, and the massive greenstones as interleaved diorites. In the vicinity of Negaunee the lowermost beds are quartzites, replaced locally by limestones and interbedded with chlorite-schists, and above these is a schist complex of a white and brown banded quartzite, red jaspers, and hematites, and beds of pure hematite, with two interbedded diorite sheets and a bed of chlorite-schist. The character of the ores is discussed. Limonites replace the hematites locally, as at the Foster mine, and magnetites replace them elsewhere. In some of the mines, as at the Lake Superior and the Cleveland, the ores are closely associated with octahedral crystals resembling magnetite, except that they possess a red streak. The magnetites, hematites, and limonites are believed to represent different stages of development in the alteration of the same mineral substance. The hematite is regarded as an oxidation product of magnetite, as is indicated by the pseudomorphs of the former after the latter mineral in the chlorite-schists. The limonite is hydrated hematite. As for the origin of the magnetite, it is thought possible that this was precipitated from a solution produced by the action of carbonated waters on carbonate of iron, and that the entire cycle of changes from the carbonate to limonite was completed before the beginning of Cambrian time.

The lower portion of the Huronian, represented, according to the author's view, by the "chlorite-schists" north of Marquette, is cut by dikes of diorite, and north of Light-House Point by a dike of red syenite containing fragments of diorite, aphanite, quartzite, chlorite-schist, and hematite. These diorites and the syenites, he declares, are the only eruptive rocks observed by him in the iron-bearing region.

The chlorite-schists referred to are not now regarded as members of the iron-bearing series, so that the liorites and the syenite cutting them are not necessarily younger than the iron series. The syenite dike containing fragments of quartzite and hematite has not been seen by any one but Credner.

A geological map and several geological sections accompany the article.

The work on the Marquette district up to the close of the sixties and the establishment of the geological survey of Michigan had been concerned with the general relations of the rocks to one another and their separation into large groups or series. Foster and Whitney had succeeded in differentiating the pre-Cambrian rocks from later formations, calling the former the Azoic series. The granites associated with the Azoic rocks were claimed to be intrusive into these. The greenstones so abundantly present in the Marquette area were regarded as metamorphic rocks, with the exception of the small, well-defined dike masses, and the jasper ores were thought to be largely eruptive. The ores bedded with conglomerates were recognized as sediments. Hunt added the next important suggestion in the study of the region by declaring the ore-bearing rocks Huronian, and hence younger than certain other portions of the Azoic, which represented the Laurentian. Kimball then made as thorough a study of the Marquette region as the conditions allowed, and reached conclusions directly at variance with those of Foster and Whitney. Kimball found the Azoic divisible into the Laurentian and Huronian, to the latter of which series the ore beds belong. Both the Huronian and the Laurentian series, together with the greenstones in the Huronian, were concluded to be metamorphic, while the granites were thought to represent metamorphosed sediments older than the rest of the Laurentian. This conclusion, of course, was directly opposed to that of Foster and Whitney, who believed the granites to be eruptive. The ores of the Marquette district were likewise thought to be sedimentary exclusively. No evidence of an eruptive origin of the ores was found.

The remainder of the publications on the district, up to the time of the appearance of the abstract of this monograph, were confined largely to the following problems: (1) The divisibility of the "Azoic," (2) the origin of the granites and greenstones, and (3) the origin of the ores. The first problem could not be solved until a very detailed examination of the entire district had been made. The solution of the second problem awaited the introduction of the microscope as a working tool of the geologist. The third problem became the principal bone of contention.

The establishment of the geological survey of Michigan and the appointment of Maj. T. B. Brooks to investigate the iron district were important steps in the solution of the three problems referred to. Since the appearance of Foster and Whitney's report in 1851 almost nothing had been added to our knowledge of the geology of the Marquette district except what had been contributed by Kimball in 1865 and by Credner in 1869. The problems to be solved in the district were so perplexing and the physical difficulties to be overcome in solving them were so enormous that it demanded the aid of the State to enable geologists to study the area with any degree of completeness.

1871.

WINCHELL, ALEXANDER. Report on the progress of the State geological survey of Michigan. Lansing, 1871. 64 pages.

The second State geological survey of Michigan was established in May, 1869, with Alexander Winchell as State geologist. Under its operation several valuable reports were made, and a new era in the history of geological work in the Marquette district was ushered in—an era of activity such as had not been known since the days of Burt, Hubbard, Jackson, and Foster and Whitney.

In his report of progress the State geologist mentions the condition of the work intrusted to his care, and outlines the contents of the proposed volumes intended to be issued by the survey. With relation to the Marquette district, he states that—

the rich masses of magnetic and hematitic ores of iron are found not to be those erupted outbursts which the older geologists were inclined to regard them. They are simply constituents of the system of sedimentary deposits which make up the Huronian system of Michigan. The diorites of the region appear to be equally of sedimentary origin, and are found strictly interstratified with chloritic, silicious, talcose, argillaceous, micaceous, and hematitic schists. * * * (Pp. 26–27.)

A few other references are made to the geology of the Marquette district, and a scheme of superposition for the rocks found there is given; but the same subjects are treated more fully in Brooks's report.

1873.

BROOKS, T. B. Iron-bearing rocks (economic). Geol. Surv. of Michigan, Vol. I, 1869–1873, New York, 1873, Part I. 319 pages. With maps.

In this report the author first gives a history of the development of the iron-ore industry on the Upper Peninsula, and then briefly characterizes the different systems of rocks occurring therein and outlines their distribution. He recognizes the Laurentian, Huronian, Copper-bearing, and Lower Silurian series, and after a few remarks on the topography of the region underlain by the rocks of each series he proceeds to the detailed description of the Marquette area. It is with this portion of his paper that we are most concerned.

The major lithological groups recognized in the Marquette district are the ores; the ferruginous, siliceous, and jaspery schists; the diorites, diorite-schists, and related rocks; the magnesian (chloritic) schists; the quartzites, including conglomerates, breccias, and sandstones; marble, argillite or clay-slates, and related rocks; mica-schists; anthophyllite-schists; and carbonaceous shales.

The ores comprise five varieties, viz: the red specular, including slaty and granular aggregates of martite and magnetite; the magnetic ores; the mixed ores, consisting of interbanded jasper and specular ore; the soft hematites, which are the most ferruginous portions of a limonitic siliceous schist, from which silica was probably removed by thermal waters; and the flag ores, embracing ferruginous schists, in which silicate minerals are often present. These latter are often like the mixed ores, from which they differ principally in geological occurrence.

The diorites and their schists are obscurely bedded rocks, varying in texture from aphanitic to coarse-grained and sometimes porphyritic. They are composed of a nonmagnesian hornblende and a plagioclase. They occur in beds, where they present "in mass precisely the same phenomena as regards stratification as do the accompanying schists and quartzites." In the Laurentian area rocks similar to these occur as dikes and veins, and probably as beds. In the Marquette district the greenstones are abundant and are very closely associated with the iron ores.

The magnesian schists are problematic rocks, consisting largely of talc or chlorite. Their cleavage is distinct, but their bedding planes are obscure. In color these schists vary from grayish to green. They are intercalated with the pure, hard, and mixed ores at most of the mines worked; but in a few of the mines, and in the quartzite ridge north of the outlet of Teal Lake, they form "slate dikes." The author finds it impossible to draw the line between the chloritic schists here considered and certain dioritic schists like those mentioned above. At the Marquette quarries typical chlorite-schists are found bedded with granular diorites.

The quartzites are recognized as occurring in three principal horizons. One of these is near the base of the Huronian, the most important one is just above the hard-ore formation, and the third is near the top of the series.

The first is known as the lower quartzite and the second as the upper quartzite. The lower quartzite is often calcareous, grading in places into a marble. Sometimes it is talcose. Occasionally it is interbedded with argillite. The upper quartzite has none of the characteristics of the lower bed, but on the other hand it is frequently conglomeratic, at times passing into a true conglomerate. The lower bed is rarely, if ever, ferruginous, while the upper one is composed, at several places, of alternate bands of quartz and magnetite sands. The marbles, which are dolomitic in a large measure, are regarded as a phase of the lower quartzite, which they overlie. This marble is usually siliceous, and is filled with crystals of calcite or dolomite that resemble orthoclase in appearance.

The argillites and clay-slates are present in several beds, whose relations to other beds will be mentioned later. These rocks are true slates, and many of them are above the upper quartzite.

The mica-schist group embraces a number of different rocks, whose predominant feature is the possession of a micaceous constituent. Sometimes they are more nearly micaceous quartzites than true schists. The mica-schists often contain crystals of andalusite, seams of black hornblende, and bunches of white quartz. Three horizons of the schists are noted, the most important of which is near the top of the series in the western portion of the district.

The anthophyllite-schist lies immediately below the highest mica-schist horizon. It is a slightly magnetic rock, varying in color from brownish black to dull slate. It shows a tendency, in some places, to pass into limonitic schists, and so may pass into a merchantable ore. Other horizons of the schist are mentioned and their places in the series fixed.

The carbonaceous shale may be a carbonaceous variety of the clay-slate, with which it might appropriately be placed. It contains a large quantity of graphite, which burns off when the rock is heated, and leaves it white.

After characterizing the lithological peculiarities of the rocks found in the district, Brooks describes in detail each of the principal mines worked at the time the survey was made.

Near the Republic mine outcrops of Huronian and Laurentian rocks were seen in such relations to each other that, although no contact of the two series was observed, the author nevertheless concluded that the former series is unconformably upon the latter.

The Republic and Kloman mines are described in more detail than most of the others. The author here discovered the relations of the different formations to one another. He publishes a map of the area around these mines, which is so accurate and comprehensive that the district has served as a type district and a starting point for all geologists who, since Brooks's time, have worked on the Marquette iron range. We quote the author's description of Republic Mountain (formerly Smith's Mountain):

> The numerous outcrops of rock and ore at this mountain, the strong magnetism possessed by three of the beds, the remarkable uniformity in thickness of the several formations, and the bold topographical features presented, all of which were carefully surveyed and are faithfully represented and explained on the accompanying * * * maps and charts, * * * leave but little more to be said in this place regarding the general structure of Republic Mountain.
>
> * * * The ten formations, represented by colors on the map, * * * will now be enumerated, commencing with the lowest, which reposes nonconformably on the Laurentian granites and gneisses.
>
> The lowest bed of the series will be numbered V, for reasons which will hereafter appear. (Pp. 125–126.)

Then follows the enumeration of the beds, which is given here in more concentrated form than appears in the author's report.

At the bottom of the series is a quartzose rock (V), followed above "by a magnetic, bright, banded, siliceous, and chloritic schist" of various colors (VI). "The greenish layers are apparently chloritic, the whitish and grayish are quartz, and the brown and dark gray are siliceous layers of the red and black oxides of iron." Following the schists is a diorite (VII), and above the diorite another magnetic siliceous schist (VIII) like VI. A diorite (IX) again appears overlying VIII, and another schist (X) similar to VI and VIII overlies the diorite. This schist often contains enough iron to make it a fairly rich flag ore. Formation XI is a coarse diorite, schistose in places, and XII is a reddish quartz or jasper-schist. The iron formation

(XIII) lies above the jasper-schist. It consists of beds of mixed ore and jasper, in which the laminæ are contorted and twisted, indicating the presence of larger folds in the formation as a whole. Conglomerates were also seen by the author in portions of this belt. Specular ore, magnetite, and a bed of magnesian schist make up the balance of the iron formation. Above the iron formation is the upper quartzite (XIV), which near the contact with the ores is conglomeratic, and above the quartzite is another bed of diorite (XV), which has some resemblance to the micaceous clay-slate of Spurr Mountain. It will be observed that the author has fairly good evidence here of the existence of an erosion interval between portions of the iron formation and the upper quartzite; but unfortunately he regarded the presence of the conglomerate at the base of the upper quartzite as possessing little significance. This conglomerate is the same as that reported by Foster in 1849. It will be referred to again and again in the present volume, for it is largely on the evidence afforded by the presence of such conglomerates that the Huronian within this district has been divided by later authors into an upper and a lower series.

The outcrops of the above-mentioned formations present on the surface a horseshoe-shaped form, which, taken in connection with the dip of the strata, leaves no doubt as to the structure of Republic Mountain. "It is evidently the southeast end of a synclinal trough, with Smith's Bay in the center, under which, at an unknown depth, all the rocks represented would be found, and in the same order." (P. 129.)

On the opposite side of the Michigamme River from Republic the continuation of the Huronian bands was not found where expected, and so a fault was supposed to exist through the bed of the stream.

The account of the geology of Republic Mountain includes descriptions of Formations V to XV. At the Spurr mine the formations from XVI to XIX were observed as follows: The lowermost (northerly, since the beds here dip south) bed at Spurr Mountain is a clay-slate (XV), followed to the south by a soft, brownish, ferruginous rock (XVI), which may be a decomposed variety of the anthophyllite-schist (XVII) which overlies it. The ferruginous rock is soft and is not found in outcrops at this place, but it is seen in a ledge east of Champion, near the Keystone mine. The anthophyllite-schists are exposed at the Champion furnace, where they lie above the ferruginous schist. Formation XVIII is not seen at Spurr Mountain, but it is found at the west end of Lake Michigamme, where it appears to lie between the anthophyllite-schist (XVII) and the mica-schists (XIX) exposed on the south shore and on the islands of the lake. The bed is a gray quartzite, the supposed third quartzite of the region, to which reference has already been made. The mica-schists are the youngest members of the iron-bearing series, and are very abundantly developed.

With respect to the position of the strata below V the author is not so confident. He thinks that the iron ores and the associated rocks of the Magnetic, Cannon, and Chippewa locations in the vicinity of Republic belong here. These rocks are different from any of those described as occurring in Formations XV–XIX. From their proximity to the Laurentian they are supposed to be the oldest members of the Huronian. They are beds of siliceous ferruginous schists, alternating with chlorite-schists and diorite.

The geological structure in the mines of the western portion of the district is simple. It becomes more complicated in those in the vicinity of Ishpeming and Negaunee. Beyond these towns the iron-bearing horizons are lost. At the Lake Superior mines the ores are in a series of troughs with east-and-west axes. Above and below these are beds of chloritic schists. On the east side of the mine the relations of the rocks are so complicated that the author does not attempt to explain them.

The remarkable features are the great masses of light grayish-green chloritic schist, having a vertical east-and-west cleavage, no discernible bedding planes, and holding small lenticular masses of specular ore, which conform in their strike and dip with this cleavage, and which seem to have no structural connection with the main deposits. They appear like dikes of ore squeezed out of the parent mass, which we may suppose to have been in a comparatively plastic state when the folding took place; or they may have been small beds, contained originally in the chloritic schist, and brought to their present form and condition by the same causes, which produce[d] the cleavage in the schist. (Pp. 139–140.)

In the hanging wall of this mine Brooks found, instead of the usual quartzite, a magnesian schist, similar to the schist associated with the ore.

After the rapid survey of the most important mines is concluded, the author writes as follows (p. 143):

Looking back over the field we have now hastily surveyed, * * * it will be seen that, while there are many irregularities, on the whole the ore basin gradually widens toward the west, from a mere point at the Jackson mine to a width fully 5 miles at the west end of Michigamme Lake, beyond which too little is known to enable us to accurately define its limits. It follows, therefore, that all the Huronian rocks north, east, and south from the Jackson mine are below, or *older than the ore formation* (XIII), and all the rocks to the westward and inside of the ore basin are *younger*, hence above it.

The country southeast of the Jackson mine produces dark-colored, earthy hematite.

I believe these ores all belong to one formation, No. X, in which, up to this time, no merchantable ores, except the Lake Angeline hematite, have been mentioned as occurring. It is at least certain that they are older than Formation XII, which embraces the Lake Superior and Winthrop deposits. (P. 143.)

The Cascade range lies south and east of Negaunee, extending east and west through the southern portion of T. 47 N., R. 26 W. The ores here are jaspery oxides with a "flaggy structure." They are near the Laurentian, and the whole series is overlain by a talcose quartzite, believed by the author to be the equivalent of No. V of the Republic series, and to be a continuation of the same bed that forms the hills north of Teal Lake and becomes calcareous at Morgan furnace. On this supposition the Cascade ores are older than those of Republic, and are the equivalents of the ores of the Magnetic, Cannon, and Chippewa mines. The absence of ores north of the Teal Lake quartzite is thought to require investigation, since the ores of the Cascade range are supposed to be immediately beneath the continuation of this quartzite.

The most prominent of all the formations of the Marquette district is this lower quartzite. It is so uniformly present and at such a constant horizon that an account of its distribution is largely an account of the structure of the entire iron-bearing series.

A brief description * * * of the great geological basin formed by this quartzite, which embraces within its folds the great mass of the Huronian rocks, and nineteen-twentieths of all the ore, will possess interest. Like the ore horizon (XIII), which we saw came to a point at the Jackson mine, and widened to the west, so the opposite croppings of this quartzite converge to the east and come together at the Chocolate Flux quarry [on the shore of Lake Superior]. * * * From this starting point the *south rim* of the basin bears away toward Goose Lake, where some minor folds and low dips make it the surface rock for a large area northeast of the lake. From the south end of the lake west, the formation has a prevailing talcky char. acter, often argillaceous and sometimes conglomeratic; it has a great thickness and strikes west by south. West of the Cascade it seems to assume more the character of a chloritic gneiss and protogine, or at least a well-defined bed of protogine rock occupies the position in which we would expect to find the quartzite.

The *northerly rim*, starting also from the Chocolate quarry, maintains a nearly due-west course, crossing the railroad at Morgan Furnace, * * * passes north of Teal Lake and south of Deer Lake, [is seen] occasionally at various points further west, and last, so far as I know, north of the Spurr Mountain, nearly 40 miles west of Lake Superior. (Pp. 149–150.)

The general geology of the entire district covered by his report is described by Brooks in a chapter on the magnetism of the iron-bearing rocks. This we quote:

Rocks of the four oldest geological epochs yet made out on this continent are represented on the Upper Peninsula of Michigan; two belonging to the Azoic, one to the Lower Silurian, and one between these, of questioned age. The equivalency of these with the Canadian series has not been fully established, but the nomenclature of the Canadian geologists will be employed provisionally.

The Laurentian of the Upper Peninsula is like that of Canada in being largely made up of granitic gneisses, but differs in containing no limestone so far as I have seen, and little, I may say practically no iron ore, and very little disseminated magnetite. Next above the Laurentian, and resting on it nonconformably, are the Huronian or iron-bearing rocks; these are also called by the Canadian geologists "the lower copper-bearing series." This series comprises several plainly stratified beds of iron ore and ferruginous rock, varying in the percentage of metallic iron from 15 to 67 per cent, interstratified with greenish tough rocks, in which the bedding is obscure, which appear to be more or less altered diorites, together with quartzites (which pass into marble), clay-slates, mica-schists, and various obscure magnesian schists. The maximum thickness of the whole in the Marquette region is not far from 5,000 feet.

While the great Huronian area of Canada north of Georgian Bay bears, so far as I am aware, little or no workable iron, and derives its economic importance from its ores of copper, the Marquette series, supposed to be of the same age, are eminently iron-bearing, and have as yet produced no copper. It is doubtful if in the same extent and thickness of rocks, anywhere in the world, there is a larger percentage of iron oxide than in the Marquette series. In the order of relative abundance, so far as made out, the ores are the *flag*, the red *specular* hematites, soft or brown *hematites*, and *magnetites*. These all exist in workable beds, and all as disseminated minerals in rocks usually siliceous. * * * So far there seems to be the greatest concentration of magnetic ores in the Michigamme district of the Marquette region. From this the relative proportion of magnetite seems to decrease as we go east, north, west, and south.

Next younger than the Huronian are the copper-bearing rocks of Keweenaw peninsula, * * * the age of which has led to much controversy. * * * The relations of the copper-bea ing rocks to the Huronian are not fully made out. In tracing the dividing line from Bad River in Wisconsin to Lake Gogebic, Michigan, last fall * * * we found them nearly, if not precisely conformable, but widely different in lithological character * * *.

The next series of rocks in ascending order are the horizontally bedded Lower Silurian sandstones, which skirt the south shore of Lake Superior nearly its whole length, called by Foster, Whitney, and Dr. Rominger, Potsdam, and assigned by the Canadian geologists, under the name St. Mary's, to a later period. * * *

We will now return to the Huronian or highly magnetic series, taking up its structure in some detail. About nineteen lithologically distinct beds or strata make up the series; of these, six and probably seven are so magnetic as to cause considerable variations in the needle. These beds vary from 40 to several hundred feet in thickness, and strike and dip in all directions and at all angles. The prevailing strike, however, is easterly and westerly, and the dip at high angles often vertical. * * * (Pp. 215–218.)

The sequence of the strata in the Marquette series is outlined as follows:

I, II, III, IV are composed of beds of siliceous ferruginous schist, alternating with chloritic schists and diorites, the relations of which have not been fully made out; V is a quartzite, sometimes containing marble and beds of argillite and novaculite; VI, VIII, and X are siliceous ferruginous schists; VII, IX, and XI are dioritic rocks, varying much in character; XIII is the bed which contains all the rich specular and magnetic ore, associated with mixed ore and magnesian schist; XIV is a quartzite, often conglomeratic; XV is argillite or clay-slate; XVI is uncertain; it contains some soft hematite; XVII is anthophyllitic schist, containing iron and manganese; XVIII is doubtful; XIX is mica-schist, containing staurolite, andalusite, and garnets. * * *

These beds appear to be metamorphosed sedimentary strata, having many folds or corrugations, thereby forming in the Marquette region an irregular trough or basin, which, commencing on the shore of Lake Superior, extends west more than 40 miles. * * * While some of the beds present lithological characters so constant that they can be identified wherever seen, others undergo great changes. Marble passes into quartzite, which in turn graduates into novaculite; diorites, almost porphyritic, are the equivalents of soft magnesian schists. * * * The total thickness of the whole series in the Marquette region is least at Lake Superior, where only the lower beds exist, and greatest at Lake Michigamme, where the whole nineteen are apparently present, and may have an aggregate thickness of 5,000 feet. (Pp. 83–84.)

With regard to the *associations of the various ores*, it may be said that magnetic and specular ores are often found together, as are also the specular and soft hematite ores; but so far the magnetites and hematites have not been found in juxtaposition. If we suppose all our ores to have once been magnetic, and that the red specular was first derived from the magnetite, and the hydrated oxide (soft hematites) in turn from it, we have an hypothesis which best explains many facts, and which will be of use to the explorer. (Pp. 220–221.)

Besides the magnetic charts, three geological maps pertaining to the Marquette district accompany the report. One represents the general geology of the entire Upper Peninsula (see Pl. III), the second is a detailed map of the whole of the Marquette district, and the third is a large-scale map of Republic Mountain. The northern boundary of the iron rocks is placed much farther north by Brooks than it is in this monograph. Brooks included with his Huronian all of the greenstone-schists north of the iron-bearing rocks, and made their contact with the granite the boundary line between the Marquette iron-bearing rocks and the Laurentian. These schists are Group XIII of Brooks's series, and are regarded by him as high in the series. In this volume they are placed below the whole of the iron series.

Several appendixes are added to Brooks's report and published as Vol. II of the Michigan State survey. Some of them are of great scientific interest. Those of Julien and of Charles E. Wright are the first articles in which the lithological features of the Marquette rocks are described in detail.

JULIEN, ALEXIS A. Lithological descriptions, etc., of 259 specimens of the Huronian and Laurentian rocks of the Upper Peninsula. Geol. Surv. of Michigan, 1869–1873, Appendix A, Vol. II, New York, 1873, 197 pages.

The aim of Julien's report, in the words of its author, as given in the letter of transmittal addressed to Brooks, "is but a provisional one, viz, to give a somewhat popular description of such characteristics of the common varieties [of the Marquette rocks] as may be easily discerned (with a very few exceptions) in the field, * * * and also to propose a temporary nomenclature and classification for the present use of your report."

The rocks are divided into three great divisions, the simple rocks, the mixed crystalline rocks, and the fragmental rocks. The first division is subdivided into calcareous, quartzose, silicate, iron ore, and carbonaceous rocks, and the mixed crystalline rocks into older and younger feldspathic rocks. The former includes granites, gneisses, mica-schists, greenstones, and trappean diorites, and the latter only diorite-aphanite. The fragmental rocks examined were sandstone-schists.

The greenstones comprise diorite, amphibolite, serpentine, chloritic diorite, diorite-wacke, diorite-schist, amphibole-schist, diorite-greenstone, micaceous greenstone-schist, schalstone, aphanite-schist, and chlorite-potstone. All these varieties are supposed to be derivatives of diorite, and none of them were believed to be derived from diabase. "I am decidedly of the opinion," writes Julien, "that no augite occurs in these rocks, and that there is no diabase whatever in this region" (p. 42). The trappean diorite and the diorite-aphanite are intrusive basic rocks, but according to the author they contain no pyroxene.

The simple silicate rocks determined are amphibolite, amphibole-schist, hornblende-schist, anthophyllite-schist, chloritic schist, argillite, and talcose schist. The argillites are placed in this division rather than among the fragmental rocks because some of them were believed to be composed of greenstone (diorite) ash.

A few mineralogical notes close the report.

Brooks, T. B., and Julien, A. A. Catalogue of the Michigan State collection of the Huronian rocks and associated ores. Geol. Surv. of Michigan, 1869–1873, Appendix B, Vol. II, New York, 1873, pages 199–212.

The second appendix is a classified list of the collections of Michigan rocks distributed by the State to certain colleges and institutions in this country and abroad.

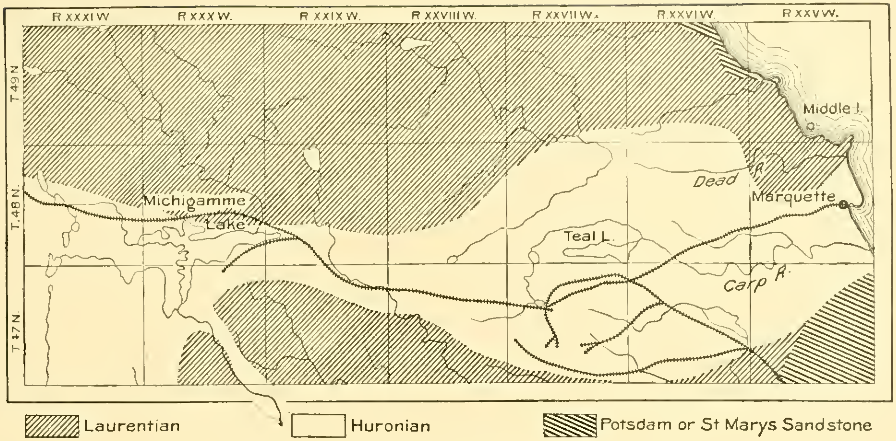


FIG. 1.—PORTION OF BROOKS'S MAP OF THE UPPER PENINSULA OF MICHIGAN.

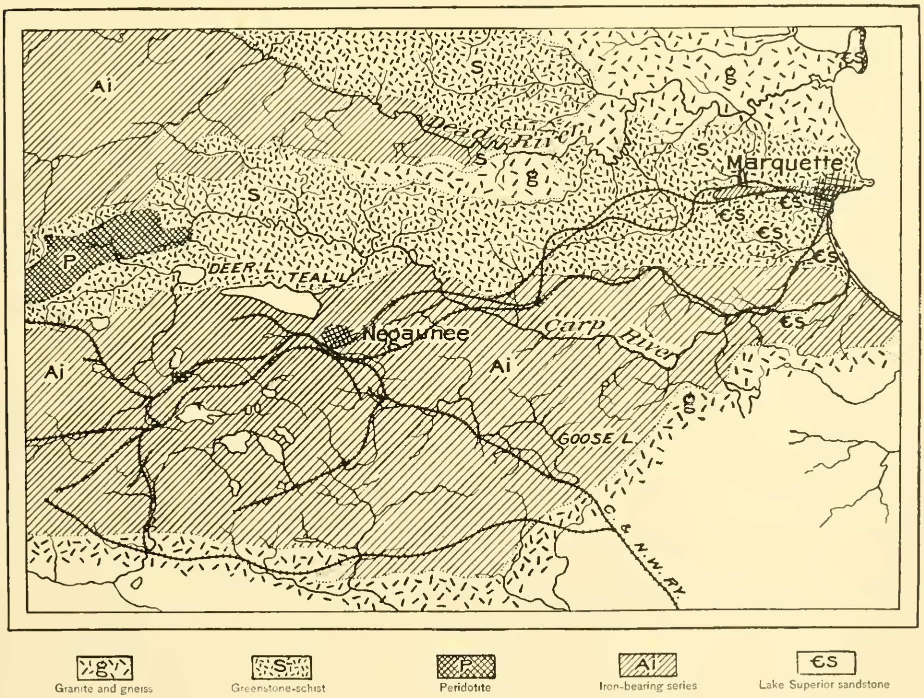


FIG. 2.—IRVING'S OUTLINE MAP OF THE MARQUETTE DISTRICT.

WRIGHT, CHARLES E. Microscopic determinations and descriptions of 78 specimens of Huronian rocks and ores. Geol. Surv. of Michigan, 1869–1873, Appendix C, Vol. II, New York, 1873, pages 213–231.

In the third appendix Wright classifies for the first time the rocks of the Marquette area in accordance with their microscopical features. Diorites, diorite-schists, chlorite-schists, hornblende-schists, anthophyllite-schists, quartzites, argillites, and various specimens of ores were submitted to the author, who describes them briefly, but with sufficient fullness to make their recognition possible. Wright surmises that diabase may exist among the greenstones of the region.

HOUGHTON, DOUGLASS. Remarks on rocks between Chocolate River and Granite Point, embracing Marquette Harbor. From unpublished MSS. Geol. Surv. of Michigan, 1869–1873, Appendix E, Vol. II, New York, 1873, pages 239–246.

These notes, which comprise the fifth appendix to Brooks's report, possess only a historical value because of the long delay in their publication. It is unnecessary to refer to them further than to state that the author discovered and figured the unconformity between the Lake Superior sandstone and the quartzite near the mouth of the Carp River.

BROOKS, T. B. The lamination, plication, and faulting of banded ore and jasper (mixed ore), with illustrations (figs. 19 to 29). Geol. Surv. of Michigan, 1869–1873, Appendix K, Vol. II, pages 283–292.

The final appendix is one added by Brooks himself. It comprises eleven figures of banded jasper and ore, with their explanation. Its object is to illustrate the way in which the original parallel lamination of the ore and jasper may be entirely obliterated, and may be replaced by a mechanical brecciated structure. The figures are very interesting and suggestive.

ROMINGER, C. Paleozoic rocks. Geol. Surv. of Michigan, 1869–1873, Vol. I, Part III, New York, 1873, 104 pages.

In the same volume of the Michigan survey in which Brooks's report occurs is one by Rominger on the Paleozoic rocks of the Upper Peninsula. The only portions of this report in which we are now interested are those relating to the unconformity between the Huronian and the Potsdam beds near Marquette, and the description of the Presque Isle rocks.

The unconformity mentioned by Foster and Whitney as occurring near the Carp River is described by Rominger in these words (p. 90):

We find here vertically erected white quartzite beds of the Huronian group, projecting into the lake, which have preserved their granular sandstone structure and are distinctly ripple-marked. They are surrounded by brown sandstone and conglomerate ledges, horizontally abutting against them. The sandstones, which are of very irregular discordant stratification, closely adapt themselves to all inequalities of the cliffs, which exhibit under the sandstone covering a rounded, water-worn surface, indicating their long exposure before they were enveloped by the sandstones.

He describes Presque Isle as formed by—

a protrusion of peculiar rock masses, differing considerably from the rock beds of the Huronian group in the vicinity. Lowest is a black, unstratified, semicrystalline magnesian rock, resembling a half-decomposed basalt or a highly ferruginous serpentine. It forms considerable cliffs at the north end of the spur; more to the south we find it overlaid by a more light-colored, once stratified rock, which is involved in the upheaval, with its ledges bent and broken up in great confusion. * * * The principal rock mass, which is found in all forms, from compact crystalline to an absorbent, earthy condition, is chemically a dolomite. * * *

On the south portion of Presque Isle this dolomite is unconformably overlaid by a conglomerate and succeeding sandstone layers, which are identical with the sandstones of the Marquette quarries. The sandstone strata some distance off from the protrusive rocks [the "dolomites"] are nearly horizontal. In immediate contact with them they have a considerable dip, corresponding to the convexity of the underlying surface. It is possible that the strata were slightly uplifted after their deposition, but I am more inclined to explain the existing dip as an adaptation of the sediments to the surface on which they were deposited. The conglomerate beds at the base are 5 feet thick and contain numerous fragments of the underlying dolomitic rocks and of their inclosed jaspery minerals. (P. 92.)

On Light-House Point the author noted that the bands of diorite, which had been so frequently mentioned by earlier authors as interstratified with the Huronian schists, "are connected among themselves by transverse bands cutting across the strata of the schists," and therefore the diorites are believed to be intrusive (p. 93).

Rominger thus makes the Presque Isle dolomitic rock older than the sandstones associated with it, and the green schists of Light-House Point he regards as intrusive.

Again, following the reports of the Michigan survey, there is a dearth of articles of a general nature on the Marquette rocks. This period of little activity was brought to an end by the publications of the Wisconsin survey in 1879. A number of volumes, in which reference is made to the geology of the Marquette district, were published in this interval, but the statements in them are largely based on the work of others than their authors. A number of short articles also appeared during this time, but they are devoted mainly to the elucidation of special points in the discussion.

1874.

DANA, J. D. Manual of geology. 2d ed., New York, 1874.

In the second edition of his Manual, Professor Dana makes the same statements regarding the origin of the Marquette ores and of the Archean rocks in general as were made in 1865, when he accepted Foster and Whitney's views. With regard to the geological position of the beds, we find that the author has discovered evidence enough for separating the Azoic (now Archean) beds into two series, the Laurentian and the Huronian, but he is not satisfied that the Marquette ores are not members of the first series. On one page (p. 151) he places them with the Laurentian, and on another page (p. 159) with the Huronian, mainly in deference to the opinions of the Lake Superior geologists, who emphasized the lithological differences between the acid schists of the Laurentian and the basic ones of the Huronian. "The evidence as to age is far from conclusive," writes the author. "The extent of the beds of iron ore affords some reason for believing, as shown by Whitney, that they are true Laurentian" (p. 159).

Exactly the same statements concerning the Marquette region are given in the third edition of the Manual, published in 1880.

NEWBERRY, J. S. The iron resources of the United States. The International Review, Vol. I, 1874, pages 754–780.

This author gives a general review of the iron resources of the United States, and refers to the Marquette ores as magnetites, hematites, and hydrated sesquioxides, inclosed in Huronian terranes. The "ore beds were once horizontal strata, deposited in conformity with many other stratified sediments, but they are folded and broken in such a way that their true nature was for a long while misunderstood" (p. 758). The distribution of the ore bodies is believed to be "dependent upon the immense surface erosion which this region has suffered. This has removed by far the greatest part of the ore that originally existed here, leaving it only where it formed masses of unusual magnitude and solidity, which have resisted the erosive action, or where, in synclinal troughs, it has been beyond the reach of the glaciers, which have ground off all the more elevated portions" (p. 758).

In this view the ores are manifestly supposed to have existed as an extensive bed over the Marquette Huronian area, of which the present ore bodies are the remnants. This we now know to be contrary to the facts. The irregular distribution of the ore bodies in the region is not the result of erosion, but is the result of the action of secondary processes under especially favorable conditions, prevailing only here and there throughout the district.

1875.

PUMPELLY, RAPHAEL. On pseudomorphs of chlorite after garnet at the Spurr Mountain iron mine, Lake Superior. Am. Jour. Sci. (3), Vol. X, 1875, pages 17–21. With plate.

This article is of a mineralogical nature. In it the author describes the well-known chlorite pseudomorphs of garnet occurring in the chlorite-schist overlying the ore bed at the Spurr mine. The chlorite-schist is composed of minute flakes and needles of chlorite, through which are scattered small octahedra of magnetite and the garnet pseudomorphs. From the result of his investigation of the rock the author infers that the schist was originally an argillaceous limestone or marl that was changed by metamorphic processes into its present form.

WHITTLESEY, CHARLES. Physical geology of Lake Superior. Proc. Am. Ass. Adv. Sci., Vol. XXIV, 1875, pages 60–72. With map.

Whittlesey denies the existence of a true Laurentian series in Michigan. The granitic rocks, heretofore regarded as belonging in this series, are eruptive, as shown by their analyses. In some instances in the Marquette region, the author writes, these eruptives "have pushed up through the Huronian beds, cutting them and the Potsdam at the same time," but he does not give particulars. The ores of the Marquette area and their associated rocks are believed to belong in the Huronian system, which in Michigan and in Canada possess a remarkable similarity. Incidentally the author gives a sketch of the relations between the trap and sandstone at Presque Isle. The former is represented as penetrating the sandstone and producing on the contact a friction conglomerate.

1876.

BROOKS, T. B. On the youngest Huronian rocks south of Lake Superior, and the age of the copper-bearing series. Am Jour. Sci. (3), Vol. XI, 1876, pages 206–211.

In his Michigan report on the iron-bearing series Brooks places the granites with the gneisses of the Upper Peninsula, and regards them all as belonging with the Laurentian, unconformably beneath the Huronian beds.

In 1876, however, in an article dealing more particularly with the Menominee iron district, the same author notes the discovery of granites cutting micaceous and hornblendic schists similar to those in Formation XIX of the Marquette series. If this formation is the topmost portion of the series, as is supposed, the granite must be Huronian. Moreover, the Huronian series is so different lithologically from the copper-bearing series, and the movements that have been undergone by the two series are so different in amount, that it is necessary to conclude that the copper-bearing series is much younger than the Huronian. "We are therefore justified, I think, in regarding the copper-bearing rocks of Lake Superior as a distinct and independent series, marking a definite geological period which separates the Silurian from the Huronian ages." For this series the author proposes the name "Keweenawian," unaware that Hunt[1] two years earlier had reached the same conclusion and had proposed as the name of the series "Keweenian."

This article, though dealing almost exclusively with a region outside the Marquette area, is of interest, since it contains the first definite statement

[1] Trans. Am. Inst. Min. Eng., Vol. I pp. 339–341.

that the Huronian of Michigan, including of course the Marquette Huronian, is a distinct and older series than that to which the copper-bearing rocks belong.

The question of the age of the Keweenawan was contested long and bitterly, and it was finally decided to the satisfaction of most geologists that the view suggested by Hunt and Brooks is the correct one. The copper-bearing rocks are younger than the iron-bearing series of the Upper Peninsula and entirely distinct from them. The literature of this subject need not be referred to again. The subject is mentioned here merely to simplify and make clearer the geology of the Marquette rocks, which in this district had been included with the copper-bearing series as forming a portion of Foster and Whitney's Azoic.

BROOKS, T. B. Classified list of rocks observed in the Huronian series south of Lake Superior, with remarks on their abundance, transitions, and geographical distribution; also a tabular presentation of the sequence of the beds, with an hypothesis of equivalency. Am. Jour. Sci. (3), Vol. XII, 1876, pages 194–204.

In another article in the same year Brooks gives a revised classification of Huronian rocks, based on microscopic examinations of thin sections made by A. Wichmann, Charles E. Wright, and Frank Rutley. The classification includes Huronian rocks from the then known iron-bearing areas of this age in Michigan and Wisconsin. We are concerned only with the Marquette series. This, exclusive of the youngest observed member (the granite bed), according to the author, has a thickness of not more than 6,000 feet. The sequence of the beds is shown in the following table, in which the italicized names are those of the rocks possessing greatest lithological interest:

LOWER SILURIAN.

Copper series (wanting).

HURONIAN.

XIX. Grayish black *mica-schist*, often *staurolitic*, and holding *andalusite* and garnets; rarely chloritic schist. Quartz in bunches and veins, and hornblende seams, rare. Quartzyte. (?)

Probably soft slate.

XVII. *Anthophyllitic* (?) *schist*, usually magnetic, and containing manganese.

XVI. Banded ochrey porous *quartz*-schist.

XV. Blackish *argillaceous slate*, with imperfect cleavage, rarely micaceous, and sometimes holding garnets.

XIV. Grey arenaceous *quartzite*, often semi-schistose and sometimes micaceous; quartz conglomerate.

XIII. Pure specular *hematite* and *magnetite* ores; ferruginous banded *jaspery* schist, with interstratified beds of *chloritic* and hydromicaceous schists. "Trap dykes" at Washington mine.

XII. Red arenaceous *quartz schist*, banded with *micaceous iron; quartzose limonitic* ores.

XI. *Dioryte, hornblende-schist, chloritic schist*, chloritic-looking *mica schist;* rarely hornblende gneiss.

X. Siliceous *hematitic* and *limonitic* schistose ores, often *manganiferous; siliceous* schists; garnetiferous anthophyllitic (eklogyte) schists; obscure compact chloritic (?) magnetic schists, with conchoidal fracture.

IX. *Hornblendic rock* and related *diorite* and *diabase*, often micaceous.

VIII. Ferruginous *quartzose flags; clay-slate; quartzite;* rarely chloritic and anthophyllitic (?) schist.

VII. *Hornblendic rocks*, with related greenstones. (?)

VI. *Ferruginous quartzose* schist; *clay* and *chloritic* slates.

V. *Quartzite* graduating into *protogine*, with interstratified beds of *dolomitic marble; novaculite;* rarely chloritic and micaceous schist, and dikes of chloritic schist.

Syenite (quartzless), *diorite, diabase, hornblende-schist*, and obscure chloritic slates, conglomeratic *quartzite* and various *quartzose* iron ores. Well-characterized *talc*-schist is found in this horizon only at Marquette.

Nonconformable with Laurentian.

Diabases are recognized as occurring among the greenstones, contrary to the earlier opinion of the author. These rocks, together with the diorites and the related schists, are still regarded as "metamorphic."

Lithologically the division is into (1) fragmental rocks, exclusive of limestone: (2) metamorphic rocks, not calcareous; (3) calcareous rocks; and (4) igneous rocks. Among the fragmental rocks are noted quartz-conglomerates in the middle horizon of the series. The second division includes granite, the gneisses, schists and slates, syenite, diorite, gabbro, diabase, and the pyroxenic, the garnetiferous, the olivinitic, and the chloritic and talcose rocks, besides quartzite, jasper, chert, and the iron ores. The eruptive rocks are the granites, traps, and the hydrous magnesian schistose rocks observed in dike-like masses. Sometimes these latter rocks are believed to have been "formed from the abraded material of the walls of a fault."

Wichmann, Törnebohm, and Zirkel, according to the author, all agree in regarding many of the greenstones as diorites and diabases of eruptive, and not of metamorphic, origin. Among them they would place also many of the dioritic schists and chloritic diorites. The author, however, still regards them as metamorphic, and so includes them with the metamorphic rocks.

1878.

Hunt, T. Sterry. Special report on trap dykes and Azoic rocks of southeastern Pennsylvania. Part 1, Historical introduction. 2d Geol. Surv. of Pennsylvania, E, 1878, 253 pages.

Hunt refers to the Marquette rocks as belonging partly in the author's White Mountain or Montalban series and partly in his Green Mountain or Huronian series. Those belonging to the Montalban are the micaceous and hornblende schists of Brooks's Formation XIX and the granites associated with them (Formation XX). The Huronian rocks underlie the Montalban. In Michigan they include the greenstones, diorites, serpentines, carbonaceous argillites, and porphyries. The author agrees with most of the earlier writers on the district in regarding the greenstones as indigenous, that is, as formed in their present position by the metamorphism of sediments.

1879.

Wright, Charles E. First annual report of the Commissioner of Mineral Statistics of the State of Michigan for 1887–88 and previous years. Marquette, 1879. 229 pages.

In this report Wright briefly sketches the geology of the Upper Peninsula. The author accepts, with some modifications, Brooks's view as to the sequence of rocks in the Marquette district. He believes that there are two metamorphic granites in the district—one Laurentian and the other occupying a position in time between the Marquette or Lower Huronian rocks and the members of the copper-bearing or Upper Huronian series. The greenstones are believed to exist in beds, and to be represented in some places by slates and magnesian schists. Bed X of Brooks is a layer of siliceous ferruginous schists, from which, locally, silica has been removed, leaving deposits of soft ores. These ore bodies are noticed to be in those portions of the series where the disturbance has been greatest. The quartzite and jasper-conglomerates were also observed in many mines forming the hanging walls of the ore bodies, but their significance was not realized by the author any more fully than it was by Brooks. Below Bed V, which is the lowest identified by the latter geologist, Wright places a quartzite and a garnetiferous mica-schist.

The author also reports the discovery of a series of sharp ridges composed of serpentine, marble, magnesian schists, etc., about 3½ miles northeast of Ishpeming. The rocks are similar to those occurring at Presque Isle.

WICHMANN, ARTHUR. A microscopical study of some Huronian clay-slates. Quart. Jour. Geol. Soc., Vol. XXXV, 1879, pages 156–164.

In this paper Wichmann gives a detailed description of the slates of the Marquette district. He divides them into clay-slates, "deposited on the upper strata of quartzite" (forming Bed XV of Brooks and Bed VIII of Credner), and occurring also in the marble series (Bed V of both Brooks and Credner), novaculites, and carbonaceous shales. The slates are similar to those of later periods. Often they contain small tourmaline and hematite crystals. The novaculites are hard, brittle clay-slates containing garnets and quartz. In the carbonaceous slates carbonaceous material is present in large quantities, and crystalline components are absent. The paper ends with a discussion as to the processes of formation of slates, but reaches no decided conclusions.

IRVING, R. D. Note on the stratigraphy of the Huronian series of northern Wisconsin; and on the equivalency of the Huronian of the Marquette and Penokee districts. Am. Jour. Sci. (3), Vol. XVII, 1879, pages 393–398.

In 1879 Professor Irving began his series of valuable contributions to the geology of the Marquette district with a note in which he calls attention to errors in Brooks's scheme of equivalency for the strata of the different

Huronian districts in the Lake Superior region, and proposes a new scheme, which he claims shows clearly the equivalency of the Penokee and the Marquette series.

CROSBY, W. O. On a possible origin of petrosiliceous rocks. Read March 5, 1879. Proc. Boston Soc. Nat. Hist., Vol. XX, 1878–80, pages 160–169.

Crosby compares the felsites and "petrosilexes" with the siliceous red clays dredged by the Challenger Expedition from the deep seas. With respect to the Marquette jaspers and ores he says (p. 168):

One of the most interesting rocks in the Marquette iron district, in the Upper Peninsula of Michigan, and the one most closely associated with the iron ore, is a brownish or reddish jasper; it sometimes becomes chloritic or micaceous, passing into chlorite-schist, etc., but for the most part it is a distinct and beautiful stratified jasper. This Lake Superior jasper, like all the petrosiliceous rocks so far as known, belongs to the Huronian formation, and may, apparently, be fairly taken to represent the petrosilex and felsite characterizing many other Huronian areas, but apparently wanting here. Its association with the iron ore is usually very intimate; the two substances being interlaminated in such a manner as to give rise to a banded structure which matches in all important particulars the banding of the petrosilex of eastern Massachusetts and other regions, the hematite simply taking the place of the feldspar. The extreme irregularity of the banding in many cases makes it not only proper but necessary for us to conclude that, as in the case of the petrosilex, it is largely the result of a segregation process, the two constituents, hematite and jasper, having been originally more intimately mixed

With very few exceptions this Marquette ore always contains some oxide of manganese, usually from 1 to 2 per cent, though the ore from one bed contains nearly 7 per cent.

Here, then, so far as chemical composition is concerned, we have a formation almost identical with some of the siliceous oozes of the deep sea; while the chief structural distinction consists in the different forms of the segregated masses of the iron and manganese oxides, lenticular layers taking the place of irregularly rounded nodules, certainly a distinction of no great importance.

The author does not claim to prove that the jaspers and ores originated from deep-sea oozes, but only to show the close analogy existing between these ancient rocks and the deposits now being formed in the ocean's depths. There are several misinterpretations in the description of the jaspers given. The author had not visited the Marquette district, so he must have obtained his notions of the relations of the jaspers from the literature on the area. The jaspers had frequently been described as interstratified with chlorite-schist, etc., but nowhere had it been shown that the two rocks grade into each other. Moreover, the Marquette ore does not usually contain from 1 to 2 per cent of manganese.

1880.

BROOKS, THOMAS BENTON. The geology of the Menominee iron region (east of center of Range 17 E.), Oconto County, Wisconsin. Geology of Wisconsin, 1873–1879, Vol. III, pub. in 1880, Part VII, pages 429–599.

The Wisconsin reports, although they are devoted mainly to the discussion of Wisconsin problems, contain numerous references to the geology of Michigan. In Brooks's report on the geology of the Menominee iron range are several references to the Marquette rocks. There is, besides, a new table of the formations in the Marquette Huronian. The principal difference between this table and that published in the Michigan report is the addition of Formation XX, which embraces the "granites" southwest of Lake Michigamme, thought to be younger than the mica-schists of the vicinity. The references to the Marquette series are mainly with respect to their correlation with the Menominee series.

As an appendix to this report (pp. 661–663) Brooks gives a brief sketch of the Laurentian rocks in Michigan. This series includes mica-gneisses, hornblende-gneisses, hornblende-schist, chloritic gneisses, chloritic schists, often derived from the mica-gneisses and hornblende-gneisses, and granites. The latter rocks are the massive varieties of gneiss "in which all interior evidence of bedding is obliterated by metamorphic action." All the granites of the Laurentian, with the exception of the dike granites "and certain great irregular red masses," are thought by the author to be altered sedimentary rocks.

The Laurentian rocks are cut in all directions by dike-like masses of granite and greenstone, of which the latter are "far thicker, more regular and persistent than those of the granite."

WICHMANN, ARTHUR. Microscopical observations of the iron-bearing (Huronian) rocks from the region south of Lake Superior. Geology of Wisconsin, 1873–79, Vol. III, 1880, pages 600–656.

A series of about 500 thin sections of rocks from the Penokee, the Menominee, and the Marquette iron districts was submitted by Brooks to Arthur Wichmann for microscopical study. Wichmann's report announces the results of the study and the conclusions reached by him concerning the origin of some of the rocks investigated—conclusions that have already been referred to in some instances. The rocks are divided into lithological groups as follows: nonfragmental rocks, including simple rocks, massive rocks, and schistose rocks; and fragmental rocks, including clay-slates, sandstone, and chert-breccia, of which the latter occurs only in the Penokee district. Among the simple rocks are found limestone, dolomite, quartzite, magnetite-schist, jasper-schists, chert schists, hematite-schist, and serpentine; among the massive ones, granite, syenite, diorite, and diabase; and among the schistose ones, gneiss, mica-schist, hornblende-schist, chlorite-schist, augite-schist, talc-schist, sericite-schist, and eklogite. The serpentine is an altered olivine rock. Diabases are abundant in the Marquette district, and are eruptive in origin. By addition of hornblende to the diabases, diorites result; hence the diorites are also eruptive. The talc-schists described by Brooks in Bed XIV are sericite-schists of sedimentary origin.

HUNT, T. STERRY. Letters and notes on the iron-bearing and associated rocks of the Marquette region, and comparisons with the Archean of Canada and of the eastern United States. Appendix A, Geology of Wisconsin, 1873–79, Vol. III, 1880, pages 657–660.

In the same volume in which Brooks's report is published are several letters and notes by Hunt on the iron-bearing and associated rocks of the Marquette district. One of these letters is from Hunt to Alexander Winchell, and is dated November 26, 1869. In this Hunt mentions the difficulty of assigning names to the greenstone-schists of northern Michigan, which include altered varieties of many distinct rocks. In a letter to Brooks dated February 22, 1871, an attempt is made to correlate various members of the Marquette series with the Huronian and Montalban rocks of New England and the Adirondacks. In a third letter Hunt expresses doubt as to the alteration theory with respect to the origin of the rocks of the Marquette district. He is inclined, apparently, to regard these rocks as direct sediments.

WADSWORTH, M. E. Notes on the geology of the iron and copper districts of Lake Superior. Bull. Mus. Comp. Zool., Vol. VII, 1880, 157 pages and 6 plates.

In this paper Dr. Wadsworth submits in great detail his views on the origin of the Marquette ores. As a preface to his own observations he gives a summary of the work done in the region, as follows (pp. 26–27):

In general, then, in looking over the views advocated by past observers, we find, in brief, the following opinions held.

The rocks of this district (excepting the sandstones) were all taken as Azoic by Foster and Whitney, and not considered to be capable of subdivision into geological periods. We must also notice that Prof. H. D. Rogers regarded them as of Primal or Potsdam age. On the other hand, we find that this formation is divided by Murray, Hunt, Kimball, Winchell, Credner, Brooks, and Wright into the Huronian and Laurentian. This division is based upon lithological characters, and on unconformability said to exist between the two. Rivot considered the whole as Potsdam. The granite is regarded as an eruptive rock by Foster and Whitney, Bigsby, and Whittlesey; and as of sedimentary origin by Rivot, Kimball, Brooks, Hunt, and Wright. These latter, with Credner, take it as being older than the schistose rocks associated with the iron ores, and, excepting Rivot, with its accompanying gneissoid rocks composing the Laurentian formation. Foster and Whitney and S. W. Hill regarded the granite as younger than, and eruptive in, the schists.

The gneisses and schists were taken by all the observers as being of sedimentary origin, except possibly Whittlesey, whose language is as obscure as the formations about which he writes.

The metamorphism of the schists is supposed by Hubbard, Rivot, Kimball, Hunt, Brooks, and Wright to be occasioned by chemical agencies, accompanied, as part thought, by galvanism. Foster and Whitney and Bigsby considered that the metamorphism was brought about by the presence of eruptive rocks, and their accompanying chemical agencies. Foster and Whitney regarded the "diorites" of this region as eruptive rocks, but Rivot, Kimball, Hunt, Winchell, Credner, Brooks, and Wright, as sedimentary ones and interstratified with the schists. The iron ores are regarded as all of sedimentary origin by Foster, Kimball, Dana, Hunt, Winchell, Credner, Brooks, Newberry, and Wright, but are believed for the most part to be of eruptive origin by Whitney, and by Foster and Whitney. These ores were said to be in the upper portion of the Huronian series by Kimball, Brooks, and Wright, with the "diorites" underlying them.

It will thus be seen that, while Foster and Whitney regarded certain of the rocks in the Huronian as eruptive, Hubbard, Rivot, Kimball, Hunt, Credner, Brooks, and Wright regarded all, with a few slight exceptions, as sedimentary; and Houghton, Hubbard, Locke, Kimball, Rivot, and Brooks teach that they pass by gradual transition into one another.

The most important points, then, about which there has been or is difference of opinion, are the age and relation of the granite and schists, the origin of the diorites and iron ores, the passage of one rock into another, and the presenee or absence of eruptive rocks. These and other questions relating to this district admit in many cases of no middle ground; one or the other party must be mistaken in their observations or conclusions, or both.

After reviewing the literature on the Marquette area the author proceeds at once to attempt the solution of the problems that present themselves. He studied the district minutely, and so compelled others who disagreed with his conclusions to make a similar close study of it. Consequently, Wadsworth's paper may be regarded as the opening chapter of a new volume on the geology of the district. As we shall see, several of the author's conclusions were subsequently proved untenable, but the work required to prove them wrong was necessary before a correct knowledge of the geology of the district became possible. The article is especially valuable for its detailed description of the relations existing between the various rocks.

The contacts of the jasper and ore with the schists associated with them are shown to be like those of an eruptive with an older rock. At the Lake Superior mine, for instance, the jasper and ore were seen in contact with the chlorite-schist.

The junction of the two is very irregular, the banding of the jasper and ore following the irregularities of this line, while the schist is indurated and its laminæ bear no relation to the line of contact. Stringers of ore project into the schist, which near the jasper is filled with octahedrons of magnetite. The schist loses its green color generally, and becomes apparently an indurated argillite. The contact and relations of the two rocks are not such as are seen when one sedimentary rock is laid down upon another, but rather that observed when one rock is intrusive through another; and in this case the intrusive one is the jasper and its associated ore. (P. 30.)

Observations of the same character were made at the New York, Jackson, and other mines, and in all of these the contacts of the jasper and ore with the surrounding schists were found to have the peculiarities of eruptive contacts. The "bosses" of schist so frequently met with in mining operations are likewise regarded as proofs of the eruptive origin of the ore.

This structure evidently is consonant with the theory of the eruptive origin of the jasper and ore. They break obliquely up through the schist, and send off branches, which, pursuing the same general course, leave wedge shaped masses between them and the trunk. (P. 31.)

At the Home mine, on the Cascade range, at the Pittsburg and Lake Superior mine, on the same range, at the Lake Superior mine, Ishpeming, and at a number of other places dike-like masses of the jasper are reported as cutting schists and ferruginous sandstones overlying the ores. At the Pittsburg and Lake Superior mine, "while in general these little dikes follow approximately the bedding [of the quartzite], they are seen not to exactly do this, but cut the laminæ obliquely through much of their course."

In order to determine, if possible, what was the original state of the ore and jasper, the author examined thin sections of both. Of the jasper he writes (p. 33):

Microscopically this section is composed of a fine granular aggregate of quartz and hematite, and a more coarsely crystallized portion made up of octahedrons of magnetite or martite, and of quartz of secondary origin. The quartz in the first part is largely filled with minute globules and grains of ore, which also occur in irregular masses and in octahedrons. The quartz associated with the more coarsely crystallized portion is water clear, and shows the usual fibrous granular polarization of secondary quartz. Wherever the iron is in a distinguishable crystalline form it is in octahedrons.

Of other sections of jasper and ore he writes (p. 33):

The structure of the quartzose portion is like the devitrification structure of the rhyolites and felsites. * * * The jaspery portion is finely banded, and shows an apparent fluidal structure. We are inclined to regard the structure as fluidal, but in a rock so deeply colored it is difficult to make satisfactory examinations.

It was impossible to determine whether or not the ores were all originally magnetic. In some cases the magnetites are believed to be secondary, since the hematite where in contact with diorite dikes is often changed to this mineral.

At the Republic mine magnetite and martite (hematite pseudomorphs after magnetite) are frequently found near the "quartzite" of Brooks (Formation XIV). For this reason, and because the quartzite is firmly welded to the ore, and breaks across its laminæ, cutting them and sending tongues into the "mixed jasper and ore," the rock is supposed to be eruptive (intrusive). In one place (pp. 54–55) the author describes it as greisen. The quantity of magnetite present at any place is thought to be dependent largely upon the abundance of eruptive dikes and their proximity to the ore deposit.

The question as to the origin of the basic massive rocks of the region the author answers decidedly. He finds many examples of fresh and altered diabases occurring in dike-like forms, cutting the green schists near Marquette, Ishpeming, and Negaunee, and traversing a "breccia or conglomerate" near Deer Lake and other places. The material of the dike in the Deer Lake conglomerate "is so altered that it resembles a chlorite schist, and in the thin section is seen to be composed of chlorite, quartz, and mica. It holds some ferruginous masses resembling the product of the decomposition of titaniferous iron, as well as one or two that probably resulted from the decomposition of olivine or brown hornblende. * * * We regard the rock simply as a more highly metamorphosed condition of the diorites of the region" (pp. 42–43). Other dikes were seen at the Jackson and the Washington mines, cutting the ore, and south of the Champion mine, traversing the granites and gneisses. In many cases the dikes show their intrusive character in the field, and exhibit under the microscope the features usually regarded as appertaining to crystalline rocks.

The "magnetic siliceous schist" of Brooks is learned to be composed of actinolite, hornblende, magnetite, and garnet, and together with other similar rocks, including Wichmann's eklogite, is believed to be eruptive. The actinolite-schist south of Humboldt passes into a quartzite rock made up principally of alternating layers of quartz and actinolite, and is therefore sedimentary. The author thinks that the actinolite-schists were formed of the detritus of the garnetiferous actinolite rocks, which are intrusive.

From these studies it is plain that the eruptive nature of many of the massive beds of "diorite" described by earlier writers as interstratified with the Huronian schist is proved conclusively. They were regarded as sedimentary by the earlier geologists, because, as stated by them, they were found to grade insensibly into the "green schists" associated with them. Wadsworth, however, declares that this is not the case. The massive beds are distinct from the schists. The contact between the two rocks is often sharp, and the one rock does not grade into the other. The large masses of diorite, like that south of Teal Lake, are not interstratified beds, but are true dikes. Thus the origin of these massive beds is set at rest. As to the origin of the green schists so frequently associated with the dikes, nothing is said. It is true that the author found some of the diabase and "diorites" becoming schistose, and others passing into typical chlorite-schists and hornblende-schists, but the origin of the older schists, through which all the dike rocks were supposed to cut, has been left unsettled.

With respect to the origin of the soft hematites, the author is in accord with the majority of those who had studied them. He places them, however, in the same formation with the jasper ores, and not in a different and lower formation, as does Brooks. The soft ores are believed to have been formed through the decomposition of ferruginous schists by thermal waters. The geology of the Salisbury mine and its situation seem to the author to lead to this view. The ores are most abundant where the schists, jaspers, etc., are most fractured and shattered, and hence are found in the acute angles between interpenetrating diorite dikes, provided, of course, the "diorite" is younger than the jaspers and ores, as is supposed to be the case. Near Ishpeming and Negaunee "the dip of the jasper increases as it approaches the 'diorite,' sometimes standing nearly vertical. It was not observed in contact with the 'diorite,' but we feel that the constant uptilting of the jasper and associated schist when near these intrusive rocks is good evidence that the 'diorite' eruption was later than that of the jasper" (pp. 51–52).

The next problem attacked is the relation of the granite to the Huronian schists. If it is intrusive in the schists, it is younger than they and can not be of Laurentian age, as had been thought by earlier writers. The author describes a number of localities where granite veins traverse gneisses and micaceous and green schists, and where, consequently, the granite is younger than the schists. If these schists are Huronian, as was believed to be the case, then the granite is not Laurentian. More significant, if found correct, are the author's observations that the granite is intrusive also in quartzite. On the line of the Chicago and Northwestern Railway, south of Ishpeming, the granite is mentioned as cutting a quartzite "that resembles the ordinary 'Huronian' quartzites." Southeast of Champion it is said to cut a sedimentary micaceous and magnetite schist.

If these observations are correct, some of the granites of the Marquette region are younger than the quartzites associated with the ores; but apparently later observers could not anywhere find quartzite intruded by granite.

The microscopic features of the various granites mentioned by Wadsworth, and of many of their associated rocks, are described by him. At Republic a fine-grained rock, composed essentially of quartz and mica, was found in actual contact with typical granite or very near the latter rock. This, together with the "quartzites" of Formation XIV, at the same place, is regarded as the modified edge of the granite, and, from a purely petrographical standpoint, as gneiss.

After describing the characteristics of the Potsdam sandstone, the author discusses the nature of the Presque Isle trap and its relations to the sandstone associated with it. By microscopic examination he finds the "trap" to be a peridotite composed of olivine, enstatite, and diallage in its freshest portions, and a serpentine elsewhere. The serpentine has evidently been derived from both the olivine and the diallage of the original peridotite. With it is always a large quantity of dolomite, so that it seems probable that Rominger's stratified dolomite at this place is simply a very much decomposed portion of the peridotite. With respect to this latter rock the author says (p. 62):

> We regard this peridotite as an eruptive rock, younger than the sandstone overlying it, and agree in this particular with Dr. Houghton. The portion filled with veins, that was taken by him as a sedimentary rock belonging to the sandstone, or a mixture of sandstone and trap: as a volcanic sand or ash, by Messrs. Foster and Whitney; and as a dolomite, older than both trap and sandstone, by Dr. Rominger, we regard as simply the upper portion of the intrusive mass, modified by its contact while heated with the overlying sandstone, and by the percolating waters since.

He gives as his reasons for this conclusion the observations that the sandstones were "found to conform in their stratification to the contour of the whole mass" of peridotite; that the lower portions of the overlying rock are altered, as though by the action of heat and heated waters; the absence of pebbles and fragments of the peridotite from the conglomerates of the sandstones. The serpentine northwest of Ishpeming, first mentioned by Wright, from its microscopic features is thought by Wadsworth to be an altered peridotite.

The author summarizes his work and conclusions in a few pages, from which we extract these passages:

The observations and figures given in the preceding text show conclusively that the statements of Messrs. Dana, Kimball, Hunt, Brooks, and others, that the iron ore is interstratified in the associated schists, are incorrect, and only return to the view advocated by Mr. Foster in his early publication. So far as geologic science has now advanced, the facts observed can only be explained by the eruptive origin of both the ore and jasper, as they make the same formation. The only escape from this conclusion is the supposition that the ore and jasper have been rendered plastic *in situ*, while the chlorite-schist has not been. * * * That the ore and jasper have been thus rendered plastic, while the schists, quartzites, and other associated rocks have not been, is too absurd, chemically or geologically, to be tolerated for a moment as an hypothesis. * * * The ore and jasper show that they are the intrusive bodies by their breaking across the lamination of the schists and other rocks, by the changes that take place in the latter at the line of junction, by horses of schist being inclosed in the ore, by the curvature of the lamination produced by the intrusion of the ore and jasper, etc. Not the slightest sign of the plasticity or intrusion of the schists relative to the ore or jasper was seen. That the present lamination of the schist existed prior to the intrusion of the ore and jasper is shown by the effect of the latter upon and its relations to it. That this lamination is the original plane of deposition is for part of the schists not known; * * * The lamination, however, coincides with many of the well-stratified rocks adjacent, and in some of these the ore and jasper were unmistakably intrusive. * * * In the finer-grained detritus composing some of the schists it is quite likely true that the lamination does not coincide with the original bedding; but if it does not, then the breaking of the ore across any chosen plane whatsoever, except the lamination plane, can be shown more easily than in the former case. * * * We are well aware that objections from a metallurgical or chemical standpoint have been raised against the theory of the eruptive origin of hematite and silica together, in such forms as we now find them. If the ore was magnetic at the time of eruption, and has since been altered, this objection is then done away with. The secondary changes that have occurred in the rock since eruption, as shown by microscopic examination, may also help. It is well known that there are facts in every science that it is not able to explain at any one given time; but the facts exist the same, and the science in time rises to meet them. So in this case the fact is they are eruptive, and the burden of chemical explanation rests upon the chemist, not upon us. He must explain it sooner or later, unless he disproves our observations. Crystals of hematite crystallizing from the molten magma of trachytes and rhyolites have long been known, and are described in all the standard works of micro-lithology. These then offer the same problem, and prove that hematite can be crystallized directly out of the same molten magma, and at the same time with the silica and silicates. It is the business of the chemist to meet the facts, and not for us to make the facts conform to his knowledge or theories.

We have found that a large proportion of the rocks said to be interstratified, and to pass by insensible (or any other) transitions into the adjacent rocks, are eruptive, and do not so pass into the country rock. The assumption that they were stratified was based on their foliation being parallel to their walls, on their being intrusive approximately parallel to the lamination of the schists, [and on] their general resemblance to the country rock of similar composition * * *. The intrusive rocks belong in general to the basalts, but are of course old, and in the majority of cases greatly altered. One probable andesite as well as intrusive felsites (rhyolites) was discovered. * * *

The "soft hematites" are doubtless produced by the decomposition of the jasper and its ore, brought about by the fracturing of the rocks by the intrusives and by the secondary action of water, presumably hot, on account of the microscopic characters of the quartz deposited by it. Besides the "soft hematites" there occur the quartzites and conglomerates derived from the ore and jasper, as well as the sandstones and schists impregnated by iron, which are sometimes mixed to a slight extent.

We have heretofore seen that the view that the "Huronian" unconformably overlies the "Laurentian" has been only supported by the fact that the foliation of the latter did not conform in its dip to the lamination of the former. This proof is of no value unless it can be shown that both rocks are stratified and *in situ*. That the latter is not so, we have seen in numerous localities. Heretofore the two systems have not been observed in contact, but recently statements have been published that their junctions have been seen in other regions. * * *

So far as the Marquette district is concerned we have shown very much stronger and more abundant evidence to prove that the "Laurentian" granite is younger than the "Huronian," and an eruptive rock, than has been advanced by Mr. Brooks (the only man who has advanced anything called proof) to show that it is older. * * * (Pp. 66–70.)

The general structure of the country would seem to be as follows. The schists, sandstones, etc., having been laid down in the usual way, were then disturbed by the eruption of the jasper and ore; this formed the knobs of jasper, the banding belonging to the fluidal structure, and not to sedimentation. Besides occurring in bosses, the jasper was spread out in sheets, and intruded through the rock in wedge-shaped masses, sheets, and dikes. Much of the original rock still remained horizontal, and new sedimentary deposits continued to be formed out of the jasper and the other rocks. Next came the eruption of "diorites," which completed most of the local folding and tilting of the strata. Finally, the granite eruption took place on both sides of the "Huronian," uplifting and contorting the strata near it, and perhaps laterally compressing the inclosed iron-bearing rocks. No basis exists so far, then, for the scheme of formations laid down by Mr. Brooks, as it was founded on the supposition that all the rocks were sedimentary.

Although, in deference to the common custom we have employed the term *jasper* in writing of the siliceous eruptive rocks associated with the ore, in reality it it not properly called so. * * * It is more acid than the rhyolites, the silica being above 80 per cent. * * * We would propose, therefore, that all the acidic eruptive rocks, whose chemical and physical constitution carries them above the rhyolites should be designated as *jaspilites*, * * * in accordance with a suggestion of Professor Whitney. (Pp. 75–76.)

1881.

Wadsworth, M. E. On the origin of the iron ores of the Marquette district, Lake Superior. Read March 17, 1880. Proc. Boston Soc. Nat. Hist., Vol. XX, 1878–1880, pages 470–479.

The banded ores of the Marquette district, as will be remembered, are regarded as eruptive by Foster and Whitney and as sedimentary by Kimball. Since 1865 Kimball's notion regarding them had been generally accepted; at any rate it was not seriously questioned until Wadsworth reopened the discussion as to their origin.

The author first states that the ores in question do not, except in some few cases, present the characters of vein-stones. The question to be decided is as to whether "the ore and jaspilite were deposited as sediments in situ or are of eruptive origin."

The grounds upon which their sedimentary origin had been advocated are these:

(1) Bog-iron ores are forming at the present day.

(2) On account of the banding or lamination of the ore and jaspilite.

(3) The bandings show foldings and contortions.

(4) The jaspilite and ore are jointed and show cleavage.

(5) The associated rocks are sedimentary, and on account of the alternation with schists, the ore and jaspilite, as well as the schists, must be metamorphosed sedimentary rocks.

(6) The presence of phosphoric acid.

These arguments are then taken up and discussed separately. That numbered (1) is summarily dismissed as no argument. We will let the author himself reply to the others.

(2) The banding and lamination of the jaspilite and ore do not appear to us to be proof of sedimentary origin, since a similar banding is strongly marked in the rhyolites the modern lavas approaching nearest the jaspilite, in dikes of felsite, in furnace slags, etc. * * * This structure is common to both sedimentary and eruptive rocks, hence per se is of no value either way. The structure of the banding does often show the origin of the rock when it has been studied with care. Those advocating the sedimentary origin of the above mentioned ore have rested their claim on the simple fact that the rock was "striped," and not on the character of the banding. We have studied the banding and can find nothing in it that proves sedimentation or is inconsistent with that repeatedly seen by us in known eruptive rocks.

(3) The folding and contortion of the banding would take place in any rock whatever its origin, after it was in position, if subjected to proper conditions. * * * Hence folding and contortion of banding in rocks, like the banding, is common to both sedimentary and eruptive rocks, and like the latter (banding) is no proof of either origin.

(4) Joints and cleavage planes are well known to be common to both sedimentary and eruptive rocks, hence their presence can not be taken as proof of either origin.

(5) Whoever advanced the view that since the associated rocks were sedimentary, therefore the jaspilite and ore must be, * * * must have been aware that this principle would prove the great majority of dikes and veins to be sedimentary. A dike passing through slate must be sedimentary because the slate is sedimentary. * * *

(6) The presence of phosphoric acid could only have been taken as proof of sedimentary origin by those who had no knowledge of eruptive rocks, since it is well known to occur in many of the latter. * * *

We have now taken up all the evidence which we are aware has been used to prove the sedimentary origin of the jaspilite and ore. The characters used as proof seem to be such as are common to both sedimentary and eruptive rocks or are of no weight. (Pp. 473–475.)

The evidence given in behalf of the eruptive origin of the jaspilite and ore are the eruptive relations that are shown to exist between them and the associated rocks at their contacts. "The jaspilite and ore are found to break in various directions across the lamination of the associated rocks, to indurate them at the line of junction, to send stringers and tongues into them, to cut the laminæ in every direction; in short, to behave always like an eruptive rock and never like a sedimentary one" (p. 476). This theory assumes the sedimentary origin of the schists associated with the ores and jaspilite.

The author thinks that if the ores were originally magnetite, or if they have always been hematite, there is no chemical difficulty in the way of believing in their eruptive origin, for magnetite is present in all eruptive rocks, and hematite in many of them.

> We rest our conclusion that the jaspilite and iron ore in the Marquette district are eruptive upon the fact that they possess characters which eruptive rocks exhibit, especially in relation to other rocks, and which no sedimentary rock, proved to be such, has been known to have. They offer no characters inconsistent with those that known eruptive rocks have, but they do exhibit those, as said before, that no stratified rock has, so far as our present knowledge, not theory, goes. (P. 477–478.)

The paper closes with a statement of the conditions demanded by the sedimentary and the eruptive theories. It is pointed out that the conglomerate over the ore would, according to the sedimentary theory, necessitate the belief in a time interval between the ores and the overlying rocks, whereas according to the eruptive theory this would not be required.

ROMINGER, C. Marquette iron region. Geol. Surv. of Michigan, Vol. IV, Part I, New York, 1881, pp. xiv and 154. With map.

In the year 1881 C. Rominger, who had been appointed State geologist of Michigan to complete the survey begun under Alexander Winchell, published a report based on three seasons' field work. In this time its author was able to accomplish an immense amount of geological work, and to accumulate a great mass of facts concerning the geology of the district studied. This report is intended as a supplement to that of Major Brooks. It deals solely with the scientific aspects of the case, while

Brooks's report considered the district principally from the economic standpoint. The map furnished by Rominger is extremely accurate in its delimitation of the various formations recognized by its author. It has proved of incalculable value to the present writers in their field work in that portion of the district covered by it. Its topography, as well as its geology, shows evidence of the immense amount of careful labor put upon it.

In general the author regards the Marquette iron-bearing rocks as Huronian and as lying in a synclinal trough formed by the upheaval of the edges of the granite basin in which they rest. By the rising of these edges the inclosed sedimentary rocks were uplifted and compressed into parallel folds. The upheaved granitic and sedimentary rocks are traversed by rock belts, which represent lava streams that were intruded from below at different periods after the formation of the traversed rocks. The author declines to regard the granitic rocks of the region as Laurentian, since as a series they do not correspond lithologically with the Canadian Laurentian, and since the discordances described as existing between them and the Huronian rocks are not discordances between the two divisions at their immediate contacts. Even if discordances do exist they would prove nothing, according to the author, in beds so much disturbed as are those in the Marquette district

As far as my own observations go, I have never been able to discover any positive proof of an existing discordance between the granites of Marquette and the adjoining Huronian beds; on the contrary, outcrops of the two kinds of rock supposed to represent the contact of the two formations exhibit everywhere a remarkable parallelism in strike and dip, and in a good many localities, where belts of granite are found interlaminated between the Huronian schists, the conformity is perfect; but I am far from believing that these conformably interstratified bands of granite ever had been formed there as regular members of the sedimentary series; I consider them as intrusive masses * * * which came to the surface after the Huronian beds were already formed, and by their eruption caused not only the great dislocations of the Huronian formation, but the half-molten plastic granite masses induced by their contact with the Huronian rock beds, also their alteration into a more or less perfect crystalline condition, and commingled with them so as to make it an embarrassing task to find a line of demarcation between the intrusive and the intruded rock masses. (P. 6.)

Rominger thinks Brooks's subdivisions are more numerous than is necessary in discussing the formations present in the Marquette series. He recognizes only six "groups," as follows, beginning with the lowermost: the granitic, the dioritic, the iron, the quartzite, the arenaceous slate, and the mica-schist. The members of the "granitic groups" are confined to the northern and southern limits of the Marquette area, where they exist as the predominant rocks, intimately associated with diorites, green schists, etc., with which they often seem to be interlaminated.

The granites on both sides of the synclinal basin are similar in composition and structure. They consist essentially of red orthoclase, quartz, and a micaceous mineral that often resembles chlorite. Sometimes this is replaced by a hydromicaceous substance which imparts to the granite a subschistose cleavage. Such granites are found at a few places in the northern granite belt and on the south side of the synclinal basin, on the line of contact between the normal granites and the lower quartzite formation. Here they appear to be metamorphosed quartzites, "as we find all degrees of transition from the ordinary quartzite into a regular granitic rock mass" (p. 15).

Associated with the granites are also belts of gneissoid rocks, consisting of dark mica or a dark-green hornblende, feldspar, and quartz.

> This stratified banded rock, in contiguity with the granite and alternating with it in parallel belts, often becomes completely intermingled and entangled with it. The granitic masses intersect the gneissoid, enter wedge-like between them in the direction of the lamination or transversely, inclosing strips of the gneissoid ledges between the loops of the anastamosing granite seams, and, moreover, frequently the so-intermingled masses are curved into the most curious coils and serpentine flexions, which evinces their almost liquefied, plastic condition at the time their intermixture took place. (Pp. 16–17.)

The granites and gneisses are cut by large and small dikes of hornblende-rocks, by diorites, and by seams of quartz. In the northern halves of secs. 20, 21, 22, and 23, T. 48 N., R. 26 W., is a range of genuine syenitic rock composed of dark hornblende and a reddish-gray orthoclase.

From these descriptions it is seen that the granite is considered an eruptive rock intruding certain dioritic and hornblendic schists that must be older than the granite, and yet the author places the granite in the oldest formation of the series. Naturally, if the granites as eruptive rocks produced the folding of the Huronian beds, they must be the youngest of all the rocks occurring in the series, and can not possibly be the oldest in their present position. The author explains this anomaly in the following words (pp. 22–23):

> The granites, considered in their present surface position, are, in relation to the stratified sedimentary rocks of the Huronian series, actually the younger rocks. * * * The hypothesis of their contemporaneous eruption is therefore well admissible. But supposing this to have been the case, one may ask, Of what nature, then, was the substratum on which the Huronian sediments were deposited? I answer, Nothing contradicts the possibility of their deposition on a surface of granite already formed; it is even probable to me that it has been so; but if we reflect upon the high degree of plasticity and the almost perfect liquefaction which the concerned rocks subsequently underwent, and upon the dislocating forces, causing the softened * * * masses to intermingle almost chaotically, we can no more wonder that the traces of the originally existing former relative position of the rocks among themselves are greatly obliterated.

The meaning of this is that the Huronian rocks were laid down upon a crust of granite which had not become rigid. Subsequently the granite rose and was erupted through the beds that had been piled upon it.

The "granitic group" contains a great many beds of green schists, hornblende-rocks, and diorites, but the granites are the predominant rocks. The "dioritic group," on the other hand, is made up of a large succession of schistose beds interstratified with massive belts of diorite almost identical chemically with the schistose beds. The lines of demarcation between the granitic and the dioritic "groups" are not sharp; indeed, as the author declares, they are "artificial lines of demarkation for the convenience of description." "I do not intend to indicate by these subdivisions (into groups) separate, distinct epochs."

The various crystalline hornblende-rocks associated with the granites are considered to be remelted Huronian sediments. Those more remote from the eruptive are much altered, but the author believes that he can detect in them the sedimentary structure. Through them have been intruded the lower melted portions of the series, either as dikes or as sheets of a dioritic character.

The schists constituting the greater part of the "dioritic group" are dark-gray or blackish-green rocks, composed of hornblende, chlorite, and mica, with feldspar and quartz. Chlorite frequently replaces the hornblende and often seems to be a product of its decomposition. A part of the schists belonging to the group are composed largely of a hydromicaceous constituent.

> The dioritic rock-belts are usually imbedded conformably with the schists, and not rarely an insensible gradation from the schistose condition to the massive dioritic can be observed. In the exposures the massive body of diorite generally forms a nucleus around which, eccentrically, the inclosing rock masses assume more and more a perfect schistose structure. * * * Other, generally narrower, diorite belts intersect the schists transversely, which differ little in composition from the conformably interstratified masses, and may, as I previously intimated, represent the lowest, more completely liquefied portions of the rocks in progress of alteration. (P. 24.)

The schists of this "group" are described as occupying an area south of the northern granite belt, as far west as they were examined, viz, the west side of the eastern tier of sections in R. 28 W. On Dead River, above Bancroft's, a succession of schists and diorites, measuring 3,000 feet in aggregate thickness, was traversed, but these figures are not regarded as indicating positively that the thickness of the series is as great as this. There may be folds in the rocks at this point, causing a repetition of the same beds on opposite sides of the axis of folding. They were, however, not detected.

In its northern portion the schist belt comprises dark rocks with a delicately laminated schistose structure. At Marquette there is interstratified with them a belt of banded quartz-schist, which in places becomes a lean magnetite ore. Farther south the schists are lighter-colored and their structure is more fissile and slate-like. Some of the layers are tinged with red oxide of iron, and irregular belts of hematitic iron ore are interstratified with them, as at the Harlowe or Eureka mine. Argillite-like beds are met with on the hillside south of Ridge street, in Marquette, and immediately north of these is a belt of novaculite more than 100 feet in width. South of the argillites are again diorite-schists, and south of these is found a repetition of the argillites. Still farther south the rocks have an inverted dip, and the novaculites and argillites are found just beneath the "quartzite group." From the facts observed with respect to the distribution of the schists in the schist belt, the author concludes that "we must necessarily infer the existence of repeated plications of the strata exposed * * * and an overturned position of the northern part of the layers, as the novaculites and argillites underlying them are beyond doubt the equivalents of those seen on the south side next below the quartzite, and upon the dioritic layers, and represent the uppermost beds of the dioritic rock-group" (p. 32).

Very many detailed descriptions of individual exposures are given by the author, but they are not necessary to an understanding of his discussion of the district. It is interesting, however, to mention the discovery of great beds of conglomeratic schists in the upper part of the "dioritic group" in the neighborhood of Deer Lake. These are spoken of as conglomeratic or brecciated seams, because a part of the pebbles are angular and a part rounded. "The majority of them consists of granular, somewhat porous feldspathic substance, which on fresh fractures contrasts little from the surrounding schistose mass, but shows itself very plain on weathered surfaces, on which the pebbles turn white or pale reddish" (p. 36). Other conglomerates exist in which the schists are the groundmass and the pebbles granite. Some of these are in the same horizon as are the Deer Lake conglomerates, while others, interstratified with the schists, are much lower in the series.

The greenstones with the iron formation, like those near Ishpeming and Negaunee, were regarded by Brooks as interstratified, metamorphosed sedimentary beds. Rominger, on the contrary, regards them as the lower, fused portions of the dioritic series that were forced up into their present position. In other words, he looks upon them as eruptives which were forced between the beds of the iron formation as sheets, but which in origin are fused sedimentary rocks, as indicated above.

The quartzite formation succeeds the "iron group" in age, but precedes it in the author's discussion of the two series in question. A number of sections are described across the formation. They are so nearly alike in general features that we need refer to only two of them in this place. In particulars, however, they vary widely.

The quartzites of the Mesnard range, near Marquette, are interbedded with argillites and hydromicaceous schists or slates, and with ferruginous and siliceous slaty seams, all dipping south nearly vertically. Conformably superimposed upon the quartzite is a series of siliceous limestones, interlaminated with bands of novaculitic slaty seams of a purplish color. The limestone is folded and corrugated. Farther south quartzites again appear, and, following these, a band of conglomerate inclosing quartzite pebbles and novaculitic schistose fragments, which "are cemented together by a paste of similar schistose material, and intermingled with quartz-sand and octahedric crystals of martite." South of the conglomerate belt is a recurrence of the entire series, but in reversed order, though the dip continues to be southerly.

At the west end of Teal Lake is another wide exposure of quartzites, whose description, given in the author's words, will express his notion of the relation of the "quartzite group" to the underlying diorites:

> Large and very instructive exposures of the quartzite formation and of its connection with the underlying dioritic series are observable at the west end of Teal Lake. The south slope of the hills is formed by a thick belt of compact, heavy-bedded, whitish quartzites, which project in long rock walls, dipping southward under an angle of 65° to 70°; north of this belt we find dark-colored slaty rocks richly impregnated with minute crystals of martite in connection with seams of lighter colored, not ferruginous, argillitic or novaculitic schists, amounting to considerable thickness; another thick body of quartzite ledges follows on their north side, which forms the edge of the northern slope of the hillside, on which a descending section through the lower portion of the formation down to the dioritic series is well exposed: novaculitic seams alternating with bands of quartzite form the upper part of the slope; beneath them follows a large succession of silky, shining, hydromicaceous slate-rocks, with a crystalline, granular, aluminous groundmass in different shades of color, and in some of the seams charged with large proportions of granular crystals of martite and magnetite. These slaty rock-beds are on their north side conformably adjoined by chloritic and dioritic schists with inclosed massive diorite belts, which rock series composes all the hill ranges farther north to the valley of Carp River and those on the north side of the valley. (P. 45.)

Near Lake Cooper "the quartzite formation forms * * * the basal girdle of a much higher mountain body of dioritic rocks, which occupies the central part of the above-named section; and here frequent opportunities are offered to see the intimate connection existing between the two groups, linked together by uninterrupted succession, and by gradations in the change of the material of the rock beds" (p. 46). Thus there is no unconformity between the dioritic schists and the overlying quartzites, but, on the other hand, the rocks grade into each other; hence the diorites are but little older than the quartzites. At the contact of the quartzites with the granite the former rock is often altered. Its structure becomes schistose and in composition it approaches granite. The author quotes several occurrences of this character as illustrations of "the transformation of sedimentary strata into a granite-like rock" by exposure to contact with eruptive granite. From the descriptions so carefully given it is clear that the quartzite formation is folded into a large synclinorium, composed of numerous small synclines and anticlines. The upper portion of the quartzite is calcareous, as has been remarked. It comprises a series of siliceous limestones and calcareous slates, which is called the "marble series."

Conglomerates and breccias are often to be found associated with the quartzites, especially when the latter are near granite. In the south half of sec. 22, T. 47 N., R. 26 W., certain hills are "composed of a very coarse granite breccia, inclosing blocks of large size, several feet in diameter, cemented together by an arenaceous and chloritic interstitial mass of a laminated, evidently sedimentary structure, which exhibits itself plainly in some portions of the rock, in which the rock fragments are more thinly scattered through the cementing groundmass. In certain portions of these knobs the granite appears in solid masses, too large to be taken for fragments pertaining to the breccia which fact induces me to suggest the nucleus of all these hills to be a solid granite mass, whose shattered surface portions are recemented on the spot by sedimentary débris washed into the interstices" (p. 62). A little farther south in the same section are other conglomerates, whose "inclosed waterworn grains are in part granite, in part slate fragments." Near the southwest corner of the section are other conglomerates, whose matrix is a slate and whose pebbles are waterworn granites. In all these cases the conglomerates are associated with the members of the quartzite formation near the granite.

Other conglomerates of a different nature were found above the iron-bearing formation. These are generally coarse quartzite-conglomerates, composed partly of rounded waterworn pebbles, partly of angular fragments of flinty quartzite, of red-banded ferruginous jasper, of novaculitic or argillitic schist, and of other rocks. At the Cascade mine the conglomerate has "partly the structure of a very coarse sandstone with a micaceo-ferruginous cement, being partly formed of an agglomeration of large pebbles and angular fragments, some of which have the size of a man's head, which are all firmly cemented together by a micaceo-chloritic, sandy, interstitial mass, often disseminated with granules of martite. The pebbles are glassy or flinty quartzite, jasper-banded siliceous iron ores, novaculitic and argillaceous slate fragments, and dioritic rocks. These conglomerates have the thickness of from 50 to 60 feet, and can be followed in one continuous sheet all the way east to the Gribben mines" (pp. 66–67). Among the other occurrences of this conglomerate and breccia described are those of the Home, Jackson, Cleveland, Gibbon, Salisbury, Lake Superior, Champion, Saginaw, Goodrich, Keystone, Republic, and Michigamme mines. Although the full significance of the widespread occurrence of this conglomerate above the ore formation was not realized, Rominger nevertheless was led by its existence to suggest "that disturbances of not only a local extent must have occurred at the end of this era of iron sediments."

In discussing the iron-bearing formation the author declines to admit the existence either of the two iron formations of Brooks or of his two quartzites. Only one iron-bearing formation is recognized by the author, and only one quartzite, and this is the upper quartzite of Brooks.

The surface rock of the environs of Negaunee and Ishpeming is almost exclusively formed of the iron-bearing rock series. * *

The strata are in an extremely disturbed condition, folded and distorted in every possible way, usually without causing a rupture of the beds, but in some other instances the laminated banded seams composing the thicker ledges have ruptured, and the ends often came in a faulted position to each other, and were so recemented by the siliceous groundmass. * * * These disturbed beds lie, in every instance, directly, but very often inconformably, on chlorito-hydro-micaceous schists, or on crystalline dioritic masses which are constant associates of these chloritic schists, or sometimes dioritic schists, as hornblende and chlorite substitute each other, or are both components of them.

Overlooking the extremely plicated and corrugated condition of the strata, they form, considered in their totality, a synclinal basin hemmed in between dioritic ridges. (Pp. 72–73.)

After describing the general structural features of the ore formation Rominger proceeds to describe the different mines, giving details too numerous to mention in this review. He begins with the Jackson mine, which he says is in the upper part of the formation whose lower portion is found on the diorite hills south of Negaunee. The ores are in a banded jasper rock, and are usually associated with "belts of argillitic schists called soapstone by the miners." The ore bodies are irregularly distributed through the jasper-hematite-schists, except that—

a very rich seam of ore is almost invariably found on top of this jasper-banded rock-series, immediately beneath the quartzites which form the terminal strata in all these exposures. This upper ore belt is almost regularly brecciated in its upper part, and the same is true of the lower quartzite beds, which often are a mixture of ore fragments with quartzite pieces held together by an arenaceous cement. As this is the case in nearly all the mines of the district, we must suggest that great disturbances, of not only a local extent, must have occurred at the end of this era of iron sediments. (P. 74.)

In another part of the series, it is declared, there is a great thickness of argillitic rocks, all impregnated with red oxide of iron, and in these are intercalated ore seams in such quantity as to make this one of the most productive fields for the miner.

These ore deposits are not regular sedimentary layers, originally formed of iron oxide in this state of purity, but are evidently the product of decomposition of the impurer mixed ferruginous ledges by percolating water, leaching out the siliceous matter and replacing it by deposition of oxide of iron held in solution. (P. 75.)

The ores are dark or yellow soft ores, composed partly of hydrated and partly of nonhydrated oxide, and containing often globular and concretionary masses with a radiating or fibrous structure or "with the granular crystalline form of goethite." Pyrolusite and other manganese compounds, quartz, barite, and nodular masses of a soft aluminous silicate are associated with these ores. Where the ore beds are in contact with the diorites there is usually an unconformity between them.

All the ore beds of Negaunee are placed together. The hard-ore formation is not separated from the lower soft-ore series, the latter ores being regarded as local phases of the former. East of Negaunee the lower portion of the iron series is found.

The absence of the upper ore-bearing, red jasper-banded rock series, with inclosed seams of hard specular ore, and of the quartzites incumbent on it, from the exposures of the lower part of this group on the east side of Negaunee, is remarkable, because younger strata, which elsewhere have their place above these eliminated beds, directly succeed the others. These younger rock beds cover most of the surface east of this place for many square miles, and no more of the iron formation can be discovered in that direction. (P. 80.)

After his description of the mines the author declares that "every one of these localities differs somewhat from the other in the character of its layers, but the unity of all these deposits as coordinate members of one formation is plainly obvious" (p. 87). At Teal Lake the entire series is overturned with the quartzite under the ore formation.

The actinolitic schists of the western portion of the iron range are placed in the iron formation.

At the Republic mine the diorite beds that were reported by Brooks as interbedded with the sedimentary formations are found by Rominger to be "intrusive belts of short local extension" (p. 101). At the Spurr and Michigamme mines, however, diorite forms the base of the series and this rock, which is often chloritic, exhibits sometimes obscure traces of former stratification.

The formation lying above the quartzite is termed the "arenaceous slate group," because so many of its members are "sandy, siliceous layers," alternating with "slaty argillitic beds." The character of the strata differs in different places, but on the whole the nature of the series is as indicated. The rocks comprising this series are found sometimes lying upon the quartzites, sometimes upon the iron formation, and often directly upon the diorite series. The most easterly exposures of them are near the center of the SE. ¼ sec. 6, T. 47 N., R. 25 W., where they are represented by black slates. From this point the formation extends westward, with a few interruptions, to Lake Michigamme. Sandy micaceous flagstones, black carbonaceous and light slates, and sand-rock, interspersed with ferruginous layers, referred to as "flag ores," are all included in the "group." They are the equivalents of the great slate formation at L'Anse and on Huron Bay. All the slates of the series are cleaved, with the cleavage planes usually inclined to the stratification. The sequence of the different members of the formation was not determined, though the lighter-colored layers in the west appear to be the upper portion of the series, with the older members farther east.

Above the "arenaceous slate group" near the railroad, west of the Michigamme mine—

are outcrops of dark blackish-gray rock beds, partly of slate structure, partly in well-laminated, banded, more compact seams, which succession of beds follows immediately above the actinolitic rock series, dipping in conformity with that southward. These rock beds consist of a subporous groundmass, formed of very minute granules of white translucent quartz, in intermixture with a large proportion of brightly glistening black mica scales, and not rarely also with chlorite. In the softer, quite fissile schistose or slaty beds the mica overbalances the granular quartz, and they have a silky luster. In the compact banded ledges the quartzose groundmass prevails and their aspect is dull. Certain seams inclose an abundance of brown garnet crystals, from the size of a mustard seed to that of a pea. These beds I consider as representatives of the upper horizon of the fifth group; they correspond with the micaceous schists * * * on the north side of the Keystone mines. * * * On the south shore of the lake, [Michigamme] opposite Michigamme village, the rock beds come to the surface near the water's edge; we find there silvery-shining gray-colored mica-schists, some smooth, even bedded, others much corrugated, which essentially consist of the same minutely granular quartzose groundmass mingled with lighter-colored mica scales, which composes the schists on the west side of the Michigamme mines. This great similarity in the sedimentary material is an evidence of the close connection between this mica-schist group and the arenceous slate group, which proves the immediate succession of the first to the other more reliably than it is done by the southern dip of the strata, conformable with those of the Michigamme mine. * * * The dip of the nearly vertical rock beds is almost uniformly to the south, but the succession of beds is so immensely large that there must be suggested a frequent doubling up of the strata, which, in a belt of several miles in width, retain from one end to the other almost the same general rock character." (Pp. 131–132.)

There are many varieties of these schists, from almost black to silver-white in color. Some are garnetiferous; others contain andalusite. All are regarded as sedimentary.

This concludes the author's observations on the iron-bearing series. The remainder of the report is devoted to the serpentines and the eruptive dikes met with in his explorations. He describes for the first time in detail the serpentines northwest of Ishpeming. Both the Ishpeming and the Presque Isle serpentines occur in "nonstratified masses, which, if they ever originated from mechanical sedimentary deposits, are by chemical action so completely transformed as to efface all traces of their former detrital structure. They resemble a volcanic eruptive rock, forced to the surface in a soft plastic condition" (p. 135). The dolomitic and other phases of the rock are all accurately described, but nothing is added to our knowledge of its age or origin.

The eruptive dikes cutting the Huronian deposits, including the granite, consist, in the order of their age, of diorites, dolerites, and certain schistose rocks, probably originally diorites. The diorite dikes vary in width from a foot to 50 or 60 feet, the wider ones being, as a rule, coarser than the narrow ones. The dolerites are found only in the highest formation. Most of these are massive, but many of them, cutting granites, are schistose through pressure.

The quartz and other vein rocks of the district are described as fissure veins.

1882.

COLUMBIA UNIVERSITY. The Marquette iron region. By the students of the Summer School of Practical Mining, Lake Superior, 1881. School of Mines Quarterly, Vol. III, 1882. I, November, 1881, pages 35–48; II, ibid., January, 1882, pages 103–117; III, ibid., pages 197–207; IV, ibid., pages 243–253.

In the summer of 1881 the students of a class in the Summer School of Mining connected with Columbia University spent a few weeks in the Marquette district, and in the following year published a record of their observations in a series of articles. Parts III and IV of the series and a portion of Part II are devoted exclusively to descriptions of the mining operations of the district. Part I and the remainder of Part II deal largely with a theory to account for the deposition of the ore bodies.

The general geology of the district is described as in previous articles. The Laurentian rocks are apparently regarded as metamorphosed sediments, for it is related that "the beds of rock constituting the system are usually tilted at high angles, the whole series having been upturned and flexed, broken and displaced, until little evidence of the original deposition in horizontal strata remains." The Huronian rocks were observed to be tilted nearly vertical. "They have been raised into folds or crumpled into groups of irregular flexure, forming a series of irregular synclinal troughs." The diorites and diorite-schists are believed to be the prevailing rocks of the series, and apparently are regarded as sedimentary in origin. Conglomerates containing pebbles of jasper were found grading into quartzite. The ore bodies lie in the strata, forming minor folds.

The most interesting portions of the paper are those dealing with the character and origin of the ore bodies. The Champion, Michigamme, Lake Superior, New York, Cleveland, and Jackson mines are described briefly, and some points in their geology are touched upon. At the Michigamme mine the chlorite pseudomorphs of garnet were found by Messrs. Dawes and Oothout (pp. 46–47), but their nature was regarded as doubtful, since most of them were thought to be monoclinic in crystallization. This, of course, is an effect of the distortion to which the crystals have been subjected. Messrs. Crocker and Porter examined the Jackson mine (pp. 107–109). Here they found great complications in the stratigraphy. The "ore masses were deposited in the jasper by some action of water, and over and between them layers of 'soap rock' were deposited."

The description of the occurrence of the ore bodies in the Champion mine, by C. Q. Payne, gave Prof. H. S. Munroe an opportunity to suggest a theory for the deposition of the ore. Payne states that the Champion mine deposit lies in one of the minor folds of the iron-bearing rocks. It consists of a number of overlapping lenses, with the west end of one lens usually lying to the north side of the next western lens, and overlapping the underlying lens on the hanging-wall side (see fig. 2). "The foot wall of the ore bed is dioryte and the hanging wall quartzyte. Chloritic schist occurs in large quantity between the lenses and forms in nearly every case the rock-bedding under the different lenses. * * * Jasper occurs mostly on the foot-wall side of the lenses and back of the chlorite-schist." The author then, assuming that the ore was accumulated by the transporting and oxidizing action of water, proceeds to account for its deposition by supposing the original drainage of the area to have had an east-west course through a number of small lakes. In these lakes precipitation of limonite may have taken place, which, upon metamorphism, was transformed into hematite and magnetite. The different lenses of ore may represent the accumulations in different lake basins, or portions of the accumulation in a single basin, in which the process of deposition was interrupted at intervals. On this theory the overlapping of the lenses is explained by slight shifting of the localities of deposition, brought about by the same causes as produced the suspension of deposition. The sequence of the deposits, viz, ore, quartzite, and slate, is thought to be due to a sep-

FIG. 2.—Horizontal section of ore bodies at the surface of the Champion mine.

aration of the material in the lakes through the mechanical action of wind-disturbed water.

Professor Munroe, in referring to this theory of Payne's, calls attention to the fact that the water of a lake, disturbed by the action of the wind, would not separate a mixture of substances into its component portions.

> The deposit formed in the bottom of a lake would be no richer, on the average, than the sediment flowing in. There might be local patches of concentration, due to wave action on the shores of the lake, or to the deposition of heavy sediment at the mouths of small streams, but the deposit would be like the immense beds of "mixed ore" found in the iron regions. * * *

Munroe believes, however, that the mechanical action of water has in some cases played an important part in the concentration and purification of the rich ores, but he believes that the water was in the form of running streams. The heavy and purest ores were concentrated above the lighter and less pure ones, which were carried farther downstream, while the lightest particles were washed away from the neighborhood of the concentrates. Thus the ores upstream grade into less pure ores farther downstream, and these into beds containing no ore. The section illustrated in fig. 3 was supposed to lend aid to this view.

The four lenses shown in the section, with the intercalated seams of chloritic schist, suggest in their arrangement the false bedding or cross bedding sometimes found in sandstone strata. This false bedding is due to the action of running water depositing sediment in successive layers on a sloping bank. * * * For example, during and after a freshet any stream heavily charged with sediment will deposit beds of sand having this structure in the pools and wider portions of its bed.

According to this theory, magnetitic or limonitic sand would be deposited even where the current was swift, while the more common sand and clay would be carried onward. After the freshet, when the velocity of the stream

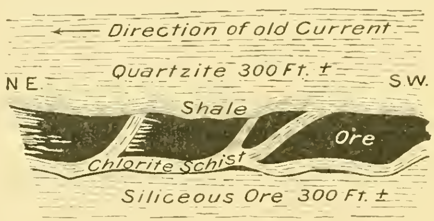


Fig. 3.—Cross-section through ore bodies at the Edwards mine.

decreased, the lighter substance would be deposited upon the iron sand, and this, when metamorphosed, would give rise to various schists. During subsequent freshets most of the lighter material would be washed away, leaving the ore bodies covered with a thin film of mud or sand. "The lighter 'tails' of the deposit being swept away, there would be left a place for a new deposit of ore beyond and overlapping the older one." The distribution of the ore bodies of the Edwards mine is thought to correspond in all respects to the distribution expected of deposits thus formed; "the pure ore is in each case at the head and the mixed ore at the tail of the natural puddle, as indicated in the sketch." When the ore lenses consist partly of magnetite and partly of specular ore, the former is found at the head, the latter in the middle, and mixed ore at the tail of each lens. This theory is intended to explain more particularly the manner of concentration of the hard ore on the Marquette range, though nowhere so stated, since nearly all of the observations upon which it is based were made in the hard-ore mines. It is interesting in that it recognizes the sedimentary origin of these ores and ascribes their concentration to the action of moving water, an agency whose geological importance in this district had hitherto been largely overlooked.

The large regular beds of ore formed in the district are thought to have been deposited originally as beds of bog ore.

CLAASSEN, EDO. Mineralogical notes. Am. Jour. Sci. (3), Vol. XXIII, 1882, page 67.

In this year also Edo Claassen published a note giving the record of an analysis of orthoclase crystals found implanted on hematite in one of the Cleveland mines. He also describes polyhedral cavities in several micaceous hematites, supposed to have been produced by the removal of crystals of pyrite from the midst of the ore.

1883.

IRVING, R. D. The copper-bearing rocks of Lake Superior. Third Ann. Rept. U. S. Geol. Survey for 1881–82, Washington, 1883, pages 89–188. With geological map of Lake Superior region.

The year 1883 marks the entrance of the geologists of the newly organized United States Geological Survey into the discussion of the Marquette problems. Prof. R. D. Irving was appointed to take charge of the work in the Lake Superior region, and from the date of his first report under the auspices of the Survey until his death in 1888 he devoted himself energetically to the solution of the problems concerning the correlation of the Lake Superior formations and those connected with the geology of the iron-bearing rocks, more particularly those relating to the Penokee and to the Marquette series. It is safe to say that, considering the short time in which he worked, no one has added more to the clear understanding of the relations existing between the various rock series in the Marquette district than has Professor Irving.

In a preliminary account of the Keweenawan series Irving discusses the relations of this series to the older rock series associated with it. In this connection he describes the Marquette Huronian schists as occurring in intricately folded troughs. He points out that the principal difference between the Huronian in this region, as described by Brooks, and that on the north shore of Lake Superior, consists in the presence in the Marquette district of diorites and other greenstones, syenites, granite, gneisses, sericite-schists, chlorite-schists, and talc-schists, jasper and chert-schists, augite-schists, and amphibolites. Otherwise the rocks in the two areas are alike. The diorites of the Marquette district are uralitic diabases. Brooks's syenite is an altered diabase rich in orthoclase. The chlorite-schists fall into two classes, in one of which the rocks are altered greenstones, while in the other they are related to hornblendic and micaceous schists. The gneisses and granites rise from beneath the schists that are associated with the iron-bearing rocks. Other schists which are interbedded with the gneisses must be regarded as belonging with them. The Keweenawan, or copper-bearing series, is distinctly younger than the Huronian.

On the map accompanying the report the Marquette Huronian occupies approximately the same area as it does on Brooks's map, except in the area southeast of Michigamme Lake, where the gneisses and granites are colored for the Archean (pp. 166–173).

Irving, R. D. The copper-bearing rocks of Lake Superior. Mon. U. S. Geol. Survey, Vol. V, Washington, 1883, xvi and 464 pages. With maps. The Marquette and Menominee regions, pages 393–409.

The same year that saw the preliminary report on the Keweenawan series saw also the full report of which the preceding paper is an abstract. About the only additional idea concerning the Huronian rocks, embraced in the detailed report, is imparted in one of the conclusions, which is as follows:

> The Huronian sediments are metamorphic, whatever the nature of the metamorphosing process may have been—and the metamorphism has always been greatest where the folding has been greatest—while the Keweenawan sediments are unaltered. The metamorphism and folding may have taken place before or during the period of Keweenawan eruptions and depositions, or both. Our present knowledge of the Huronian is too incomplete to allow of a very firm opinion as to this point. (P. 409.)

1884.

WHITNEY, J. D., and WADSWORTH, M. E. The Azoic system and its proposed subdivisions. Bull. Mus. Comp. Zool. Harvard Coll., Geol. Ser., Vol. I, 1881, pages xvi and 331–565.

In this article Whitney and Wadsworth review all the literature relating to Foster and Whitney's Azoic system, and conclude that no basis exists for its subdivision. The "diorites" of the Marquette district are again asserted to be eruptive, as are also the iron ores and jaspilites of the area. "The only evidence that the Wisconsin geologists have that the Laurentian and Huronian are what they purport to be is lithological, and they have advanced no sound argument showing that they form distinct ages in the Azoic system" (p. 497).

JULIEN, A. A. Genesis of the crystalline iron ores. Eng. and Min. Jour., Vol. XXVII, February 2, 1884, pages 81–83.

The author maintains the sedimentary origin of the jasper ores of the Marquette region. He advances the view that they were originally fragmental rather than chemical sediments. The ores are supposed to have been washed as fragments from preexisting rocks, and to have become mixed with other similarly derived detritus. Their present condition is thought to be due to metamorphism.

SMOCK, JOHN C. Geological distribution of the iron ores of the eastern United States. Eng. and Min. Jour., Vol. XXXVII, January–June, 1884, pages 217–218 and 230–232.

Smock, in his geological classification of the important iron-ore deposits of the country, places the magnetite and hematite of the Marquette district in the "Huronian period."

WADSWORTH, M. E. Lithological studies. Memoirs Mus. Comp. Zool. Harvard Coll., Vol. XI, Part 1, Cambridge, 1884, pages 136–139, 7 plates.

In his classification of the basic terrestrial and meteoric rocks the author describes thin sections of the Presque Isle and Ishpeming serpentines.

He declares that in both localities the rock was originally a lherzolite, as he had already some time earlier declared the Presque Isle rock to be. The limestones associated with the serpentine are also believed to be altered lherzolites. The peridotite is still believed to be intrusive in the overlying sandstones, and for the same reasons previously given. Fourteen thin sections of rocks were examined. Their descriptions leave no further doubt as to the correctness of the author's view concerning the origin of the serpentine. A colored plate containing three lithographic reproductions of the microscopic appearance of thin sections of lherzolite, serpentine, and dolomite illustrates the descriptions.

IRVING, R. D., and VAN HISE, C. R. On secondary enlargements of mineral fragments in certain rocks. Bull. U. S. Geol. Survey No. 8, Washington, 1884. With plates of thin sections.

Irving and Van Hise announce some of the results of their study of thin sections of Potsdam and St. Peter's sandstones—results which had already been announced in a brief form by Irving in an article published in June, 1883, in the American Journal of Science—and add a number of new facts concerning these and similar rocks of other horizons. The authors show conclusively that many of the quartzites, quartz-schists, graywackes, etc., of the Lake Superior and other regions are sandstones whose interstices have been filled with secondary quartz, largely by deposition of this material around the fragmental quartz grains in optical continuity with their substance. This conclusion is important in that it indicates that a part of the quartzites and graywackes that make up a considerable proportion of the Marquette iron-bearing series are not extremely metamorphosed rocks, but are simply sandstones hardened by quartz infiltration. Much of the mica-schist of Brooks's lower quartzite, north of the Michigamme mine, and of Formation XXI in the Penokee region shows enlarged quartz grains, and the jaspers and cherts so common in the iron formation of the Marquette Huronian sometimes contain enlarged fragmental grains of quartz in a matrix of chalcedonic silica. This latter fact is in opposition to the view of an eruptive origin for these rocks, and in favor of that which ascribes to them a sedimentary origin. A large number of thin sections are described in detail. They all confirm the conclusions outlined above.

1885.

Irving, R. D. Preliminary paper on an investigation of the Archean formations of the northwestern States. Fifth Ann. Rept. U. S. Geol. Survey, for 1883–84, Washington, 1885, pages 175–242. With maps.

In this paper we find for the first time a definite statement of the problems to be attacked in working out the structure of the Lake Superior region, and a report of the author's success in solving them.

The first problem which he attacks is the stratigraphic relation of the bedded rocks. "In the purely granitic areas this question will not present itself, and it is very doubtful whether anything in the way of a determination of a succession of layers can be accomplished in the regions where the rock is mainly gneissic." In some of the Huronian areas the succession of layers can easily be worked out, but in the Marquette area, "besides the obstacle of frequent heavy drift covering, an additional and more serious difficulty is met with in the complex folding to which the rock layers have been subjected."

The second problem which presents itself for solution is the structural relations of the plainly sedimentary rocks to others that are, or may be, of eruptive origin, such as the greenstones of the district provisionally called Huronian.

The third problem is the origin of the gneisses and granites, of the schists associated with these rocks, and of the iron ores and jaspers among the Huronian rocks.

The fourth problem is one of correlation between the rocks of different portions of the lake region. This does not concern us at present.

With respect to the Marquette series, the author writes (pp. 189–190):

The rocks of this series are highly folded, and their structure is often very difficult to work out. Moreover, the metasomatic changes which the crystalline members of the series have undergone have often been extreme; added to which difficulties are frequent interruptions by drift covering.

Although studied more minutely and by more different authorities than any other portions of the region, the divergencies of view as to structure and genesis in this region, even among the later writers, have been very great. * * *

After having obtained a thorough acquaintance with the rocks of this region and those of the type region of Lake Huron, no doubt remains in my mind as to the correctness of the position of those who have heretofore regarded the two series as equivalent. I came away from the Marquette region, indeed, with a good deal of doubt as to whether some of the greenish schists included by Brooks, Rominger, and others within the lower portion of the iron-bearing series, might not really belong with the older gneissic formation. Excluding these schists, the remainder of the series has a distinctly Huronian aspect. Like the latter, it may be described as, in the main, a fragmental slate and quartzite series, including a large proportion of basic eruptives. * * * Besides the quartzites, magnetitic schists, chert-schists, iron ores, limestones, dolomites, clay-slates, mica-slates, and greenstones, which make up the bulk of the Marquette series, a number of other less abundant kinds have been described as occurring. It is among these kinds that the lithological differences between the rocks of this region and those of the typical Huronian area of Lake Huron are found. * * *

A considerable proportion of these unusual kinds are plainly but the results of metasomatic changes upon the ordinary basic eruptives of the series, and in the list of rocks so produced come, I think, in all probability, a number of the so-called hornblende-schists and actinolite-schists.

These schists had been regarded as sedimentary by many observers because of their schistose structure, but to Irving they seem unquestionably eruptive.

The question as to the succession of beds in the Marquette district is left unsolved. Neither Brooks's nor Rominger's scheme is accepted, nor is any other one adopted. The greenstone layers, XI, IX, VII, and those below V of Brooks's divisions, including hornblendic and chloritic schists, are all believed to be eruptive, some contemporaneous with the sedimentary layers, and others intrusive in and between them.

With respect to the origin of the jasper ores, the author writes (pp. 192–193):

My studies in this connection are as yet incomplete, and I feel unwilling, therefore, to advance any general theory. But several points with regard to these ores which have impressed themselves upon our attention may be mentioned. In the first place, I may say that I am quite unable to accept any of the jaspery ores as of eruptive origin. From the most highly contorted and confused forms we have every gradation to forms in which the sedimentary lamination seems so distinct as to render irresistible the conclusion that all are of one origin. * * * Jaspery and quartzitic ores, which must, I think, be admitted by all to have had the same genesis with those of the Marquette region, occur in the Penokee-Gogebic belt, and again in the Animikie formation of the National boundary, in a relatively undisturbed position and under such circumstances that their original sedimentary deposition seems to be placed beyond doubt. What has been the origin of the iron oxide of any of these ores, whether fragmental or chemical, or both, I do not undertake now to discuss, but that much of the quartzitic material mingled with them, particularly in the Penokee belt, has had the same fragmental origin with the associated quartzites I have convinced myself from study in the field and from study of the thin sections. Besides this fragmental siliceous material, however, and occurring frequently intermingled with it, and again at times almost or entirely excluding it, is a chalcedonic or amorphous silica. Much of the jasper of the Marquette ores seems to be made up of purely crystalline quartz, but much of it also is chalcedonic or amorphous. * * * So far as our study has extended it has seemed evident to us that this chalcedonic silica is of original formation, or at least that it existed in its present condition prior to the formation of much of the series.

Reference is made to the fact of the existence of fragments of ore and jasper in the quartzite-conglomerate overlying the ore formation, which, it is admitted, proves that the ores are older than the quartzite, and that they were in their present condition prior to the deposition of the quartzite, but this is not regarded as proof that the ores and associated jaspers are eruptive.

At the time the paper was published work was being done on the schistose and gneissic areas of the district, but it had not progressed sufficiently to allow of a statement regarding the relations of the rocks of these areas to those of the Marquette sediments. The article concludes with petrographical descriptions of the different rocks met with in the Lake Superior region, among which are many from the Marquette area. The serpentine of Presque Isle is found to be an altered peridotite, as Wadsworth had shown. Wadsworth, however, believed it younger than the overlying sandstones, while Irving regarded it as older. The Ishpeming serpentines were found to b. similar to those of Presque Isle.

The examination of thin sections of the Huronian rocks showed plainly that—

the rocks which form the bulk of the Huronian in all areas do not properly fall under the head of metamorphic rocks. Of the remaining rocks met with in these areas, the various augitic and hornblendic geeenstones, peridotites, and felsitic porphyries I now look upon as in all probability of eruptive origin. There remain to be accounted for the various hornblende-schists, chlorite-schists, mica-schists, hydromica-schists, jaspery and chert rocks, and limestones. As stated above, the chloritic and hornblendic schists I regard as in part the products of the alteration of basic eruptives, and the hydromica-schists of acid eruptives. The chert and jasper rocks I am inclined to look upon as of some sort of original chemical origin; certainly they are not the results of a metamorphism of sedimentary material. The limestones do not, as far as I know them, appear in any essential respect different from many met with in the unaltered formations of later date. There remain the mica-schists and slates, and some of the hydromica-schists and chlorite-schist. That these latter often contain much of the original fragmental material we have satisfied ourselves, but how far those of their constituents which are plainly of original crystallization were so crystallized when the rocks were in the state of mud, or have been produced by purely pseudomorphic change upon fragmental material, or how far, finally, they may be the result of a genuine recrystallization or metamorphism, are questions for which I have no answer. However they may be answered, it seems to me that it will remain true that the various formations here classed as Huronian, including the original type Huronian, are in the main not properly strongly metamorphic formations, as, for instance, the older gneisses must be, if of sedimentary origin. (Pp. 241–242.)

The general map of the Lake Superior region published with this report, so far as it relates to the Marquette district, does not differ essentially from that accompanying the earlier paper on the copper-bearing rocks.

At the close of the paper is an abstract of the bulletin by Irving and Van Hise on the enlargement of quartz and other grains in fragmental rocks.

Irving, R. D. Divisibility of the Archean in the Northwest. Am. Jour. Sci. (3), Vol. XXIX, 1885, pages 237–249.

In the paper just quoted Irving referred to the gneisses and schists as older than the Huronian series. In another paper published in the same year he gives his reasons for regarding them as much older than the latter rocks. In the Penokee-Gogebic district he finds six reasons for concluding that the succession of formations is as follows: Gneiss-granite-green-schist formation; great unconformity; iron-bearing slate formation; unconformity; Keweenawan series. In the Marquette district the iron-bearing rocks are in a highly folded condition, and there is thus this difference between the Marquette and the Penokee districts. The author agrees with Rominger in believing that the "dioritic group" of this author is the basement upon which the rest of the series was spread. The members of this "group," if sedimentary, are in a highly metamorphosed condition.

Where these greenish schists come into contact with the bounding granite the latter penetrates them in the most intricate manner, so that we can not resist the conclusion that it is the more recently formed rock. From this unmistakable relation, regarding his Dioritic Group as the lowest member of the slaty or iron-bearing series, Dr. Rominger naturally passes to the conclusion that the granites are, in large measure, subsequent to his entire series. * * * To me, however, it seems plain that in the greenstone-schists at the base of the Marquette iron-bearing series we have the equivalents of those * * * south of the Penokee-Gogebic iron-bearing series, like which they form, as I conceive, part, not of the higher, but of the lower formation. * * * The slate series above the greenish schists, in the main composed of relatively little altered rocks, was originally built up upon a basement composed of granite, gneiss, *and* these greenish schists themselves, and subsequently was pushed into trough-like forms by lateral pressure. (Pp. 245–246.)

The proofs given in support of this view are the same as those advanced in the case of the Penokee district.

The penetration of the greenish schists by the granites where the two come into contact, as contrasted with the entire absence of any such relation where the bounding granite forms contacts, as it does at a number of places, with the slates and quartzites above the greenish schist group; the occurrence in the lower series of only highly altered sediments, gneiss and granite, while the higher rocks are relatively little altered; the occurrence in the higher series of fragments from the lower, "recomposed" rocks, occurring at points where the quartzites of the upper series come into contact with the gneisses of the lower—all of these arguments hold here as well as in the Penokee region. Here, then, again it seems to me plain that we have to deal with a *lower* or *greenish-schist, gneiss-granite member*, and a higher, unconformably overlying, *slaty, iron-bearing member*. (P. 246.)

Irving thus argues that there are two portions of the Azoic or Archean series in the Marquette district, and that the two portions are separated by an unconformity. To these two parts he gives the names Laurentian and Huronian, following Logan's example for the region north of Lake Huron. The names are not new, nor is the idea new that the pre-Keweenawan rocks of the Marquette district may be divided into two series. But we have here for the first time sufficient reasons given for their separation into two distinct series, and for the first time we find the green schists separated from the iron-bearing rocks and placed unconformably beneath them in the same series with the granite.

1886.

Irving, R. D. Origin of the ferruginous schists and iron ores of the Lake Superior region. Am. Jour. Sci. (3), Vol. XXXII, 1886, pages 255-272.

Irving continued the discussion in the following year, when he published an article devoted exclusively to the origin of the iron ores of the Lake Superior region, but mainly of those of the Penokee district. The conclusions reached in this paper had already been foreshadowed in the bulletin on the Enlargement of Quartz Grains in Quartzite, etc. In its introduction the author gives the status of the problem at the time of the publication of his paper. Two theories had been proposed to explain the origin of the ores and jaspers of the district in question—an eruptive and a sedimentary theory. Of the former, advocated by Wadsworth among later geologists, the author states that the phenomena cited in its favor are with one exception—

mainly trivial matters occurring within the space of a few inches, or feet, at most, and * * * all are more easily explicable as irregularities in original deposition, as irregularities due to the crumpled condition of the strata, or, and this chiefly, as due to infiltrations of iron oxide and silica into cracks in the rocks, and the replacement of rock material by such substances—on theories of original sedimentation of the iron beds than on those of an eruptive origin. * * * The occurrence of fragments of the banded jasper in the immediately overlying quartzite deserves more consideration, since it certainly indicates that, to some extent at least, these substances had reached their present condition at an early day. But cooling from a state of fusion is not the only way of reaching rapidly the indurated condition, and a former fused condition seems to be negatived at once by the nature of the material,—quartz and iron oxide. (P. 256.)

He then dismisses the eruptive theory as improbable, and proceeds to argue in favor of a sedimentary origin for the ores in question, first stating briefly the nature of the sedimentary theories already proposed.

Those who have maintained the theories of a sedimentary origin have relied chiefly upon the common intimate interlamination of siliceous and ferruginous materials; upon the manifest restriction of the ores and jaspery schists to definite stratigraphical horizons; upon their interfolding with other members of the same series, and upon their apparent gradation in places into plainly fragmental deposits. These conditions being taken to indicate original sedimentation, different authors have imagined the unaltered deposits to have been argillaceous carbonates like those of the coal measures; to have been brown ores, like those found under bogs, or accumulating in shallow lakes, at the present day; or to have been magnetic sands like those of modern sea shores. All of these theories appear to regard the silica of the jaspery schists and ores as having been sand: its present nonarenaceous, nonfragmental condition being taken to be the result of metamorphism. (P. 255.)

The studies of the author were confined largely to the Penokee-Gogebic district, where the rocks are less disturbed than they are in the Marquette district, but their conclusions are made to cover also the ores of the latter area.

While holding the sedimentary origin of the ores and jaspers, it is shown that the close association of these rocks with nonmetamorphosed quartzites, graywackes, etc., precludes the notion of a metamorphic origin for the former rocks. Moreover, "all theories of a formation of these ferruginous rocks by metamorphism or recrystallization in situ from some sort of sedimentary deposit seem to regard the jaspery or cherty material as representative of a fragmental siliceous ingredient in the original deposit. On these theories this substance has been recrystallized from a fragmental material" (p. 259). But the microscope shows that the jaspers and cherts are composed largely of chalcedonic silica, like that deposited from solution. It contains intermingled with it fragmental grains of quartz that have lost none of their original angularity, and which are easily distinguished from the chemically precipitated chalcedony. Hence, the metamorphic theory is abandoned and a chemical theory advocated in its place. According to this theory the original sediments were ferruginous carbonates. The least altered of the ferruginous schists still contain carbonaceous material, and often little rhombohedra of siderite, and the amount of this carbonate present varies inversely with the amount of disturbance and alteration the rocks have suffered. In the Penokee district a bed of hematite was traced directly into one of these carbonate-bearing schists. In this and the other unfolded Huronian iron districts there is excellent proof that the origin of the ores and jaspers was as indicated. In the Marquette district the complication of the structure obscures the evidence to a considerable extent, but from the similarity between the rock associations in this and in the less folded areas the author has no doubt that the ores and jaspers here have the same origin as in the Penokee district.

> A good many of the ore bodies, and more particularly some of the so-called soft hematites, appear to have resulted, partly at least, from a direct oxidation of the iron carbonate of some of the cherty schists. In other cases the ore bodies owe their origin and general shape, we think, to processes of infiltration and replacement. (P. 267.)

Thus after the carbonates were precipitated they were subjected to metasomatic processes.

The conclusion reached by Irving as the result of his extensive studies may be summarized as follows:

(1) The original form of the beds of the iron-bearing horizons was that of a series of thinly bedded ferriferous carbonates interstratified with carbonaceous slaty layers, like the carbonate-bearing beds of the Coal Measures.

(2) By a process of silicification these carbonaceous beds were transformed into the various ferruginous rocks. The silicification varied in degree, sometimes producing only a few seams of silica, which traverse the otherwise unchanged rock, at other times completely substituting the original rock, in which case cherts were formed.

(3) The iron thus removed during silicification passed into solution and was redeposited as it became further oxidized, making ore bodies in one place and forming the coloring matter of the jaspers in other places. The hematite interlaminated with the jasper is taken to be mainly the result of a secondary infiltration following the banding of the original rock, though it may be imagined to have been formed at times by direct oxidation from iron carbonate seams.

(4) Sometimes, instead of leaching it out completely, the silicifying waters seem to have decomposed the iron carbonate in place, producing most of the actinolitic magnetite-schists.

(5) The rich ore bodies have probably had different origins in different cases. Some of the red hematites seem to have resulted from a direct oxidation in place of the original carbonate, since in some of them pseudomorphs

of the carbonates may be detected. Some of the magnetite mines appear to be working on the richer portions of the magnetitic schists.

(6) Some of the silicifying process went on before the folding of the formation, and some of it afterward; and to the later period belong the larger bodies of crystalline ore, the crumbling and shattering of the layers affording the best conditions for the action of the silicifying waters.

PUMPELLY, RAPHAEL. Report on the mining industries of the United States (exclusive of the precious metals), with special investigations into the iron resources of the Republic, etc. Department of the Interior. Census Office. Vol. XV, Washington, 1886, pages 1–82. With maps and plates.

In the report of the Tenth Census on the iron ores, Pumpelly gives a brief survey of the Marquette district and records a number of analyses of its ores. Very little that is new concerning the geology of the district is communicated, as the work is largely a compilation. The ores are stated to be in the Huronian, which is regarded as the upper member of the Archean, unconformably reposing upon the schists of the Laurentian.

While the iron series occurs uniformly in the lower part of the Huronian, its structure and character vary in different places. In the Negaunee district it consists of a lower and an upper series. The lower is made up of flag ores, siliceous and ferruginous schists, and some argillaceous and talcose slates and anthophyllitic schists and beds of diabase. * * *

The upper series, which is separated from the lower by a bed of diabase and a thinner bed of chloritic and talcose slate, contains the rich ores. It consists of a thick mass of banded iron and "jasper," the iron ore being pure and the jasper generally colored red. * * * In places subsequent chemical action has removed portions of the jasper, while the space thus formed has been filled with limonite in large quantities, as at the Lake Superior mine. The upper part of this upper series has generally a bed of talcose slate, in which the fissile cleavage is wholly independent of the bedding, and which is impregnated with small octahedra of martite. The ore in contact with this slate has the same structure and is impregnated with similar crystals of martite. The upper portion of the upper series consists of beds of rich ore, often granular martite, with talcose schists and very talcose quartzites. (Pp. 7–8.)

The author notes that in the western part of the Marquette basin the ores are largely magnetic. The basin itself narrows and then widens out to form "the broad Huronian area of the central part of the Upper Peninsula," where the slates of the uppermost horizons are the predominant country rocks. From the south end of the wider portion of Lake Michigamme a loop of Huronian rocks extends southeastward, culminating at Republic Mountain, where the entire lower and upper series are beautifully represented.

It is needless to add that Pumpelly's Upper and Lower Huronian are not coordinate with the Upper and Lower Marquette as understood in the present volume. Some of his Upper Huronian rocks are unquestionably members of the Lower Marquette. Many of the "beds of diabase" are now known to be intrusive masses.

PUTNAM, BAYARD T. Notes on the samples of iron ore collected in Michigan and northern Wisconsin. Ibid., pages 421–437. With geological map.

In the same volume Putnam, in the introduction of his remarks upon the analyses of the Marquette ores, declares that the Marquette strata "form a broad synclinal trough, corrugated in the direction of its axis by several minor folds, resting on Laurentian rocks." He repeats some of Pumpelly's statements and gives an abstract of portions of Brooks's report. Samples of ores were taken from all the important mines of the district and were analyzed. In addition to the geological map accompanying the report, which, by the way, is a reproduction of the Brooks map, there are sketch maps of the New York, Lake Angeline, and Salisbury mines.

1887.

IRVING, R. D. Is there a Huronian group? Am. Jour. Sci. (3), Vol. XXXIV, 1887, pages 204–216, 249–263, 365–374. Read before the Nat. Acad. of Sci., April 22, 1887.

In this paper Irving returns to the discussion begun by him in 1885 The purpose of his present article is—

to inquire if there can be carved off of the upper portion of the great complex which has been called Archean, a series of *Huronian* rocks, a series entitled—by structural and genetic separateness, by elastic origin, by largeness of volume, and by being made up of subordinate divisions of the formation rank—to the rank of a group, i. e., to a rank equal in classificatory value to the Cambrian, Silurian, etc. (P. 207.)

After deciding that the series of rocks on the north shore of Lake Huron, called Huronian by Logan and Murray, deserves the title of group, Irving proceeds to discuss the relations to one another of the other supposed Huronian areas in the Lake Superior region. With respect to the Marquette area, he refers to the two views held as to the age of the granites, etc., on the sides of the Huronian trough, explaining that Kimball, Brooks, and others regarded them as unconformably beneath the bedded rocks, while Wadsworth and Rominger, among the later geologists, regarded them as eruptive into the bedded series. Irving himself finds that the green schists, which on account of their banding had always been placed with the fragmental beds as part of the iron-bearing series, are cut by granite dikes, whereas, on the other hand, the granites and their associated schists are separated from other members of the stratiform series by unconformities and by basal conglomerates containing great bowlders of the underlying granites, etc. This is explained by making a division of the rocks of the district into two series, an older one comprising the green schists, than which the granite is younger and into which it is intrusive, and a younger series composed of the bedded fragmentals and their associated rocks, into which the granite never sends dikes, but to whose lower layers it has yielded pebbles and bowlders and large quantities of finer detritus.

The upper series is composed mainly of detrital rocks, of whose fragmental nature there can usually be no doubt, though in many cases the rocks are somewhat sheared, and have had developed in them secondary sericite. With the detrital rocks are bedded limestones, cherts, etc., that are believed to have been originally chemical sediments, and interbedded diabasic eruptives. This series is a unit among the formations of the Lake Superior region, and is so similar to the originally described Huronian in its lithology and in its structural relations with other overlying and underlying formations, that it may safely be correlated with this and be called Huronian. Investigations in the other supposed Huronian areas lead to the same conclusion, viz, that the Huronian "is a true sedimentary group in origin, in volume, in chronological distinctness from other groups above and below it. It is not only *comparable*, as to volume, with the ordinarily recognized rock groups, it *exceeds* most of them; besides which it is separated from the adjacent rocks by tremendous unconformities, representative of immense lapses of time." (Pp. 370–371.)

The Huronian and the Keweenawan series together represent a great interval between Archean and Cambrian times. They may be included in one group, comprehending the fragmental series between the Archean crystallines and the Cambrian fragmentals. For this group the author proposes the designation Agnotozoic, because there are here and there traces of life in some of the rocks belonging to it, but the nature of this life is unknown. For the Marquette area, then, as well as for the remainder of the Lake Superior region, he gives the following succession:

(1) The great Basement Complex, of crystalline schists, gneiss, and granite, as to whose further divisibility or nondivisibility no opinion is now expressed. Unconformity.

(2) The Huronian series, mainly of detrital rocks Unconformity.

(3) The Keweenawan series, of interleaved detrital and eruptive beds. Unconformity. (Absent from the Marquette range proper.)

(4) The Potsdam or Upper Cambrian sandstone.

1888.

IRVING, R. D. On the classification of the early Cambrian and pre-Cambrian formations. A brief discussion of principles, illustrated by examples drawn mainly from the Lake Superior region. Seventh Ann. Rept. U. S. Geol. Survey, for 1885–86, Washington, 1888, pages 365–454.

In the following year the same author published a paper which has already become one of the classics of geological literature. In it he enunciates and discusses the principles that should determine the classification of nonfossiliferous rock series, and illustrates their application by appeal to the pre-Cambrian formations in the Lake Superior region.

After explaining in full the significance of unconformities and basal conglomerates and of lithological differences in establishing time relations between contiguous formations, the author cites examples from the Marquette district, among others, to emphasize his points.

Time gaps are shown to have existed between the deposition of the lowermost layers of the Potsdam sandstone and the formation of the underlying granites, and between the production of the former rocks and of the fragmental beds usually classed as Huronian. A picture of the unconformity between the sandstone and the granite on the lake shore near Marquette is given, and several sections are published which illustrate a similar unconformity at Granite Point, and unconformities between the sandstone and the Huronian beds at L'Anse, and on the lake shore south of Marquette (pp. 409–411). Several of these unconformities had been known as far back as Foster and Whitney's time.

Another time interval is shown to have elapsed between the formation of the granitic rocks and the deposition of the oldest Huronian beds, provided the green schists of the district are separated from the Huronian and placed with the granitic series, as had been advocated by the author in 1887. The discordance between the two series "may be proved on the ground by the discordant positions of the schists of the two series, when in contact or near proximity, by the large development of basal conglomerates where the two formations come together, by the indifference in position of the belts of the upper series to those of the lower, by the striking contrast in amounts of alteration of the upper and lower schists, and by the totally dissimilar relations of the two sets of schistose rocks to the plainly eruptive granite masses" (p. 433). Three generalized sections across the Marquette district and a reproduction of a photographic view of a hillside 2 miles south of Marquette illustrate this portion of the paper (pp. 431–435).

The Marquette iron-bearing series is described as a bedded accumulation of carbonaceous slates, ferruginous and jaspery schists, limestone, quartzite and quartzite-schists, graywacke and clay-slates, and eruptive greenstones, amounting in all to from 5,000 to 10,000 feet in thickness. The series is separated by unconformities from the gneissic and schistose beds below it, and from the Potsdam sandstone above it, and so possesses a distinct individuality, a fact emphasized in the paper of 1887.

REYER, E. Geologie der amerikanischen Eisenlagerstätten (insbesondere Michigan). Oesterr. Zeitschr. für Berg- und Hüttenwesen, Vol. XXXV, 1887, Nos. 10 and 11. Abstract in Neues Jahrbuch für Mineral., 1888, Vol. I, pages 248–249.

The original of this article has not been seen, but from the abstract of it given by Stelzner in the Neues Jahrbuch we learn that its author regards the iron-bearing series of Michigan as an association of sediments and eruptives, the latter having been poured out on the bottom of the ocean. The siliceous sediments are thought in part to have been produced through the decomposition of the eruptive masses, in part to have come from the surrounding land as erosion detritus, and in part to have been formed by the accumulation of the remains of organisms. The iron ore associated with these rocks is thought to have been deposited from springs whose iron constituent was derived by solution from the eruptive rocks. The chemical processes concerned in the formation of the ore beds were supposed to be the following: The basic eruptives contained iron as oxide and chloride. Its chloride was dissolved in the sea water, and from this dilute solution the iron was precipitated as an ocherous deposit of the hydroxide. This was subsequently dehydrated and changed into hematite. Stelzner, in the review of the article, declares that the theory rests upon the assumption that the diorites associated with the ores are eruptive, and this he states had not yet been proved.

WILLIAMS, G. H. Some examples of the dynamic metamorphism of the ancient eruptive rocks on the south shore of Lake Superior. Proc. Am. Ass. Adv. Sci., thirty-sixth meeting, 1888, pages 225–226.

In this preliminary notice of the results of microscopical work on the Marquette banded green schists Williams states that this series of rocks owes its schistosity to pressure and not to original bedding. The rocks are believed to be squeezed and stretched eruptives. The reasons for these conclusions and the descriptions of the observations on which they are based were not published in full until 1891.

BIRKINBINE, JOHN. Iron ore mining in 1887. Mineral Resources of the United States, calendar year 1887, Washington, 1888, page 34.

This author, in connection with statistical tables showing the ore production of the various American iron-ore districts, incidentally refers to the deposits of the Lake Superior mine as lying in "a synclinal fold trending east and west, the western extremity outcropping." The entire deposit is said to be underlain by chlorite-schist and to be overlain by hematite-jasper.

WINCHELL, N. H. The iron-bearing rocks at Marquette, Michigan. Geol. and Nat. Hist. Surv. of Minnesota, Sixteenth Ann. Rept. for 1887, St. Paul, 1888, pages 40–54.

A. Winchell and N. H. Winchell made a rapid trip through the Marquette district in the summer of 1887, and published records of their observations independently. At Negaunee, Ishpeming, and Marquette, N. H. Winchell made a few observations that are of some interest. In the Negaunee area the mines east of the town were the special objects of study. Here a gradation is reported between coarse quartzites, through an impure hematite banded with chalcedonic silica, into an earthy, hematitic, jasperoid rock. "This shows a common origin for them all rather than a chemical or eruptive source for the jaspilyte and not for the others" (p. 42). At the Iron Cliffs mine siderite was seen associated with the hematite. The most important observations were made in the Cascade area, where there is described as unconformably overlying the iron formation a quartzite-conglomerate. It contains pebbles of red jasper, chert, and hematite. This is the conglomerate so frequently described by the earlier geologists. N. H. Winchell appears to have been the first to have noticed that it lay unconformably upon the iron formation. It is regarded at Cascade as the southern rim of the syncline whose northern rim is in the quartzite bluffs of Teal Lake. From the character of the pebbles found in this conglomerate, "it is apparent," writes the author, "that the iron-ore formation *must have been constituted in pretty nearly its present state prior to the formation of the conglomerate*" (p. 44). This conclusion, it will be noticed, is the same as that arrived at by Wadsworth and by Irving. A little farther west, at the Saginaw mines, in the Ishpeming district, the same unconformable relations were observed between an overlying conglomerate and the underlying iron formation. Two figures are given illustrating these unconformities, in the first of which the conglomerate is labeled Potsdam (p. 45). It is evident that the author did not at this time perceive the full meaning of the facts.

North of Ishpeming the conglomeratic greenstones of Deer Lake were examined. They are described as soft, quartzless, schistose rocks, without any bedding structure that can be attributed to sedimentation. They appear to be unconformably beneath the quartzite. These conglomerates and the serpentine of the district are regarded "as one group, the serpentinous condition prevailing whenever, locally, greater alteration has taken place in the original rock, which was an eruptive, basic one. It overflowed and mingled with the rocks of the iron-bearing series unconformably, and where it is now in contact with them it constitutes, at least in some places, the 'soapstone' and the 'chloritic rock' of the mines. Subsequently the rocks of the Huronian were deposited unconformably on the iron-bearing and serpentine groups" (p. 48). The iron-bearing beds are thus placed under the Huronian, with the unconformity between this series and the Archean above the iron formation, rather than some distance below it, where Irving placed it.

The geology of the Michigamme mine is also described, and, north of it, an unconformable contact between granite and quartzite. At this contact is a conglomerate, but the author is not sure which of the two rocks is the overlying one.

At Marquette the green schists north of the town, which Irving placed below the Huronian, were examined. These are regarded as inseparable, genetically and geographically, from the serpentine group. They are believed to be eruptive, and to underlie unconformably the quartzite, and thus to constitute a part of the "iron formation."

This greenish schist * * * is heavy, dark within, free almost, or entirely, from original quartz. On its weathered surface its structure is indicated by bands of varying shades of green, and in the seams it glitters with hydro-mica. These bands of color are not continuous, but consist rather of an interrupted, narrow striping in which the color lines become lost by running to needle-shaped points or by fading into each other. The single light-colored lines sometimes continue for only a few feet or a few inches; and in some cases, when narrow, they rise and disappear in the space of less than an inch, bringing the darker lines into contact so as to present the aspect of a nearly homogeneous green rock. * * * In other places * * * the striping, which resembles that of sedimentation, is more evident and persistent, and in some parts could be more correctly denominated a banding, some of the bands being 2 or 3 inches in width; but even then they lose their identity in 10 or 12 feet and give place to a finer schisto-fibrous lining. (Pp. 51–52.)

A plat of Light-House Point is given. Here the schist is made out to be the oldest rock. This is cut by quartz-porphyry and other dikes.

WINCHELL, ALEXANDER. The Marquette iron region. Ibid., pages 171–185.

In many points Alexander Winchell differs with his brother as to the significance of the facts observed. In other points the two are agreed.

Among the points brought out by Alexander Winchell are the interstratification of the ore beds with the associated rocks, and the occurrence of a conglomerate above the ore beds in the Lake Superior mine.

The downward succession of beds in the Ishpeming syncline is thought to be as follows: red slate; black slate and mixed ore; ore; talcose rock; diorite. The red slates are banded hematite and jasper; the black slates are magnetic jaspers; and the talcose rock is an argillitic variety, as is also the miner's "soap-rock."

The Deer Lake conglomerates are regarded as sedimentary because "they contain foreign pebbles."

The contact of the granite and quartzite north of Michigamme, where N. H. Winchell reported the existence of a conglomerate, is given a peculiar interpretation (p. 177):

Immediately in contact with this [the granite] is a greenish quartzyte, which passes by transition into the granite. * * * It might also signify that the "granite" was originally a sedimentary rock, but, containing more feldspar-making elements than the quartzyte, metamorphism changed it to a rock of the granite series, but could not make anything but a quartzyte of the overlying beds.

Near the Buffalo mine the author saw a black argillite, which was thought to be unconformable on quartzite.

After describing other phenomena seen by him, Winchell sums up his study in these conclusions (p. 185):

The Marquette iron-bearing rocks are not of Huronian age. * * * That they are older than Huronian is shown by a fourfold line of evidence. (*a*) *The rocks are different.* In the original Huronian the argillites are almost exclusively black and carbonaceous or magnetitic, instead of bluish or ashen and hæmatitic. They are more prevalently siliceous or flinty. The quartzytes attain a more enormous development, are much purer, especially the upper, and hold position entirely above the argillitic member. (*b*) *The Canadian Huronian succeeds immediately beneath the Palæozoic system.* The Marquette strata do not. The Marquette strata are succeeded immediately downward by crystalline schists. The Huronian strata are not. (*c*) *Some evidences exist of an unconformable overlying sub-Palæozoic system in the Marquette region.* I refer here both to the unconformability described in the * * * vicinity of the Buffalo mine, and to Major Brooks's brief notices of highly carbonaceous black slates occupying a position higher than the Marquette argillytes. (*d*) *Proof is to be adduced in this report of the unconformable subterposition of the Vermilion iron schists relatively to the Animike slates.* If the Marquette and Vermilion rocks are mutual equivalents, the former must hold position beneath the same system—that is, beneath the Huronian. *The Marquette iron-bearing rocks belong to a system not yet defined.* If they underlie the Huronian they equally overlie the Laurentian. They are not separated from the Laurentian by a structural unconformability, but by the evidences of a long intervening lapse of time and a most important change in the action of the geologic forces. Strata fully crystalline and strata essentially earthy, though found in conformable juxtaposition, must necessarily belong to two different ages and modes of geological activity.

For this "older system" in Minnesota the author suggests the name Marquettian (p. 365).

1890.

WADSWORTH, M. E. A sketch of the geology of the Marquette and Keweenawan districts. Along the south shore of Lake Superior. Published by Duluth, South Shore and Atlantic R. R., 1890, pages 65–82.

In 1890, after having been appointed State geologist of Michigan, Wadsworth published a very interesting article, which, though written for the traveling public, gives a succinct and strictly scientific account of the geology of the iron and copper districts of Michigan from the author's point of view.

All of the rocks under the Potsdam sandstone are placed in the Azoic system. They are stated to have been formed in three ways: (1) By mechanical means; (2) by eruptive, igneous, or volcanic agencies; and (3) by chemical action.

The rocks of mechanical origin are the detrital quartzites, argillites, gneisses, schists, conglomerates, etc.

These rocks were invaded by eruptive material forcing its way irregularly through the soft sedimentary materials, indurating them, bending their planes of deposition, changing their color, and sending tongues, arms, and dikes through them in every direction. It has also been protruded through the schists in large masses, contorting them and tearing them across, and oftentimes ending in small arms or branches. This eruptive rock is now very greatly metamorphosed, and is termed jaspilite. Like the siliceous eruptive rhyolites and felsites, it is generally more or less banded in its character, which banding is due to its having flowed, the same as is seen in the banding of the siliceous furnace slags. * * * It is this fluidal structure or banding that is so often mistaken in the rhyolites, felsites, trachytes, and jaspilites for the planes of sedimentation. (P. 69.)

The ore associated with the jaspilite is said to be a concentrate from its magma. In places the rocks have been shattered and their cracks filled with ore through the action of percolating water. After cooling, the jaspilites were acted upon by the waves, yielding a detritus that was deposited upon the underlying ore deposits, forming true sedimentary deposits, many of which have been since worked for ore.

Three kinds of ores are distinguished, magnetite, hematite, and martite. The ore associated with the jaspilite is usually of the latter kind.

The argument in favor of the eruptive origin of the ores and jaspilites is outlined, and it is stated that in 1885 Charles E. Wright, at that time State geologist of Michigan, had proved to his own satisfaction that the ores are eruptive. The author dismisses Irving's argument for their sedimentary origin by declaring that he "starts out with either denying or ignoring the occurrence of the very facts which the present writer has figured, and which caused him to hold the eruptive view. A theory of the origin of the iron ores that starts out with denying the facts that it ought to explain can hardly be accepted until it recognizes these facts and explains them" (p. 71).

After the eruption of the jaspilites and their denudation, other rocks were forced through the strata in a molten condition. Diabases and diorites were the first rocks introduced, and they added so much volume to the already existing rocks that these were thrown up into folds. Many of these diabases and other basic rocks have become schistose, but they do not pass into sedimentary schists, as has been supposed by some observers. "The two look closely alike and are similar to each other in composition, but do not pass into one another any more than water and oil do, although a hasty observer might not see the line of separation between the two" (p. 72).

The author mentions that at the Cleveland mine and elsewhere the "schistose diabase and diorite come in contact with the sedimentary schists" (p. 72).

Granite eruptions succeeded those of the basic rocks, as did also those of serpentine. The age of the latter with respect to the granite is not determined.

The principal deposits of chemical origin in the district are the soft ores. The jaspilites and their associated ores and rocks have been leached by percolating, usually hot, waters, and their iron oxides dissolved and deposited elsewhere along the channels through which the waters flowed, or the silica has been removed and the ore left behind or locally concentrated. On top of the Azoic rocks and unconformable with them lies the Potsdam sandstone.

The two important points to be noted are that the author had not, up to this time, changed his views as to the age of the granite, which he still believed to be younger than the ore beds, nor as to the origin of the ores associated with the jaspilites, both of which latter rocks are still regarded as eruptive.

1891.

IRVING, R. D. Explanatory and historical note. The greenstone-schist areas of the Menominee and Marquette regions of Michigan. Bull. U. S. Geol. Survey No. 62, Washington, 1891, pages 11–24. With map.

In 1891 appeared the paper by G. H. Williams on the greenstone-schist areas of the Menominee and Marquette regions, in which it was shown that the banded green schists (which had been regarded by most geologists as sedimentary and had been placed by them in the iron series, and which Irving had separated from the Huronian and placed in the Basement Complex) are fragmental volcanic rocks and lavas.

As an introduction to the discussion, Irving gives an account of the general relations of the schists to the granite and to the fragmental rocks associated with them, and explains in more detail than had been done hitherto his reasons for separating them from the Huronian series and placing them with the underlying granites and gneisses.

Besides occurring here and there more or less confusedly mingled with masses of granite and other rocks, these greenish schists occur also in large continuous areas, which they entirely occupy, except for certain relatively unimportant basic and acid intrusives. * * * The bulk of these areas is composed of nondescript fine-grained greenish schists, which appear to grade into the more massive greenstone-like forms on the one hand, and into the more distinctly developed chloritic and hornblendic schists on the other. As a rule these various schists present no parallel structure other than that which seems referable directly to secondary causes; that is to say, they do not present such banded varieties as would suggest the action of sedimentation during their production. However, such banded varieties do occur in subordinate quantity, presenting then very strikingly regular, rapid alternations of light and dark bands. (P. 11.)

In some places within the greenstone areas there occur schists with a more or less obscure fragmental appearance, which is much more pronounced on the weathered surface than on the fresh fracture. As a rule these schists are without any parallel structure except the slaty cleavage which all the green schists present. Among them are the rocks observed by A. Winchell and N. H. Winchell at Deer Lake.

In his description of the map (Pl. III, fig. 2) accompanying his paper the author writes (pp. 14–15):

The line of demarkation between the schists and the granites * * * is not a sharp one, since the two seem to mingle more or less confusedly on each side of the somewhat arbitrary line indicated upon the map. Southward of this greenstone-schist area * * * are belts of country occupied mainly by detrital rocks, such as quartzites and various fragmental slates; with these, however, are large bodies of crystalline limestone and several phases of ferruginous schist, all of which have in common an entire lack of anything like a fragmental texture. In addition to these rocks these areas include also sheets of diabasic greenstone, which are interbedded with the detritals and ferruginous schists alluded to.

The author contrasts the schists with the detrital rocks to the south of them. He agrees with the earlier workers in the district as to the inferior position of the greenstone-schists with respect to the stratiform series, and as to the intrusion of the schists by the granite. But he disagrees with previous geologists who regarded the green schists as belonging in the stratiform series and the granite as younger than the detrital series.

In other words, it thus far appears to me that there is good reason to believe that these greenstone-schists along with the granites, gneisses, etc., form a portion of the basement upon which the overlying detrital iron-bearing series was once horizontally and unconformably spread.

The granites are shown to be unconformably beneath the detrital series and to be at the same time younger than the greenstone-schists;

hence these latter rocks must be much older than the detrital beds. In the conglomerates separating the granites from the overlying stratified beds there are often fragments of schists, and frequently there is a matrix composed of comminuted greenstone. In the SW. $\frac{1}{4}$ of SE. $\frac{1}{4}$ sec. 29, T. 48 N., R. 25 W., a conglomerate composed of fragments of granite, quartz, and green schist, cemented by a dark slaty material, lies immediately on the contact of the greenstone-schist area with that of the detrital series.

Such occurrences as these, when considered in connection with the manner in which the granite penetrates the greenish schists and is involved with them, seem to render necessary the belief that, while it is plainly younger than the green-schists, it is nevertheless greatly older than the overlying detrital rocks; and, more than this, that when the latter rocks were spread, the granites and greenstone-schists together had already suffered disturbance and deep denudation. It does not appear possible to escape this conclusion by supposing that, since granite and greenstone-schists are eruptives, they may have furnished fragments to almost contemporaneous sedimentary deposits; for, in the first place, both the greenstone-schists and the gneissoid granite must have received their schistosity before yielding the fragments. Moreover, whatever may have been the depth at which the schistose rocks were first formed, the granite masses which intruded them, according to all the later developments and doctrines of petrography, must have been crystallized in depth, and must therefore have had removed from over them great masses of materials before yielding fragments to wave action. (P. 23.)

These remarks refer to the coarse granites of the district, and not to the fine-grained red granites which intrude the coarse granite and may be even as young as the iron-bearing series, though none of its dikes have been seen cutting the detrital rocks in the Marquette area.

* * * Accepting Professor Williams's conclusions as to the surface origin of most of the greenstone-schists of the Marquette region, I should suppose that, after the accumulation of these rocks to the thickness of several thousand feet, they were intruded by granite bosses. These bosses perhaps may have been merely softened portions of the underlying gneissic basement, which, indeed, may be represented in an unaltered condition in portions of the granitic areas themselves, for all that has yet been determined to the contrary. Subsequently mountain-making movements brought about the folding and alteration of these enormous sheets of eruptive material, now represented by the greenstone-schists. Following this was the great denudation which brought to light the previously buried granitic masses. This erosion was

followed in turn by the accumulation in the usual horizontal position of the iron-bearing detrital series, whose folding and erosion were still later processes. And yet this folding and erosion all preceded the deposition of the horizontal Cambrian sandstones of the region. (Pp. 23–24.)

A confirmation of these conclusions is furnished, according to Irving, by the similarity between the great dikes cutting the greenstone-schists and the sheets of eruptive greenstone in the iron-bearing series.

For the latter greenstones are in large measure interstratified with the sedimentary layers of the iron-bearing series, following the bending of its layers; so that, even if these greenstones are in the nature of intruded sheets, it seems necessary to believe that their intrusion took place before the folding of the iron-bearing series. Now, the corresponding dikes in the greenstone-schist area were evidently intruded subsequent to the production of the schistosity of the intruded rocks. If, then, these are facts, the time when the iron-bearing series was folded was very much subsequent to that time at which the greenstone schists received their schistosity. (P. 24.)

The map accompanying Irving's paper is practically Rominger's map interpreted according to Irving's view. That is, the greenstone-schists are placed with the granites below the iron-bearing series. In the legend of the map we see for the first time the use of the term Algonkian, by which it was decided by the United States Geological Survey to designate the fragmental series lying between the Archean crystallines and the base of the Cambrian. The term stands in the period place as equivalent to the Agnotozoic group.

WILLIAMS, G. H. The greenstone-schist areas of the Menominee and Marquette regions of Michigan. Bull. U. S. Geol. Survey No. 62, Washington, 1891, pages 134–217. With plates of thin sections.

Williams's paper deals primarily with the microscopical features of the green schists already so frequently mentioned.

The author divides the district studied into four areas: (1) The Eastern area, near Marquette; (2) the Western area, immediately north of Teal Lake, in the town of Negaunee; (3) the Northern area, lying north of Dead River; and (4) the Deer Lake area. The Eastern area is further divided into a northern and a southern half.

In the north half of the Eastern area the layers of the schists—

are alternately of a darker and lighter shade of green, which gives these particular greenstones their characteristic striped appearance. In these banded rocks * * * intrusions of comparatively little altered acid and basic matter are abundant. These are for the most part conformable to the bedding of the schists, and embrace granites, gneisses, schistose prophyries, diorites, and diabases. Whenever, in these undoubtedly eruptive rocks, a schistose structure is apparent, this is conformable to the bedding of the banded greenstone-schists.

The southern portion of the area * * * is occupied by much more massive and homogeneous greenstones of a nearly uniform light-green color and an almost aphanitic structure. These are characterized by their division into oval or lenticular areas which interlace and which are separated by a finely schistose material of much finer grain. This peculiar parting, * * * at first glance, resembles the spheroidal weathering of many eruptive rocks. There is, however, better reason for regarding it as of mechanical origin. * * * Intrusive rocks are rarer than in the banded greenstones of the northern portion of this area. (P. 137.)

A large number of thin sections of these schists are carefully described. Some of the descriptions will be referred to in the body of this monograph. At this point it will be necessary simply to quote the author's conclusions.

With reference to the rocks of the Northern area he writes (p. 158):

* * * The structure of these greenstone-schists is such as to necessitate a belief in the original nature of their stratification; while, on the other hand, their chemical as well as their mineralogical composition renders it impossible to separate them from the massive and highly altered greenstones (uralite, diabases, etc.) with which they are more intimately associated. Their parallel banding indicates a fragmental, but their chemical and their mineral composition indicate an igneous origin. The only satisfactory reconciliation of these opposite sets of characters is to be found in that group of rocks intermediate between sediments and lavas, known as volcanic tuffs.

In the opinion of the writer, then, the banded greenstone-schists of the Northern Marquette area are to be regarded as consolidated and highly metamorphosed *diabase tuffs*. These are intimately associated with numerous contemporaneous flows of diabase and quartz-porphyry, together with tuffs of the latter rock; while all have been broken through by much younger dikes, both basic and acidic.

The rocks of the Southern area are not banded. "They are, for the most part, massive, pale green in color, and apparently homogeneous in structure."

Of these the author says:

> The occasional survival of the characteristic diabase structure even in some of the more foliated forms, taken in connection with their evident identity with and gradual transition into the massive varieties, appears to be sufficient proof that, with the exception of certain unimportant tuff deposits, these green-schists have been derived from basic eruptives through the agency of intense mechanical and chemical action. (P. 165.) Originally [they were] massive basic flows. (P. 163.)

The greenstones of the Western or Negaunee area, the second chosen for examination, are like the schists of the Southern Marquette area, while those of the area north of Dead River are essentially similar to the rocks in the Northern Marquette district.

Of the Deer Lake area Williams has little to record. A transcription of portions of Irving's field notes describes this area as underlain by the greenstone-conglomerates referred to in his published papers and in the articles of Rominger, N. H. Winchell, Alexander Winchell, and others. Williams recognizes these as composed of volcanic detritus, ejected by an explosive force at the earth's surface. He calls them agglomerates, which term is used "to designate a tumultuous assemblage of volcanic ejectamenta, bombs, foreign blocks, etc., of all sizes and shapes, cemented by a fine-grained paste of volcanic ash" (p. 190).

VAN HISE, C. R. An attempt to harmonize some apparently conflicting views of Lake Superior stratigraphy. Read before Wisconsin Acad. Sci., December 30, 1890. Am. Jour. Sci. (3), Vol. XLI, 1891, pages 117–137.

In this article the author points out the significance of the existence of the conglomerates above the ore horizon. He calls attention to the fact that Foster, Foster and Whitney, Brooks, Rominger, Wadsworth, Irving, and the Winchells had all recognized and described these conglomerates, and that they all had detected in them fragments of the underlying formations, but the Winchells only regarded them as marking a break in the succession of beds of sufficient importance to warrant placing the rocks above and below it in different geological ages. N. H. Winchell believed the break so great that the overlying rocks were provisionally referred to the Potsdam.

The author describes the occurrences of the conglomerate at the Goodrich, Saginaw, Fitch, Barron, Winthrop, Cascade, Wheat, Jackson, Lake

Superior, Barnum, Boston, Spurr, Michigamme, and Republic mines, and shows that in many instances its stratification is unconformable with that of the ores and jaspers in contact with it and below it. He publishes a photograph of the contact at the Goodrich mine, which exhibits the layers of the jasper abutting against the conglomerate, and the latter unconformably upon them. Since this conglomerate, as well as other similar ones, contains ore, chert, and jasper fragments in precisely the same condition in which they occur in the underlying formation, it is plain that the latter had reached its present condition before the conglomerate was deposited. There is thus evidently a large time break, represented by this unconformity, in the series of rock beds lying above the granites and schists and beneath the Potsdam sandstone. In other words, the rock series heretofore known as the Huronian in reality includes two series, one above and the other below the conglomerates lying upon the ore-bearing formation.

Those [the rocks] upon the lower side of this break, in the exceedingly contorted jasper, in the schistose character of its quartzites, and in the general assumption of a semicrystalline character, show the evidence of profound dynamic action. In the upper series, on the contrary, the folding has not been intense; the fragmental character of the slates and quartzites under the microscope is evident at a glance, and no indication of great dynamic action is seen. While subsequent to the deposition of the upper series the whole region has been subjected to a new folding, great enough in places to give the later series a dip of 60° or 70°, as at the Goodrich, it has not suffered since that time such intense dynamic movements as have produced the more thoroughly crystalline and folded character of the earlier series. (P. 122.)

These facts confirm the correctness of the view that the two series belong to fundamentally different geological epochs.

In a footnote Van Hise refers to Wadsworth's anticipated objection to this theory in view of the fact that the ores and jaspers are regarded by him as eruptive, and states that this author's facts "indicate the eruptive origin of the ore and jasper only if the schists are of sedimentary origin." His own investigations show, however, that the Marquette iron-bearing members "contain many schistose dikes, and also that in many cases the massive greenstone knobs of the Marquette region vary by imperceptible stages into the schists associated with the iron ore and jasper. The schists are then, in part at least, of eruptive origin. * * * This view reverses

Dr. Wadsworth's, and makes his sedimentary rocks eruptive and his eruptive ones sedimentary" (pp. 123–124).

The remainder of the paper is devoted mainly to the correlation of the several Huronian areas in the Lake Superior region, and to a discussion of principles of nomenclature. The terms Upper Marquette and Lower Marquette are used by the author to designate those portions of the Huronian above and below the unconformity in the Marquette district, and these together comprehend all the Algonkian series in this district. Below the Lower Marquette is the Fundamental Complex of schists, granites, etc., (the Archean rocks), and above the Upper Huronian lies the Potsdam sandstone.

Of course, where the Upper Marquette is in contact with the Archean there are conglomerates and unconformities between the two series, just as there are between the Archean rocks and those of the Lower Marquette series. In each of the two series there is believed to occur an iron-bearing formation. The banded jaspers and ores immediately under the conglomerates belong in the Lower Marquette, and the cherty ores of the Daliba, Wetmore, and Beaufort mines, all of which are in black slates, belong in the Upper series.

WADSWORTH, M. E. A sketch of the geology of the Marquette and Keweenawan districts. Along the bowstring or south shore of Lake Superior. Published by General Pass. Dept., Duluth, South Shore and Atlantic Railroad, 1891, pages 77–91.

In a second edition of the little handbook of the Duluth, South Shore and Atlantic Railroad we find Wadsworth's views on the origin and relations of the Marquette rocks rapidly changing, as the result of the studies by the Michigan survey, of which he had been the chief for several years.

Instead of classing all the formations of the district in the one "Azoic" group, the author separates them into three divisions, naming them the Cascade, the Republic, and the Holyoke formations.

In the Cascade formation are placed the hornblende-schists which are invaded by granite and other eruptive rocks south of Palmer, and certain detrital rocks composed of their débris, besides the eruptive jaspilites and ores associated with these. No new facts are given with respect to the origin of the ores, but the author repeats his former view and emphasizes the notion of the eruptive origin for these particular ores.

Above the ores, and forming the base of the succeeding Republic formation, he places a series of fragmental deposits of ore and jaspilite. These are described at much greater length than in the earlier article. The ores constitute a large proportion of those mined. They pass upward into quartzites. The contacts between the fragmental and eruptive jaspilites and ores can be seen at the Jackson, Lake Superior, and other mines. In the Cascade range all the jaspilite is of the fragmental kind; its layers are interlaminated with those of quartzite.

Above this fragmental jaspilite formation, with its associated quartzites and schists, both at Republic and at Cascade, there is another fragmental series, composed of conglomerates, quartzites, schists, etc. This formation is well seen at the Holyoke mine, and hence has been called the Holyoke formation.

The diabases and diorites are still believed to have been erupted after the denudation of the nonfragmental jaspilites—that is, in Republic time. Of the granite, however, two eruptions are now recognized. One of these "is older than the detrital jaspilite, if not older than any of the ore-bearing formations, while another occurred subsequently to the eruptions of the beforementioned * * * diabases and diorites."

The peridotite of Presque Isle is now regarded as younger than the granite in its proximity, while that northwest of Ishpeming is shown to be younger than any other of the large intrusive masses in the Marquette district.

The most important facts brought out in the paper, especially important because they are opposed to the author's earlier opinions, are: the divisibility of the Azoic into three formations of different geological ages; the recognition of an old granite, older than most of the ore deposits; and the acknowledgment of the sedimentary origin of many of the ores and jaspilites. The green schists are presumably still placed above the oldest formation of the district.

HUNT, T. STERRY. The iron ores of the United States. Trans. Am. Inst. Min. Eng., Vol. XIX, New York, 1891, pages 3–17.

In his Pittsburg address to the mining engineers Hunt gave a rapid review of the geological relations of the iron ores of the United States. The pre-Paleozoic rocks for the entire country are divided by him into the Laurentian, Norian, Avonian, Huronian, Montalban, and Taconic systems, and the rocks comprising them are believed to have been deposited in a hot ocean highly charged with active chemical agents. The Marquette ores are placed in the last of the above divisions—the Taconic—and in that division of it which the author denominates the Animikie. With regard to the ores of these pre-Paleozoic terranes the author writes:

> We moreover reject as untenable the notion of the igneous origin of the iron ores themselves, which appear to be in all cases deposited from water, generally contemporaneous with the inclosing rocks, but more rarely by subsequent processes in fissures, after the manner of mineral veins. (P. 5.)

GOETZ, GEORGE W. Analyses of Lake Superior ores. Ibid., pages 59-61.

Goetz gives a record of the analyses of ores from thirty-six mines in the Marquette district.

LANE, A. C., KELLER, H. F., and SHARPLESS, F. F. Notes on Michigan minerals. Am. Jour. Sci. (3), Vol. XLII, 1891, pages 499–508.

The authors identified the chloritoids of Humboldt, of the Fitch and the Champion mines, referred to briefly and only incidentally by the geologists who had studied the district, as a triclinic chlorite similar to masonite. It occurs "in altered arkoses or similar rocks, in one case both in the cement and in the basic and acid pebbles of a conglomerate." They also find that the hornblende in the "actinolite" or "anthophyllite" schists, associated with the ores, especially of the western portion of the Marquette area, is a monoclinic iron-amphibole or a grünerite.

VAN HISE, C. R. The pre-Cambrian rocks of North America. Compte-rendu 5th sess. Internat. Cong. Geologists, Washington, 1891, pages 109-150.

This article is a condensation of the eighth chapter of the correlation bulletin on the Archean and Algonkian of North America which is referred to on pages 133–135.

Van Hise, C. R. Pre-Cambrian geology of the Lake Superior region. Ibid., pages 489–512. With maps.

In this paper, which is explanatory of a trip made through the iron districts of Lake Superior with some members of the International Congress of Geologists, the author gives descriptions of the general character of the Basement Complex and of the Upper Huronian and Lower Huronian series. Very little is contained in these descriptions that had not been given in earlier publications, of which it is largely an abstract. The maps are reproductions of those published by Brooks, Irving, G. H. Williams, Pumpelly, and Van Hise.

1892.

Van Hise, C. R. The iron ores of the Marquette district of Michigan. Am. Jour. Sci. (3), Vol. XLIII, 1892, pages 116-132.

In this paper Van Hise gives a résumé of the results of a preliminary examination of the Marquette district.

Two ore-bearing formations are recognized in the district—one belonging in the Lower Marquette and the other in the Upper Marquette series, as defined by the author.

The ore deposits of the Lower Marquette series consist of the banded jasper and ore so many times described. The jasper is not a fragmental rock. It is composed of individualized silica, forming bands which, when white, are known as chert. When the grains are stained with red oxide of iron they give rise to jasper. The siliceous bands are not regular in thickness. They sometimes extend for long distances with a nearly uniform width. Sometimes they wedge out abruptly. Often they occur as rows of lenticular masses. Near the top of the formation the silica is nearly all jasperized. Farther down, as a rule, it is more cherty, until in the lower portions of the formation the siliceous bands are white.

Actinolite-magnetite-schists are also associated with the ores, especially where these are magnetites.

Another and important component of the ore-bearing formation is a cherty carbonate of iron. This has been found most frequently where the formation dips under a greenstone. Cutting these rocks are bosses and dikes of "greenstone," which were originally, in most cases, diabase. In their present condition they consist of diorites, chlorite-schists, talc-schists, and other similar rocks which are known locally as "soapstones," "paint rock," etc.

The rocks overlying the ores are the conglomerates and quartzites at the base of the Upper series. The rocks occupy a great synclinal fold, which in some places is corrugated into minor folds.

After thus outlining the general features of the lower iron formation, the author proceeds to discuss the mode of origin of the ores. He classifies the deposits as follows: (1) Those at the contact of the quartzite-conglomerate and the ore-bearing formation; (2) those resting upon soap-rock, which grades into massive diorite; (3) those resting upon soap-rock dikes cutting the formation; (4) those interbedded in the jaspers and cherts.

Deposits of the first kind consist usually of specular or magnetic ore. They occur either within the underlying jasper-ore formation or within the basal layers of the conglomerate. In the latter case they are genuine detrital concentrations. Those deposits within the jasper, but at the contact of this with the conglomerate, are found usually where the former rock is shattered, or sharply folded, or where cut by dikes. The jasper often passes into the ore gradually.

> In following a jasper band toward the ore it was found that instead of remaining solid it becomes porous and frequently contains considerable cavities. These spaces in the transition zone are lined with crystalline ore. In passing on toward the ore deposit more and more of the silica is found to have been removed, and the ore has replaced it to a corresponding degree. An examination at many localities led to the conclusion that the transition from the banded ore and jasper to the ore takes place as a consequence of the removal of silica and the substitution of iron oxide. Often in these cases the fine-grained part of the ore is that of the original rock, while the coarser material is the secondary infiltration. (P. 121.)

The deposits of the second class comprise many of the soft ores and some of the hard ores. In either case the ore body follows along the contact plane between the impervious "soapstone" and the unchanged jasper.

In deposits of the third class the ore, which is usually soft, may lie upon both sides of a vertical dike. When the dike is inclined at a high angle the ore lies on its upper side only. In the troughs formed by interpenetrating dikes or by offshoots from large masses of "diorite" the ore deposits are the thickest.

Large ore bodies of the fourth class are unknown.

All the ore bodies of the second, third, and fourth classes lie wholly within the lower iron formation, and at any horizon within it, provided in the second and third cases there be present a "soapstone." Thus the distribution of the ores is similar to their distribution in the Penokee district, where they have been shown to be dependent upon the presence near them of some rock impervious to water.

All the facts bear toward the conclusion that the ore is a secondary concentration produced by the action of downward percolating water. * * * The ore deposits occur at places where circulating waters are sure to be concentrated. The soap rock accommodates itself to folding without fracture, and while probably allowing more or less water to pass through, acts as a practically impervious stratum, along which water is deflected when it once comes in contact with it. * * * On the other hand, the brittle, siliceous, ore-bearing formation has been fractured by the folding to which it has been subjected, so that where these processes have been extreme water passes through it like a sieve. That the tilted bodies of diorite or soap rock, especially when in a pitching synclinal or forming a pitching trough by the union of a dike and a mass of diorite, must have guided downward-flowing waters is self-evident. * * * It is also plain that the contact plane between the quartzite-conglomerate and the ore-bearing formation, that is, the plane of unconformity between the Upper and the Lower Marquette series, must have been a great horizon for downward-flowing waters. (P. 125.)

Along these channels silica was removed and iron oxide concentrated.

After arguing the question the author concludes that the concentration of the ores occurred, in all probability, "during and later than the folding and erosion subsequent to Upper Marquette time" (p. 126), through the long continued action of percolating waters, flowing downward along channels whose courses were determined by the existence of impervious rock masses cutting through less impervious ones, or were directed by the contact plane between the Upper and the Lower series. The iron probably came from the formation in which the ore now occurs, and the diabases in their alteration to "soapstones" provided some of the alkalis necessary to dissolve the silica.

The difference between the soft and the hard ores is supposed to be due to the fact that the latter were first deposited in a crystalline condition and were afterward sheared, and that the schistosity of the ore at the contact of the Upper and Lower series, as well as that interbanded with the jaspers, is the result of this shearing. The magnetic ore in the contact deposit is thought to have been directly deposited in that form, while that in the actinolite-schists may have been formed by direct oxidation of an original iron carbonate.

The Upper Marquette ores have in general the same origin as the Lower ones. The impervious strata here are often beds of black slate. Unaltered carbonate is often found associated with the ores, and there is little difficulty in recognizing all the stages of alteration between this and the oxide ores.

Sometimes a single ore body may belong in part to the Lower Huronian and in part to the Upper Huronian, the replaced ore of the former and the mechanical ore of the latter, at the contact of the two formations, being welded together by secondary infiltrations.

VAN HISE, C. R. The iron ores of the Lake Superior region. Trans. Wisconsin Acad. Sci., Arts, and Letters, Vol. VIII, 1892, pages 219–228.

The author treats the same subject in this article as in the last. The discussion in the present paper, however, is more comprehensive and less technical than that in the preceding one.

VAN HISE, C. R. Correlation papers—Archean and Algonkian. Bull. U. S. Geol. Survey No. 86, Washington, 1882, pages 52–208, and Chapter VIII. With map, page 48.

This is the correlation essay to which reference has already been made. In it the author reviews the literature on the Lake Superior region, summarizes it, and interprets it with the aid of his own experience. The conclusions as to the succession in the Marquette district are in accord with the author's views as published in earlier papers.

Some of the general conclusions reached in the study have a direct bearing on the geology of the Marquette district, since this is one of the areas that have yielded premises for the conclusions.

It is shown that the schistose crystallines under the Huronian rocks in this district are older than the latter, forming a basement on which the fragmental rocks were deposited.

The basement series—

consists of a most intricate mixture of nearly massive rocks, among which granite and granite gneiss are predominant; of gneissic and schistose rocks, all of which are completely crystalline, and so folded and contorted that nowhere has any certain structure ever been made out over considerable areas. * * * The minerals in the rocks generally show evidence of dynamic action; they do not have the clear-cut, definite relations characteristic of the later plutonic rocks. * * * Further, the basal complex is not only recognized by its positive but by its negative characters. Nowhere in it is a persistent thick formation of quartz-schist (although vein-quartz is abundant), of limestone or marble, of a graphitic schist, or of a conglomerate. (P. 476.)

This complex, in its positive as well as in its negative characteristics, is unique among the geological formations; hence, observes the author, it deserves a descriptive name (Archean) to distinguish it from the clastic formations above it.

Concerning the origin and stratigraphy of this complex little is known.

The only division generally applicable to the Archean warranted by present knowledge is its separation into (1) fine grained mica-schists, feldspathic mica-schists (technically gneisses), hornblende-schists, hornblende-gneisses, etc., and (2) the granites and granitoid gneisses, with their associates. (P. 488).

The term Laurentian is proposed for the lighter-colored, gneiss-granite portion of the complex, and Mareniscan for the darker, schist portion.

The classification of the Marquette rocks, then, in its general features, is as follows:

Paleozoic	Cambrian	Potsdam.	
Agnotozoic or Proterozoic	Algonkian	Keweenawan.	
		Huronian	Upper.
			Lower.
Archean	Archean	Mareniscan and Laurentian.	

In the Lake Superior region, between the Archean and the Potsdam sandstone, the great Algonkian system is subdivided into three series, which are separated by very considerable unconformities. The lowest series is closely folded, semicrystalline, and consists of limestones, quartzites, mica-slates, mica-schists, schist-conglomerates, and ferruginous and jaspery beds, intersected by basic dykes, and in certain areas also by acid eruptives. It includes volcanic clastics, often agglomeratic, and a green chloritic, finely laminated schist. The thickness of this series has not been worked out with accuracy, but at its maximum it is probably more than 5,000 feet. As the term Huronian has been for many years applied not only to the Upper Huronian series, but to this inferior series about Lake Superior, it is called Lower Huronian.

Above this series is a more gently folded one of conglomerates, quartzites, slates, shales, mica-schists, ferruginous beds, interbedded and cut by greenstones, the whole having a maximum thickness of at least 12,000 feet. * * * In its volume, degree of folding, and little altered character the Upper Huronian is in all respects like the upper series of the original Huronian, and can be correlated with it with a considerable degree of certainty. Above the Upper Huronian is the great Keweenawan series. * * *

The unconformity which separates the Lower Huronian from the Upper Huronian and that which separates the latter from the Keweenawan each represents an interval of time sufficiently long to raise the land above the sea, to fold the rocks, to carry away thousands of feet of sediments, and to depress the land again below the sea. That is, each represents an amount of time which perhaps is as long as any of the periods of deposition themselves. In parts of the region the lowest clastic series rests unconformably upon the Fundamental Complex, but in certain areas the relations have not been ascertained. The upper of the three clastic series, the Keweenawan, rests unconformably below the Cambrian. (Pp. 499–500.)

Wadsworth, M. E. A sketch of the geology of the iron, gold, and copper districts of Michigan. Nature, December 1, 1892, page 117.

In this same year, at a meeting of the Geological Society of London, Wadsworth gave an advance abstract of his report for 1891–92 as State geologist of Michigan. In this paper all the rocks below the Cambrian are still called Azoic, but they are separated into three formations, beginning with the Cascade as the oldest, as in the brochures of the Duluth, South Shore and Atlantic Railway. The Cascade formation embraces gneissoid granites, basic eruptives and schists, jaspilites, and the associated iron ores and granites. Next follows the Republic formation. Beginning with the oldest beds, this embraces conglomerates, breccias and conglomeratic schists, quartzite, dolomite, jaspilite and associated iron ores, argillite, schists, granite, felsite, diabase, diorite, peridotite, and porphyrite. In view of discoveries made by the State survey of Michigan and by the United States Geological Survey regarding the jaspilites, the author is inclined to give up his former view of the eruptive origin of these rocks and their associated ores. The newest Azoic formation is the Holyoke (the Keweenawan is regarded as Cambrian). This comprehends conglomerates, breccias, conglomeratic schists, quartzites, dolomite, argillite, graywacke and graywacke-schist, granite, felsite (?), diabase, diorite, peridotite, porodite, serpentine, and melaphyr or picrite.

WADSWORTH, M. E. Subdivisions of the Azoic Archæan in Northern Michigan. Science, December 23, 1892, page 355.

In this article the author further subdivides the "Azoic," adding two new formations to those recognized in the preceding paper. The table he publishes shows the supposed equivalency between his own formations and those proposed by Van Hise.

	Michigan Geological Survey.	United States Geological Survey.
Azoic or Archean system:		
Laurentian (?) period	Cascade formation	Fundamental Complex.
Huronian period	Republic formation Mesnard formation	Lower Marquette series.
Michigan period	Holyoke formation Negaunee formation	Upper Marquette series.

GRESLEY, W. S. A hitherto undescribed phenomenon in hæmatite. Am. Geologist, Vol. IX, 1892, pages 219–223.

Gresley describes a specimen of fibrous red hematite from the Lake Superior region that seems to consist of fragments of botryoidal masses. In the midst of the masses are cavities, around which the fibers sometimes curve. No theory is proposed to account for these. It is suggested, however, that hematite, in "growing," encountered obstructions that have since been removed.

1893.

WADSWORTH, M. E. Report of the State Geologist for 1891–92. State Board of Geol. Surv. for the years 1891 and 1892, Lansing, 1893, pages 61–73. Signed October 17, 1892.

In this paper the author gives an account of the work done under his direction by the Michigan survey during the years 1891 and 1892. The discovery of the conglomeratic base of the Republic formation, resting upon the old gneisses and granites of Cascade age, south of the Winthrop mine, is reported. The quartzites of Teal Lake are described as probably belonging with the Holyoke formation, because their basal portion is a thin conglomerate resting upon chloritic and sericitic schists that resemble certain of the schists in the Republic formation. This quartzite is unconformably above the marbles or dolomites of the eastern portion of the Marquette district, which in turn are conformably above the Mount Mesnard quartzite. There are thus two quartzites here, one above and the other below the marble.

The marbles and the underlying quartzites appear to be unconformably above the Republic formation, which, according to the author, includes sericite-schists and green schists, and at the same time to be below the Holyoke formation. This series of rocks is known provisionally as the Mesnard formation. One of the difficulties in determining the exact relations of the Mesnard rocks to the neighboring series is due to the fact that there is believed to exist above the Holyoke series, and unconformably above it, another series of graywackes, quartzites, etc., which is designated the Negaunee formation. The existence of the Mesnard and the Negaunee formations is not proved beyond doubt, but it is thought to be probable.

The sequence in the Marquette district is thought to be that indicated in the scheme published in Science the preceding year.

WADSWORTH, M. E. A sketch of the geology of the iron, gold, and copper districts of Michigan. Ibid., pages 75–155. Dated March 26, 1892.

The details upon which the conclusions of the preceding article are based are given in this article in the same report.

The author begins this paper with a discussion of the means by which the various Marquette rocks were produced, and gives a table of rock classification. In these preliminary remarks he refers to the green schists north of Teal Lake and those near Marquette as altered or metamorphosed detrital deposits, in which class he also places many of the chlorite-schists of the iron mines, the grünerite-schists and mica-schists in the western portion of the area, and certain ottrelite-schists near Palmer, on the Cascade range.

The Cascade formation shows best its relations to the younger formations near the Volunteer mine, on the Cascade range.

Here one finds an old hornblendic schist that has been invaded by eruptive granite and other volcanic rocks. * * * It is not impossible that the hornblendic schist may be an altered eruptive or volcanic rock, instead of being a sedimentary one, although the evidence thus far obtained points to the latter origin.

Near the mine the Republic formation, with a basal conglomerate, may be seen reposing unconformably upon the Cascade rocks, and unconformably above these may be seen the Holyoke rocks.

The rocks comprising the Cascade formation have already been mentioned. Some of them are detrital accumulations derived either from an older formation or from some volcanic source. It may be that the Cascade series should be divided into two parts, since it appears that in a few areas some of the gneisses are eruptive in origin instead of fragmental, as is the case with most of the Cascade gneisses, which are younger than the eruptive gneisses and contain fragments of them. All these gneisses are cut by granites and by basic dikes.

The composition of the Republic formation has already been outlined. In it are most of the jaspilites of the district. These, it is stated, may still be regarded as eruptive at Ishpeming and Negaunee, though elsewhere they seem to be sedimentary. The phenomena formerly supposed to prove the eruptive origin of the jaspilites and ores are shown to be explained by the eruptive nature of the green schists with which they are in contact.

The sedimentary origin of the jaspilites is plainly shown in the Cascade range, south of Palmer, where these rocks are interlaminated with quartzites, often in thin beds. Some of the beds contain fragments of banded jaspilite, which would indicate that there is an occurrence of this rock somewhere beneath the Republic formation. Moreover, most of the jaspilites interlaminated with the quartzites "appear to be composed of a fine jaspilite mud derived from the jaspilitic débris."

The belief in the existence of jaspilite in the Cascade formation rests upon the evidence just given; but the author thinks it possible that the jaspilite fragments in the conglomerates may have come from veins in the older rocks, although these are rarely observed.

The Republic formation as a whole is separated from the Cascade formation below and from the Holyoke formation above by conglomerates and unconformities. The conglomerates are well known at a number of places. Objections are raised to the acceptance of Irving's theory of the origin of the ores from an original ferruginous carbonate, since it is believed that the carbonate is itself secondary and that the phenomena of alteration reported are "due to surface action on the iron-bearing schists."

More detailed accounts of the eruptive rocks cutting the Republic formation are given in this report than in the abstracts already referred to. Granites, felsites, diabases, diorites, and porphyrites are all recognized as intrusive in the Republic rocks. Many of the green schists of the formation are thought to be eruptive, though it appears that some of them are still regarded as sedimentary.

The porodites, or volcanic ashes, are common in both the Republic and the Holyoke formations, though "more apt to be seen in the former."

In treating of the Holyoke formation Wadsworth refers to his former belief that Brooks's quartzite tongue in the iron formation at Republic is an eruptive greisen. He now corrects this earlier statement and acknowledges the rock to be quartzite, but supposes the iron-schists below and above this tongue to be of different ages. The former he regards as Republic and the latter as Holyoke. At this place and at several other localities there were observed in the Republic rocks fissures filled with Holyoke sediments. These the author proposes to call clasolites.

Very little information is given with respect to the rocks of the Holyoke formation other than that contained in previous papers.

The Marquette and Ishpeming serpentines are believed to be proved the youngest of the large intrusive masses in the district, and to be younger than any of the dike rocks except the youngest diabases and the melaphyrs.

Under the heading of chemical deposits the author places the soft iron ores of the district and the quartz veins, some of which carry auriferous pyrite and native gold.

Chapter IX of the report contains a description and an analysis of a new fibrous mineral from the Champion mine, which A. C. Lane calls beaconite, and also analyses of a chloritoid, an amphibole, and a clay. A list of minerals occurring in the Upper Peninsula concludes the chapter.

LANE, A. C. Microscopic characters of rocks and minerals of Michigan. Rept. of State Board of Geol. Surv. for 1891–92, Lansing, 1893, pages 176–183.

In an appendix to Wadsworth's report Lane describes very briefly the microscopic characters of some of the most interesting rocks of the Marquette district.

Among these the class of the quartz-diabases is mentioned as well characterized by the presence of quartz, sometimes, indeed, only in small quantity. The rocks are the youngest eruptives of the district. They occupy well-defined dike fissures, and have altered the slates adjacent to them. Their quartzose component is usually in the interstices between the diabasic constituents, and is frequently intergrown with plagioclase. It is regarded as original. The rocks are present in some of the mines, and in these cases they seem to have aided in guiding the aqueous currents active in producing the ore, but they are different from the miners' "diorites," and are younger than these.

The amphibolites and hornblende-schists of the author include the "diorites" referred to. They are all secondary rocks, having been derived, in all probability, from diabases. In the alteration of the latter rocks into the former ones iron oxides were removed and were condensed into ore bodies. Transitions from chlorite-schists, which are often but marginal forms of the amphibolites, into ore bodies can be seen at the Champion mine, the magnetite replacing the eruptive rock in places. The author ascribes to some of the ores of the district this origin, but excludes the soft ores from the category.

PATTON, H. B. Microscopic study of some Michigan rocks. Ibid., pages 184–186.

In another appendix Patton deals with the microscopic features of some of the rocks referred to in Wadsworth's report. Aplitic diorites are mentioned as occurring in the SE. ¼ sec. 14, T. 48 N., R. 25 W., and on the Middle Picnic Island.

Birkinbine, John. Iron ores. Mineral Resources of the United States, calendar year 1891, Washington, 1893, pages 10–46.

We find in this paper an abstract of the reports of C. D. Lawton, commissioner of mineral statistics for Michigan, explaining the occurrence of the ores in the Marquette district. The rocks associated with the ores are stated to be built up of the detritus of the Laurentian rocks. The ore formation is folded, the ore bodies being found in the troughs of the folds, with a hanging wall of quartzite, which is often separated from the ore by "soap rock" (p. 17).

Van Hise, C. R. The succession in the Marquette iron district of Michigan. Bull. Geol. Soc. Am., Vol. V, 1893, pages 5–6.

The first announcement of results reached by the Lake Superior division of the United States Geological Survey in the detailed examination of the Marquette area was made in 1893 by Prof. C. R. Van Hise, in a short paper read at the Madison meeting of the Geological Society of America.

The oldest group of the district is called the Basement Complex, following Irving's suggestion. It consists of granite, gneisses, hornblende-schists and mica-schists, green schists, and greenstone-conglomerates, which appear to be surface volcanics, in part lavas and in part tuffs. The schists are intruded by granite and gneissoid granite. No sedimentary rocks are known in the group.

Unconformably on this group is the Lower Marquette, consisting, in ascending order, of conglomerates and quartzites, and the iron formation, including actinolite-magnetite-schists, ferruginous cherts, jaspers, etc.

The Upper Marquette rests upon any one of the lower formations. Broadly speaking, it is a shale, mica-slate, and mica-schist formation, although at its base are often found quartzites and conglomerates. Where the underlying rock is the iron-bearing formation of the Lower Marquette the basal member of the upper series consists of a recomposed iron-bearing formation, which may, in consequence of secondary concentration, afford workable ore bodies. Another iron-ore horizon occurs at from several hundred to 1,000 feet above the base of the series. This formation is not much unlike the corresponding formation in the lower series.

In the eastern portion of the district is the Mesnard formation of the Michigan survey. In this the succession comprises: (1) A lower quartzite and conglomerate; (2) a dolomite interstratified with slates and cherty quartzites; and (3) an upper quartzite. The true position of this formation is not yet determined.

Great intrusive dikes and bosses of altered diabase have broken through the Marquette series and have been the causes of minor folding in them. In the upper series is also an extensive area of contemporaneous volcanics, largely tuffs, running from north of the Saginaw mine to Champion. The locus of the ancient volcano was southeast of Clarksburg. In passing east and west from this center more and more waterworn sediment is found intermingled with the volcanic débris, until finally the rocks pass into the ordinary sediments of the district.

WINCHELL, N. H. Field observations of N. H. Winchell in 1892. Twenty-first Ann. Rept. Geol. and Nat. Hist. Surv. of Minnesota for 1892, Minneapolis, 1893, pages 86–99.

A few hastily taken field notes and a statement claiming priority in the discovery of the existence of two Huronian formations in the Marquette district comprise the only portions of N. H. Winchell's Twenty-first Annual Report that deal with the area under discussion.

The Republic mine is placed by the author in the Keewatin formation. With respect to the second part of the article, it will be sufficient to relate that Winchell appeals to his discovery of the conglomerate in the Saginaw mine in 1888 as evidence that he recognized the existence of two ore-bearing members of the Huronian in the Michigan iron district. He omits reference to the essential fact that he placed the rocks above the conglomerate in the Potsdam. The Saginaw deposits are now placed in the Taconic. There accompany the article several sketches of the contacts between the conglomerate and the underlying iron formation as the author saw them in the Saginaw and Goodrich mines.

WINCHELL, HORACE V. Historical sketch of the discovery of mineral deposits in the Lake Superior region. Proceedings of the Lake Superior Mining Institute, 1893, pages 19–22.

In this article Horace V. Winchell recounts, among other things, the incidents leading to the discovery of the ore deposits of the Jackson, Cleveland, Republic, and other mines.

Smyth, H. L. A contact between the Lower Huronian and the underlying granite in the Republic trough, near Republic, Michigan. Jour. of Geol., Vol. I, 1893, pages 268–274.

Smyth describes as existing south of the Republic mine, in the bend of the horseshoe made by the outcroppings of the iron-bearing rocks, the first proved unconformity between what is regarded as the lowest member of the Lower Huronian series in the Marquette district and the underlying Basement Complex. The existence of this unconformity was inferred by Brooks from the fact that the strike of the quartzites and actinolite-schists near this place runs directly across the foliation in the neighboring granite. Smyth discovered the actual contact of the two series, and found the basal member of the overlying one to be a coarse conglomerate containing large bowlders of the same granite as that below the contact. Between the conglomerate and the granite is a thin band of a schistose rock, in all probability representing a sheared portion of the granite or of the conglomerate.

Van Hise, C. R. An historical sketch of the Lake Superior region to Cambrian time. Jour. of Geol., Vol. I, 1893, pages 113–128. With map.

Much of the information imparted in this summary statement of the knowledge concerning the relations of the pre-Cambrian formations to one another in the Lake Superior region is contained also in the correlation essay on the Archean and Algonkian, already referred to. There are described, however, a few additional facts of detail that are of interest.

The Lower Huronian is now said to be composed of three members, instead of the two recognized in earlier papers. In ascending order they are as follows: (1) Conglomerates and quartzites; (2) limestone and chert; (3) the iron-bearing formation. These three members are not often seen in a single section, in consequence, in some cases at least, of the entire absence of one or the other of them. Basic eruptive rocks are also abundant in the Lower Huronian, and acid eruptives occur not infrequently.

At the end of Lower Huronian time the Lake Superior region was raised above the sea, folded, and subjected to erosion, and the Upper Huronian sediments were deposited upon the Lower Huronian ones. Like the Lower series, the Upper series consists also of three formations, which are all less crystalline than the three formations of the Lower series. These are: (1) A lower slate, passing locally into a quartzite or conglomerate, (2) an iron-bearing formation, and (3) an upper slate member. Where the lowest member of this series rests immediately upon the Lower Huronian, the underlying member may be any one of the three older formations, and the character of the overlying conglomerate varies accordingly.

Volcanics, as distinguished from intrusive eruptive rocks, occur interlaminated with the Upper Huronian sediments. "In the Michigamme iron district is an extensive area of greenstones, greenstone-conglomerates, agglomerates, and surface lava-flows, many of which are amygdaloidal" (p. 121).

At the end of Upper Huronian deposition the land was again raised above the sea, and after the rocks had been folded, gently as a rule, but intensely locally, the atmospheric agents once more began their work of cutting them down. The land was then again submerged, and after some time (during which elsewhere the Keweenawan rocks were formed) the Potsdam sandstone was laid down upon them.

1894.

Smyth, H. L. The quartzite tongue at Republic, Michigan. Jour. of Geol., Vol. II, 1894, pages 680–691.

The subject of discussion in this paper is the origin of the quartzite tongue mapped by Brooks as penetrating the iron-bearing formation at Republic, on the western side of the eastern heel of the horseshoe. It is this quartzite that was stated by Wadsworth in 1880 to be an eruptive greisen, and was later (in 1892) determined to be a quartzite whose position between two portions of the iron-bearing formation was explained by supposing that the rocks on the different sides of the "tongue" were of different ages—that on the western side belonging with the Holyoke formation, and the larger eastern mass of the same rocks to the Republic series. An unconformity was shown to exist by Wadsworth between the quartzite and the eastern jaspilites and ores.

Smyth explains the phenomenon as due to a fault along the contact plane between the quartzite and the iron formation, which is also a plane of unconformity. The iron-bearing rocks on both sides of the quartzite are of the same age, and, indeed, are portions of the same formation; consequently there are not two ore horizons in the Republic area, as Wadsworth supposed.

The Republic structure is described as a syncline some 7 miles long. Its axis runs about northwest, and is nearly horizontal, except at its southeastern end, south of Smith Bay, where it dips about 45° to the northwest. The rocks are thus exposed in a horseshoe-shaped curve. They have been squeezed nearly into parallelism on the two sides of the axial plane, the Lower Marquette rocks dipping a little more steeply than those belonging in the Upper Marquette series. The radius of the curve at the toe of the horseshoe, measured from the base of the upper quartzite, can be very little greater than the thickness of that formation. The pressure caused by this sharp folding has not only crushed some portions of the more brittle rocks affected by it, but has also produced three synclines and two anticlines subordinate to the main syncline.

1895.

WINCHELL, N. H. The origin of the Archean greenstones. Twenty-third Ann. Rept. Geol. and Nat. Hist. Surv. of Minnesota, 1895, pages 4–35.

N. H. Winchell criticises Williams's work in the greenstone-schist areas of the Marquette and Menominee districts, but adds nothing to our knowledge concerning them. The author seems to believe that Williams had concluded that the greenstone-schists of the Marquette district are mainly squeezed irruptive rocks, whereas the strong point of his paper is the doctrine that they were originally basic tuffs and surface lava flows. After discussing the problem somewhat at length, Winchell reaches very nearly the same conclusion as does Williams, i. e., he concludes that the greenstone-schists are mainly altered tuffs of basic rocks. He does not believe, however, that they reached their present condition through the action of dynamic metamorphism, but the processes by which they have become schists are not clearly set forth.

The author furthermore ascribes to the schists a definite horizon at the close of the Archean, and places under them an iron-bearing formation, chlorite-schists, clay-slates, graywackes, conglomerates, and quartzites. He also states that the greenstone knobs in the neighborhood of Negaunee are outliers of the greenstone-schists, older than the iron-formation rocks by which they are surrounded; but he cites no proofs of the correctness of this statement.

DANA, J. D. Manual of geology. Fourth edition. American Book Company, 1895.

Professor Dana, in the last edition of his Manual, declines to recognize the Algonkian system as distinct from Archean. He places the Marquette ores in the Huronian as recognized by Logan and Murray, and accepts the conclusions of Irving and Van Hise as to their origin from a carbonate by metamorphism (pp. 449–450).

ROMINGER, C. Geological report on the Upper Peninsula of Michigan, exhibiting the progress of work from 1881 to 1884. Iron and copper regions. Geol. Surv. of Michigan, Vol. V, Lansing, 1895, pages 1–94.

This is the long-delayed report by Rominger on the iron and copper districts of Michigan, to which reference has already been made several times. In justice to its author it should be stated that the work upon which it is based was done in the years 1881 and 1882, and the manuscript was completed in May, 1885, but the publication was deferred for the reason, given in Rominger's own words, that "the description of all the results obtained comprises the space of about 50 or 60 printed pages, too small for a separate publication in book form." It was not until the fall of 1893 that enough additional material had been accumulated by the Michigan survey in proper shape to be incorporated with Rominger's report and make a volume of sufficient size to warrant its publication by the State board of geological survey.

The report is a continuation of that of 1881. Some of the conclusions reached in it are different from those reached in the previous report, but on the whole the author maintains his original position with respect to most of the disputed points. He still declines to regard the Marquette rocks as comprising portions of two distinct series, as "no tenable line of demarcation between an older Laurentian and a younger Huronian group unconformably deposited on the first could be observed" (p. 1). The entire series of rocks observed in the district is classed as "Huronian."

The granites and gneisses of the lowermost portion of the series are now thought to have the characters of eruptive rather than of sedimentary rocks. A solid crust of granite served as the substratum on which the Huronian beds were laid down, as is proved by the occurrence of belts of granitic conglomerate and breccia in different horizons of the series.

Two occurrences of these conglomerates associated with the granites are particularly described, viz, that in the SE. ¼ sec. 22, T. 47 N., R. 26 W., and that in the N. ½ sec. 29, T. 48 N., R. 25 W. The first locality furnishes excellent proof of the correctness of the author's conclusion. Here are several knobs with nuclei of massive granite surrounded by mantles of coarse breccia, made of fragments of granite in a cement composed of well-laminated quartzose material, and around these are hydromica-slates interbedded with heavy belts of compact quartzite, which are conformable with the breccia. At the second locality the conglomerate is interlaminated with diorite-schists, and is at some distance from any known outcrops of granite.

In the former report the author described a gradation of the granite into quartzite. The outcrops thought to show this gradation were again visited. The gradation rocks are now regarded as a mixture of granite fragments and of sand material.

Granite was upheaved, according to the author, and was intruded into the overlying strata near the close of Huronian time, since it is found in contact with all the Huronian strata up to the youngest, though intrusive belts of it are rarely found higher than the iron-bearing formation. Moreover, the beds in contact with the granite are always dislocated. The dislocation, however, is not always due to the upheaval and intrusion of the granite. It has been caused in part by diorites and diabases, which intersect the granite as well as the incumbent beds.

The greenstones intersecting the granite are identical with those intersecting the schists of the Huronian series, and with those interlaminated with these rocks. Their massive forms grade into greenstone-schists. This fact led the author in his previous report to regard the diorites as fused sediments, representing the lowermost beds in the sedimentary succession. In the second report he does not look upon them as belonging with the sediments, but believes them always to be later eruptives. Of the two kinds of greenstone the diabases are regarded as the younger. They are often found cutting the diorites. The latter rocks, on the contrary, are old rocks. Although in a few cases they were observed to contain the remnants of decomposed augite, the greater portion of them are thought to be original rather than secondary rocks (uralitic diabases) derived from diabases by alteration. In this respect the author differs from those geologists who are inclined to look upon all the diorites of the district as altered diabases.

As the result of closer investigation, an iron-bearing horizon was discovered in the arenaceous slate group, so that the author now recognizes two ore horizons in the Marquette district instead of one only, as originally was the case.

HOBBS, W. H. Mineralogical notes. Am. Jour. Sci. (3), Vol. L, 1895, pages 121–128.

2. Barite and manganite from the Lucy mine, Negaunee, Michigan, pages 123–125.

3. Chloritoid from blocks on the south shore of Michigamme Lake, Michigamme, Michigan, pages 125–127.

The first of these two notes is purely mineralogical. The two minerals described are from the Lucy mine, in the SW. $\frac{1}{4}$ sec. 6, T. 47 N., R. 26 W.

In the second note the author calls attention to the existence of a chloritoid with the composition of masonite in specimens of a phyllite-schist picked up on the south shore of Lake Michigamme. The rock is not known in situ. The chloritoid is the same as that described by Lane, Keller, and Sharpless in 1891.

CHAPTER II.

BY W. S. BAYLEY.

THE BASEMENT COMPLEX.

Below the Algonkian deposits of the Marquette area are schistose and massive phases of crystalline and pyroclastic rocks, so different from the Algonkian sediments that there is rarely any difficulty in distinguishing between them and the clastic rocks above them. These inferior rocks are unconformably below the lowest members of the Marquette series. It is probable that they embrace members of widely different ages, but up to the present time no separation of the schists into sharply defined subgroups upon the basis of age has been attempted, because of the complexity of the relations existing between the various rock types, due largely to the many vicissitudes through which they have passed and the consequent alterations to which they have been subjected.

Divisions corresponding to the Laurentian and Grenville series of Canada, as defined by Adams,[1] and even the lithological ones, Laurentian and Mareniscan, proposed by Van Hise,[2] are not clearly distinguishable in all of the district that has been studied. But the work on the pre-Cambrian areas is as yet far from complete. A more careful investigation of large areas will probably show that, in a general sense, such broad distinctions as those recognized in the terms "Laurentian" and "Mareniscan" do exist in the Michigan "Archean." The present study of the Marquette district was primarily directed to the Algonkian series. In the pre-Algonkian

[1] A further contribution to our knowledge of the Laurentian, by F. D. Adams: Am. Jour. Sci. 3d series, Vol. L, 1895, p. 58.

[2] Correlation papers—Archean and Algonkian: Bull. U. S. Geol. Survey No. 86, 1892, pp. 488–490.

part of the district it has been prosecuted only carefully enough to insure accurate mapping of the main areas.

In consequence of the widespread occurrence of the granites and schists beneath the sedimentary formations, and the complexity of their structural relations, the term "Basement Complex," first proposed by Irving, has been used to designate them, as indicating that they constitute the basement upon which the Marquette sediments were laid down.

This Basement Complex in the Marquette district, as elsewhere in the Lake Superior region, consists of a series of acid and basic schists, cut by veins and dikes of granite and other acid rocks, dikes of basic eruptives, and bosses of acid, intermediate, and basic materials. The whole comprises a confusing mass of crystalline rocks, the relations between which may sometimes be discovered, but which more frequently are not decipherable. So different are these rocks from the members of the Marquette series in appearance, structure, and composition that even where there is no apparent structural break between the two series, on lithological grounds alone they would naturally be regarded as of different ages, or at least as having been produced under very different conditions. It is partly for the purpose of contrasting their characteristics with those of the Algonkian rocks that the members of the Basement Complex are here described.

The Marquette rocks are bounded both to the north and to the south by areas of the Basement Complex. The northern area differs somewhat from the southern one in the nature of its rocks, and therefore the two are discussed separately. In addition to these two large areas, there are smaller ones that are entirely surrounded by the Algonkian beds, like islands in a sea of rocks. In these areas the rocks are not materially different from those of the larger areas, but for the sake of clearness in picturing the structure of the Marquette range they will be referred to separately and described briefly.

SECTION I. THE NORTHERN COMPLEX.

Throughout nearly its whole extent, from Lake Superior as far west as beyond Lake Michigamme, the Marquette series is limited on the north by a belt of crystalline and pyroclastic rocks, cut by basic, intermediate, and acid dikes and bosses and by granite and quartz veins. Near Lake Superior the two series are separated by a small area without outcrops, except occasional ledges of Potsdam sandstone. Whatever rocks may underlie this area, they are buried deep beneath Pleistocene sands and gravels. Elsewhere the exposures of the two series are close together, and at many places actual contacts may be seen.

The rocks comprising the Northern Complex are gneissoid granites, syenites, greenstone-tuffs, greenstone-conglomerates, greenstone-schists, peridotites, aplites, vein granites, diabases, diorites, and epidiorites. The first five are at many places highly foliated, while the last six are massive, or but slightly schistose. The former occupy the greater portion of the belt, so far as it is within the limit of the map (Atlas Sheet IV). They are older than the latter, which cut them in the form of dikes and bosses.

The foliated rocks occupy areas whose boundaries are not so well defined as is the case with the Marquette fragmentals, since the schists and the granitoid gneisses and syenites gradually pass into one another, through the intrusion of the basic rocks by dikes and veins of the acid ones. Nevertheless, an attempt has been made to map these areas. In their interiors the different phases of schists, granites, and syenites are well characterized, but on their peripheries there is always a complex mixture of the various schists with one another or with the granitic rocks. The respective colors on the map are believed to cover the areas within which the corresponding rocks predominate largely over other rocks. The boundary lines separating the different areas are drawn at about the places where the different varieties are found in approximately equal quantities.

The greenstone-schists include two classes. The rocks of the first class are nonconglomeratic green schists. These are called the Mona schists, because good exposures are found on hills of this name southwest of Marquette. Those of the second class contain pebble-like bodies, and these are discussed separately. Their best development is on the Kitchi Hills, in the neighborhood of Deer Lake, northwest of Ishpeming, and hence they are called the Kitchi schists. They have frequently been referred to in the literature on the district as the Deer Lake conglomerates or agglomerates.

THE MONA SCHISTS.

The Mona schists embrace green and gray fibrous rocks with a well-characterized schistosity, dense greenish-gray ones that are not pronouncedly schistose, and highly foliated dark-green ones with the aspect of hornblende-schists. These are interbanded with one another, and with certain light-pink, yellow, or white talcose and sericite-schists, described later under the heading "acid schists." The green schists are all composed of the altered constituents of diabases. They are probably all derived from the lava or the tuff form of this rock. They are referred to as greenstone-schists to distinguish them from the true amphibole-schists, which are composed essentially of amphibole and quartz, and which are without the distinctive features of an altered eruptive, whatever their origin may have been.

DISTRIBUTION AND TOPOGRAPHY.

The Mona schists, with the associated acid schists, occupy the eastern portion of the Northern Complex, extending westward from Lake Superior on the east to about the west line of R. 26 W., where they are replaced by the Kitchi schists. In its eastern portion the area stretches northward a mile beyond the northern limit of the accompanying map (Atlas Sheet IV) to a great area of gneissoid granite, which is similar in its characteristics to the granites farther west. A mile west of the east line of R. 26 W. the belt narrows and has a width of only 1½ or 2 miles. Here it is bounded on the north by a narrow belt of coarse red syenite, lying partly within the limits of the map. On the south the schists are in contact with the transgression quartzite of the Lower Marquette series throughout its entire extent, except toward the east, where they pass beneath the Pleistocene deposits bordering the lake.

The topography of the area is, in a minor way, rugged in the extreme. Large and small hills of the schists rise with rough, precipitous faces above the level of the surrounding country, and lift their smooth, glaciated heads from 200 to 900 feet above the level of the waters of Lake Superior. When the hills are low their tops only project as smooth, round knobs above the drift deposits surrounding them (Pl. IV, fig. 1). The higher hills are

FIG. 1.—GREENSTONE-SCHIST KNOB, DEAD RIVER.

FIG. 2.—RIVER COURSE THROUGH MONA SCHIST

composed of groups of these knobs, raised high above the valleys between them. Their sides are ragged and rough, or smooth and vertical, and their tops are rounded knolls

The streams flowing over the schists have not yet succeeded in trenching their channels to any considerable depth. Their courses are marked by rapids and cascades, over which the waters tumble in a series of low falls. The rocks in the beds of the streams and along their sides are usually rough surfaced, in consequence of their highly developed schistosity. As a result, we find the drainage channels through the greenstone-schists presenting an entirely different aspect from those through the granite areas or through the areas underlain by the Algonkian rocks. The view shown in Pl. IV, fig. 2, is typical for the larger streams through this district.

RELATIONS TO ADJACENT FORMATIONS.

It has already been stated that the green schists pass gradually into the gneissoid granites to the north through the intrusion of the former by apophyses of the latter. In referring to this contact Williams writes:[1]

> There is no such sharp line of contact as is represented on Rominger's map, but, on the contrary, as Rominger himself explains, there is a complete interpenetration of the two rock masses. The granite has intruded itself into the schistose greenstones, for the most part following their bedding and forcing apart their strata. The amount of the acid rock gradually diminishes as we go southward.

At a greater or less distance from the contact the granite is completely absent, and the green schists occur alone, except for the dikes of aplite and diabase that everywhere cut through them, as well as through all other members of the Basement Complex, and the narrow bands of acid schists with which they are interlaminated.

The stratigraphic separation of the Mona schists from the Kitchi formation to the west has not yet been possible. In passing from the former area into the latter, beds of the conglomeratic schists are found more and more frequently between those of the nonconglomeratic kinds. As we shall see later, many of the Mona schists are probably altered tuffs, while

[1] The greenstone-schist areas of the Menominee and Marquette regions of Michigan, by G. H. Williams: Bull. U. S. Geol. Survey No. 62, 1890, p. 146.

others are squeezed basic lavas. A sharp line of demarcation between these rocks and the tuffaceous greenstones of the Kitchi formation to the west is therefore not to be expected, for the former are probably only much metamorphosed phases of rocks like the latter.

From the Algonkian beds to the south the schists are separated by conglomerates and great unconformities. In the conglomerates large bowlders of the schists are often found; consequently there can be no question but that the latter rocks were consolidated and had been made schistose before the basement beds of the overlying clastic series were laid down upon them.

The Mona schists are therefore pre-Algonkian. They are older than the granites of the Basement Complex, and are of about the same age as the rocks of the Kitchi formation, which are probably their western equivalents.

PETROGRAPHICAL CHARACTER.

The structure of the schists varies within wide limits. In some places the rocks are very fine grained and as fissile as slates; at others they are coarser-grained, fibrous, and distinctly foliated; again they may be very coarse grained and fibrous but possessed of only indistinct foliation; and, finally, they may be dense and apparently quite massive. In the latter case they always yield to fracture much more readily in one direction than in others, and in thin section under the microscope they are seen to have a schistose structure. The schistosity of all the well-foliated varieties dips at high angles, and strikes nearly east and west, approximately parallel to the trend of the Marquette trough.

Dr. Williams, who has studied the rocks of this area in detail, divides the eastern portion of the area into a northern and a southern half, in the former of which banded schists prevail; in the latter, aphanitic varieties. In neither half, however, are the rocks of either variety excluded by those of the other. Farther west the dense and the banded fibrous schists are associated in the most intimate manner.

BASIC SCHISTS.

The dense varieties.—The aphanitic schists as a rule have a light-green color, sometimes shading to grayish or pinkish green, and a uniformly fine grain. Occasionally their texture is so fine that hand specimens resemble greenish cherts in appearance, or massive graywacke-like sediments. In the ledge the rocks present a rudely schistose structure, which is lost in the specimens. In some exposures, as in the knob in the NE. ¼ NW. ¼ sec. 28, T. 48 N., R. 26 W. (Atlas Sheet XXX), the rock is divided into oval or lenticular masses, separated from one another by schistose material of the same nature as that composing the oval masses, but of much finer grain. This structure, as has been pointed out by Williams, is neither concretionary nor agglomeratic. It is similar to the structure of certain Saxon schists which Rothpletz has shown to be mechanical in origin.

In thin section the aphanitic schists are found to be nearly as uniform in composition as they are in appearance. They consist of granular epidote, small flakes and needles of chlorite and hornblende, and altered plagioclase, with the addition usually of calcite, leucoxene, a little quartz, and mosaic areas of albite and quartz. The plagioclase may sometimes be detected in small lath-shaped crystals, lying in all azimuths amidst the other components, but more frequently the mineral is so much decomposed that its original form can no longer be recognized. The epidote grains are usually scattered through the slide. Not infrequently, however, they are aggregated into little groups with the cross-sections of feldspars. The plates and needles of chlorite and the needles of hornblende, which are rather abundant in some sections of the rocks, are quite small. They are intermingled with a few sericite flakes, a little calcite, and small areas of the clear mosiac already referred to. Usually these constituents inclose the leucoxene and the altered plagioclase crystals in the same way as glass incloses the crystal components in a glassy basalt. In other cases the use of crossed nicols brings out an arrangement of the various constituents in such a way as to resemble the structure of fine-grained diabases, and even of gabbros. In still other instances, in the apparently heterogeneous aggregate of components, under crossed nicols a structure resembling that of tuff is discerned. Broken pieces of altered plagioclase are discovered in a fine-grained matrix with no well-defined structure. In composition the greenstones are altered diabases or basalts, and their structure, when discernible, is either that of basic lavas or that of tuffs.

The schistosity of these greenstones, which is seen both in the ledge and to a limited degree in thin section, where the chlorite spicules are found to lie with their long axes in a uniform direction, is explained best as a result of movement, as Williams has already observed. This geologist declares that the study of these pale-green aphanitic greenstones seems to indicate that they were not originally to any great extent tuff deposits, but that they were massive flows of diabase, which have since suffered profound chemical and structural changes, in consequence of having been subjected to intense dynamic action. Perhaps the greater portions of these dense greenstones were originally lava flows, as suggested by Williams. A large portion of them, however, were tuff deposits. The significant fact in connection with them is that they were all surface materials.

Many of the dense schists have been weathered until they now consist largely of calcite and epidote, so that no evidence of their original character remains.

The banded varieties.—The banded schists, best exposed in the northern portion of the Mona schist area, are composed of alternate layers of darker and lighter shades of green, giving them a striped appearance. Their texture is much coarser than that of the aphanitic greenstones described above, and their structure is characteristically schistose. They all contain an abundance of secondary amphibole, and consequently they are all more or less fibrous. Where their fibrosity is pronounced and their schistosity marked they form very fissile schists. Where the schistosity is less marked the rocks may still be fibrous, but the fibers are grouped around centers scattered through the specimen, and the rock has the aspect of a uralitized diabase or gabbro.

On account of their banded character these schists have been regarded as sedimentary by nearly all geologists who have studied them. "The alternation in the color and composition of the layers is so frequent and so constant, and their parallelism to the east and west strike of all the rocks of this neighborhood is so exact," writes Williams, "that no hypothesis of their originally massive character will satisfactorily account for the observed facts. On the other hand, the chemical and the microscopical characters of these schists agree closely with those of associated massive greenstones which are known to have been derived by the alteration of basic eruptive rocks."[1]

Normally these schists show in thin section large or small sheaf-like bundles of bluish-green hornblende scattered through the slide indiscriminately or aggregated into groups with irregular outlines and frayed edges, and embedded in a groundmass consisting of much decomposed plagioclase and a mosaic of colorless grains of albite and quartz. With the hornblende, chlorite is frequently associated, the areas occupied by the two minerals sometimes having the outlines of an amphibole or a pyroxene crystal. Much leucoxene is observed in most sections, and not infrequently granular epidote is intermingled with the components of the mosaic. In addition to these substances, which are well defined, there are certain obscurely outlined plagioclases, which present between crossed nicols the shapes of sharp-edged fragments. In none of the slides of these rocks has anything been detected that may be regarded as a waterworn sand grain.

The plagioclase, whether in the fragments or in the indefinite areas that serve as a sort of groundmass to much of the hornblende, is altered to epidote, sericite, chlorite, and calcite. The mosaic filling the interstices between everything else is in all probability secondary, as it not infrequently fills little veins cutting through the hornblende, chlorite, and altered plagioclase. This mosaic is like that described by Lossen[2] in the schistose diabases of the eastern Harz, which have been shown to owe their foliation to mashing.

The Marquette banded schists show the structure sometimes of massive rocks and sometimes of pyroclastic ones, but more frequently they exhibit no structure from which their origin can be inferred. Their composition, however, is that of diabases. Their field aspects are very different from those of most schistose diabases. The rocks are banded, like sedimentary ones. A possible explanation of these opposite sets of characters is that the rocks exhibiting them are water-deposited clastics of volcanic origin,

[1] The greenstone-schist areas of the Menominee and Marquette regions of Michigan, by G. H. Williams: Bull. U. S. Geol. Survey No. 62, 1890, p. 154.

[2] Zeitschr. Deutsch. geol. Gesell., Vol. XXIV, 1872, p. 730; Jahrbuch K. preuss. geol. Landesanstalt, 1883, p. 640; 1884, p. 528.

like the tuffs of modern volcanoes, which have been tilted from their original position and have been rendered schistose by mashing, as have also many of the dike masses that intrude them. They possess many of the characteristics of dynamically metamorphosed tuffs, and others due to weathering processes.

Other varieties.—In addition to the aphanitic schists and the banded schists of this area, there are three other phases that should be mentioned. The first phase strongly resembles schistose varieties of the dike rocks to which the name "epidiorite" is often given. These rocks probably represent the coarser lavas that were associated with the glassy and fine-grained lavas and the tuffs that gave rise to the more common types of schist in the district.

In the second phase the structure is plainly diabasic, but the quantity of hornblende is so great that the rocks might well be called amphibolites. In a rock from about 200 paces east of the NW. corner of sec. 35, T. 48 N., R. 27 W. (Atlas Sheet XXVII), for instance, the hornblende is very abundant. It is a fibrous variety, consisting of long, almost colorless needles or thin prisms scattered through a felt of greener fibers, the mass forming pseudomorphs after diabasic augite. Feldspar is not abundant in the rock. That which is present is penetrated by needles of hornblende and spicules of chlorite to such an extent that its characteristic features are often almost completely obscured.

The third phase is more nearly like the true crystalline schists than are any others of the greenstone-schists. This is the least common type in the Mona schist area. It appears to be confined to its northeastern portion. In the hand specimen the rocks of this type are dark-green in color, very fine in grain, and extremely schistose. Under the microscope they appear to be much fresher than the other green schists. They are composed almost wholly of long, narrow prisms and needles of light-green hornblende, lying in a mass of tiny, clear grains of plagioclase, which interlock in the manner of the grains of a crystalline schist. Intermingled with these clear feldspars are a few larger grains of reddish, altered ones, clouded by inclusions of epidote, kaolin, and sericite. On their edges some of these seem to be passing into the clearer, fresher-looking feldspar, which is no doubt a new product, derived from the plagioclase of an older rock. Epidote in small, almost colorless grains is quite common in and between the new plagioclase particles, sometimes as single individuals, sometimes as clusters of grains that are so thickly crowded as to be almost opaque. Plates of the common yellow-green epidote are occasionally met with, and crystals of zoisite are common in the altered plagioclases of some sections. As a rule, ilmenite and leucoxene are not so widely spread in these rocks as they are in some of the other schists. In the schists derived from dike material and from the compact and coarse-grained lavas leucoxene is abundantly present, whereas in the banded schists, supposed to be altered tuffs, and in the amphibole-schists, it is uncommon. In a rock from 1100 steps[1] N., 100 steps[1] W., SE. corner of sec. 2, T. 48 N., R. 26 W., however, the section is sprinkled with little black particles of ilmenite, each one of which is surrounded by a rim of colorless leucoxene. These schists are like those described by Williams[2] from the "Brook section" west of Marquette. Thus far they have been found only in the southern halves of T. 48 N., R. 25 W., and T. 48 N., R. 26 W., although they no doubt exist in other portions of the northern greenstone area. It is impossible at present to decide whether these schists are squeezed tuffs or squeezed lavas, but they are no doubt mashed rocks derived from basic volcanic material of some kind.

ACID SCHISTS.

In a number of places within the area of the Mona schists the green schists are associated with light-colored rocks that are very like certain schistose acid dikes that cut across the greenstones. There is great difficulty in determining whether these light schists were derived from eruptive porphyries or from their tuffs. In many instances the latter is supposed to be the case. The larger decomposed fragments that lie in the fine-grained groundmass of these rocks are so badly shattered, and the different pieces near together fit into one another so imperfectly, that it would seem hardly

[1] In this volume locations will frequently be given from the southeast corners of sections, in steps at the rate of 2,000 per mile.

[2] The greenstone-schist areas of the Menominee and Marquette regions of Michigan, by G. H. Williams: Bull. U. S. Geol. Survey No. 62, 1890, pp. 156-157.

possible that they could be fragments produced by the crushing of crystals. Besides, these white or pink schists and the green ones occur side by side in the same ledge, and the two apparently grade into each other.

In many of the sections cut from the acid rocks only quartz and sericite, with perhaps a little epidote, can be discovered. The three minerals form a very fine grained aggregate, resembling strongly the mosaic of many devitrified rhyolites. The tiny quartz grains are separated from one another by flakes of sericite, arranged with their longer axes in a single direction. At present the rocks are sericite-schists. In a few of them obscure traces of feldspathic fragments may be detected when their sections are examined with low powers between crossed nicols, but from most of them every trace of fragmental material has disappeared and the rocks are now thoroughly crystalline.

Schists like these have been described by Williams,[1] who regards them as metamorphosed acid tuffs. They may possibly have been acid sheets interstratified with the basic lavas and tuffs that formed the greenstones, but when the fact is considered that they grade imperceptibly into the green schists and that in some of them traces of fragments may be recognized, it seems more probable that they were, as Williams supposes, originally acid tuffs which have been altered and made schistose by processes similar to those that changed the diabasic lavas and tuffs into the greenstone-schists.

THE KITCHI SCHISTS.

Many of the green schists of the Northern Complex are noticeable for the pebble-like and bowlder-like bodies scattered through them. These fragments stand out so plainly on the weathered surfaces of the exposures on the Kitchi Hills in the vicinity of Deer Lake (Atlas Sheet XXVII) that they may be seen from long distances. They are usually so well rounded that the rock containing them looks very much like a sedimentary conglomerate. Indeed, so conglomeratic are their features that they have frequently been called the Deer Lake conglomerates. (See fig. 4.) The rocks are, however, plainly basic tuffs, but they have preserved their

[1] The greenstone-schist areas of the Menominee and Marquette regions of Michigan, by G. H. Williams: Bull. U. S. Geol. Survey No. 62, 1890, p. 151

tuffaceous character so much more perfectly than have the banded varieties of the Mona schists, from which they differ also in composition, that they have been designated by the distinctive name Kitchi schists.

DISTRIBUTION AND TOPOGRAPHY.

The Kitchi schists occur just west of the Mona schist area, stretching from the east line of R. 27 W. to the west line of secs. 25 and 36 in T. 48 N., R. 28 W., with a width varying from 2 miles to 3½ miles (Atlas Sheet IV). At the west end the schists are in contact with a coarse gneissoid granite.

FIG. 4.—Cliff of Kitchi schists, in sec. 33, T. 48, R. 27.

Both to the north and to the south the "conglomerate" area is bounded by Algonkian deposits, on the north by those belonging in the Dead River or Silver Lake area, and on the south by those of the Marquette district. It is not to be understood that these conglomeratic schists occupy this area to the exclusion of all other rocks. There are associated with the conglomeratic phases many greenstone-schists, similar to those farther east, in which no traces of a fragmental structure can be detected until their thin sections are examined microscopically, and also some light-colored acid schists, identical in all their features with those among the Mona schists. All these schists are cut by large and small dikes of altered diabase, and by a few acid dikes. But the conglomeratic schists are the predominant ones, and are those that give character to the western portion of the green-schist area.

The topography of the country covered by these rocks is not very different from that of the country underlain by the Mona schists. Isolated rounded knobs are not so frequent in the area of the "conglomerates" as in that of the Mona schists, but the larger hills have the same character in both areas. Drift is less thick in this district than in that of the Mona schists, the larger hills being oftener separated from one another by swamp lands than by drift deposits.

RELATIONS TO ADJACENT ROCKS.

The relations of the Kitchi schists to the altered tuffs of the Mona schists have already been described. The relations of the Kitchi schists to the granite on the west are observable north of the west end of a pond in the SW. ¼ sec. 26, T. 48 N., R. 28 W. (Atlas Sheet XXI), where they seem to be the same as the relations existing between the Mona schists and the granite north of these rocks. In passing from the schist to the granite, dikes of the latter rock first appear in the former; then the granite gradually becomes predominant, schist layers being interlaminated with the dikes or anastomosing through the granite in an irregular manner. Passing into the granite the schists are found included in it as angular blocks, and finally the massive rock appears completely free from the schistose one. The granite is therefore clearly intrusive in the Kitchi schists. The sedimentary rocks north and south of the schists repose unconformably upon the latter, from which they are separated by true conglomerates.

PETROGRAPHICAL CHARACTER.

BASIC SCHISTS.

Macroscopical.—Irving, in his introduction to Williams's article, already repeatedly referred to, describes the Kitchi schists as greenish schists, with a tendency to schistose structure that is never very pronounced, but which varies considerably in its degree of development. The rocks contain pebble-like bodies varying in size from 2 feet in diameter down to minute fragments.

Occasionally these appear to be well rounded, but more commonly they are subangular and flattened in a direction parallel to the schistosity planes in the inclosing rock. On exposed surfaces the "pebbles" stand out by virtue of their whiter weathering. (See fig. 4, p 161.) On a fresh fracture they are not nearly so apparent, but seem to differ from the rest of the rock by their finer grain and their pinkish or greenish color, the body of the rock having usually a dark greenish-gray tint.

This description applies well to the exposures along the Deer Lake road. Elsewhere the "pebbles" are more commonly rounded than angular. Many of them are as rounded as the waterworn pebbles of a modern beach. (See Pl. V.) In many places they may be seen disposed in bands of different widths that run parallel to the schistosity of the rock, whose strike is about east and west and whose dip is at some high angle to the south. Between these bands are others from which the "pebbles" are absent, or in which they are very scarce. These nonconglomeratic beds are like the matrix of the conglomeratic ones, except that there are scattered through the rock small, light-colored grains of feldspar. These are often mashed into lenses, or even into thin, sheet-like layers, running parallel to the planes of schistosity, when the rock presents somewhat of a gneissic aspect. In these rocks sharp-edged fragments of plagioclase may not infrequently be detected in the midst of a fine, satiny groundmass of chlorite plates and calcite grains, entirely different in character from the matrix of any schistose sedimentary rock met with in the district. The rocks are evidently basic tuffs.

Another variety of the schistose tuff occurs most commonly near the edges of the area, especially at the contacts with the Marquette beds. In the field notes the rock is called a sericite-schist. It is a pink to white, platy, and schistose rock, with a very pronounced soapy feel. On surfaces of the hand specimens that are at right angles to the schistosity sharp particles of different minerals are to be seen, but on the surfaces parallel to the foliation the rock appears to be a typical sericite-schist or talcose schist.

Except for the arrangement of the pebble-like masses in bands, there is little in the macroscopic appearance of these rocks that resembles the bedding of water-deposited materials. In two or three hand specimens a fine banding was detected, a slight difference in tint between the alternate layers leading to their recognition, but this is all.

Microscopical.—The conglomeratic green schists are so much decomposed that it is difficult to learn from their thin sections much more concerning their original character than can be learned from their study in the field.

The pebble-like masses scattered through the schists are fragments of a purplish-pink, fine-grained rock, speckled with tiny green dots of chlorite and red or white ones of altered plagioclase. Enough of the feldspar remains to exhibit traces of twinning bars, although most of it has been replaced by sericite, calcite, and quartz. These plagioclases were originally well-outlined crystals. They lie in a groundmass composed of small feldspar laths, grains of epidote, and a weakly polarizing felsitic substance that is probably a devitrified glass. The rock of which the pebbles were a part was probably a porphyrite, unlike anything that has yet been found in place within the limits of the district.

The schistose groundmass in which the pebbles are embedded consists of sharply angular fragments and complete crystals of altered plagioclase in a matrix composed of much chlorite and sericite, small fragments and crystals of plagioclase, always some calcite, and a fine-grained mosaic of secondary quartz. To these is sometimes added epidote in grains and plates. It is noteworthy that in these rocks chlorite has replaced the original iron-bearing silicate, while in the tuffs of the Mona schists to the east these silicates are now represented by hornblende. Whether this difference in composition is due to differences in the nature of the alteration processes to which the different rocks have been subjected, or to the fact that the rocks of the greenstone-conglomerate area have suffered the effects of weathering to a greater extent than the Mona schists, is not certain. It seems most probable, however, that both causes are responsible for the differences.

PEBBLES FROM KITCHI SCHIST.

The larger feldspar pieces in the groundmass have been referred to as crystals and fragments of crystals. In most cases they are unquestionably fragments. In many instances the pieces lying close together are dissevered portions of the same crystal, fractured across at right angles to the planes of schistosity in the rock. The fragments thus formed have been moved apart in the planes of foliation. The fracturing and the movements of the fragments are believed to be an effect of mashing, which is shown also in the rock's foliation. Many fragments are ragged in outline. They do not

FIG. 5.—Outlines of plagioclase grains in nonconglomeratic band of Kitchi schist.

correspond with other fragments in their vicinity, nor have they the straight-edged contours of the fractured crystals. These are like the fragments in modern tuffs. They are in all probability pieces of crystals blown from volcanic vents (fig. 5).

The chlorite in the groundmass is in small prisms and needles, arranged usually in approximately parallel directions, forming narrow bands, which may be laminæ in some places and in others may expand into comparatively large lenticular masses. Chlorite occurs also in oval and irregular areas, formed by the aggregation of its plates intermingled with grains of epidote, of calcite, and of great numbers of rutile crystals that are usually included within the chlorite. As Williams has suggested, these areas may represent the basic fragments of the tuffs that have been altered beyond recognition. The sericite is as abundant as the chlorite in some specimens, while in others it is present in small quantity only. It appears as colorless or light-green flakes that lie scattered among the other constituents, especially between the chlorite prisms, and as tiny spicules that penetrate the grains of the mosaic matrix. Of the calcite nothing need be said, except that it occurs as nests or as grains between the other minerals. In some of the more compact tuffs a second carbonate is sometimes met with in the form of small rhombohedra. The substance is more opaque than the calcite, and is of a yellow or yellowish-brown color. It is probably ankerite or ferruginous dolomite.

The matrix in which all the components of the groundmass lie resembles very closely the silicified background of many aporhyolites. Under very high powers of the microscope it is seen to be made up of intricately interlocking, colorless grains. Their aggregate polarizes like a fine-grained quartz mosaic. No twinning bars were seen in any of the grains examined, but many grains exhibit an undulatory extinction. This groundmass is therefore regarded as quartzose. Some of the quartz may have been derived from the original constituents of the tuff by alteration, but most of it, in all probability, has been introduced from without. The rocks have evidently been silicified, for we find ledges cut through and through by quartz veins, and in the microscopic section these veins can be followed as they break up into smaller and smaller ones, until their ramifications are finally lost in the mosaic above mentioned.

The evidences of pressure resulting in mashing are not so abundant in these schists as they are in some of the other rocks of the district, it may be for the reason that many of its effects are obscured by the secondary substances produced subsequent to its action. Many of the larger feldspar particles are broken and their fragments are displaced laterally; the longer axes of all the fragments are often approximately in the same plane;

the little chlorite rods are arranged likewise with their longer axes in the same direction, and the lenticular areas of the mineral are elongated in the same way. Around the fragments, large and small, the laminæ of chlorite and sericite bend, and occasionally one of the larger grains of the mosaic matrix exhibits undulatory extinction. These are the only evidences of the action of pressure within the schists, but they are sufficient to show that the rocks have suffered mashing. Where the schistosity is greatest the quantity of chlorite and sericite present in the rock is greatest; where the foliation is scarcely discernible there may be present much chlorite, but little sericite.

In addition to the tuffaceous schists in the Kitchi formation, there are others in which no fragmental material can be detected. In the field these rocks were taken for the more massive phases of the tuffaceous schists. Under the microscope, however, a difference in the structure of the rocks is detected. The feldspars of the nontuffaceous bands are in crystals, and not in fragments of crystals, and the association of feldspar and chlorite approaches the ophitic association of the plagioclase and augite in diabase, or the association of feldspar laths and glass in certain feldspathic basalts. In composition the fragmental and the nonfragmental schists are identical. In all probability these bands represent the lava flows or sheets that accompanied the extravasation and deposition of the tuffs. Whether they were surface flows or intrusive sheets can not now be told, for all the finer detail of their structure has disappeared.

ACID SCHISTS.

The sericite-schists—most abundantly developed on the south side of the Kitchi area, in contact with the Marquette beds, but occurring also elsewhere, interbedded with the basic schists—in thin section are essentially similar to the green schistose rocks interbedded with the conglomerates. They differ principally in having the sericite, rather than the chlorite, as their principal micaceous component. Many of these light-colored schists are composed almost exclusively of sericite and quartz, but most of them contain chlorite also. By increase in the proportion of chlorite in them they pass gradually into the green tuffs.

ORIGIN OF THE KITCHI SCHISTS.

The Kitchi schists are evidently fragmental deposits. Their composition, however, is so different from that of water-made sediments that we must ascribe some other origin to them. The banding of certain of the conglomerates and the alternation of layers in some of the finer-grained varieties would indicate that there was a partial sorting of the fragments, but the nature of the fragments themselves, and the composition of the matrix in which they lie, would seem to preclude the notion that the materials were furnished by the wasting of preexisting rocks.

In one or two of the several hundred sections examined roundish quartz grains were observed, but these are so very rare that they can afford no basis for a theory of origin of the rocks containing them.

The composition of one of the green schists (I) and of one of the sericite-schists (II) associated with them is given below. The first is composed largely of plagioclase, chlorite, and quartz; the second consists principally of sericite and quartz. Both analyses were made by George Steiger in the Survey laboratory.

Analyses of Kitchi schists.

	I.[1]	II.[2]
SiO_2	61.35	70.76
TiO_2	.26	.33
Al_2O_3	16.45	14.83
Fe_2O_3	.94	1.46
FeO	4.20	3.09
CaO	3.46	.36
MgO	3.12	1.99
K_2O	1.05	3.50
Na_2O	5.24	.47
P_2O_5	.18	.26
CO_2	1.98	....
H_2O at 100°	10	.09
H_2O above 100°	2 51	2.70
Total	100 84	99 84

[1] Green schistose rocks speckled with red-weathering feldspars. No. 22062. From near center of sec. 34, T. 48 N., R. 27 W.

[2] Light grayish-green sericitic schist from between two well-characterized conglomeratic beds of the green schist. No. 22085. From about 200 paces south of northwest corner of same section.

From their composition and structure it is evident that the acid schists associated with the greenstone-conglomerates, as well as these latter rocks themselves, are tuffaceous deposits which suffered dynamic metamorphism and weathering until their original composition was entirely changed. The darker-colored schists have now the characters of "schalsteins;" the lighter-colored ones are sericite-schists. The former were originally basic tuffs, and the latter, in all probability, acid ones interstratified with the former. The basic rocks are much the more abundant. The pebbles occurring in the conglomerates are all of the same general character. They are very similar to the schistose matrix in which they are embedded, but are less schistose. They must be looked upon as volcanic bombs or as large fragments of the lavas whose ashes produced the matrix. If fragments, they have become rounded by the mashing that caused the foliation of the finer particles.

Since the green schists are surface materials, they must have been deposited upon some previously existing basement. This basement has not yet been identified. It can not be the gneissoid granite, for the granite is intrusive in the schists.

THE GNEISSOID GRANITES.

The granites and gneisses of the Northern Complex are closely related genetically. Both are coarse-grained, both vary in color from dark greenish-gray to bright-red, both are usually granular, and occasionally porphyritic, with large red phenocrysts lying in a coarse red groundmass, and both have suffered more or less severely the effects of mashing. The gneisses differ from the granites only in the perfection of the foliation that has been imparted to them and in the amount of dynamo-clastic material discoverable in them. The gneisses are indisputably foliated phases of the granite, which is always more or less schistose. Since the origin of these gneisses is known, it seems better to designate them by a name that will indicate their origin, leaving the term "gneiss" to cover those foliated rocks of the composition of granite whose origin is problematic.

DISTRIBUTION AND TOPOGRAPHY.

The gneissoid granites occupy two distinct areas in the Northern Complex. Although widely separated, the rocks occurring within them may be treated together, since they are alike both in macroscopic and in microscopic characters, and so far as can be learned they bear exactly the same relations to the surrounding sedimentaries and crystallines. The easternmost of the two areas is north of the Mona schists and beyond the limits of the map (Atlas Sheet IV). It extends northward nearly to the lake shore, and westward until it connects outside the limits of our work with the eastern limb of the second area. This second area begins at the western side of the Kitchi formation and extends westward beyond the district treated in this paper. On the south it is bordered by the Algonkian beds of the Marquette area, and on the north by the slates and quartzites of the Arvon district.

The granites, whether massive or gneissoid, form knobs with rounded and smooth surfaces, where they have been exposed clearly to view by the removal of their forest covering. At many localities these are isolated from one another by stretches of glacial or lake sands. At others a number of knobs together form large, rugged, boss-like masses, having as many independent eminences as there are individual knobs comprising the main one. The hills never assume the dignity of mountain peaks. The surface features of the area underlain by the granite are thus essentially similar to those of the green-schist area. There is a difference, however, that is usually recognizable in those portions of the district where ledges are abundant. In the areas of green schist the surfaces of the ledges are usually rough and broken; in the areas of granite the surfaces are smooth as a result of glacial action, so that, whereas the bare tops of hills and the bottoms of stream channels in the greenstone-schist are rough and uneven, in the granite they are comparatively even and smooth. (See Pl. VI.)

RELATIONS TO ADJACENT ROCKS.

The relations of the granites to the green schists with which they are in contact have already been mentioned. The granites and their accompanying gneisses are younger than the schists. They are, however, older than the fragmental beds above the schists, since none of their dikes intersect these, even when the granitic rocks are in contact with the sedimentary

RIVER COURSE THROUGH GRANITE.

ones. On the other hand, bowlders of the former are often found in the lower beds of the latter.

Since the granites and their accompanying gneisses can not be the foundation upon the surface of which the materials of the green schists were spread, and since these latter are all fragmental volcanic rocks and surface lavas, it follows necessarily that there must have been a basement beneath the green schists which is older than these and the gneissoid granite that intrudes them. This basement, however, has not yet been identified in the Northern Complex. Occasionally a small mica-schist ledge is met with in the midst of granite ledges, and this may represent a series of rocks underlying the green schist and older than they; but no evidence either in favor of this view or in opposition to it has yet been collected.

THE BIOTITE-GRANITES.

PETROGRAPHICAL CHARACTER.

Macroscopical.—As has already been stated, the more massive and the more schistose phases of the granites—the gneissoid granites and the granitoid gneisses—are believed to be portions of the same rock mass, and therefore they are discussed together. Further investigation may show that some of the gneisses are older than some of the granites, but up to this time no discrimination between the massive and the schistose granites has been attempted in mapping.

The rocks vary in color from grayish-green to bright-red, the color of the former varieties being due to the abundance of chlorite in them. Their feldspar is rarely white. It is usually of a light-red or pink color. When bright-red it gives the entire rock of which it is a part a red tint, which varies in brilliancy according to the quantity of feldspar in it. In a few instances bright-red orthoclases are scattered through a groundmass of gray granite, but this variety is usually found only near the contacts of the rock with the greenstones or in its apophyses that intrude the latter.

Microscopical.—The granites and their gneissoid varieties are all composed of clouded orthoclase, microcline, plagioclase (the first-named mineral predominating), quartz, and brownish-green biotite or its decomposition products. Occasionally chlorite is present. This appears from its shape to have been derived from hornblende, but no undoubted amphiboles have been detected in the northern granites. With few exceptions the rocks are all biotite-granites or granitites. The accessories are small crystals of sphene, some leucoxene and magnetite, and an occasional zircon.

The original constituents of the granites require no special description. The orthoclase and plagioclase are altered to kaolin, sericite, and calcite. These products, together with a red earthy dust, probably an ocher, are so thickly clustered that they very nearly obscure the twinning bars of the plagioclase and cause it to be confounded with the orthoclase. The biotite was originally a brownish-green variety. At present but few remnants of the mineral remain. It has been changed to single plates and aggregates of flakes of a pale to bright green chlorite, polarizing with blue tints. This chlorite is sometimes intergrown with muscovite, but only in those cases where the latter is evidently a product of dynamic action.

The quartz appears in two forms, either as irregular grains of the usual character of granitic quartz or as little masses filling triangular areas between the other components and sending arm-like projections into them. Some of it is in all probability original; much of it is unquestionably secondary. All of it is marked by the undulatory extinction, and a part of it is completely shattered.

No specimen of the granites examined is free from the effects of mashing. In every slide placed under the microscope more or less distinct traces of dynamo-metamorphism are recognized. The feldspar is granulated peripherally and the quartz is more or less completely shattered. The fragments thus derived are mingled with chlorite flakes, epidote grains, and occasionally a little muscovite, and the whole is cemented by newly formed feldspars, among the most prominent of which is microcline. This mineral was evidently formed in large quantity after the crushing of the original minerals of the granite. It inserted itself into every crevice and space between these; in some cases it has even formed tiny veins cutting across quartz grains.

Not only is microcline present in this fragmental aggregate, but it occurs also as colorless rims around the cloudy orthoclase, and also often replacing the material of the latter. A large, cloudy orthoclase may in many cases be found completely saturated with clear, colorless microcline substance. There is no sharp line of contact between the two feldspars, but they seem to grade into each other. As the microcline replaces the orthoclase it absorbs the alteration products of this mineral, the resulting new feldspar thus being free from inclusions, while the original feldspar is full of them.

Dr. Williams, in his report on the Marquette greenstones, referred to the microcline in the granites as more probably the effect of pressure twinning in orthoclase than the product of chemical alteration. To the writer it appears more probable that the microcline is all, or nearly all, new material, produced by chemical agencies. In evidence of this view, and against that which regards the mineral simply as a pressure-twinned orthoclase, we would cite the freshness of the latter mineral as compared with the orthoclase, its freedom from inclusions, its irregular occurrence within the orthoclase grains, and its existence in large quantity in veins and as the cement of the crushed mosaic.

Fresh plagioclase is also a common new product in some sections. It occurs as grains among the crushed materials, and sometimes it surrounds cloudy feldspar as a clear, colorless zone. Its twinning bars are commonly much bent, and nearly always they present a few or more of the usual features due to movement.

The epidote grains in the mosaic need no description. They are very light in color, and therefore show no pleochroism. The muscovite that is in some cases associated with the biotite or chlorite is found with these minerals only where they are in the mosaic aggregate, and then only where in contact with orthoclase, a large mass of chlorite in some cases being separated from the orthoclase by a rim of muscovite. This mineral is also present in laminar aggregates of flakes, which in some slides penetrate the mosaic, but which in most slides separate it from the unfractured original granitic components.

The mosaic of fractured minerals and new products is always more or less schistose. This structure is produced by the lengthening of the fragments in a common direction, and by the development of the chlorite and muscovite in large, narrow flakes and groupings of flakes. The mosaic is also traversed by bands in which the fragments are very much smaller than elsewhere, as though the rock had slipped along certain planes and had ground into powder the neighboring fragments. These bands run in the same direction as do the stringers of chlorite and muscovite, and so help to impress schistosity on the mosaic. They are microscopic shear zones.

The structure of all these granites is that described by Tornebohm under the name of "mortar-structure." Williams has already referred to it as characteristic of the granites of this region, and has cited its existence as evidence that the rocks in which it is found have been subjected to severe dynamo-metamorphism.

The gneissoid granites differ from the more massive phases of the rocks simply in the possession of more marked foliation. The mortar-structure is most beautifully exhibited in all the sections. The larger remnants of the crushed original components are embedded in the mosaic, which surrounds them as the crystalline matrix surrounds the eyes of an "augen-gneiss," the combination of fragments and mosaic producing lenticular areas, separated from other like areas by narrow bands of very fine mosaic.

It is not uncommon to see in a slide of the gneissoid granite a grain of orthoclase or of plagioclase broken into three or four pieces and the pieces separated from one another by distances of a quarter millimeter. The fissures between the fragments are filled with an aggregate of crystallized quartz and microcline, or with a portion of the fragmental mosaic.

The quartz grains have suffered crushing, but their parts have not been separated. Quartz areas now consist of nuclei peripherally granulated, or of several grains differently orientated, the whole forming a lenticule. Each component of the lenticule exhibits undulatory extinction.

THE MUSCOVITE-GRANITES.

Nearly all of the granites of the Northern Complex are biotite-granites. A very few of a different character are found whose relations to the common granite have not been determined. In the SW. $\frac{1}{4}$ sec. 29, T. 48 N., R. 28 W. (Atlas Sheet XVIII), for instance, is a mediumly fine grained, light grayish-pink rock, forming a small ledge between the coarser biotite-granites south and the quartzite north of it. The rock may be a dike in the coarser granite, and probably is, though no observations on this point are recorded in the note-books. The rock is so badly shattered that it is difficult to determine its original composition. The thin section shows no more evidence of schistosity than does the hand specimen. It does exhibit, however, a crushed mass of plagioclase, orthoclase, quartz, and muscovite, cemented by finer-grained débris of the same minerals and microcline. Between the finer grains there is sometimes quartz and sometimes muscovite, but usually the grains interlock with one another. All of the large grains are sharply angular, and many of them are cracked across in various directions. Others that were single fragments have been broken into many small ones that are now separated from one another. Enlargements of quartz and plagioclase fragments are noted. The muscovite is in large colorless flakes that, like the other components, are shattered. The cracks are filled with fine shreds of the same mineral, and the edges of the plates are frayed out into smaller shreds, which form a matted mass of tiny muscovite fibers, in which the larger plates lie. These fibers appear to be the broken portions of the larger plates that have been split by the force that crushed the quartz and feldspar. The matted aggregate of fibers is thicker where a large plate has been fractured into four or five fragments than where it is halved. Muscovite is also in minute laminæ between the crushed portions of the other constituents, where it is no doubt a product of the alteration of orthoclase. The rock is evidently a muscovite-granite that has been crushed but has not been rendered schistose.

ORIGIN OF THE GRANITES.

As to the origin of the granites and their gneissoid phases there can be little question. The rocks appear like eruptives in the field. The clastic grains discoverable in their thin sections are evidently of dynamic origin. All are sharply angular. None have the rounded outlines of waterworn grains. The structure of the rocks is very similar to that of schists elsewhere that have been shown to be mashed eruptives; hence there is no reason to believe the granites and gneisses of the Northern Complex to be anything but altered igneous rocks. It is impossible to trace them back to an earlier source than a molten magma; therefore, whatever may have been the origin of this magma, we are justified in calling the rocks igneous. There is no evidence of any kind to support the belief that the gneissoid granites in this portion of the Marquette district were ever water-deposited sediments that have been crystallized by metamorphic processes.

THE HORNBLENDE-SYENITE.

DISTRIBUTION AND TOPOGRAPHY.

The syenite, with its gneissoid phases, so far as has been observed, is found only in a narrow belt, from a quarter of a mile to a mile in width, lying between the green schists on the south and the fragmental beds of the Silver Lake Algonkian area on the north. The belt is about 5 miles long, and it lies almost entirely within T. 48 N., R. 26 W. (Atlas Sheets XXX and XXXIII). The syenite is so like the granite in its nature that but little remains to be said concerning it, except to describe its microscopical features. The topography of the area occupied by it is exactly like that of the granitic country.

RELATIONS TO ADJACENT ROCKS.

The relations of the syenite to the surrounding rocks are also like those of the granite. Its apophyses cut the green schists, and its main mass is unconformably beneath the Algonkian sediments. As to the relations existing between the syenite and the granite nothing is yet known positively. A very few ledges of the gneissoid granite have been found within the limits of the syenite area, and these, when examined with reference to the latter rock, appear to have been intruded by it. The appearances, however, are not decided enough to warrant an expression of opinion as to their meaning.

PETROGRAPHICAL CHARACTER.

The primary constituents of the syenite are orthoclase, plagioclase, hornblende, sphene, magnetite, and, very rarely, biotite. Its secondary components are plagioclase, microcline, chlorite, quartz, epidote, muscovite, and leucoxene.

The primary feldspars are clouded with alteration products, while the secondary ones are clear. The primary and the secondary minerals bear the same relations to one another as they do in the granites. The hornblende is in dark brownish-green crystals that are idiomorphic in the prismatic zone, but badly terminated at their extremities. It is nearly always more or less completely altered to chlorite. The sphene is also rarely fresh. It is usually changed into a cloudy, light-colored substance that looks yellow in reflected light. In general appearance it resembles the leucoxene so often seen surrounding ilmenite or titaniferous magnetite in greenstones, and hence it is regarded as this substance.

A similar alteration[1] of sphene into leucoxene has been described by Werveke, von Kuch, Velani, and Groth, the latter author regarding it as a product of weathering. In the Michigan rock the leucoxene forms perfect pseudomorphs, which retain the diamond-shaped cross-section of the original sphene. Whether it is a product of weathering or a result of dynamic metamorphism can not be told.

The quartz, which is always present to some extent, but never so abundantly as in the granites, occurs sometimes as small grains with an undulatory extinction, sometimes as larger ones broken up into an aggregate of differently orientated particles Most of the mineral, however, is in the angular spaces between the feldspars or in the cracks traversing the older constituents. A small portion of the quartz may be original, but the greater portion is thought to be secondary.

The structure of the gneissoid syenites is identical with that of the granites; so it needs no discussion in this place. The syenite, as well as the granite, is an igneous rock that has suffered dynamic metamorphism. The latter is a quartz-biotite-orthoclase rock, and the syenite an aggregate of hornblende and orthoclase. Even were the two rocks not distinguished by the abundance of quartz in the one and its rarity in the other, they would be distinguished by the presence of the biotite in the granite and of the hornblende in the syenite.

[1] Lehrbuch der Petrographie, by F. Zirkel, Vol. I, 1893, p. 410.

THE INTRUSIVES IN THE NORTHERN COMPLEX.

The granites, gneisses, and schists of the Northern Complex are cut by numerous dikes of basic and acid material and certain boss-like masses of peridotite, or of its altered form, serpentine. Of the dikes the basic ones are much more common than the acid ones, if we exclude from the latter those that are but apophyses of the coarse granite.

THE BASIC DIKES.

The basic dikes cut the gneissoid granite, the syenite, and the schists indiscriminately, though they may be most abundant in the greenstone-schist areas. They vary in width from an inch or two to 75 feet or more, and some of them have been followed 2 or 3 miles.

These dikes have been so well described by Williams[1] that there is little left to be said in this place concerning them. Diabases, epidiorites, and diorites were distinguished by this author. The diabases are of the usual types. The epidiorites are thought to be uralitized and epidotized diabases, since their structure is plainly ophitic, the feldspar occurring in lath-shaped crystals, and the amphibole forming fibrous wedge-shaped masses between the plagioclase laths. The diorites differ from the epidiorites mainly in structure and in the nature of their hornblendic component. The amphibole in the diorites is compact and idiomorphic, and hence it was considered by Williams as original. In some slides of these rocks, however, are cross-sections of a compact brownish-green hornblende that is perfectly idiomorphic, while at the same time nests of light-colored augite may be seen included within its mass. If this hornblende is secondary, as it seems to be, then it is probable that many of the supposed diorites of this district are altered diabases, just as are the epidiorites, which contain fibrous amphibole.

The freshest diabases, those still containing large quantities of pyroxene, are quite massive, even when the rocks through which they cut are completely schistose. These, then, must have been intruded in the schists after

[1] The greenstone-schist areas of the Menominee and Marquette regions of Michigan, by G. H. Williams: Bull. U. S. Geol. Survey No. 62, 1890, pp. 138–146, 168–175, 180–184, 189–190.

the latter had become foliated, and must be younger than the diorites and epidiorites, all of which are schistose.

In texture the diabases may be very coarse grained, very fine grained, or they may contain some glass. Mineralogically they present no special features. Most of them are nonolivinitic; a few contain pseudomorphs of chlorite and limonite after olivine.

An example of one of the freshest of the coarse diabases is found in a dike 75 feet in width cutting granite at 1,230 steps N., 450 steps W. of the SE. corner of sec. 23, T. 48 N., R. 28 W. (Atlas Sheet XXI). So coarsely granular is it that the rock approaches a gabbro in structure, though the augite is younger than the plagioclase and fills the interstices between the laths of this mineral. The components of the rock are magnetite or ilmenite, apatite, labradorite, and pyroxene, besides various alteration products of the two last-named minerals. The fresh pyroxene has the pink tint so common to the monoclinic pyroxene of Lake Superior rocks. On its edges it is altered to fibers of light-green hornblende, with which are interspersed a few grains of magnetite. The plagioclase is mainly well preserved. Its twinning lamellæ are broad and clearly defined, and the symmetrical extinction on each side of the twinning line is about 21°. In the small areas between the most altered pyroxene grains the feldspar is decomposed. It is reddened by cloudy secondary substance, and is filled with chlorite and amphibole flakes and needles. In these portions of the slides the largest apatites are to be found.

Sections of other fresh granular dikes present nearly the same phenomena as those above described. In most of them the diabasic structure is very pronounced and the grain is finer than in the case of the dike last mentioned. Moreover, in nearly all, alteration has progressed a little further. Green biotite and brown hornblende in small quantities are nearly always the accompaniments of the green hornblendic and chloritic decomposition products of the pyroxene. They occur in small flakes on what were the peripheries of the original pyroxene areas, and no doubt owe their origin partly to the feldspar. Upon further alteration the brown hornblende passes into a chlorite, while the green mica retains its properties.

Occasionally the structure of the diabases is porphyritic rather than ophitic. In the SW. ¼ sec. 23, T. 48 N., R 25 W. (Atlas Sheet XXXVIII), for instance, is a fine-grained dike that may be called a diabase-porphyrite. It contains phenocrysts of plagioclase and augite in a groundmass composed of a plexus of small plagioclase laths, round augite grains, and crystals of magnetite, with the intersertal structure as defined by Rosenbusch. A second diabase-porphyrite differs from the type just mentioned in the absence of pyroxene phenocrysts and in the presence of magnetite in large quantities. The latter mineral is found not only in the little grains between the constituents of the groundmass, but also in large, irregular masses scattered through the rock and in skeleton crystals resembling the microlites in basic glasses (fig. 6). These microlitic growths form long, slender, straight rods cutting indiscriminately through the grains of the groundmass and through phenocrysts.

FIG. 6.—Magnetite in fine-grained diabase or basalt

Most of the basic dikes in the Northern Complex are epidiorites, that is, they are rocks showing unmistakably the diabasic structure, but in which the augite has been entirely replaced by uralite or some other green hornblende. They are always more or less schistose, and therefore are much older than the fresh diabases. They vary from one another mainly in the form of their hornblendic constituent and in the freshness of their plagioclase. In some of them the augite has been pseudomorphed by green hornblende. In others the hornblende is in isolated or in grouped acicular crystals,[1] the ends of which often extend far out into the altered plagioclase surrounding the areas originally occupied by ophitic augite. In the least altered epidiorites the plagioclase is fresh, and in these varieties augite cores often remain as nuclei within the amphibole areas. As alteration progresses the plagioclase becomes more and more clouded by secondary products until finally it becomes an aggregate of epidote, chlorite, amphibole, and calcite. .

Fine examples of leucoxene are seen in many specimens. The mineral occurs as little cloudy masses around titanic-iron grains, and also as

[1] The greenstone-schist areas of the Menominee and Marquette regions of Michigan, by G. H. Williams: Bull U. S. Geol. Survey No. 62, 1890, fig. 2 of Pl. XII.

pseudomorphs of the latter mineral, replacing it completely in some cases. In other cases bars of the opaque iron oxide form a network in whose meshes are the white opaque grains of leucoxene. In the thicker aggregates the leucoxene passes into a dense yellowish-brown mass with the pleochroism of sphene.

The character of the alteration that changed diabases into epidiorites, coupled with the existence of schistosity in the latter rocks, is thought to be sufficient reason for ascribing the origin of the epidiorites to dynamometamorphism.

The "diorites" of the Northern Complex are probably altered diabases in which the new hornblende has assumed a compact rather than a fibrous form. The hornblende crystals in these rocks are always frayed out at their ends, but in cross-section they are compact and idiomorphic. The original feldspar has been entirely replaced by a transparent plagioclase that is cut through and through by slender needles of hornblende, at whose ends terminal planes may often be detected. Under crossed nicols large areas of the plagioclase break up into many small ones, interlocking with one another by sutures which follow the most intricate courses. This feldspathic mass differs so greatly from that of the epidiorites in appearance, in freshness, and in its structure that we must regard it as essentially different in origin. The feldspar of the epidiorites is a decomposed plagioclase, while that of the diorites is apparently a recrystallized one. The diorite as it now exists is not an original rock. It has been formed from some preexisting eruptive, but whether from an original diorite or a diabase is not certainly known.

The final products of weathering of all the basic rocks described as occurring in dikes are chlorite, epidote, kaolin, calcite, and quartz. A number of dike masses are known in the Northern Complex that consist principally of these minerals. Most of them present the ophitic texture of diabases, while in others the granitic texture of diorites and gabbros is recognizable. All are highly schistose. Chlorite is by far the most abundant component in them, and the rocks therefore are practically chlorite-schists. All that have been studied are unquestionably squeezed eruptives.

THE ACID DIKES.

The acid dikes cutting the rocks of the Northern Complex are not so numerous as are the basic ones, but their variety is greater. They include coarse granites and granite-porphyries, fine-grained granites, aplites, quartz-porphyries, and the aplitic form of quartz-diorite known as malchite.

No descriptions of the coarse granites and granite-porphyries are necessary. They are apophyses of the great granite masses north of the schists and do not differ in character from these. They are of the same age as the gneissoid granites, and hence are older than the various aplitic and diabasic dikes that intrude the granite.

The remaining acid dikes are usually of inconsiderable size when compared with the great basic dikes that traverse the schists and granites. They are also of various ages. Some are foliated and others are massive. The former were intruded before the last effects of pressure had been impressed upon the schists, and the latter long after the schists were made, for they intersect even some of the massive diabase dikes. None of them, however, intersect any of the members of the Algonkian series. The color of the dikes varies from pinkish-gray, through pink, to a bright red. Their material is always compact, and except when here and there it is microlitic it is also very fine grained. Many of these dikes are fine-grained granites with no peculiar features. Their feldspar is usually red or pink, and their principal bisilicate is a chloritized biotite. Others partake more of the aplitic character. Their feldspathic component possesses more or less perfectly quadrangular cross-sections, and their quartzes circular ones.

Both the granites and the aplites are altered. Their orthoclase is kaolinized and their biotite is so completely changed to chlorite that it is often difficult to determine what were the original components. Epidote is not infrequently an alteration product of the plagioclase present, and it is apparently often a result of the decomposition of biotite.

A few dikes of a fine-grained, dark-gray rock are of interest, since they represent the aplitic form of quartz-mica-diorite, named malchite by Osann.[1] The best specimen of this rock came from a dike 600 steps north of the

[1] Mittheil. Gross. Bad. geol. Landesanstalt, Vol. II, p. 380. Cf. also Microscopic study of some Michigan rocks, by H. B. Patton: Rept. State Board Geol. Surv. Michigan 1893, pp. 184–186.

SE. corner of sec. 18, T. 48 N., R. 28 W. It is an aggregate of plagioclase, orthoclase, quartz, and biotite. All the components are much altered. The biotite is chloritized, the orthoclase kaolinized, and the plagioclase saussuritized. Plagioclase and quartz compose the greater portion of the rock. The former is in little grains with irregular outlines that exhibit a tendency to become quadrangular, and the latter in grains between the plagioclases. In structure the rock is panidiomorphic.

The quartz-porphyry dikes have already been studied by Williams. The rocks are light-colored. They sometimes still have their original characters sufficiently well preserved to exhibit the porphyritic structure. In other and more numerous instances the rocks are schists. Their porphyritic orthoclases are broken and their fragments displaced, their porphyritic quartzes are granulated, either entirely or only peripherally, while the quartz-orthoclase mosaic that originally constituted their groundmass is now a schistose aggregate of quartz and sericite. In not a few of the porphyries plagioclase accompanies the orthoclase as phenocrysts, and chlorite, filled with tiny brown rutile crystals, is distributed through the groundmass as laminæ apparently replacing an original biotite.

THE PERIDOTITE.

The serpentine and peridotite form high, ragged bluffs that are noticeable for their dark color and jagged contours. One of these bluffs forms Presque Isle, on the shore of Lake Superior, about 2½ miles north of Marquette. The principal occurrences of the two rocks are, however, northwest of Ishpeming, in the area of the Kitchi schists.

THE PRESQUE ISLE AREA.

The rocks of the Presque Isle area (Atlas Sheet XXXVIII) are so well known, thanks to Dr. Wadsworth,[1] that we need give them little attention. They were all originally peridotites, but they have undergone alterations due to weathering until they are now largely serpentines and dolomites. Among the freshest phases of the rock lherzolites, picrites, and wehrlites have been distinguished.[2]

[1] Lithological Studies, by M. E. Wadsworth, 1884, p. 136.

[2] Report of the State Geologist for 1890–91, by M. E. Wadsworth: Rept. State Board Geol. Surv. Michigan 1893, pp. 134–138.

The peridotite and its altered varieties form an immense knob underlying Potsdam sandstone. Since the conglomeratic lower layers of the fragmental rock contain pebbles of the peridotite, and since a diabase dike in the latter is overlain by horizontal layers of the sandstone, it is concluded that the peridotite is older than the sandstone. Its age with respect to the Algonkian fragmentals is not yet known. It is probably younger than the green schists, for it is similar in all essential features to the peridotite of the Opin area, and this intrudes the Kitchi schists.

Analyses of the serpentine of Presque Isle were made by Whitney[1] in 1859. They are of those portions of the rock that were decomposed by fused sodium carbonate, and are evidently not complete.

Analyses of serpentine from Presque Isle.

	I.	II.	III.
SiO_2	36.95	37.25	....
Fe_2O_3	16.50	6.75	12.90
FeO	....	14.14	19.52
MgO	33.07	28.67	14.83
Na_2O	.97	1.16	....
H_2O	10.40	10.89	....
Total	....	98.86	....

THE OPIN AREA.

The rocks in the vicinity of Opin Lake, in T. 48 N., R. 27 W. (Atlas Sheets XXI and XXIV), that have been classed as peridotites and serpentines, embrace also dolomitic serpentine and almost pure dolomites. Phases intermediate between these four types are very numerous, so that there is no difficulty in tracing almost pure peridotites through serpentinous varieties into pure serpentines and these into dolomites.

The Opin area includes a number of detached exposures, the larger from 1 to 3 miles long, surrounded by green schists and greenstone-conglomerates. The combined areas, each composed of from few to many boss-like knobs, trend diagonally across the various belts of schist. The peridotite is never schistose except along shear-planes. Both acid and basic

[1] Notice of new localities and interesting varieties of minerals in the Lake Superior region, by J. D. Whitney: Am. Jour. Sci., Vol. XXVIII, 1859, p. 18.

dikes intersect the schists, whereas all dikes, except the very freshest of the diabases, are absent from the peridotite. These facts would indicate that the peridotite is an irruptive of later age than the schists. Dr. Wadsworth has recently described an irruptive contact of the serpentine with the schists, and a dike of the peridotite intruding diabase, diorite, and felsite. There can be no question, then, that the peridotite and its derivatives are younger than the Deer Lake Kitchi schists. From the relation of the various dike masses to it, it would seem to be the latest intrusion in this area, with the exception of the fresh diabases, whose irruption continued until the close of Upper Marquette time.

The freshest peridotite obtained in this area came from a large bluff near the center of the E. ½ sec. 27, T. 48 N., R. 27 W. The rock is composed of fairly well preserved diallage, olivine, magnetite, and plagioclase. The olivine is in well-defined crystals, embedded in large plates of pale-pink, almost colorless diallage that nearly fill the section. In the small interspaces between the diallages occurs the plagioclase, as a weakly refracting, altered, white or colorless substance, occupying the same relation with respect to the diallage and olivine as glass does to the crystals in a hypocrystalline rock. The olivine and diallage are both serpentinized in part, and the diallage is in places uralitized and chloritized, especially near its contact with the plagioclase. The small amount of magnetite present is found amongst these decomposition products, as are also a few flakes of biotite. Calcite fills cracks in the other components and the spaces left between them. The rock has the composition, but not the structure, of wehrlite. Its analysis, made by W. F. Hillebrand in the Survey laboratory, is given on the next page.

From this analysis it is seen that the rock is more altered than would be judged from the investigation of its single thin section at hand. It is also noticeable that, like many other peridotites, it contains small percentages of several rare metals, as titanium, chromium, manganese, and nickel, besides traces of strontium and barium.

From most of the sections of specimens taken from the Opin peridotite the olivine and diallage or other pyroxene have entirely disappeared and serpentine or dolomite has taken their places. In many of these the original structure of the peridotite may still be detected, while in others nothing can be seen but fibrous masses of serpentine, irregular areas and tiny veins of dolomite, and some magnetite and earthy products. When the serpentine predominates, the rocks are well-characterized calcareous serpentines; when the dolomite prevails, they become almost pure dolomites. These latter rocks are not so abundant in quantity as the serpentines are. They are found usually as veins cutting the latter rocks, and as indefinitely defined bands bordering cracks and joint planes in them.

Analysis of the peridotite from the Opin area.

	Per cent.
SiO_2	39.37
TiO_2	.66
Al_2O_3	4.47
Cr_2O_3	.68
Fe_2O_3	4.96
FeO	9.13
MnO	.12
NiO	.21
CaO	3.70
SrO	Trace.
BaO	Trace.
MgO	26.53
K_2O	.26
Na_2O	.50
H_2O below 110°	.87
H_2O above 110°	7.08
CO_2	1.23
P_2O_5	.17
Total	99.94

No. 17972; from 1220 paces N., 500 paces W., of the southeast corner of sec. 27, T. 48 N., R. 27 W.

FERRUGINOUS VEINS IN THE NORTHERN COMPLEX.

At various places within the schist areas of the Northern Complex there are small masses of ferruginous slate, ferruginous chert, and magnetite-grünerite-schist which are identical in hand specimen and in microscopical character with similar rocks of the Negaunee iron formation. The best-known locality at which these rocks are found is in the northern part of the city of Marquette, a short distance west of Light-House Point. The largest masses of the ferruginous rocks are seen on Michigan street, from which place they extend east and west for some distance. At Michigan street the rocks are separated into two parts by a layer of green schist. A short distance to the east but a single mass is found, and this, as it is followed farther east, becomes much smaller. It finally disappears at the end of one outcrop separated from others by an interval of 10 feet. The ferruginous rocks at this place have a strike and dip closely corresponding with those of the foliation of the schists with which they are associated, but when examined minutely the two are found to be discordant.

East of this place, on the neck of Light-House Point, various narrow seams of iron-bearing rock, from a few inches to a foot wide, are found. These are interlaminated with the green schist of the point. One of them can be traced for a distance of 100 feet or more, while the other smaller ones disappear within a short distance. Some of these narrow masses have become soft and hydrated, and such resemble the ferruginous material taken out from the Eureka mine 2 or 3 miles to the west. The Eureka ore is a soft hematite in the green schist.

The belt of green schists from the Eureka mine to Light-House Point, in common with the entire green-schist area, shows evidence of extensive dynamic action, the rocks all having a schistosity, and in some places being broken up into lozenge-shaped blocks, between which solutions might readily pass. It is believed that all of the ferruginous deposits of this area, in their banding, in their relations to the surrounding green schists, in their great variability in thickness, and in the rapidity with which they die out, correspond in every respect to infiltrated veins, and are, therefore, secondary to the country rock.

In sec. 2, T. 48 N., R. 27 W., just north of the old Holyoke mine, outside of the area mapped, there are also found within the green schist of the Northern Complex various masses of sideritic slate, ferruginous slate, ferruginous chert, and grünerite-magnetite-schist. In their relations to the surrounding rocks they in all respects resemble those adjacent to Marquette.[1]

[1] In one of the Archean islands, in sec. 23, T. 47 N., R. 26 W., are also found narrow veins of jasper, the widest being less than a foot thick.

The formation of veins of ferruginous materials must have been prior to Marquette time, for in the lowest formation of the Marquette series, as seen on a succeeding page, are found fragments of ferruginous rocks like the veins in the Basement Complex. The Holyoke conglomerate at the base of the Huronian series in this locality contains very numerous large fragments of various ferruginous rocks which are identical with the veins in the green schists below, and there can be no doubt that the ferruginous detritus was derived from the veins.

SUMMARY.

In the preceding pages it is shown that the basement upon which the Marquette sediments were deposited, as it exists in the Northern Complex, consists mainly of foliated rocks, including greenstone-schists, gneisses, gneissoid granites, and syenites, that are cut through and through by intrusions of acid and basic rocks in the form of dikes and are penetrated by bosses of peridotite. All the dikes, except a very few fresh diabases, are older than the upper beds of the Marquette series. They are schistose, and most of them are much altered. The massive diabase dikes were probably formed during Keweenawan time. The peridotite is younger than the Cambrian sandstone and older than the greenstone-schists of the Basement Complex. Its age has not been determined more accurately.

The gneissoid granites and syenites differ from one another in composition, the former consisting essentially of biotite, quartz, orthoclase, plagioclase, and microcline, and the latter of hornblende and the feldspars. Both rocks owe their foliation to mashing, and both have had developed in them large quantities of new minerals, the most noticeable being microcline, plagioclase, and muscovite. The gneisses differ from the granites simply in the greater perfection of their schistosity and in the greater quantity of new minerals developed in them. These acid rocks have the structure of plutonic intrusives. They cut through the greenstone-schists and are intermingled with them so confusedly that accurate outlining of the areas underlain by the acid and the basic rocks, respectively, is practically impossible. From their structure it is evident that the granites and syenites were intruded into the schists when these were at some considerable distance below the existing surface. Since, however, the granites were exposed at the surface, when the basal beds of the Marquette series were formed (as shown by the numerous bowlders of granite in the basal conglomerates), it necessarily follows that the interval between the intrusion of the granites and the formation of the first of the Marquette beds was of great length. Since, moreover, the green schists are older than the granites, it further follows that the schists are very much older than the oldest members of the Marquette series.

The greenstone-schists studied are all squeezed surface materials. They are nearly all recrystallized basic tuffs or altered lavas. The few schists of doubtful origin were probably lava flows of coarser grain than the predominant ones. As these rocks were surface forms, it is evident that there must have been a foundation upon which they were laid down. The gneissoid granites can not have composed this foundation, because they are younger than the schists. The former, however, are the only other class of rocks, with the exception of the dikes, that have been discovered in those portions of the Northern Complex studied; hence it follows that the surface on which the basic lavas and tuffs were laid down has not yet been found. It is barely possible that the original surface rocks have disappeared, as Lawson[1] has suggested in explanation of a similar set of phenomena in the Rainy Lake district of Canada, and that the granites and gneisses are their fused representatives; but in the Marquette district there is no evidence to show that this is the case, and we must therefore content ourselves for the present with the statement that the basement on which the schists were deposited is unknown.[2]

It is to be remarked in conclusion that, whatever may have been the original condition of the granites, all the members of the Northern Complex

[1] A. C. Lawson, Report on the geology of the Rainy Lake region: Ann. Rept. Geol. and Nat. Hist. Surv. of Canada for 1887–88, Vol. III (new ser.), F., pp. 1–196; and Am. Jour. Sci., 3d series, Vol. XXXIII, 1887, pp. 473–480. Also Congrès géol. internat., Compte-rendu 4th sess., London, 1888, pp. 130–152.

[2] Rominger's theory of the structure of the district under consideration is very similar to Lawson's theory, so far as it concerns the relations of the granites to the other members of the Fundamental Complex and to those of the Marquette series (see Chapter I, p. 81), and Rominger's statement was published much earlier than Lawson's. The same remarks that apply to Lawson's suggestion apply as well to Rominger's theory.

exhibit proof that they once existed as igneous magmas, from which they were formed by cooling, so that in their present condition they are all of igneous origin. Not a sediment of any kind has been detected among them. In this respect the Northern Complex differs essentially from the Marquette Algonkian, which consists almost exclusively of well-preserved sediments.

The relations of the granites and the gneisses to the greenstone-schists are those that obtain between the Mareniscan and the Laurentian series of Van Hise, the greenstone-schists representing the Mareniscan, and the granite-gneisses the Laurentian. Nothing corresponding to Adams's Grenville series has yet been discovered in this district, and perhaps nothing corresponding to his Fundamental Gneisses.

SECTION II.—THE SOUTHERN COMPLEX.

So far as our studies have gone it has been found impossible to map the rocks of the Southern Complex even as definitely as has been done in the case of the Northern Complex. Except in its eastern portion, there are no large distinct areas in that part of the southern district studied that are occupied almost exclusively by one kind of rock. Most of the area is occupied by granites, gneisses, hornblendic and micaceous schists, and greenstone-schists, together with the various acid and basic eruptives that intrude them.

The relations existing between the rocks of the Southern Complex and those belonging in the Marquette series are referred to at the proper places in connection with the discussion of the lowermost beds of the Algonkian. Where their contacts are seen there are found marked unconformities between the two series, as will be explained later. At other places the crystallines, as well as the fragmental rocks, are mashed to such an extent that it is difficult to draw a line between them. Along such contacts there are often developed light-colored sericitic schists and gneisses, whose origin is problematic. At many other places, notably in Rs. 27 and 28 W., the granites and schists are separated from the Algonkian sediments by a strip of country devoid of exposures. Often swamps intervene between the last outcrops of the bedded rocks and the first ones of the schists. At other times drift covers the contacts. In such cases the relations of the two series can not be determined. Nevertheless, there is no reason to believe that they are different from those observed where the rocks are seen in actual contact.

DISTRIBUTION AND TOPOGRAPHY.

The topography of the Southern Complex differs but little from that of the northern granite areas. In its eastern part the drift is thicker than in the western part, and consequently the ledges are frequently small isolated exposures, single knobs, or collections of knobs, that are presumably the tops of hillocks with several peaks, separated from one another by little defiles. The hillocks themselves are separated by drift deposits, so that the Southern Complex in its eastern portion consists in reality of distinct areas.

Between the north-and-south center line of R. 27 W. and the west line of R. 28 W. the country is swampy and ledges are rare. When they occur it is as small, low outcrops in the midst of the swamps. Farther west hills and swamps alternate, and the surface has the usual aspect of pre-Algonkian topography.

In its eastern portion the rocks comprising the Southern Complex form a narrow belt bordering the Marquette sediments and extending southward under a broad sand plain, above which here and there isolated knobs of granite protrude, thus indicating the presence of pre-Algonkian rocks beneath the sands. To the west the belt expands, until, near the Michigamme River, it is many miles in width. Here the area is divided by the Republic tongue of the Marquette rocks into a large eastern portion and a narrow western one, which, uniting just south of the city of Republic, merge into one large area.

To the east, near Lake Superior, granites predominate. Westward from the lake shore for 10 miles these are about the only members of the Southern Complex met with. Farther west schists become involved with the granites in the most intricate manner, so that frequently it is impossible to declare whether the former or the latter rocks are the more abundant. As the work in the Southern Complex progresses it is probable that the schist areas and granite areas will be differentiated from each other, and that a correct map will show large granite areas surrounded by schistose rocks and separated from each other by areas in which schists are largely predominant.

COMPARISON WITH NORTHERN COMPLEX.

As compared with that portion of the Northern Complex studied, it is found that the southern area contains fewer greenstone-schists. Moreover, in the southern area hornblendic and micaceous gneisses and schists are abundant, whereas in the northern area they are absent. The granite is intrusive in these schists, and also in the few greenstone-schists present. The relations of the greenstone-schists to the hornblendic and micaceous ones are not known, but it is thought probable that the latter are older than the former, and that this fact would account for their absence in the northern area, where, if they ever existed, they must be buried beneath the tuffs and lava flows that have produced the schistose greenstones.

THE SCHISTS.

The schists of the Southern Complex comprise hornblendic and micaceous schists and greenstone-schists similar to the greenstone-schists of the Northern Complex, granite-gneisses, and the Palmer gneisses, which, because they are so closely allied to the granite-gneisses are discussed with the latter rocks.

The best exhibition of the various hornblendic and micaceous schists is in the area lying southeast of Lake Michigamme and southwest of Champion, constituting the northeast quarter of T. 47 N., R. 30 W. (Atlas Sheet IX). The district is covered with small knobs and large hills with bare tops, on which the relations of the schists and the granite may be easily studied. Occasionally a knob may consist exclusively of granite or of the schists, but usually both schists and granites are found in it, the granite often occupying the higher parts. The schists include both hornblendic and micaceous kinds, of which the latter are the more common, though the former are not rare. The micaceous varieties are well banded with light and dark layers, measuring from a line or so to several inches in breadth. On weathered surfaces the bands show plainly, but on fresh surfaces they are often scarcely perceptible. Where undisturbed by granite intrusions the bands strike about northeast and dip northwest at a very high angle. Near the contacts with the granite they are much contorted. The hornblendic schists are sometimes banded, but the banding is not so regular as in the case of the micaceous rocks.

There can be no question that the granite is intrusive in the schists. Its dikes and veins cut the schists in all conceivable directions. Perhaps more frequently than otherwise the dikes run parallel to the banding of the

Fig. 7.—Mica-schist intruded by granite, south of Champion mine.

intruded rocks, but they nevertheless often cut across them, crumpling and contorting the bands. The most easily accessible locality at which these relations may be seen is on a little knob just south of the middle shaft of the Champion mine, where the coarse white granite, so abundant farther south, sends broad dikes with branching arms into a black, glistening mica-schist (fig. 7). The same granite a little to the southwest contains numerous large, sharp fragments of a similar schist, which it has evidently taken up in its passage to its present position.

Although more abundant in this portion of the southern area than elsewhere, the hornblendic and micaceous schists are not confined to it. Small exposures of them are found scattered among the granite knobs as far east as the east line of sec. 34, T. 47 N., R. 26 W. (Atlas Sheet XXXV), and as far west as Republic (Atlas Sheet XI), forming almost as great a proportion of the rocks in this vicinity as they do in the neighborhood of Champion. In the interior of the area they are probably also quite common. Wherever found, most of the schists are more or less definitely banded and always distinctly foliated. The general direction of their banding varies in its strike from north to northeast, and in its dip from 45° northwest or west to as much southeast or east. Usually the dips are very steep, and often they are perpendicular.

Occupying less extended areas are the other foliated rocks of the Southern Complex. These are the greenstone-schists and the various gneisses. The former occupy a distinct but very small area near the shore of Lake Superior (Atlas Sheet XXXIX), where they present the same features as some of the corresponding rocks in the Northern Complex. Their foliation strikes about east and west, and their dip is nearly vertical. Occasionally similar schists are found in other parts of the southern area, interspersed among the other rocks. Under these conditions they appear to be mainly schistose dikes.

The gneissoid granites are more common in the western portion of the Southern Complex than in its eastern portion, though they are found also in the latter area. Their distribution is quite uniform throughout the granite, but their abundance is inconsiderable when compared with their abundance in the Northern Complex. No definite relations as to distribution have been determined to exist between these gneisses and the massive granite.

The Palmer gneisses are found only along the southern side of the Marquette syncline. Their general distribution is indicated on the map (Atlas Sheet IV). Further reference to them and to the gneisses is deferred until the granites are discussed.

From the statements already made it is evident that our information concerning the distribution and relations of the schists of the Southern Complex is very incomplete. So little detailed work has been done in the area that we are obliged to limit ourselves to descriptions of the microscopical features of the specimens collected near the borders of the Algonkian sediments, and to content ourselves with suggestions as to the legitimate conclusions to be drawn from them. For this purpose we may divide the southern schists into the micaceous and the hornblendic varieties, leaving the Palmer gneisses to be treated with the gneissoid granites.

THE MICACEOUS SCHISTS.

The micaceous schists include true mica-schists, consisting essentially of quartz and muscovite, or quartz and biotite; feldspathic mica-schists, containing, in addition to quartz and biotite, a large quantity of feldspar; and hornblendic, micaceous schists, which differ from the feldspathic varieties in possessing some green hornblende. These varieties grade into one another insensibly, so that there is represented in hand specimens a complete succession of types from the typical mica-schists to rocks that might be called hornblende-mica-gneisses. Even in a single hand specimen the alternate bands may consist of feldspathic and nonfeldspathic schists, or of the latter and the hornblendic varieties. There is such an intimate relationship exhibited between all these rocks, when their thin sections are examined under the microscope, that there can be no doubt as to their genetic connection. The separation into classes is merely for convenience in description.

MUSCOVITE-SCHISTS.

The muscovite-schists are rare. They are highly foliated, silvery-gray rocks, with contorted folia. They are not so definitely banded as are the less markedly foliated rocks, though bands can still be detected in some specimens. In general appearance they are typical mica-schists.

Under the microscope their thin sections show only elongated quartzes, muscovite, biotite, limonite, a few grains of magnetite, and tiny plates of hematite. The muscovite occurs as little laminæ cutting through the quartz grains and as long wisps between them. It is to the existence of these long wisps and of the elongated quartzes that the schistosity of the rock is due. The biotite, which is present in small quantities only, appears as small brown flakes scattered through the quartzes. Some irregular areas of a matted mass of tiny sericite or kaolin fibers may represent an original feldspar, but if so, no other evidence of its former existence remains.

BIOTITE-SCHISTS.

The biotite-schists are much more abundant than the muscovitic varieties. As seen in the hand specimen, they vary from compact or slightly schistose, dark-gray rocks (No. 16922, analysis, p. 202), resembling fine-grained, dark quartzites, to sandy, slaty, light-gray ones (No. 16913, analysis, p. 202), resembling friable sandstones.

Under the microscope they sometimes appear almost massive. Usually, however, their mica flakes are arranged with their long axes approximately parallel, and their other components are more or less elongated in the same direction. Quartz is the principal component. Its grains are elongated, and where they are in contact they interlock by irregular sutures. They frequently contain, as inclusions, spicules of green hornblende and small flakes of biotite. Feldspar is also abundant. A few irregular grains of clear plagioclase and kaolinized grains of an untwinned feldspar, probably orthoclase, lie between the quartzes, but they are found only occasionally. The greater portion of the feldspar is altered into kaolin, chlorite, etc. Biotite is the characteristic component. It is found in large and small reddish-brown flakes lying between the quartz grains, and often including several of them. Magnetite, zircon, epidote, limonite, and hematite are found in all sections, but in very minute quantities. Muscovite is a little more plentiful, but this also is rare. It is present in the kaolinized feldspar, but not elsewhere in the slides. In some few cases the biotite has been changed to chlorite, when it loses its brown color. Otherwise the rocks are very monotonous in their features (see fig. 8, on the opposite page).

FELDSPATHIC BIOTITE-SCHISTS.

The feldspathic schists are more varied in character, mainly because of the large quantities of feldspar present in them. This, by its alteration, gives rise to various secondary products. The rocks are very much like graywackes in their macroscopic appearance. They are fine-grained, fragmental-looking, gray rocks, with bands of lighter and darker shades (No. 16765, analysis, p. 202). In thin section they are seen to be composed mainly of elongated quartzes, brown biotite, plagioclase, and orthoclase or its decomposition products, kaolin, sericite, and epidote. Garnets are present in some sections, and in others tourmaline occurs in very small quantity. The quartz and the biotite present no unusual features. The latter mineral is often chloritized, as is also some of the orthoclase, so that the quantity of chlorite is much greater in these rocks than it is in the nonfeldspathic schists.

The feldspars are the most interesting constituents. They are nearly always much altered, the orthoclase more so than the plagioclase. In the triclinic feldspar the twinning bars are always recognizable and the material of the grains is often clear. With the orthoclase the case is different. Occasional traces of Carlsbad twinning are obscurely visible, but the mineral is so clouded with flakes of sericite, kaolin, chlorite, and brown biotite, with grains of epidote and quartz, needles of green hornblende, and the dust of magnetite, that its original nature in most cases is difficult to prove.

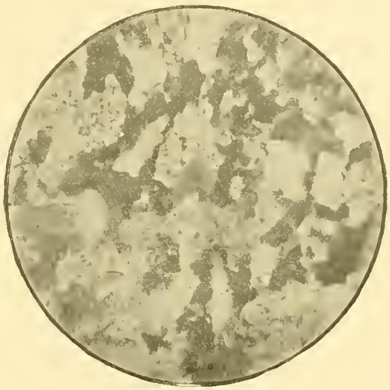


FIG. 8.—Thin section of feldspathic biotite-schist. No. 16903, from 875 steps N. 125 steps W., of SE. corner of sec. 3, T. 47 N., R. 30 W. Section shows typical structure of the coarser schists, rich in feldspar. The light-colored, irregular grains are quartz, the cloudy ones feldspar, and the dark ones biotite. Natural light X 55.

The arrangement of the decomposition products of the orthoclase is irregular. Within the body of the mineral they form a web of interwoven spicules, in the interstices of which are little grains of quartz and small areas of the undecomposed feldspar. Portions of the secondary aggregate extend beyond the original outlines of the grains and penetrate between the primary quartzes and the biotites. Thus it frequently seems as though the rock were a fragmental one, since we find rounded grains of quartz and irregular flakes of brown biotite embedded in a fibrous groundmass which in appearance is not unlike the material of a biotite-slate. A close inspection of the aggregate, however, shows that the quartz grains have not the outlines of waterworn grains, nor does the fibrous and finely granular groundmass in which they lie bear the same relations to them as does the fine-grained fragmental matrix to the larger grains in a sandy slate. Large areas of the matrix polarize with indefinite outlines, resembling the irregular outlines of crystalloids of feldspar in a granite—a phenomenon due to the remains of slightly altered feldspar left between the meshes of its alteration products. The larger quartzes embedded in this groundmass of decomposed feldspar are all compound. The elongated grains are made up of a coarse mosaic of smaller grains, the direction of whose longer axes appears to be independent of that of the larger aggregate. Under crossed nicols these rocks resemble a lot of nests of quartz mosaic in a groundmass composed of ill-defined plagioclase grains and large flakes of brown biotite in a matrix of small grains of quartz and fibrous decomposition products of orthoclase. They thus simulate very strongly certain sedimentary schists.

As the quantity of feldspar increases the superficial resemblance of the schists to fragmental rocks becomes stronger, for the alteration products are greater in quantity and the original outlines of the feldspathic grains are more and more obscured.

HORNBLENDIC BIOTITE-SCHISTS.

The hornblendic micaceous schists differ from the feldspathic varieties in that they contain large crystals of green hornblende that are idiomorphic in cross-section and are frequently twinned. They form very much larger plates than do any other minerals in the rocks, and often these plates surround and inclose a half dozen or more grains of quartz or feldspar. The hornblende is evidently the latest mineral formed in the rocks in which it occurs, and is quite certainly secondary. Otherwise the hornblendic varieties are similar to the feldspathic micaceous schists.

STRUCTURE.

The structure of the muscovite-schists, and of many of the biotitic varieties, is that of typical schists (see fig. 8, p. 197). Others of the biotite-schists, particularly those containing much feldspar, have the cataclastic structure, which in many cases resembles the fragmental structure of a sedimentary rock. However, although their components are broken and shattered, there can not be detected among the fragments any that present the least evidence of being waterworn. Their quartz grains are in all cases either very sharp-edged fragments or they interlock with the other components by very irregular sutures. The feldspars have been fractured also, but in this case too the fragments are very sharp-edged. Occasionally an altered feldspar has escaped rupture and has preserved its original form, when it appears as a phenocryst in a cataclastic matrix.

In the most altered phases of the feldspathic schists the thin sections present a strikingly sedimentary aspect. Rounded grains of quartz and feldspar are embedded in an aggregate of secondary substances, just as the grains of quartz in a sandy slate are embedded in a fine-grained aggregate of kaolin, etc. But in this case the rounding of the grains is plainly due to decomposition (see pp. 197–198), since numbers of them that are side by side extinguish simultaneously between crossed nicols. In no instance have any waterworn grains been detected in any of these rocks, and hence none of them exhibit any evidence of a sedimentary origin, however much they may at first glance look like sediments.

The foliation, which all the micaceous schists exhibit, is the result of the flattening of their larger quartz and feldspar grains in a uniform direction and the arrangement of the larger biotite flakes with their longer axes in the same direction. The cataclastic grains (those formed by the fracture of the larger grains) are not necessarily elongated, though many of them are so, and where they are their longer axes are not always uniformly orientated. The banding of the schists is due mainly to the greater abundance of biotite in certain planes than elsewhere

Whatever may be the origin of the banding of these rocks, it is clear that their foliation is the result of mashing. The bending of large biotite plates, the cracking of the feldspars, and the granulation of the quartzes, so frequently observed in thin sections, and the presence of cataclastic grains in general, are proof that the rocks have been subjected to crushing forces. That there has been mashing is shown also by the streaming of biotite flakes around the porphyritic feldspars. In a rock (specimen No. 16764) from near the NW. corner of sec. 2, T. 47 N., R. 30 W. (Atlas Sheet IX), for instance, there is a large Carlsbad twin of orthoclase, surrounded by lines of biotite flakes that are bent to conform with the outlines of the crystal. Phenomena of the same kind are met with in so many sections that the belief in a dynamic origin for the foliation of the schists is irresistible. The schistosity was imposed upon the rocks prior to the alteration of the feldspar in some cases, and in other cases it was produced subsequent to this alteration. This is easily accounted for on the supposition that the feldspars were partially altered before the rocks containing them were mashed, and that the alteration continued after the mashing. While in some cases the alteration products are arranged as in a fine-grained schist, with the schistosity planes parallel to the elongation of the quartzes and to the longer axes of the large biotite flakes, in other instances no such general arrangement is noticeable. In these cases the small biotite flakes in the secondary aggregate lie in all azimuths, except where their positions have been determined by the structure of the mineral from which they were derived. In the section of rock, No. 19034, for example, the tiny biotites are often found in two series of lines crossing each other approximately at right angles, having been formed apparently in the cleavage cracks of feldspars.

COMPOSITION AND ORIGIN.

The micaceous schists are so much altered that the nature of the original rock from which they were formed is not known. The existence of large crystals of orthoclase with the outlines of phenocrysts in the midst of a cataclastic groundmass would seem to indicate that the original rock was an acid porphyry, but these are so rare that any broad generalization based upon their presence must be of doubtful value. It is true that no sedimentary grains have been discovered in any of the thin sections, and this fact would seem to point to a similar conclusion. But all the rocks have been so greatly altered in structure by the changes they have undergone that it would be surprising if any evidence of their original structure were discoverable.

From the evidence of the microscope, all that can be said regarding the origin of the schists is that they are more probably igneous rocks than sedimentary ones. Their banding may be accounted for on the supposition that they occurred as flows of lava, for, though they are as evenly banded as many modern slates and sandstones, the micaceous schists are seen in the field to be interbedded with hornblende-schists of whose igneous origin there can be little doubt. It may be that some of the schists are altered tuffs, and that their banding is due in part to the original stratification of the tuffaceous beds, as is the case with the greenstone-schists of the Northern Complex, but of this there is as little positive proof as there is of a sedimentary origin for any of the schists.

Dr. Adams[1] has attempted to get some light on the origin of the gneisses of the Grenville series in Ontario by comparing their composition with that of slates and granites. He calls attention to the fact that while the average amount of the alkalis in granites is 7.35 per cent, in 23 primitive slates it is only 4.7 per cent, or two-thirds as great. Moreover, the slates are much higher in alumina than the granites, while at the same time they are lower in silica. The slates also contain more magnesia than lime, whereas the granites contain more lime than magnesia. After making his comparisons Adams concludes that the Grenville gneisses are more nearly like the slates in composition than like the granites. Of course such a comparison as this is of doubtful utility as a means of determining the origin of rocks that have suffered such a multitude of changes since their deposition as have the schists under consideration. Even if it were known that their composition had not suffered much change under the influences of metamorphism, the comparative process could be of little aid in discovering their origin, unless the composition of both the granites and the slates which they yielded were known. Zirkel[2] has shown that the range of composition in granites is very great. His maximum, minimum, and mean figures for their various constituents are as follows:

Range of composition in granites.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO.	K_2O	Na_2O
Maximum	81.77	19.05	7.16	5.65	3.17	9.25	6.70
Mean	72	16	1.50	1.50	.50	6.50	2.50
Minimum	60.50	7.02	.20	Trace.	Trace.	.56	.01

[1] A further contribution to our knowledge of the Laurentian, by F. D. Adams: Am. Jour. Sci. 3d series, Vol. L, 1895, p. 58.

[2] F. Zirkel, Lehrbuch der Petrographie, Vol. II, 1894, p. 30.

A schist may therefore have any composition within a very wide range, and, although this composition may be identical with that of some slate, or even with the mean composition of many slates, the rock may nevertheless be a very slightly altered granite.

Three analyses of the micaceous schists, one complete and two partial, have been made (Analyses IV, V, and VI). These are compared with an analysis of Cambrian slate from Melbourne, Province of Quebec (Analysis I), and with analyses of the amphibole-granitite from Hohwald (Analysis III) and the granitite from Landsberg, in the Andlau (Analysis II). As will be seen, the two granites vary in the proportions of the alkalis and the alkali earths present, the Hohwald rock containing but 4 per cent of the former, while the Andlau rock contains 7 per cent.* In each, CaO exceeds MgO in quantity. The composition of the slate is not very different from that of the granites except in one particular—the percentage of MgO present is over five times that of the CaO.

Analyses of slate, granitites, and schists.

	I.	II.	III.	IV.	V.	VI.
SiO_2	64.20	68.967	65.810	65.06	63.83	63.50
TiO_2		.309		.24	.33	.62
Al_2O_3	16.80	14.797	18.038	15.43	17.23	17.89
Fe_2O_3		2.320	4.213	Undet.	Undet.	1.12
FeO	4.23	.850	.691	Undet.	Undet.	5.38
MnO		.010	Trace.			Trace.
CaO	.73	3.815	5.061	4.47	3.88	2.34
MgO	3.94	1.150	2.144	Undet.	Undet.	1.22
K_2O	3.26	4.538	2.236	2.39	3.36	2.43
Na_2O	3.07	2.460	1.812	2.80	.87	2.55
H_2O at 100°	3.42	.707	1.161	Undet.	Undet.	.22
H_2O above 100°				Undet.	Undet.	2.04
P_2O_5				.29	.29	.19
Total	99.65	99.923	101.166	90.68	89.79	99.50

I. Cambrian slate from Melbourne, Quebec. Analyst, T. S. Hunt. Am. Jour. Sci., 3d series, Vol. L, 1895, p. 67.

II. Granitite from Landsberg, near Barr. Analyst, Dr. H. Unger. H. Rosenbusch, Die Steiger Schiefer, etc., 1877, p. 147.

III. Amphibole-granitite from Hohwald. Analyst, Dr. H. Unger. H. Rosenbusch, Die Steiger Schiefer, etc., p. 167.

IV. No. 16765. Dark-colored, finely banded micaceous schist, from near SW. corner of sec. 35, T. 48 N., R. 30 W. Much altered. Large feldspar grains, small quantity plagioclase, irregular quartz, little hornblende, considerable biotite. Analyst, George Steiger.

Structure cataclastic, approaching sedimentary in appearance.

V. No. 16913. Light-gray banded schist, from 700 steps N., 1450 steps W., of SE. corner of sec. 3, T. 47 N., R. 30 W. Not so much altered as 16765. Feldspar, quartz, some biotite, and a very little hornblende. Kaolin quite abundant. Analyst, George Steiger.

Structure granulated, approaching sedimentary fragmental.

VI. No. 16922. Very dark gray foliated schist from 520 steps N., 1120 steps W., of SE. corner of sec. 30, T. 47 N., R. 30 W. Banded in the field, but not in hand specimen. Contains large irregular quartz grains and comparatively fresh plagioclase and orthoclase. Analyst, George Steiger.

Structure foliated, like typical crystalline schist.

Upon comparison of these analyses it will be seen that the micaceous schists are in most respects as much like the granites as they are like the slate. With reference to the percentages of CaO and MgO present in them, they are much more like the granites. The granitite contains three times as much CaO and MgO, and the amphibole-granitite two and one-half times as much, while the slate contains, on the other hand, over five times as much MgO and CaO. The biotite-schist, No. 16922, contains twice as much CaO as MgO, while in Nos. 16913 and 16765 the excess of CaO over MgO is probably even greater; so that if the analyses show anything they indicate that the schists are altered granitites rather than altered sandstones or shales. In other words, the weight of evidence, while by no means conclusive, is indicative of an igneous rather than a sedimentary origin for the rocks in question, and is in accord with the little evidence afforded by the microscopic investigation of their thin sections. Whether the rocks were flows of acid lava interbedded with the rocks that yielded the hornblendic schists, or whether they were in large part beds of tuff, has not been determined. The even banding of many of the schists may be thought to indicate the latter origin, but even banding is known to be characteristic of some lavas, and in dynamically metamorphosed rocks, like the micaceous schists, it is known sometimes to be the direct result of mashing.

THE HORNBLENDIC SCHISTS.

Those schists whose predominant bisilicate constituent is a green hornblende may be divided into two classes, between which, however, there seems to be every stage of gradation. In the one class are placed the greenstone-schists, composed of hornblende, plagioclase, and the alteration products of the feldspar, and in the other class a series of lustrous, black, foliated rocks, which we shall call amphibole-schists. They consist essentially of green hornblende, fresh plagioclase, and quartz. All of these rocks are so similar to certain phases of the green schists of the Northern Complex that their descriptions need not detain us long. The greenstone-schists are, clearly, altered and foliated basic crystalline eruptives, and since they pass by intermediate phases into the amphibole-schists, it is believed that these also are squeezed eruptives, in spite of the fact that they are often banded and that some of them contain no inconsiderable quantity of quartz.

GREENSTONE-SCHISTS.

The greenstone-schists in the hand specimen and in thin sections resemble more closely those schists of the Northern Complex that were derived from basic dikes and lava flows than they do those derived from tuffs. In the hand specimen they present a wide variation in appearance. Some of them are fine-grained, light greenish-gray, almost massive, or slightly foliated rocks; others are dark-gray, fibrous schists; while still others are finely banded, green and white schists. The latter are less common than the other two varieties.

In the thin section nearly all the rocks show plainly their original character. Altered plagioclase and green hornblende are their principal components. The feldspar is changed more or less completely into an aggregate of epidote, saussurite, quartz, and chlorite, with occasionally a small admixture of a micaceous mineral. In addition to the altered plagioclase there is also present in many sections a fine mosaic of fresh plagioclase, resembling the feldspathic mosaic of many of the greenstone-schists of the Northern Complex. An untwinned decomposed feldspar, which is thought to be orthoclase, is also met with in a few sections. Its alteration products are mainly sericite or muscovite. The green amphibole is in three forms; it exists as long, slender needles penetrating the decomposition aggregates of the feldspars, as large plates and aggregates of flakes occupying spaces formerly occupied by augite, and as compact crystals, idiomorphic in the prismatic zone. The abundance of the compact amphibole seems to increase as the schistosity of the rock becomes more marked. In the less schistose specimens the amphibole has been largely changed into chlorite and epidote, while calcite in large quantity saturates the rocks. In some of the chlorite plates are series of fine rutile needles, cutting one another at angles of 60°, as though the chlorite had originally been a biotite. Moreover, there are occasionally scattered through the chlorite yellowish-brown flakes with the cleavage, pleochroism, and extinction of this mica. Leucoxene, sphene, magnetite, limonite, and hematite are met with in most sections, and fairly large prisms of a bluish-brown tourmaline are discovered in a few.

Dynamic effects are seen in a number of the least altered schists, but they are largely obscured by the great quantity of decomposition products present in all of them. Fractured plagioclases are sometimes so abundant that the rocks look like tuffs.

From the microscopical features of the rocks and from the strong analogy they bear to the northern greenstone-schists and the schistose basic dikes that intrude them, we may safely conclude that, like the northern rocks, they are squeezed eruptives—lavas and intrusive masses in the case of the unbanded varieties, and tuffs in the case of the banded kinds.

The types of green schists described are the predominant ones in the Southern Complex. There are, however, a great many other interesting varieties met with, all of which may be traced, under the microscope, into the types just described. Certain epidotic varieties deserve mention for the great quantities of this mineral they contain. They are composed very largely of dark-green, imperfect hornblende crystals, in a matted mass of smaller chloritized flakes of the same mineral, and large and small areas of an almost colorless epidote and saussurite in plates and grains. Besides these minerals, brown hornblende in plates, small grains of quartz, little areas of feldspar mosaic, and some magnetite are always present, but of these minerals only the biotite is ever in large quantity. The biotite seems to be more abundant near the feldspar areas than elsewhere, and the epidote appears to replace this mineral.

Another type that must be briefly referred to is intermediate in its characteristics between the greenstone-schists and the amphibole-schists to be described presently. The rocks of this type present a very fresh aspect. As a rule no alteration products can be detected in them. The rocks are now composed of clear plagioclase and dark-green amphibole, and usually some biotite. The plagioclase is in mediumly coarse grains that interlock in the manner of dioritic plagioclase. These are often dusty, with small inclusions of magnetite, amphibole, etc. The amphibole is in large plates, often twinned, and nearly always idiomorphic in the prismatic zone. The mineral is cellular, possessing the structure of Salomon's contact minerals, and it is in its present form younger than the feldspar. The biotite is of the usual reddish-brown color. It occurs in small flakes that lie between the plagioclases.

In structure and composition these rocks are "diorites," like those described by Williams[1] from the Northern Complex, but they are believed to be altered basic rocks. In some cases, when the grain is a little finer than in the type described above, the origin of the rock is fairly well indicated. In addition to the components mentioned, there are often large grains of a decomposed feldspar in the midst of a mosaic of fresher ones. The former are clouded with small biotite flakes and small grains of quartz, and are bordered by a clear mosaic of plagioclase. In the more massive forms of the rocks the outlines of the original large grains may be detected. In the schistose phases these gradually disappear as the schistosity becomes more marked, until in the highly foliated phases all trace of the large cloudy grains disappears, and the rocks now are aggregates of green hornblende in a mosaic of clear plagioclase grains and brown biotite flakes. The coarser schists are believed to have the same origin as those in which the plagioclase is in the form of a fine-grained mosaic, the only difference between the two rocks being in the size of the grains of the secondary plagioclase. Both are believed to be dynamically metamorphosed forms of a basic intrusive rock which may have been a diorite, a gabbro, or a coarse diabase.

AMPHIBOLE-SCHISTS.

The amphibole-schists are distinguished from the greenstone-schists by the possession of quartz. This mineral is sometimes present in very small

[1] The greenstone-schist areas of the Menominee and Marquette regions of Michigan, by G. H. Williams: Bull. U. S. Geol. Survey No. 62, 1890, p. 146.

quantity, when the rocks are much like the last type of the greenstone-schists mentioned above. Sometimes it is present in very large quantity, when they resemble true hornblende-schists. Usually quartz and fresh plagioclase are present in about equal amounts, and in this case the rocks are intermediate in character between the greenstone-schists and the true hornblende-schists.

In the hand specimen the rocks of this class have a dark-gray or black, rather than a green, tinge. Many of them are lustrous, black, highly foliated schists that are sometimes banded with very fine parallel lines of a white and a dark-green color, but which more frequently are of a uniform dark color; others are medium-grained, dark-gray, dioritic-looking rocks, in which a foliation is clearly apparent, but is not marked in its perfection; while a few are fine-grained, black schists of a dense, uniform texture. In thin section differences in composition and texture may be detected, corresponding with differences in the macroscopic appearances of the rocks.

The less lustrous of the schists resemble most closely the greenstone-schists. Quartz and clouded plagioclase are present in very much elongated grains, between which are flakes and masses of green hornblende and chloritized biotite in small quantity. Large plates of epidote and grains of titaniferous magnetite, surrounded by leucoxene, are scattered through the aggregate. The bands that are sometimes so plainly seen in the hand specimen are not clearly defined under the microscope. They can be recognized, but they possess no distinctive features. The darker bands contain more amphibole than do the lighter ones. Otherwise the two are similar, both in composition and in structure.

The lustrous schists are very fresh looking. Now and then a turbid grain of feldspar is seen in their sections, but this happens rarely. As they are now constituted the rocks differ from the "diorites" described under the greenstone-schists in containing a little quartz. Elongated fresh plagioclase, much of which is untwinned, prisms of compact green hornblende, and grains of quartz are the only components present in any quantity. A few grains of epidote and some of magnetite, and occasionally a flake of brown biotite, are also met with, but not in noticeable amounts. In one or two instances the feldspar is in such small quantity that the rocks are essentially amphibole and quartz aggregates.

MICACEOUS AMPHIBOLE-SCHISTS.

There is a third class of schists that possess at the same time some of the characteristics of the hornblendic schists and others of the micaceous schists. Macroscopically they resemble the latter. They are finely and evenly banded arenaceous rocks of a light-gray color. Under the microscope they appear more like the hornblendic schists. Quartz in large quantity, altered plagioclase, brown biotite, and green amphibole are all present in them. The last three components vary in amount, but all are in large quantity. The plagioclase and quartz are in irregular and often jagged grains, elongated in one direction a little more than in others. The biotite, however, and usually the hornblende, always occurs in long, narrow flakes between the other components, and it is due to the fact that the longer directions of these flakes are always parallel that the rocks are foliated. The bands differ from each other only in the amount of hornblende and biotite in them. The lighter bands are devoid of these minerals, while the dark ones contain them in great abundance. In one or two instances, where the banding of the schists is very obscure, the structure is granitic in so far as the quartz and plagioclase are concerned. These two minerals occur in irregular grains that are separated from one another by numerous flakes of biotite and hornblende. The latter minerals lie with their longer axes approximately parallel to the bounding planes of the quartz and feldspar grains, as if they had been forced into this position by pressure acting perpendicularly to their predominating direction. The feldspars are more or less altered to a mosaic of quartz and sericite or kaolin, or of quartz and clear plagioclase.

ORIGIN.

All the hornblendic schists appear to have been produced by the mashing of some original basic crystalline. It is not possible to ascertain positively that quartz was not a constituent of the parent rock, but from the fact that it is so often a product of the decomposition of the original plagioclase it is thought probable that much of it, in both the micaceous and the non-micaceous hornblendic schists, is a secondary product. The biotite and hornblende are also secondary, but the mineral from which they were derived is not known. It may very likely have been augite.

THE GNEISSOID GRANITES.

The granite and granitoid gneiss of the Southern Complex, like the corresponding rocks of the northern area, are so intimately related to each other that they must be regarded as different phases of the same rock. That they are intrusives in the micaceous and hornblendic schists admits of no doubt, as their dikes cut the latter rocks wherever found, and, as has already been indicated, fragments of the schists are included in the granite.

The distribution of the rocks with respect to the schists has already been described. No repetition of the description is necessary.

PETROGRAPHICAL CHARACTER.

Macroscopical.—As compared with the granite of the Northern Complex, that of the southern area is less highly colored. In the east pink varieties predominate, but toward the west, more particularly in the Lake Michigamme district, a very fresh white granite takes its place, to the entire exclusion of the pink variety. Porphyritic facies are less common in the southern rocks, and the foliated structure which is so pronounced in the northern granite is very much less marked in these. Moreover, whereas in the former rocks there is always more or less biotite, in the latter rocks there are frequently no bisilicates present, except a little chlorite in small flakes that may have been derived from plagioclase, and in a very few cases larger masses of the same mineral that may have come from biotite. In general character, however, the rocks of the two areas are the same. In the ledge the rocks are white, gray, pink, or red, according to the color and abundance of the orthoclase present, but the red varieties are rare, and when they do occur their shade is less brilliant than that of the red granites of the Northern Complex.

The southern rocks are always moderately coarse grained, and usually are schistose. Near its northern contact with the Algonkian the granite is more schistose than elsewhere, although gneissoid phases occur throughout the entire granite area. In some places, notably south and southeast of Palmer, the granites are cut by veins of soft, yellowish-gray, sericitic schist that are believed to be mashed portions of the granite itself, and in other places they are crossed by zones of crushed rock. In the same area occur the Palmer gneisses. These are highly schistose, light-gray, pink, or yellowish rocks, forming a narrow belt between the undoubted gneissoid granites to the south and the Algonkian sediments to the north. Many phenomena indicate that these rocks are but very much squeezed granites, in which case their foliation is probably due to the fact that they exist along the plane of contact between the crystalline rocks of the Basement Complex and the sedimentary beds of the Algonkian series, a zone of great accommodation during the folding of the Marquette rocks.

Microscopical.—Under the microscope the principal components of the granites are seen to be orthoclase, albite and other plagioclases, microcline, quartz, occasionally a little biotite, and the alteration products of the feldspars. All these minerals have the same properties as they do in the northern granites. The feldspars are a little more altered, but their decomposition products are the same as those in the northern rocks. The orthoclase and microcline have given rise to kaolin and sericite, and the plagioclases have yielded chlorite, kaolin, and small flakes of some micaceous mineral. In extreme cases these alteration products are so abundant that they entirely obscure the outlines of the grains by whose decomposition they were produced. The quartz grains always exhibit undulatory extinction, they are almost always surrounded by granulated borders, and very frequently they are filled with little liquid inclosures containing movable bubbles. The biotite is present in very small quantity, and its flakes are nearly always partially changed to chlorite. A few zircons, a little magnetite, some limonite, and, very rarely, plates of hematite, are the only other minerals noted in the rock.

In the most massive phases of the granite the typical granitic structure can still be seen, though the abundance of alteration products scattered through most of the sections obscures it more or less. The structure of the schistose phases presents the same features as does that of the gneissoid granites of the Northern Complex. Their quartzes are granulated and crushed, and their feldspathic components fractured. Between the larger grains is a mosaic composed of the finer fragments of both quartz and feldspar, and scattered through this are muscovite flakes winding in and out between the other components. Between the fragments of shattered quartzes are veins of the same mosaic, and these are often completely changed to sericite and kaolin. Secondary microcline is not so common a constituent in these granitoid gneisses as it is in the corresponding rocks of the Northern Complex, although it is present, while secondary albite appears to be more common.

The microscopic features of the granites of the Southern Complex are thus similar to those of the northern area. Both rocks are composed of the same minerals, and both have become gneissoid in places through the influence of pressure. The southern rocks appear to be more altered than the northern ones, but they seem to have been the same originally.

THE PALMER GNEISSES.

The Palmer gneisses comprehend a variety of highly schistose rocks of a gray, white, pink, or light-green color, showing little lenticular "eyes" of quartz in a "hydromicaceous" groundmass that appears to have been much mashed. When the quartz is in excess the rocks resemble squeezed cherts or quartzites, and when the matrix predominates they resemble fine-grained gneisses.

RELATIONS TO ADJACENT FORMATIONS.

These rocks have already been mentioned as forming a distinct belt between the granites and the sedimentary beds in the vicinity of Palmer (Atlas Sheet XXXII). They are found also as isolated ledges at intervals as far west as Champion, always between well-defined granites to the south of them and undoubted beds of the Marquette series to the north.

The relations of the gneisses to the surrounding rocks are not always clear. At no place are the gneisses seen to grade into the granites, although the general similarity of the two rocks in their macroscopic features is strikingly noticeable. A small topographic break usually intervenes between these ledges that are nearest to each other, and in this interval it is thought gradation phases may actually exist.

With respect to the Marquette beds the relations of the gneisses differ. In secs. 34 and 35, T. 47 N., R. 26 W., the schists are unconformably beneath the conglomerates lying at the base of the Marquette series. (See Atlas Sheet XXXV.) On the west side of the large hill in the NW. ¼ sec. 35 the relations of the two rocks are plain. Here the foliation of the schist (No. 20654) strikes directly into a heavily bedded quartzite which a little farther to the north becomes conglomeratic. In the NE. ¼ sec. 34 the actual contacts between the gneisses and the conglomerates are not seen, but the two rocks are very near each other, and the conglomerates are filled with large bowlders of the schists. The little hill nearest the northwest corner of sec. 35 is composed of gneiss, which is cut through and through by so many dikes and veins that it seems to be saturated with granitic material. In this vicinity the indications point clearly to the fact that the gneisses are older than the oldest of the Algonkian rocks in their neighborhood.

In the little hill south of the Platt mine, in sec. 32, T. 47 N., R. 26 W., the relations of the rocks are apparently different. (See Atlas Sheet XXXII.) On the north side of the hill, near the top, is a large, bare ledge of a yellow schist, which, in the hand specimen and under the microscope, has the usual appearance of the Palmer gneisses. The west end of the ledge, however, is conglomeratic, and the matrix of the great conglomerate ledge on the west end of the same hill is identical with the material of the yellow schist. At this place the gneiss was originally a fragmental rock. A few hundred yards southwest of the Platt mine the conglomerate at the base of the iron-bearing formation is well exposed in a number of large, bare ledges, and in it may be seen hundreds of large bowlders of the Palmer gneisses. Evidently we have in this area two entirely different rocks with the characteristics belonging to the Palmer gneisses. One is a mashed fragmental rock at the base of the iron-bearing formation, while the other is much older than this, and is presumably a mashed form of the granites.

A third area of the Palmer gneisses deserves mention for the complication of relations it presents. Just south of Summit Mountain, in the western half of sec. 25, and through the center of sec. 26, T. 47 N., R. 27 W., is a belt of schists of varying width. (See Atlas Sheet XXIX.) It comprises well-banded, sometimes fine-grained, sometimes coarse-grained, foliated rocks of a light-gray or dark-gray color. The rude bedding which produces the banding dips about 50° northeast and strikes about 30° south of east. In some places the banding is even, while in others it is much contorted, where lenses and veins of quartz and narrow dikes of red granite are interposed between the bands. As the granite area to the south is approached the number of granite dikes in the schists increases, and these rocks themselves become more and more massive. On the north side of Lake Palmer the relations of the dikes to the schists are well seen in the almost perpendicular side of a high cliff. Here great dikes of red granite cut the schists in all directions, although there seems to have been a preference for a direction parallel to their foliation. On the ledges south of the lake, numbers of narrow parallel dikes of the same red granite occur between layers of hornblende-schists and mica-schists, producing on smooth ledges a banded structure of great beauty.

There seems to be no question but that most, if not all, of the gneisses south of Summit Mountain are properly members of the granite-schist series. The banded structure that has been noticed in most of them is due in part to the banded character of the schist-granite complex from which they were derived.

The schists with the characteristics of the Palmer gneisses therefore include foliated rocks of Algonkian age (in the neighborhood of the Platt mine) and others belonging to the Basement Complex. The line between the two, as drawn on the maps, is as accurately located as is possible after making a very thorough examination of all the ledges in its vicinity. Where well-defined conglomerates occur the line is drawn just beneath these, and the schists accompanying the conglomerates are placed where they belong, in the Marquette series. Where no conglomerates are found and nothing is discovered, either in the field or under the microscope, to indicate that the gneisses were once fragmental, they are placed in the Basement Complex, and the line is drawn above them. The Palmer gneisses of the area represented on the map (Atlas Sheet IV) are therefore regarded as members of the Basement Complex. (The meaning of apparent gradations between unconformable series is described in another place; see pp. 298–299).

PETROGRAPHICAL CHARACTER.

The key to the origin of the Palmer gneisses is discovered in the study of the altered mosaic between the large fractured fragments of quartz and feldspar in the gneissoid granites. In these rocks the mosaic (which in fresh specimens consists of tiny fragments of quartz, orthoclase, plagioclase, etc., broken from the larger grains and saturated with newly deposited microcline and albite) has been changed to an aggregate of tiny flakes of kaolin, chlorite, and sericite, small grains of quartz, and occasionally long laminæ of muscovite, besides fragments of clouded feldspar. As the alteration of the mosaic proceeds and its decomposition products increase in quantity, its structure becomes less and less clearly recognizable, until in one or two instances it can hardly be discerned. The large fragments of feldspar that are embedded in it have also suffered alteration, and the quartzes have been crushed until their positions are occupied by four or five differently orientated grains, which in the less schistose rocks may be seen to fit together into a single one. In the more highly foliated phases the parts have sometimes been moved from their places and now appear as isolated fragments.

In the Palmer gneisses all certain traces of their origin have disappeared. Under the microscope there is but little variation in the structure or composition of their different phases. Even the schistose fragmental rocks that are associated with the conglomerates are as nearly like the true gneisses in thin section as they are in the ledge. They may contain a greater quantity of quartz than do the latter rocks, and the grains of this mineral may be a trifle more rounded in outline. It is doubtful whether these rocks would have been separated from the genuine gneisses derived from the granite had their relations in the field not been plain. Even with the care that has been used, it is probable that a few rocks of fragmental origin have been included in the area of the Palmer gneisses.

In the thin sections of the gneisses quartz grains are observed embedded in a fine-grained matrix of a nearly uniform texture and composition. The quartzes are crushed, as they are in the schistose granites. Often they form lenticules of a quartz mosaic in which each separate grain exhibits the phenomenon of undulatory extinction. When not completely shattered they are granulated around their edges, and especially at the ends of the lenticules, where mosaics of fine grains have been produced. Portions of these mosaics extend out as long tails in the direction of the foliation of the rock, winding in and out among the other components, and aiding in emphasizing the schistosity. In most of the sections examined the parts of the crushed quartzes have been separated, and into the crevices between them the matrix has been forced, thus producing a genuine fragmental structure.

The matrix in which the quartzes lie is a uniform felt of kaolin, muscovite, a few flakes of chlorite, a little biotite, small masses of calcite, tiny grains of quartz, and remnants of feldspar. The sericite and kaolin are the most abundant components. Their leaflets are usually arranged approximately parallel to the planes of foliation in the rock, except where they occur in the crevices between fractured quartz and feldspar grains, when they are perpendicular to the walls of the crack. They bend around the larger quartzes, enveloping them in concentric layers, and wind in and out between neighboring grains like the matrix of many squeezed porphyries. Occasionally the remnants of feldspar left between the meshes of the matrix are optically continuous over large areas with the outlines of granitic feldspar grains, but usually when they can be detected they give evidence that they too, like the quartzes, were fractured and their parts separated during the production of foliation in the rock.

By far the greater number of the Palmer gneisses are as simple in composition as those above described. A few present special features that should be mentioned. A number of specimens collected from various points all along the belt are dotted on their surfaces with plates of a dark-green chloritoid,[1] varying in size from 2 mm. to almost microscopic dimensions. A rock (specimen No. 21999) from about 1500 steps N., 750 steps W., of the SE. corner of sec. 32, T. 47 N., R. 26 W. (Atlas Sheet XXXII), is a good type of these. Its bowlders constitute a large proportion of those occurring in the conglomerates southwest of the Platt mine. In the hand specimen the rock resembles a decomposed gneiss. In its thin section quartz grains are rare. Only an occasional one, or a quartz mosaic with the outlines of a grain, is found here and there through the schistose matrix, which is a uniform mass of sericite and kaolin flakes, with a little fine-grained quartz mosaic. Embedded in the matrix, in positions irrespective of the schistosity, are large plates of the green chloritic mineral, numerous grains and irregular

[1] Cf. A. C. Lane, Rept. State Board of Geol. Surv. for 1891-92, p. 182. Lansing. 1893; and W. H. Hobbs, Am. Jour. Sci., 3d series, Vol. L, 1895, p. 125.

masses of brown rutile, and a few rhombohedra of some almost colorless carbonate. The chloritoid is the most interesting component. It is in large tabular plates with a cellular structure, and is filled with inclusions of quartz, rutile, and portions of the rock's groundmass. As usually seen, the plates appear as prisms with a distinct cleavage parallel to their long directions, and sometimes a parting perpendicular thereto. In the direction of the cleavage their color is a deep bluish-green, and perpendicular to it a pale yellowish-green. Between crossed nicols the prisms are all striated with longitudinal twinning lamellæ, whose extinctions, measured against the cleavage lines, vary between 1° and 21°. The prisms, of course, are vertical sections of the plates, whose cleavage is parallel to the base.

Evidently the chloritoid is the youngest mineral in these rocks. Not only does its contact structure indicate this fact, and the position of its plates with respect to the foliation, but the same mineral in well-developed plates of the same habit is found not only in the bowlders of the gneisses in the conglomerates near the Platt mine, but as well in the matrix of these rocks.

Other specimens of the gneisses differ from this one mainly in the size of the chloritoid plates. In some the plates are very large, and in others they measure only a few tenths of a millimeter in their longer directions. In one or two cases the chlorite appears to be in bands in the schists, other portions of the rocks being without them. Usually its plates are disseminated irregularly.

In two or three sections there were also noticed a few small, ill-defined prisms of dark greenish-blue tourmaline, a mineral whose presence in rocks is usually ascribed to contact or fumarole action. In the present instance there is no evidence of any kind to indicate that the mineral is of contact origin. Its grains are distributed irregularly through the gneisses, without any reference to their foliation, and the mineral is consequently subsequent in its origin to the production of the gneissic structure.

COMPOSITION AND ORIGIN.

The similarity of the matrix of the Palmer gneisses to the altered mosaic of the crushed granites and to the altered feldspars of the more massive phases of these rocks, and the discovery of indefinitely outlined granitic grains of feldspar in the least altered of the gneisses, strongly suggest that these rocks are very schistose granites in which the alteration of the feldspars has proceeded so far as to destroy their original outlines and to yield a uniform aggregate of decomposition products. The destruction of the outlines of the original grains is as much due to the mashing to which the rocks have been subjected as to the alteration they have suffered, and the completeness of the alteration must itself be due largely to this same mashing, which fractured the feldspars of the border granites and rendered them more easy preys to the attack of decomposition processes than the same minerals in the more massive granites beyond the limits of the peripheral zone of maximum movement.

An analysis of one of the most schistose phases of the Palmer gneisses, specimen No. 20647, from the top of the large hill in the NW. ¼ sec. 35, T. 47 N., R. 26 W., was made by George Steiger, of the Survey laboratory. His results are as follows:

Analysis of Palmer gneiss.

	Per cent.
SiO_2	82.38
TiO_2	.14
Al_2O_3	11.32
Fe_2O_3	.97
FeO	.26
MnO	None.
CaO	.22
MgO	.17
K_2O	1.04
Na_2O	.59
H_2O at 100°	.18
H_2O above 100°	2.33
P_2O_5	.09
Total	99.69

These figures correspond very nearly to those that would be obtained upon analysis of a mixture composed of 68.6 per cent quartz, 14.6 per cent kaolin, 8.7 per cent sericite, 5.7 per cent plagioclase (0.6 per cent anorthite and 5.1 per cent albite), 1.2 per cent chlorite, 1 per cent magnetite, and

0.2 per cent apatite. They point clearly to the fact that these rocks are composed of granitic material that has been silicified.

INTRUSIVES IN THE SOUTHERN COMPLEX.

In the Southern Complex, as in the Northern Complex, the schists and granites are cut by well-characterized dikes and veins of eruptive material. The characters of the dikes in both areas are much alike. They comprise diabasic, epidioritic, and aplitic kinds. The basic dikes were evidently formed at different times, for some of them are schistose and are clearly altered diabases, while others are beautifully fresh and entirely massive. The latter must be much younger than the former. They were perhaps intruded during Keweenawan time, for they are identical in composition and general character with the smaller dikes cutting Upper Marquette sediments, while at the same time none of them have been found penetrating the Cambrian. Among the materials of the fresher dikes may be mentioned ophitic diabases, olivine diabases, basalts, luster-mottled gabbro-like diabases, and uralitic diabases.

The older and usually larger dikes are epidioritic and uralitic schistose diabases, exactly like similar rocks in the Northern Complex, and practically identical with the material of the large, boss-like dike masses in the Algonkian. (See Chapter V.)

SUMMARY.

The rocks of that portion of the Southern Complex discussed in this volume are micaceous and hornblendic schists, greenstone-schists, gneissoid granites, certain schists that have been called "Palmer gneisses," and acid and basic dike masses. The greenstone-schists, the granites, and the dike materials are similar in their essential features to the corresponding rocks of the Northern Complex. All are igneous in origin. The greenstone-schists are squeezed basic lavas or tuffs. They are older than the granite. The dike masses are in all respects like those that penetrate the northern area.

The Southern Complex differs from the northern area in the smaller quantity of greenstone-schists in the former, and the presence in it of the micaceous and hornblendic schists and the Palmer gneisses. The latter rocks are apparently in most cases extremely mashed phases of the granites. They occur only on the borders of the granitic areas, between these and the Marquette sedimentaries. The gneisses consist largely of quartz, sericite, plagioclase, and kaolin. In a few instances rocks with the characteristics of the Palmer gneisses are found at the base of the Marquette series, constituting the matrix of conglomerates in which the bowlders are largely identical with specimens of Palmer gneisses occurring beneath the conglomerates. These rocks are regarded as mashed arkoses, derived by disintegration and alteration of the granites, whose mashed and silicified forms the true Palmer gneisses are. The arkoses originally had the same composition as the granites of whose detritus they consist; consequently their altered phases are practically identical with the altered granites themselves. The area on the map colored for the Palmer gneisses is underlain by those gneisses that are believed to be mashed granites.

The micaceous and hornblendic schists are evenly banded rocks with a distinct strike and dip. Their banding is often narrow enough to be observed in hand specimens. In other cases the banding is broad, so that it is observable only in the ledges. In thin section a few of the rocks are typically gneissic. In most of them a cataclastic structure is strongly marked. All are more or less foliated, and their foliation, as well as their cataclastic structure, is ascribed to pressure. The hornblendic schists are shown to be mashed basic eruptives, and the micaceous varieties are thought to be mashed acid eruptives; but whether the schists were originally tuffs or massive rocks is not known.

The schists are older than the granites, since dikes of the latter rock intrude the former in great numbers. Their relations to the greenstone-schists are not known, since contacts of the several kinds of schists have not been observed. If the micaceous and hornblendic schists are older than the green schists, they may represent the basement upon which the latter rocks were laid down. In any event the hornblendic and micaceous schists represent the typical Mareniscan formation as defined by Van Hise in his correlation essay, and the granite the Laurentian.

As in the case of the Northern Complex, no rocks of sedimentary origin have been detected in the Southern Complex.

SECTION III.—ISOLATED AREAS WITHIN THE ALGONKIAN.

In addition to the two areas of the Basement Complex which have been discussed, there are isolated patches of pre-Algonkian rocks lying entirely within the Algonkian area. Some of these areas perhaps represent islands within the Algonkian sea, while others are portions of the pre-Algonkian mainland that have been forced upward through the overlying rocks by the forces that folded and compressed the latter. These latter constitute the axes of anticlinal folds, and are naturally longer in the direction of the strike of the folds, and when the material of the nuclei is schistose the direction of the schistosity is usually parallel to the greater diameter of the areas. They are bordered by fragmental beds belonging with the lowermost formations comprised within the folds.

The rocks forming the greater portion of the isolated areas are gneissoid granites and schistose greenstones that differ in no essential respect from the corresponding rocks of the Northern and the Southern Complex. The greenstone-schists of the isolated area south of Marquette are identical with the Mona schists. The granites consist of the same minerals as do the other granites of the Basement Complex, but they have become gneissic. Under the microscope their constituent minerals are seen to be shattered and crushed to such an extent that many sections look like those of fragmental rocks. The fragments, especially those of quartz, have been rounded by attrition, and the feldspar has been granulated so that the sections resemble those of an arkose containing large waterworn quartz grains. As alteration progresses the feldspar changes to a mosaic of sericite, kaolin, and quartz, which often becomes so abundant as to obliterate the outlines of the feldspar fragments or to wholly destroy the grains. In this extreme phase of alteration the rocks present the appearance of sericite-schists, such as are so common in the belt of Palmer gneiss in the northern border of the Southern Complex. Since many of these sericite-schists occupy zones of mashing in the granites, there can be no question as to their origin.

CHAPTER III.

By C. R. Van Hise.

THE LOWER MARQUETTE SERIES.

The Lower Marquette series consists, from the base upward, of the following formations: The Mesnard quartzite, the Kona dolomite, the Wewe slate, the Ajibik quartzite, the Siamo slate, and the Negaunee formation. At the beginning of Lower Marquette time the transgression of the ocean was from the east and the north, and as a consequence the inferior formations of the Lower Marquette series appear only in the northeastern part of the district. South of Palmer and westward the lowest formation found is the Ajibik quartzite; that is, the three inferior formations of the Lower Marquette district were not here deposited, this part of the district then being above water.

SECTION I.—THE MESNARD QUARTZITE.

The formation is given the name Mesnard quartzite because it composes the larger part of the mass of Mount Mesnard south of Marquette, and because the predominant rock is quartzite.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The Mesnard quartzite makes up a continuous belt adjacent to the Archean on the south side of the series (see Atlas Sheet IV), extending from west of Lake Mary, sec. 9, T. 47 N., R. 25 W., to the sand plains west of Lake Superior. In secs. 1 and 2, T. 47 N., R. 25 W., the formation extends north to an island of Archean in secs. 2 and 3, and, swinging both east and west of this island, it entirely surrounds it. Upon the northern side of the Lower Marquette series the Mesnard formation extends continuously, south of the Archean, from Lake Superior to the west side of sec. 29, T. 47 N., R. 25 W. For several miles to the west of sec. 29 there are no exposures, but just east of Carp River a heavy belt of quartzite again appears next to the Archean and runs westward as far as Teal Lake. The peculiar distribution of the formation is explained by its folding, which is considered below.

On account of the resistant character of the quartzite, it constitutes, south of Marquette (Atlas Sheets XXXVIII and XXXIX), three prominent ranges, the first including Mount Mesnard, the second being south of the Archean island in secs. 2 and 3, T. 47 N., R. 25 W., and the last being adjacent to the Archean to the south. As the formation grades from a pure vitreous quartzite to a slate, its resisting power is very diverse, and its complicated folding gives an irregular distribution to the different belts, so that, while the ranges have the distribution mentioned, the topography in detail is exceedingly rough. In crossing the formation one climbs a steep ledge, plunges into a sharp ravine, then ascends another bluff, to again climb down; so in crossing a range one traverses a series of exceedingly steep ridges.

FOLDING.

At the east end of the district the quartzite is folded into two closely compressed east-west synclines, with a central anticline, the quartzite occupying the entire breadth of the Algonkian in the section just east of the State prison. (Atlas Sheets XXXVIII and XXXIX.) East of this line the overlying dolomite appears in the southern syncline. In the section running south from Mount Mesnard both the northern and southern synclines show the overlying dolomite, but on the anticline between erosion has cut to the Archean North, at Mount Mesnard, another syncline appears. West of Mesnard the northern belt of quartzite has a monoclinal dip, vertical or south at a very high angle. When examined in detail, however, it is found in its slaty phases to be rolled into a set of minor overfolds, which, in passing from the Archean toward the center of the Algonkian, show steadily higher and higher members. In the southern belt the quartzite north of Lake Mary constitutes a shallow synclinal trough. (Atlas Sheet XXXVII.)

PETROGRAPHICAL CHARACTER.

Macroscopical.—Petrographically the formation consists of conglomerates, graywackes and graywacke-slates, and quartzites, with all gradations between the different phases, although quartzite is the predominant rock. Where rocks of the formation are found in contact with or close to the surrounding granite, they are a coarse granite-conglomerate, or a rock which may be called a recomposed granite where the constituent particles composing the rock are the separate mineral particles of the Basement Complex.

On the south side of the Algonkian trough the conglomerate is magnificently exposed west of Lake Mary in the SW. ¼ sec. 9 and the SE. ¼ sec. 8, T. 47 N., R. 25 W. It may also be well seen at and east and west of the line between secs. 1 and 2 of the same township, and at other places. With the fragments of granite are apparently many of vein quartz, and a few of red jasper, of chert, and of quartz-rock. In some cases this bowlder-bearing granite-conglomerate passes into a less conglomeratic, reddish rock which closely resembles the original granite.

On the north side of the trough north of Mud Lake, in sec. 29, T. 48 N., R. 25 W., the lowest horizon is again a basal conglomerate, the numerous fragments being derived mainly from the granites and schists of the Northern Complex, the latter being more abundant because immediately adjacent. The fragments vary from those of minute size to bowlders 2 or 3 feet in diameter. Here no fragments of chert or jasper were found.

The basal conglomerate at Mud Lake usually passes quickly into interstratified slate and graywacke, and then into a quartzite. The slate and graywacke are very closely folded, there being many reduplications of the same strata, all having, however, a southern monoclinal dip, and the axes of the little folds pitching steeply. So close has been the compression that the more resistant belts of graywacke in the slate have been broken into a reibungsbreccia. In some places the folding has been so severe as to entirely destroy the thin belts of graywacke, producing out of them large numbers of pebbles and bowlders. All stages of the transition are found between the continuous belts of graywacke and the pseudo-conglomerate in the slate.

The slates and graywackes usually pass quickly into the typical quartzite of the formation. Within the Mesnard quartzite is an interstratified conglomerate, from a few inches to 40 feet in thickness, in which are abundant fragments of ferruginous schist, of quartz, of chert, and of jasper.

The quartzite is in general a rather pure vitreous quartzite, very massive in hand specimens, but in the ledges often showing distinctly the bedding, and not infrequently passing into slaty phases. In many places at the east end of the Mesnard range the original ripple-marked surfaces of the layers are observed. The intricate windings of the conglomeratic chert and jasper pebble-bearing layer were traced out, and were of great assistance in determining the structure. Where the folding has been close the quartzite passes into a very vitreous rock, or even into a quartz-schist. The vitreous rock is produced by extensive fracturing, or even brecciation, and the filling of the resultant minute and large cracks with vein chert or quartz. The veins vary from those of minute size to those several inches across, and in some cases they anastomose through the quartzite in every direction. This secondary material often closely resembles the original stained or granulated quartz grains, but the rocks as a whole take on a peculiar aspect, and have been called cherty quartzites.

At the top the quartzite passes into slaty phases, and these grade into slate, a belt of which, from less than 30 to 100 feet thick, separates the quartzite from the Kona dolomite. The Mesnard quartzite may then be divided into four members: (1) Conglomerate, (2) slate and graywacke, (3) quartzite, and (4) slate. The quartzite is the predominant member. Slates and graywackes are locally intermingled with the quartzites. A single section showing all the phases is rarely found, and exposures are not sufficiently numerous to enable one to make these subdivisions in mapping.

Microscopical.—The conglomerates are of three main kinds: (1) Those adjacent to the Mona schist; (2) those adjacent to the granites; and (3) those interstratified with the graywacke or quartzite. The first occurs along the northern border of the Algonkian, the second along the southern border, and the third at various places along both the northern and southern belts.

(1) The northern conglomerate is in its lower parts a stucco of granite and green-schist fragments set in a sparse matrix. The granitic pebbles and

bowlders are well rounded. They comprise coarse-grained muscovite-granite and peculiar fine-grained granites. The green-schist pebbles have a very wide variety, including decomposed granular greenstones and various chloritic schists. Every phase of the basic and acid fragments is matched by rocks of the Northern Complex. A comparison of the fragments with the adjacent rocks of the Archean can leave no doubt that the major part of the detritus of the conglomerate was derived from this source. The sparse matrix between the pebbles is composed of well-rounded to subangular grains of feldspar, of quartz, and of the finer complex detritus of the various materials of the Northern Complex. A few complex cherty fragments are seen. In this matrix the various feldspars are especially abundant. This finer detritus is set in a still finer background of the same materials, with much chlorite and fine secondary quartz.

(2) The conglomerates adjacent to the Southern Complex have two phases—those that are coarse and distinctly show a conglomeratic character, and those that are composed of finer detritus. The latter in some cases so closely resemble granite in the field that they are with difficulty discriminated from it.

The coarser phases have as predominant pebbles coarse granite, the feldspar of which is much kaolinized, and which may be considered a kaolinic quartz-schist; large irregular areas of complex quartz, which may have been derived from a very coarse grained granite, or may have come from a quartz-schist; and complex pebbles of altered, fine-grained biotite-gneiss. As the conglomerate becomes finer-grained the complex fragments decrease in quantity and are replaced by large simple fragments of quartz and feldspar. Where the pebbles disappear the rock in hand specimen simulates granite or gneiss. In addition to the predominant pebbles of the conglomerate, there are present large complex fragments of ferruginous schist, of chert or jasper, and of a quartzite-like rock. The ferruginous schist pebbles have a very finely crystalline, quartzitic, and kaolinic background, through which iron oxide is scattered or concentrated in irregular connecting layers. These appear to be ferruginated, decomposed schistose rocks rather than true chert or jasper. The ferruginous chert or jasper pebbles are very similar to those of the Negaunee formation, but they show less banding, and the iron oxide is scattered through the homogeneous quartzose background somewhat uniformly. The major part of the supposed quartzite pebbles, as seen in hand specimen, are found to be complex interlocking quartz and much mashed and broken quartz-schist, in which a great deal of secondary quartz has infiltrated. In a less mashed phase the quartz is in distinct, closely fitting or interlocking granules, which suggest a fragmental character, but although carefully searched for, no evidence could be found of enlargement or of cores, and it is probable that the material is from veins. The chert, jasper, and quartz pebbles may have been derived from veins in pre-Marquette rocks, or possibly in part by the mechanical destruction of secondary veins within the formation itself.

The matrix of these conglomerates consists of quartz and feldspar fragments, set in a background composed of more finely pulverized and kaolinized materials of the same kind. In many cases also this background contains much very finely crystalline, cherty quartz. The slides are also cut through by veins of the same cherty quartzose material. In some cases dynamic action has broken up the cherty matrix and chert veins, producing pseudo-pebbles, and this may be the source of some of the fragments which at first sight appear to have been derived from a preexistent cherty rock. The feldspar fragments frequently show interesting micaceous and quartzose decomposition. The quartz grains are often enlarged. All of the grains, whether in the complex fragments or in the background, show undulatory extinction or fracturing. The same phenomena are exhibited by the feldspars, but to a less degree. In certain cases the fractures in the quartz are in two systems at right angles to each other, producing many little rectangular particles of quartz from a single individual.

At places near the base of the formation the much mashed, fine-grained conglomerate can not in hand specimen be discriminated from the gneiss below. As seen in thin section, the fragmental rocks are found to be kaolinic quartz-schists. The simple and complex quartz grains usually show distinct rounding, although some of them have a decided granitic shape. In many slides they are granulated and greatly elongated in a common direction by dynamic action. Feldspar fragments, if present originally, have decomposed. The quartz grains are in a matrix of finely crystalline, cherty quartz, kaolin, and sericite, the first being often predominant. Numerous veins of secondary quartz cut the matrix and the coarser grains. The gneisses adjacent differ from the clastic rocks just described in that distinct residual, although much altered, feldspar remains, in the absence of abundant secondary cherty quartz, and in the distinct granitic texture.

(3) The interstratified conglomerates differ from (2) only in that the predominant pebbles are chert, jasper, quartz, and ferruginous schists, and that granite pebbles are sparse or absent altogether, although sometimes much detrital feldspar is present.

The pure *quartzites* grade through a feldspathic quartzite into the fine-grained conglomerates. The least mashed phase of the quartzites consists almost entirely of well-rounded, uniform grains of quartz of medium size, which have become enlarged, the enlargements interlocking and nearly filling the interspaces. A very small amount of sericite, oxide of iron, and independent secondary quartz is seen between the grains. In certain less pure phases larger amounts of these materials are present. Many of the least mashed quartzites show remarkable pressure effects The grains which have been least affected show merely undulatory extinction. From this phase the grains grade into those in which minute cracks have formed However, whether the extinction is undulatory or there are distinct cracks. the breaking has been in two directions at right angles to each other. The fractures in one direction may be more marked than those in the other, and one set may disappear. Where the fracturing is distinct, each of the quartz grains is broken into a large number of parallel plates, or, if fractured in two directions, into a very large number of minute rectangular blocks. These fractures are plainly produced in the shearing planes.[1] That they in many cases can not be quartz cleavage is shown by the fact that they pass in the same direction from grain to grain. Where the fracturing is most marked iron oxide and gas and water bubbles have formed in the openings.

The pure vitreous quartzites also pass into the cherty quartzites. In these the dynamic effects upon the original quartz grains are more pronounced. Between the original grains and through them there has been a

[1] See Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 696-698.

great deal of secondary cherty quartz deposited. Also numerous veins of secondary cherty quartz are present. In these are inclosed fragmental grains derived by dynamic action from the original material. In some cases the vein material passes gradually into the ordinary rock, more and more of the original fragmental quartz appearing, until the grains are merely broken apart, with secondary quartz between them.

In one phase of the cherty quartzite it appears that after the rock had been subjected to a first dynamic movement and had been cemented by cherty quartz a later dynamic movement broke up this rock along certain zones, thus producing reibungsbreccias, the fragments of which are composed of simple grains of quartz, mingled with chert grains. The whole was afterward cemented by a later infiltration of silica and oxide of iron. This phase suggests that many of the chert fragments, and possibly some of the ferruginous chert and jasper of the quartzite, were produced by dynamic processes operating upon a rock which had been previously broken and cemented by secondary chert and jasper.

The conglomerates, in their passage to the quartzites, at many places grade through the phase of *graywackes* or *graywacke-slates*, and the quartzite also grades above into similar rocks. These graywackes have a clayey background, in which are set many small and medium-sized, well-rounded to subangular grains of quartz and the various feldspars. The feldspars are frequently altered in part to kaolin, sericite, and quartz. Occasional complex grains of cherty quartz are seen. The matrix consists of finely crystalline quartz, kaolin, and sericite, with occasional large flakes of muscovite. In many places it is stained with iron oxide. In the rock which has suffered the least from dynamic action, undulatory extinction and fracturing are seen in the grains of quartz, but the pressure has not been sufficient to give a distinct arrangement of the particles with their longer axis in a uniform direction.

In a more mashed phase of the graywackes the quartz and feldspar particles show a distinct arrangement with their longer axes in a common direction, and, with this, most marked undulatory extinction, fracturing, and even granulation. Some of the larger grains show particularly well the rectangular fractures in two directions spoken of in connection with the quartzites.

In the matrix sericite has abundantly developed, and the leaflets are parallel. The minute spaces formed by the shattering of the large fragmental grains and those in the background are filled with secondary cherty quartz, which has thoroughly cemented the rock. The larger fractures are filled with cherty quartz, forming veins. In many of these are fragmental grains broken off from the main mass of slate.

In the phase in which the dynamic action was still more severe the graywackes were shattered through and through, the particles having moved and ground over one another. As a result of this there were left innumerable minute spaces, which have been taken advantage of by the infiltrating silica, and are now filled with secondary cherty quartz. The original fragmental quartz grains are always somewhat granulated on their exteriors, and many throughout, so that a quartz grain is represented by a lenticular mass of finely interlocking quartz. In the matrix the sericite has developed in coarser blades than in the less metamorphosed rocks. It is everywhere in long, narrow leaflets having a parallel arrangement in the same direction as the elongated quartz grains. Numerous veins are completely filled with interlocking, coarsely and finely crystalline quartz, apparently all of it being secondary. If any of the original fragmental quartz grains have dropped in the crevices, they have become so shattered as to have lost their rounded outlines.

The conglomerates, quartzites, and graywackes of the Mesnard formation include rocks varying from those which are indurated mainly by siliceous cementation to those which are crystalline schists. From their macroscopical and microscopical descriptions it is plain that there has everywhere been interior movement. Even in the least altered phases of the rock every grain of quartz shows the effect of strain. From this least altered phase there are all gradations to those phases in which the rock is a shattered or mashed mass cemented by cherty quartz. Moreover, after a first shattering and cementation there was a later folding, which again shattered the rock, including both the original constituents and the secondary cherty quartz. This broken rock was again cemented by later infiltrating silica.

In certain parts of the formation, where the relief was largely by shattering the rock en masse, the clastic character of the original grains is usually still marked, and they are easily discriminated from the secondary cherty quartz. In other phases of the rock the stresses were relieved by movement affecting the mineral particles. The original quartz and feldspar grains were granulated, and the latter were decomposed. Secondary quartz formed both in the interstices and in veins, and sericite developed. This process of secondary silicification and development of sericite seems to be in direct ratio to the severity of the mechanical movement affecting the individual grains. Between the phases in which the relief is largely by brecciation and those in which it is largely by mashing there are all gradations, an intermediate phase showing the partial granulation of the fragmental grains, their cementation by silica, and at the same time numerous veins of secondary cherty quartz. As has been said, the extreme alteration of the original quartzose sandstone resulted in peculiar, vitreous, cherty-looking quartz-rocks, and that of the original feldspathic débris resulted in a sericite-schist. The facts that the sandstones became cherty brecciated rocks and that the coarse and fine muds became schists are probably explained by the brittle character of the first and the plastic character of the second, one yielding mainly by fracture, the other mainly by flow.[1]

RELATIONS TO UNDERLYING FORMATION.

The fact that basal conglomerates are found at various places near the contact of the Mesnard quartzite and the Basement Complex has already been mentioned, and the localities at which these conglomerates occur have been mentioned. These contacts are of such character as to indicate that the Mesnard quartzite is separated from the Basement Complex by a great unconformity. Since in these basal conglomerates are numerous pebbles and bowlders of granites, gneisses, and schists from the Basement Complex, the major part of the complex history of the Archean was complete before the Mesnard quartzite was deposited. Erosion had before this time cut so deeply into it as to bring to the surface in some places coarse-grained granites and in other places the truncated, foliated layers of the

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp 601–603.

schists and gneisses. In the localities where the basal conglomerates occur the proof of the unconformable relations is conclusive. In other localities the granite was apparently decomposed before the deposition of the quartzite, and here, as has been said, it yielded its small separate mineral particles to the overlying rock. This recomposed rock has been thoroughly cemented. During the subsequent folding shearing has taken place along the junction, resulting in the development of parallel schistosity in the original granite and in the recomposed rock. In such cases it is difficult or impossible to indicate the exact contact between the Basement Complex and the Mesnard quartzite. Such localities were explained by Rominger as cases of progressive metamorphism, the granite being a metamorphosed sedimentary rock. Later he abandoned this view. One of the best localities in which to observe this apparent gradation between the gneissoid granite and the quartz-schist is just north of the little granite knob on whose south side is the west quarter post of sec. 1, T. 47 N., R. 25 W. (Atlas Sheet XXXIX). This contact between the Mesnard quartzite and the Archean affords an excellent illustration of the principle that crystalline gneissoid granite may grade step by step into a rock which is an unquestionable quartzite, there being no sharp line of demarcation between the two, and yet between the two formations there really being a profound unconformity.

THICKNESS.

As the Mesnard quartzite is the first formation of a transgressing sea, it doubtless originally varied in thickness, this being due to irregularities of the Archean basement. This irregularity in the basement is indicated by the fact that the quartzite belt is in one place scarcely more than 150 feet across. As the dips are here vertical, this may be taken as the thickness of the formation. From this thickness the quartzite shows a continuous exposure at Mount Mesnard of 700 feet, which with an inclination of 80° corresponds to a thickness of 670 feet. In other places the belt is much wider than this, but here the increased width is plainly due to folding, and even at Mount Mesnard the interstratified belts of slate and graywacke may contain minor rolls which have escaped observation and the real thickness of the formation be less than 600 feet.

INTERESTING LOCALITIES.

Mud Lake.—North of Mud Lake, adjacent to the old road east and west of N.-S. ¼ line, sec. 29, T. 48 N., R. 25 W. (Atlas Sheet XXXVI), is a conglomerate, described by Irving[1] as the "State Road conglomerate." This conglomerate occurs at various points for a distance of a quarter of a mile east and west, hanging upon the southern flank of the prominent ridge of Mona schist running east and west through this and adjacent sections. The basal portion of the conglomerate is very coarse. The fragments contained in it comprise both granite and green schist. The granite fragments vary from small pebbles to bowlders 2 feet or more in diameter. They are well rounded, and in lithological character are similar to the granites which occur as intrusives in the northern part of the Mona-schist belt. While these granite fragments are abundant, green-schist fragments are still more plentiful. In size they vary from small particles to large blocks. Some of them are distinctly rounded, but many are angular, being in shape similar to the irregular schistose blocks which at the present time are broken by weathering agencies from the main mass of Mona schist. Search was made for jasper pebbles, such as occur in the conglomerate to the east, but without success. All who have examined this conglomerate agree that it is a basal one, being made up largely from the formations immediately subjacent, but containing a sufficient amount of material somewhat remote from the contact to show that it can not be a dynamic conglomerate. This belt of conglomerate is only a few feet in width, and nearly all of the localities are just north of the old State road.

Immediately south of this road occur most interesting exposures of interstratified slate and graywacke. The rock varies from a very fine grained slate to a coarse graywacke, the denser phases of which are red and felsitic-looking. Certain exposures are wholly of the graywacke, others of the slate, and others are interstratifications of the two. The most altered phases take on a schistose structure, and are difficult in hand specimen to discriminate from a crystalline schist. This rock is found to have a cleavage

[1] The greenstone-schist areas of the Menominee and Marquette regions of Michigan, by G. H. Williams, with an introduction by R. D. Irving: Bull. U. S. Geol. Survey No. 62, 1890, p. 21.

with a strike in a nearly east-and-west direction and a dip of about 80° to the southward. While the slaty cleavage has a strike approximately east and west and a uniform southern dip, when carefully examined the bedding layers are seen to be in a series of sharply compressed anticlines and synclines, with isoclinal southern dips and steep pitches. At certain places in the gray slate or graywacke background are found numerous pebbles, some several inches across, of red, felsitic-looking rock. These at first were thought to be derived from an extraneous source, but a careful examination of all the ledges discloses every gradation between these pseudo-conglomerates and the interlaminated slate and red graywacke. During the intricate folding the more rigid and brittle felsitic-looking graywacke was broken up; the fragments were ground over one another and thus rounded; at the same time they were buried in the slate and graywacke matrix. Step by step the process may be traced from the phase in which the more resistant layers are merely shattered, through the phases in which the fragments are somewhat separated but have a distinct linear arrangement corresponding to the original layer, to those phases in which no traces of the original coarser graywacke layers as such are to be seen. In their places are the dynamically rounded fragments in the slates.

It is evident from the foregoing that this whole mass of slate and graywacke has been kneaded in a most remarkable manner by the folding process. Up to a certain point the accommodations have been made by the slipping of the layers over one another, with readjustment of the minor particles within the layers, but in the most completely pseudo-conglomeratic phase the pseudo pebbles are so irregularly distributed as to indicate that the whole material must have been mashed together, the parallel layers being compressed by the forces until the originally horizontal beds are in a series of nearly vertical, isoclinal folds.

Parallel to the schistose structure of the slates and graywackes, in certain places, are veins and irregular oval lenses of impure ferriferous dolomite. These are taken to be secondary infiltration or replacement products.

There are no continuous exposures connecting the conglomerates on the north side of the road with the slate on the south side, but there is little doubt that the slate is the noncongloneratic phase of the formation. This slate, by becoming more and more quartzose, passes into vitreous quartzite, which shows large exposures just north of Mud Lake. This more resistant rock seems to have been upturned without having received the minor plications which are found in the slate. The soft slate was between the heavy beds of quartzite on the one side and the strong Mona schists on the other; and doubtless the larger part of the readjustment which was necessary when the layers were folded together took place in the slates, and are thus explained the profound dynamic effects there seen.

An examination of the conglomerates and slates in thin section fully confirms all that has been said in reference to the relations of the rocks as seen in the field. The predominant pebbles from the State road conglomerate comprise almost every phase of the peculiar rocks of the Mona-schist formation in the neighborhood of Marquette. There are also found abundantly coarse-grained granite, the peculiar red granite, and a finer-grained, feldspathic-looking granite, all of which in dikes cut the Mona schists. The matrix of the conglomerate is of the ground-up detritus of the same material, feldspar however being predominant, because of the basic character of the rocks from which the material is derived. In thin section a few chert fragments were found. These were not in the form of pebbles, but this occurrence microscopically connects this conglomerate with the conglomerate which occurs on Mount Omimi. It has been stated that probably the conglomerate grades up into the slates and graywackes on the south side of the road. The latter prove in thin section to be identical in character with the matrix of the conglomerate. The quartzites are found to be typical of the formation, and need no description.

Mount Omimi.—On the steep northern slope of Mount Omimi (Atlas Sheets XXXVI and XXXVIII), in the northern part of secs. 33 and 34, T. 48 N., R. 25 W., occurs a conglomerate, varying from 10 to 40 feet in thickness. This conglomerate has a ferruginous graywacke background, and contains numerous pebbles of banded, cherty-looking quartz, of white crystalline quartz, of ferruginous chert and jasper, of heavily ferruginous pebbles, of white schistose graywacke, and of green schist. It is underlain by coarse graywacke and slate, and is overlain by slates and graywackes, interstratified with quartzites, sometimes strongly and coarsely feldspathic. These pass into the pure quartzites which constitute the greater part of the bluff.

When this conglomerate was first examined it was thought that it marked an unconformity, but a closer examination shows it to be interstratified conformably with the slates and graywackes below, and with the graywackes and quartzites above. Those below are precisely similar to the slates and graywackes south of the State road north of Mud Lake, and apparently are at the same horizon. In the upward gradation from this to the quartzite it appears that the currents were strong enough to locally form a bed of conglomerate. The conglomerate differs from that at the base of the series north of Mud Lake in the absence of abundant granite and green-schist pebbles and in the presence of the varieties which have been given as characteristic of it. The conglomerate appears to follow along the border of the hill to the east, and in field relations apparently cuts slightly across the direction of stratification of the overlying slates and quartzites, although no actual discordance was seen at any locality. The junction of this conglomerate layer with the underlying slates and graywackes was a zone of maximum differential movement at the time of the folding. As evidence of this, the slates are broken into thin plates; they are heavily impregnated with oxide of iron; the conglomerate itself in certain places takes on a brecciated form, and its matrix, as well as some of the pebbles, is heavily impregnated with iron oxide. The graywacke pebbles contained in the lower part of the conglomerate probably have the same origin as those in the slates north of Mud Lake; that is, they are of dynamic origin. At various places the whole series is cut through by diabase dikes.

A microscopical examination of the Omimi conglomerate shows that the majority of the heavily ferruginous pebbles are decaying fragments of a schistose rock, which have been strongly impregnated by iron oxide, as has also the matrix. None of the quartzite-like pebbles are certainly fragmental, although some of them at first sight have a clastic appearance; but none of the grains show cores or enlargements, and they interlock. They appear to differ from the cherts only in that the quartz is more coarsely crystalline. Some of these complex quartz pebbles are mashed into quartz-schists. Doubtless the chert, jasper, and quartzite-like fragments are derived from the veins of these kinds which are found in the green schists of the Northern Complex, although it is possible that a part of them are derived by dynamic action from vein chert and quartz deposited in the formation itself before the final folding. The feldspathic quartzite contains very abundant simple, large grains of feldspar, which are in some cases distinctly enlarged. The graywackes, slates, and quartzites do not differ from the ordinary phases of the formation.

Mount Mesnard.—Mount Mesnard (Atlas Sheet XXXVIII) is a large bluff in the west half of sec. 35 and the eastern part of sec. 34, T. 48 N., R. 25 W. In structure this mountain is a closely compressed syncline, the formations concerned being the Mesnard quartzite and the Kona dolomite. This fold is so closely compressed as to make the dips everywhere approximately parallel, varying from 80° to the south to vertical. The major part of the mountain and the two northern of its higher points are made up of the pure, vitreous, broken and cherty Mesnard quartzite. Between this and the Kona dolomite is a layer of slate, with a transition schistose quartzite. The slate, being less resistant than the quartzite or the cherty dolomite, is marked by an irregular longitudinal depression. In the readily yielding slate are seen strong evidences of mashing, the major readjustment in folding apparently being here. Constituting the center of the syncline is a second row of points, one being the culminating peak. These are composed of the vertical layers of the closely compressed Kona dolomite. The steep south brow is composed of the slate, and on the south flank of the bluff is again the Mesnard quartzite, making the other limb of the syncline. This syncline has minor corrugations and a westward pitch, as a consequence of which the fingers of the Kona dolomite unite toward the west into a broad area of this formation. The south and southeast slopes of the bluff are composed of the Mesnard quartzite. Because of the westward pitch of the formations and the topography the belt of Kona dolomite terminates a short distance east of the culminating peak, as a consequence of which the eastern half of the ridge is composed wholly of the Mesnard quartzite folded back upon itself.

East of the State prison the south arm of the Mesnard quartzite constitutes a ridge, a point of Lake Superior, and a small island off the coast.

These exposures here are less mashed than at Mount Mesnard, and at many places beautifully show ripple marks, especially in the slaty phases. The rocks are vertical or have a dip of 80° to the south. The only indication of the direction in which they have been upturned is given by the ripple marks. An examination of these shows the south faces of the quartzites to have the normal form of the ripple marks and the north faces their casts.[1] This furnishes evidence in support of the statement first made, that these quartzites are on the south side of the fold and are a continuation of the southern part of the quartzite of Mount Mesnard.

Mount Chocolay.—On Mount Chocolay (Atlas Sheet XXXIX), about 3 miles south of Marquette, are the extreme eastern exposures of the Marquette series. This prominent bluff rises about 150 feet above the sand plans of the Chocolay River, to the south and east. The eastern abrupt face of the bluff gives beautiful exposures of the Mesnard quartzite, of the Kona dolomite, and of the underlying green schists of the Archean. The major part of the bluff is a simple syncline, the dips of the quartzite being about 60° N. on the south side and 85° to 90° S. on the north side. The quartzite exhibits nearly all phases of the formation, including the slaty and novaculitic phases, cherty quartzite, and the ordinary massive forms. The Kona dolomite constitutes the center of the syncline and the top of the bluff. As usual, between the quartzite and dolomite is a thin bed of slate. A ravine separates the Mesnard quartzite from the green schist of the Basement Complex to the south. The two, however, dip in opposite directions, the quartzite about 60° to the north and the schistose structure of the green schists about 45° to the south.

On the western end of Mount Chocolay the quartzite formation is found to pass entirely around the dolomite. In passing from the north to the south side the strike varies from west to southwest, then to south, and finally to southeast, thus showing that the whole is an eastward-plunging syncline. Superimposed upon this major fold are beautifully exposed minor anticlines and synclines. Near the base of the formation on the southwestern part of the mountain is found a thin belt of conglomerate, very similar to that on

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise. Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896. pp. 720-721.

Mount Omimi, the windings of which serve beautifully to show the minor folding of the formation.

Migisi Bluffs.—Across a transverse depression west of Mount Chocolay, in the north part of sec. 1 and in sec. 2, T. 47 N., R. 25 W., are the Migisi Bluffs (Atlas Sheet XXXIX). The eastern part of these bluffs is, in a large way, a westward-plunging syncline, but, as in the case of Mount Chocolay, this larger syncline is found to be composed of many subordinate rolls. The depression separating Mount Chocolay and the Migisi Bluffs is, then, the bridge or anticline of a large north-south fold. The complex, plunging Migisi syncline may, then, be considered as a combined effect of folding in two directions. The eastern part of the bluffs is composed of the quartzite, but, as a result of its western pitch, the Kona formation appears in the eastern half of sec. 2 in a series of fingers, each of which corresponds to a minor fold. These fingers unite toward the west and form the broad belt of the Kona formation. Beginning at the north and going east and south around the bluff, the strike changes from an east direction to a southeast, then to a south, then to a southwest, and finally to a western course on the southern side of the fold. As in other localities, separating the quartzite and the Kona dolomite is a thin belt of slate, which becomes calcareous in its upper parts. As on Mount Chocolay, the narrow belt of ferruginous conglomerate, bearing numerous pebbles of chert and jasper, is of great assistance in following the details of the minor folds. In the north part of sec. 2 appear the green schists of the Archean, and a section through the western part of the bluffs shows the complete succession from the Archean to the Kona dolomite.

On the southeastern slope of the Migisi Bluffs, north of the quarter post between secs. 1 and 2, near the section line, may be seen the actual contact of the quartzite and granite-gneiss. As the bottom of the quartzite is approached there appears a bed of conglomerate 8 or 10 feet thick, containing numerous white quartz pebbles, some of them 8 inches across. Toward the south, near the base of a cliff, the exposure becomes less conglomeratic and changes into a schistose rock. This clearly fragmental schistose rock is in direct contact with another schistose rock, which can be traced by gradations into the genuine granite-gneiss. There appears to be no discordance between the two schists. After a short interval of no exposure the normal granite appears to the south. This is one of the localities which were cited by Rominger[1] as evidence of progressive metamorphism of the quartzite into the granite. However, taking the locality in connection with others, it is certain that there is no such gradation, but an unconformity between the two. The apparent transition may be explained by the disintegrated character of the granitoid gneiss at the time of the Mesnard transgression; or the intense mashing produced by the folding at the junction of the two formations may have obliterated the pebbled granitic detritus, even if it existed. The mashing has transformed the clastic rock into a crystalline schist, and has metamorphosed the granite into a similar-looking rock.

In the northern part of sec. 3 the Mesnard quartzite may be traced in continuous exposure around the north, west, and south sides of the Archean green schist, dipping away from it in all directions. The exposures, therefore, constitute a westward-plunging anticline.

In thin section the larger masses of the Migisi Bluffs present the ordinary phases of graywacke and vitreous and cherty quartzites. However, it is on the southeastern slope of this bluff that occur the kaolinic quartz-schists described on pp. 226–227. It has been seen that in the field there is difficulty in discriminating between the mashed fragmental rock and the underlying gneiss. In thin section the two are separable. The most altered phase of the detrital rock shows distinct rounding of the quartz grains. These are set in a fine-grained matrix of kaolin, sericite, and cherty quartz. All distinct feldspathic detritus has disappeared. On the other hand, the gneissoid granite has distinctly a granitic structure, and even where most altered the feldspars, although much decomposed, may be recognized

Lake Mary.—Northwest of Lake Mary, in the SE. $\frac{1}{4}$ sec. 4 and the NW. $\frac{1}{4}$ sec. 9, T. 47 N., R. 25 W. (Atlas Sheet XXXVII), are found large exposures of quartzite, dipping away from the granite on each side and toward each other under the Kona dolomite, which appears as a westward-plunging syncline. Near the corner of secs. 8, 9, 16, and 17, T. 47 N., R. 25 W.,

[1] The Marquette iron region, by Carl Rominger. Geol. of Michigan, Vol. IV, Part I, 1878–1880, pp. 15, 52.

forming embayments on the west and southwest slopes of a large granite bluff, are magnificent exposures of a great granite-conglomerate. The pebbles and bowlders of the rocks are predominantly of coarse and fine granite, and with these are abundant pebbles of quartz and green schist, and fewer of jasper. Interstratified with the coarse conglomeratic bands are fine-grained conglomerates, which are so thoroughly cemented as to resemble original granite. The interlaminations of materials of different degrees of coarseness in places give the rock a fine banding, which makes it in a remarkable degree resemble gneiss. Nowhere was the conglomerate found in actual contact with the granite, but as the various granitic fragments are identical with the exposures of granite below, no one can doubt that the pebbles and bowlders are from that source. Southeast of the corner, in sec. 16, are exposures of schistose and feldspathic quartzite resembling gneiss. This feldspathic quartzite or recomposed granite grades into the ordinary white quartzite.

SECTION II.—THE KONA DOLOMITE.

The name Kona dolomite is given to this formation because the Kona Hills, rising from the east shore of Goose Lake (Atlas Sheets XXXIV and XXXV) as large bluffs with precipitous cliffs, are composed of typical rocks of the formation, and because dolomite is, upon the whole, the predominant rock.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Starting at Mount Mesnard (Atlas Sheet IV), the area covered by the Kona formation rapidly widens in passing westward. From south of Mud Lake the belt again narrows in going toward the west, until at Morgan Furnace it is only about a sixteenth of a mile wide. Farther to the west no exposures of this limestone are found, but its horizon may be represented by a belt of slates and quartzites east of Teal Lake.

On the south side of the Algonkian the formation has a much more irregular distribution. Starting at the sand plain just west of Lake Superior, it extends west nearly half a mile, where it disappears. About a mile to the westward, southeast of Lake Wabassin, the formation reappears and extends westward as a belt a third of a mile wide. As it reaches Carp River the formation swings southwest, and then south to Tigo Lake. Here a small arm goes to the southeast across this lake toward Lake Mary, but the main belt continues to the southward. About a mile west of Lake Mary it widens out into a broad area, varying from a mile to 2 miles in width, and extends to Goose Lake, the last exposures of the formation being found on the east side of this body of water. Also north of the Archean island in secs. 2 and 3, T. 47 N., R. 25 W., the limestone appears, just north of the Mesnard quartzite, in a narrow belt. The real extent of this area of dolomite it is impossible to give, as the Potsdam formation occupies much of the valley of the lower reaches of the Carp River.

Almost coextensive with the distribution of the formation are the exposures, they being abundant and prominent throughout most of the area. However, some of the most readily accessible places at which the formation may be studied are the exposures east of Goose Lake and those south and west of Wabassin Lake (Atlas Sheets XXXIV and XXXIX).

As a consequence of the complicated folding of the formation, below described, combined with the very different resisting powers of the layers, the topography of the formation is exceedingly jagged. The exposures constitute a set of sharp and abrupt cliffs, cut by ravines or separated by drift-filled valleys. Where north-south and east-west folds both occur the valleys cut across one another in two systems at right angles, leaving roughly rectangular masses of rock between. In places where the folds have a pitch the layers may form semicircular outcrops with vertical walls. Rather low dips prevail for much of the area, and in traveling over the belt one has to climb a series of steep hills, each of which is composed of a number of almost vertical, ragged cliffs. The descent from the elevation is of much the same character. The weathered surfaces of the ledges also are sharp and ragged in a minor way (Pl. VII, fig. 1). The cherty layers form sharp ridges. The quartzite layers project in less jagged forms. Geodal concentrations of quartz protrude from the surface of the limestone. The dolomite has dissolved from the cherty and quartzose layers, giving them a rough, vesicular appearance.

FOLDING.

The major folding (Atlas Sheet IV) of the formation will be considered in connection with the general geology of the district. It may be said here that the formation has been affected by both east-west and north-south thrusts. In some cases the east-west folds are more conspicuous, in others the north-south, while in still other areas the folds are about equally prominent in both directions, although even here the folds of one set have less amplitude and less length than those of the other As a consequence of the above, each fold has a pitch, which may be slight or very steep. Still further to complicate the structure of the area, the major folds in each direction have superimposed upon them secondary folds, and upon these are tertiary ones. In some cases, as in the largest belt east of Goose Lake, the pressure has not been so great as to give the beds very steep inclinations, the dips usually being not more than 20°, although occasionally as high as 50°. As a consequence of the nearly equal power of the folding forces in each of the directions in this broad area, the ledges give strikes in all directions.

From the above it is clear that the deformation of the Kona formation is a beautiful illustration of complex folding.[1]

To the pressure of folding the dolomite has usually yielded without prominent fractures or cleavage. The same can not be said of the interlaminated slates, graywackes, and quartzites. In many places a bed of slate has had developed across it a diagonal cleavage, which stops abruptly at the limestone layers (fig. 9). In other cases the cleavage passes into the dolomite itself, as, for instance, at the exposure back of the railroad section-house near Goose Lake. In some places the dynamic movements have produced a fissility in two directions, so that the rocks break into polygonal blocks.[2] In numerous instances the layers of chert and quartzite have been fractured through and through by folding, so as to change them into breccias resembling conglomerates (Pl VII, fig. 2, and Pl. VIII). Along the contacts of the dolomite beds and the quartz layers accommodation was necessary, and in places a bed of limestone may be seen bent into a series

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part 1, 1896, pp 626-631.

[2] Ibid., pp. 643-646.

of anticlines and synclines, the overlying quartzite not being similarly bent, but being compressed and brecciated, thus making a pseudo-conglomerate. The folded dolomite laminæ are actually cut away to some extent by the

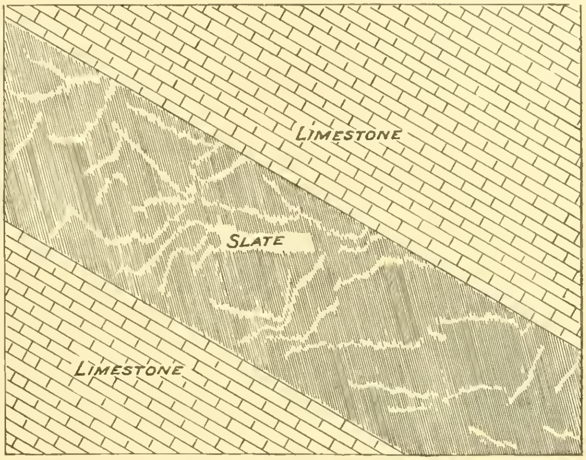


FIG. 9.—Cleavage in slate between two limestone beds.

shearing action. The result is that the layers of quartzite cut across the folds of the limestone, as in an unconformable contact, and adjacent to these truncated layers are the pseudo-conglomerates (fig. 10). Such

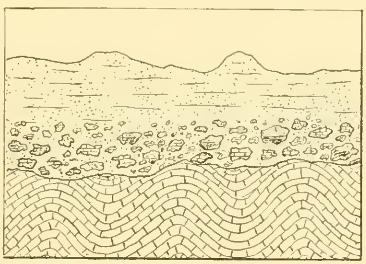


FIG. 10—Pseudo-unconformity between cherty quartzite and truncated strata of dolomite.

contacts as these, found at many places, strongly suggest an unconformity between the two, but the true explanation is undoubtedly that the apparent unconformity is merely a dynamic phenomenon.

PETROGRAPHICAL CHARACTER.

Macroscopical.—Petrographically the different exposures are very similar. The formation is not a pure dolomite, but is a cherty dolomite interstratified with layers of slate, graywacke, and quartzite, with all gradations between the various mechanical sediments and between these and the pure dolomite. In some exposures the pure dolomite does not constitute more than a third to a half of the belt. The interstratified slates and quartzites are of the same character as those of the Wewe slates and Ajibik quartzites, except that they are apt to be more or less calcareous. The dolomite beds vary in thickness from only a few inches to many feet. But even the solid belts of limestone usually contain very thin layers, which in places are in part fragmental, but which are usually wholly or in large part secondary chert. In color the dolomite varies from nearly pure white to dark-brown, depending upon its purity, and between these colors are various shades of buff, purple, pink, and red. As the interbedded slates and quartzites also have a wide variation in coloring, the ledges of the formation are very different in their aspects.

The dolomite varies from aphanitic to coarsely crystalline. Upon the weathered surface the pink and red varieties usually have a dark-brown color, due to limonite. This indicates that the carbonate carries a considerable quantity of iron, the oxidation of which has produced this outer dark-colored skin. Where the dolomite is most coarsely crystalline, as, for instance, at Morgan Furnace, it sometimes contains belts from a fraction of an inch to 4 inches wide, largely composed of pink, coarsely crystalline, and evidently rearranged dolomite (Pl. VII, fig. 1). As a consequence of weathering, the bands of original sedimentary quartz and of secondary chert protrude, giving a peculiar rough, ridgy appearance.

Microscopical.—The rocks of the Kona dolomite comprise coarsely and finely crystalline dolomite, cherty dolomite, quartzose dolomite, argillaceous dolomite, dolomitic quartzites, dolomitic slates, dolomitic cherty quartzites, and dolomitic chert.

The compact and apparently least altered, purer rock has a background consisting of finely granular dolomite, separate granules of which are

PLATE VII.

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PLATE VII.—THE KONA DOLOMITE.

FIG. 1. Weathered surface of Kona dolomite from Morgan Furnace. The background is the ordinary granular gray dolomite. The rough protruding layers are chert, a portion of which is iron stained. Natural size.

FIG. 2. Brecciated chert at the base of the Kona dolomite on the east side of sec. 13, T. 47 N., R. 26 W (Atlas Sheet XXXIV). At the bottom of the Kona dolomite chert was concentrated so as to make a layer 2 or 3 feet in thickness. Subsequent movement broke this layer into a breccia which in some places closely resembles a conglomerate. The broken fragments are cemented by later infiltrated quartz and by specular hematite and magnetite. The chert in places is iron-stained, either by limonite or by hematite. Natural size.

FIG 1

FIG 2

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FIG. 1 WEATHERED SURFACE IN KONA DOLOMITE

FIG. 2. BRECCIATED CHERT AT THE BASE OF KONA DOLOMITE.

largely rhombohedra. These very finely granular rocks vary into those which are more coarsely crystalline, and the latter grade into phases in which coarse crystals of dolomite compose most of the rock. It is probable that in these coarser rocks there has been a recrystallization. This is indicated in one case by a remarkably beautiful zonal structure, shown by all of the large rhombohedra of dolomite.

The purer phases of dolomite pass into those in which the dolomite is heavily stained with iron oxide. In some cases on the weathered surface is an outer layer of heavily ferruginous material, resulting from the decomposition of the dolomite, and showing that the carbonate is ferriferous.

These nonfragmental rocks by gradation pass on the one hand into the argillaceous dolomites or mica-slates and upon the other into the quartzose dolomites. In the argillaceous dolomites the finely crystalline quartz, feldspar, and other clayey materials are intimately intermingled with the granules of dolomite. By a further decrease of the dolomite the rocks pass into the dolomitic slates. Those which show the fragmental material in a dolomitic background are placed with the dolomites. Those which show a fragmental background in which the dolomite occurs are placed with the slates. Where the detritus is coarse the rocks are quartzose dolomites. In these we have a large amount of fragmental quartz, in well-rounded, enlarged grains. Where the quartz grains are buried in a background of dolomite they are called siliceous dolomites. By a decrease of the dolomite we have a sparse matrix of carbonate in which numerous quartz grains are set, and then the rock becomes a dolomitic quartzite. In some cases the alternations of coarse and fine material are in minute layers, a fraction of an inch across, having alternately coarse and fine grains of quartz and greatly varying amounts of dolomite. In other cases thick beds are wholly of the dolomitic quartzite.

The rocks of the formation, whatever their lithological character, have been shattered by dynamic action, and have frequently become reibungs-breccias (Pl. VII, fig 2, and Pl. VIII) These breccias, which where much mashed resemble true clastics, differ from conglomerates in the usual angularity of the fragments and in containing no material from an extraneous source.

The pure dolomites, where merely shattered, have been cemented by finely crystalline cherty quartz, or by coarsely crystalline dolomite, or by these two combined. The brecciated phases show numerous irregular complex fragments of the granular dolomite. The angularities of these dissevered fragments are frequently the reverse of the fragments adjacent, proving conclusively that they have been broken apart. In a more advanced stage of the dynamic action the complex fragments of the granular dolomite have a subangular or roundish appearance, so that the rock as looked at with a low power resembles a conglomerate. These dissevered fragments are united by cherty quartz, by coarsely crystalline dolomite, or by the two interlocking. In some cases this secondary cherty quartz has impregnated the rock through and through, so that minute irregular veins of chert or geodal areas of quartz are scattered through the dolomite. In a still further stage of silicification but a small amount of granular dolomite may be seen in the chert veins. As a result of further silicification considerable belts of chert are found interlaminated with the bands containing less chert. Frequently these belts have oval or abrupt terminations. Oftentimes after a first dynamic action and silicification the rocks have been brecciated again, and have again been cemented by infiltrating silica. In this case we have a cherty dolomite or a chert-breccia, with a cement of newer chert. It is generally possible to discriminate the earlier and later chert by the slightly different crystalline characters which it has, and also because the later chert is sometimes mingled with oxide of iron.

The argillaceous and siliceous dolomites have been brecciated and cemented in the same way as the purer dolomites. In this case we have both fragmental quartz and secondary cherty quartz intermingled. The original quartz grains uniformly show undulatory extinction or fracturing. Frequently during the folding the grains of quartz and feldspar have been broken out of their background and have fallen into the crevices. These are surrounded by and embedded in secondary infiltrated cherty quartz and dolomite.

The slates and quartzites interstratified in the Kona dolomite are not here described, as they are in all respects similar to the Wewe slates and

PLATE VIII.

PLATE VIII.—BRECCIATED KONA DOLOMITE.

FIG. 1. Brecciated chert in Kona dolomite from sec. 18, T. 47 N., R. 25 W. (Atlas Sheet XXXVII). The gray chert is broken into fragments by dynamic action. The fragments are angular. They are cemented by chert and limonite. After being thus cemented the rock was again broken by later movement. The rock was again cemented by minute veins of chert and hematite. Natural size.

FIG. 2. Brecciated chert in Kona dolomite from sec. 1, T. 47 N., R. 25 W. (Atlas Sheet XXXIX). The figure is from a chert layer between the Mesnard quartzite and the dolomite. The rock was brecciated by dynamic action. The fragments were rubbed against one another, so that many of them are partly rounded. They were then cemented by chert and hematite. Subsequent movement again slightly shattered the rock, and the cracks thus formed were healed by secondary silica. The minute veins thus produced may be seen running through both matrix and fragments. Natural size.

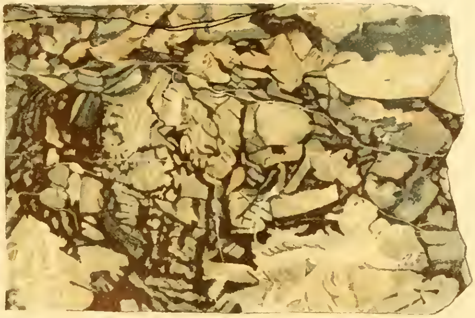

FIG. 1

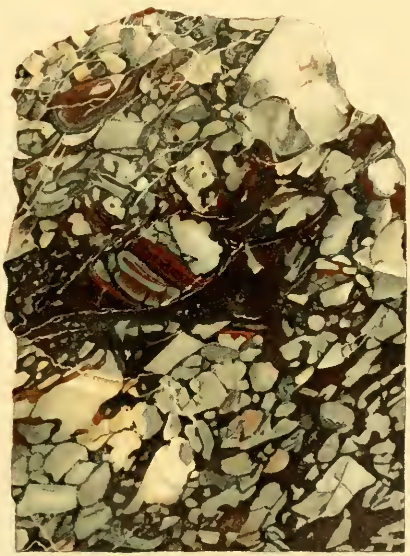

FIG. 2

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FIG. 1. BRECCIATED CHERT IN KONA DOLOMITE.
FIG. 2. BRECCIATED CHERT IN KONA DOLOMITE.

the Ajibik quartzites subsequently described, with the exception that they are more or less dolomitic.

The foregoing study of the thin sections of the Kona formation shows that it has been shattered throughout. From the field observations it was apparent that the formation had been much broken by dynamic action, but the completeness of this shattering and brecciation was appreciated only by a study of the thin sections, every one of the numerous slides showing these phenomena to a greater or less degree. It thus appears that not a half-inch cube has escaped. It is believed that this indicates that the rock when folded was not buried under so great a load as to be beyond the sustaining power of the rocks. Upon the other hand, since there are no prominent faults, and since the formation as a whole is folded in a complicated fashion, retaining its continuity, it is thought that it was buried under a considerable thickness of strata. It was therefore in the zone of combined fracture and flowage.

RELATIONS TO ADJACENT FORMATIONS.

The Kona dolomite varies through a slate into the Mesnard quartzite below. This slate appears to be a thin, persistent formation. Its thickness varies from less than 30 feet to 100 feet. In many places it appears thinner than this smaller number, but it is only at a few places that the exact contact between the slate and the formations above and below it can be seen, there usually being, however, sufficient room for the slate belt between the quartzite and the dolomite. This slate may be well observed at Mount Mesnard, where it forms a little valley separating the quartzite peak on the north from the marble peak on the south. The slate may also be well seen just west of Wabassin Lake, in sec. 2, T. 47 N., R. 25 W., where the westward-plunging syncline of the Kona formation causes the slate to appear immediately beneath the limestone. This belt of slate, which was once a shale, probably marks the time of deepening waters, when the conditions favorable to the deposition of a sandstone changed to those favorable to the formation of a limestone.

Above, the dolomite, by a lessening of the calcareous constituent, gradually passes into the Wewe slate. The appearance of this formation may have marked a time when subsidence had ceased and the limestone had been built upward until the finer-grained mechanical sediments could be carried by the waves. That this is probable, rather than that the sea had deepened so much as to make the limestone formation impossible, is indicated by the fact that above the Wewe slate follows the Ajibik quartzite, a coarser mechanical sediment.

THICKNESS.

As a consequence of the complicated folding of the district, it is exceedingly difficult to give an accurate estimate of the thickness of the Kona dolomite. It doubtless varies much, perhaps reaching its maximum somewhere near the central part of the area, and thinning out in passing to the west. South of Mud Lake the formation has an almost continuous exposure for 1,500 feet, with a dip to the south varying from 78° to 90°. If there were no minor folds, and calling the average dip 80°, this would correspond to a thickness of about 1,375 feet. However, it is certain that just to the north of this lake the slates are in a series of sharp isoclinal folds; and that this is true for the dolomite, to some extent at least, is more than possible. How much this maximum thickness should be decreased on account of this uncertain element of the problem it is difficult to estimate, but it is wholly possible that the thickness as above calculated should be reduced one-half. At Goose Lake, as has been said, there is a continuous exposure of the formation for a considerable distance. Here the thickness of the layers was carefully measured and found to be 225 feet, with a possible error of 25 feet. If the formation is supposed to have the same dip to the northward for the remainder of the detached exposures along the east shore of Goose Lake, this amount may be increased by 150 or 200 feet.

West of Tigo Lake the formation is exposed almost continuously for a distance of 1,300 feet. The dip here varies from 25° to 40°, averaging perhaps 30° or 35°. Calling the average dip 30°, this would give a thickness of 650 feet. Although the limestone occupies an area as broad as 2 miles in certain places, it can not be asserted, on the present information, that the maximum thickness of the limestone is more than 700 feet, although it may be twice this amount.

INTERESTING LOCALITIES.

Nearly all of the peculiarities of the Kona dolomite mentioned in the general description may be found at any of the localities in which the exposures are extensive, so that here there will be given but little more than a list of localities in which the exposures are numerous, to serve as guides to those wishing to study this formation.

Eastern area.—Beginning at the northwest, there are excellent exposures near the old Morgan Furnace, in the north part of sec. 31, T. 48 N., R. 25 W. (Atlas Sheet XXXVI). Numerous large exposures occur on the bluff south of Mud Lake, in sec. 32. The south half of Omimi Bluff, in sec. 34, also gives very numerous exposures (Atlas Sheet XXXVIII). On Mount Mesnard, as has been said, the crowning peak is a closely compressed syncline of the Kona dolomite. The central and higher part of Mount Chocolay, south of Marquette, is another syncline of the dolomite. On the Migisi Bluffs (Atlas Sheet XXXIX), in secs. 2 and 3, T. 47 N., R. 25 W., are very numerous large exposures of the dolomite. On account of the western pitch this formation ends at the east in a series of fingers, the general syncline, as has been said, being composed of minor synclines. The succession of the members of the formation, the dynamic effects produced by the folding, and the slate marking the transition belt between the dolomite and the Mesnard quartzite may be particularly well observed here. The hills often break off in eastward-facing cliffs, and by following from the north around the east side to the south side of such a bluff one continues parallel to the changing strike of the terminating layers. Both east and west of Tigo Lake (Atlas Sheet XXXVII), in secs. 4, 5, 8, and 9, T. 47 N., R. 25 W., are very numerous exposures of the dolomite.

Ragged hills.—Numerous typical exposures of the formation are found on all the bluffs in secs. 7, 8, 17, and 18, T. 47 N., R. 25 W. (Atlas Sheet XXXVII). On the south slope of the bluff in the SW. ¼ sec. 17 is a belt of cherty, quartzitic breccia, which on its weathered surface very closely resembles a conglomerate. This breccia contains fragments of slate, quartzite, chert, and marble. It is underlain by folded beds of marble, the minor sinuosities of which are truncated by the breccia, and it is overlain by quartzite. At first sight the appearance of an unconformity is very strong indeed. (See fig. 10, p. 243.) However, when the supposed conglomerate is followed along the strike, its brecciated character is found gradually to disappear and it changes into ordinary quartzite. The fragments, instead of being waterworn, are distinctly angular. Moreover, while at first sight there appears to be a wide variety of fragments in the breccia, all of these are obtainable from the immediately adjacent beds. It appears that when the series was folded the more plastic limestone yielded to the pressure, in both a major and a minor way, by folding, while the brittle cherty quartzite was fractured through and through, the movement of the fragments over one another, and of the bed as a whole, being sufficient to truncate the minor waves of the marble. In a large way the belt of dolomite and that of the quartzite and breccia are conformable.

In the west part of the SE. ¼ sec. 18 is exposed the contact between the Mesnard quartzite and the Kona dolomite, which here has a general strike approximately north and south and a dip to the east, but with minor cross folds with east-west axes. At the top of the Mesnard is cherty quartzite, which is followed by thin beds of novaculite and slate before the impure limestone is reached.

Kona Hills.—The most extensive exposures of the formation are on the Kona Hills (Atlas Sheet XXXIV), which rise from 300 to 400 feet above Goose Lake, and make up a great series of bluffs in secs. 11, 12, 13, and 14, T, 47 N., R. 26 W. It is from these extensive and typical exposures that the formation is given its name. Facing the southeast arm of Goose Lake are bold, almost vertical cliffs, 200 feet high. At the point where the lake widens these cliffs slope rapidly to the north, following approximately, with a somewhat regular incline, the dip of the formation. The lowest exposure here found is a very impure dolomite. Above this follows a succession of interlaminated, impure dolomites, red and black slates, cherts, quartzose dolomites, cherty quartzites, at places brecciated, and occasional beds of nearly pure quartzite, or even of conglomerate. These various strata may have thicknesses from an inch or less to a number of feet. The layers of quartzite, usually not more than a foot or two in thickness, and oftentimes less, are generally interstratified with the dolomitic slates. In one place ripple marks were seen in the beds above and below a layer of conglomerate. The close intermingling of mechanical and nonmechanical sediments suggests that at the time of the deposition of the lower half of these beds the water was not very deep, and perhaps a shore-line was not distant. The colors of the rocks vary from the dark gray of the slates, through various shades of buff and brown, to nearly white in the case of one or two of the dolomites or quartzites. Following above these beds are others comprising all of the foregoing kinds, and also heavy beds of nearly pure, coarsely granular dolomite, some of which are 20 feet thick. The total thickness of the beds thus far exposed measures about 225 feet. The argillaceous beds are extensively affected by a slaty cleavage, which frequently stops abruptly at the more massive dolomite or quartzite beds (fig. 9, p. 243).

After an interval of no exposure, the next place north on Goose Lake is occupied by coarsely crystalline, nearly pure, pink dolomite, with occasional layers of more finely crystalline material and a few layers of chert. After another interval of no exposure are very large outcrops of similar dolomite, some layers of which, however, are very quartzose, and a few layers of which are shaly. The northernmost exposure is a coarsely crystalline dolomite, containing many nodules of coarsely crystalline quartz. Of the large exposures southeast of Goose Lake, probably not more than one-third of the thickness is composed of reasonably pure dolomite, the remaining two-thirds being largely mechanical sediments. Farther to the east the proportion of mechanical material is not so great.

Of the numerous large exposures east of Goose Lake, only a few are platted on the atlas sheet, and these are mainly along the outer borders of the area. This area has, however, been sufficiently traversed to show that there are everywhere great bluffs of the dolomite.

As explained in the general folding of the area, east-west and north-south forces were about equally strong, although the folds with north-south axes are, upon the whole, of larger dimensions and less dips than those with east-west axes. It follows that strikes and dips can be found in almost any direction, and the true structure is perceived by general study rather than by taking strikes and dips. As a result of the folding, the ledges were broken in the two directions according to a rectangular system, and the topography has a corresponding arrangement. The great bluffs north of the south arm of Goose Lake are cut by deep ravines running in a north-south direction, or in a direction somewhat east of north, corresponding to one set of folds. The changing strikes and dips, showing a northward-plunging anticline compounded of the two foldings, may be seen along the face of the exposures east of the south arm of Goose Lake. Similar eastward-plunging anticlines and synclines may be observed along the west side of the north-south valley separating the exposures of the Wewe slate and Kona dolomite in the southeast part of sec. 13 and the northeast part of sec. 24, T. 47 N., R 26 W.

Along the eastward-facing cliff of limestone just west of the Wewe slate, in the southeast part of sec. 13, T. 47 N., R. 26 W., below the limestone, there is found a considerable quantity of green schist which is cut by granite veins. Upon this material is a conglomerate containing numerous pebbles of the subjacent green schist and granite. This grades quickly up into graywacke, and this above into the limestone. The green schist cut by granite is identical in character with that of the Archean, and is taken to be of Archean age. Therefore we have the Kona dolomite resting unconformably on the Archean. It follows that during the time of the deposition of the Mesnard quartzite to the east this part of the district was above the water, and that it was submerged in Kona time.

SECTION III.—THE WEWE SLATE.

The name Wewe slate is given to this formation because it occurs in typical development on the Wewe Hills, southwest of Goose Lake (Atlas Sheet XXXV), and because the predominant rock is a slate. With the slate are graywackes, conglomerate, mica-slates, and in places mica-schists.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Starting at the west side of Goose Lake (see Atlas Sheet IV), the belt extends in a general westerly course for about 3 miles, having, however, for this distance tortuous boundaries and a greatly varying width. It will be seen that the Kona dolomite begins east of Goose Lake as a broad belt.

The Wewe slate, following above the limestone, should appear both to the north and south of this belt. On the south, however, the formation is exposed only in secs. 13 and 24, T. 47 N., R. 26 W., and in sec. 18, T. 47 N., R. 25 W., where, however, it extends but a short distance before it is hidden by the Pleistocene sands. The northern arm of the slates shows outcrops in secs. 11 and 12, T. 47 N., R. 26 W., and very numerous outcrops west of the Kona dolomite in secs. 5, 6, 7, and 8, T. 47 N., R. 25 W. In this area the slate belt swings from an easterly course to a northerly, and finally to a westerly one, and extends along the southern side of the northern limestone for an unknown distance westward. There are no exposures in this area, and whether it dies out before the slates and quartzites east of Teal Lake are reached is uncertain. The black slate occurring at a somewhat persistent horizon between thick beds of quartzites in secs. 32 and 33, T. 48 N., R. 26 W., may be the most westerly representative of the northern belt. Farther west the formation was not deposited, since in Wewe time the sea encroaching from the east had not overridden that part of the district.

The slate being a less resistant formation than the Kona dolomite below or the Ajibik quartzite above, is, in general, marked by valleys, and consequently the exposures are few for much of the area of the belt. The two exceptions to this statement are the numerous prominent exposures in secs. 5, 6, 7, and 8, T. 47 N., R. 25 W., and the exposures west of Goose Lake. The appearance of the first set of outcrops is due to the cutting action of Carp River, which flows over the ledges in a number of rapids and cascades. The many exposures west of Goose Lake are due to the fact that here was the westward limit of the shore-line at this time, and therefore the sediments deposited at this place were coarser and were later changed to graywacke and conglomerate, and thus became more resistant. Also they gain in prominence by the presence of several resistant Archean islands, which they surround.

FOLDING.

The broad belt of slate running north and east from Goose Lake, then swinging to the north and west, has no especially interesting folds, as the slate everywhere dips away from the Kona dolomite below, and thus forms a great westward-plunging syncline, with the eastern termination in secs. 5, 6, 7, and 8, T. 47 N., R. 26 W.

However, the folding in the two areas east and west of Goose Lake is interesting and peculiar. In secs. 13 and 24, T. 47 N., R. 26 W., and secs. 18 and 19, T. 47 N., R. 25 W., the slate has been affected by both an east-west and a north-south folding. The north-south pressure has folded the slates into a series of minor rolls, and the same layer is repeated many times. The east-west pressure has bowed the slates into anticlines and synclines. The character of this folding is particularly well shown by the almost continuous sections which are observable along the east parts of secs. 13 and 24 and along the west side of the southeast arm of Goose Lake (Atlas Sheets XXXIV and XXXV). A major anticline causes the little east-west folds to plunge to the eastward on the east side of the area, and to the westward on the west side. The slate originally arose above the Kona dolomite of Kona Hills, but has been removed from it by erosion.

West of Goose Lake (Atlas Sheet XXXV) it has been said that the slate covers a belt of greatly varying width, in which are Archean islands. The largest of these areas covers a considerable part of the central portion of sec. 23. Another area is southwest of this, in secs. 22 and 23, and two other areas occur in sec. 22, one at the center of the section and the other in the center of the southwest quarter. The conglomerates, slates, and quartzites in sec. 23 and in part of sec. 24 have a quaquaversal arrangement around the oblong Archean area of sec. 23. In other words, the slates and quartzites constitute a part of a northwest-southeast anticline which plunges both to the east and to the west from the center of sec. 23. The strikes about this and the other areas are northwest-southeast except at the ends of the areas; the dips are all to the northeast, showing that the folds have been pushed over from the northeast or pushed under from the southwest. The dispersed distribution of the small Archean patches and the fact that basal conglomerates cover a considerable area are taken to indicate that there are several subordinate folds in this part of the district.

PETROGRAPHICAL CHARACTER.

Macroscopical.—For the areas north and east of Goose Lake the rocks of the formation are slates and graywackes. Southwest of Goose Lake the lower part of the formation becomes a quartzite or quartzite-conglomerate. These conglomerates, reposing as they do upon the gneissoid granites, are very largely composed of detritus derived from them (fig. 11). Immediately adjacent to the Archean cores on the Wewe Hills, in the centers of secs. 22 and 23, the basal rocks are no more than a mass of granite blocks, cemented by fine débris of the same material. An intermediate rock is a coarsely banded feldspathic quartzite which in the field very closely resembles the original gneissoid granite (Pl. X, fig. 1). From these basal

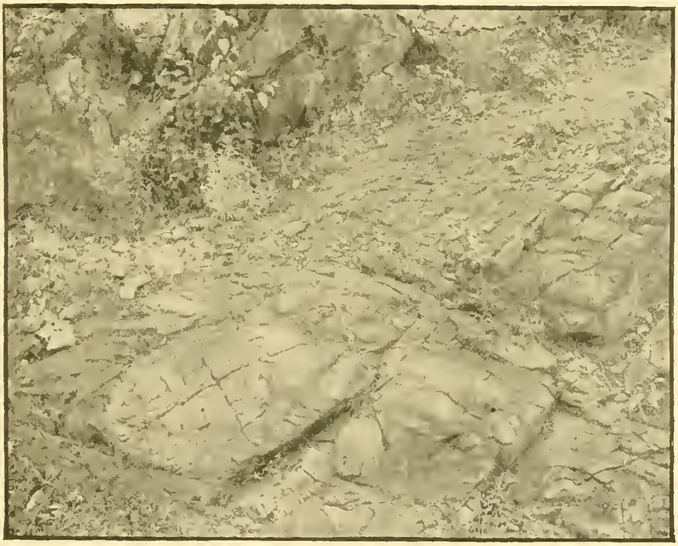

FIG. 11.—Basal conglomerate of Wewe slate, from near center of sec. 22, T. 47 N., R. 26 W.

members there are all gradations to graywackes, novaculites, and slates. The slates in places contain pebbles or bowlders of many kinds, and thus become slate-conglomerates. In the higher part of the formation the slates and graywackes pass by interstratifications and gradation into the Ajibik quartzite.

The ordinary detritus of the formation differed from very fine mud to coarse, sandy mud, and there were frequent alternations of the various phases. As the result of the compacting and modification of these beds we have shale, slate, novaculite, and graywacke. The color of these rocks varies from red to black, with various shades of buff and brown, depending upon the quantity and condition of the iron oxide. While many minor alternations occur, one part of the Wewe formation may be as a whole finer-grained than another part. For instance, at the exposures in the southeast part of sec. 13, T 47 N., R. 26 W., the black, finer-grained phases of the slates occupy a higher horizon than the coarser, novaculitic-looking phases.

As a consequence of the folding, certain of the slates, and especially those that are fine-grained, have had developed in them a slaty cleavage. Also, along the zones of sharpest folding and of mashing, the rocks pass into mica-slate, or even into a rock approaching a mica-schist. In some cases they approach knotenschiefer in appearance. As a consequence of the slaty cleavage and schistosity, in many ledges it is difficult to determine the true strikes and dips. However, the true bedding is usually indicated by frequent alternations of darker and lighter colored materials. Often parallel to the bedding are cherty-looking layers, which frequently have a lenticular character, the oval areas lying end to end, with intervening slate, or overlapping. When followed closely, they are found in places to cut in a minor way across the bedding. Often they branch into two or more parts, or send out stringers into the slate. In other cases the cherty or quartzose layers follow the schistosity rather than the bedding. Finally, the slates and graywackes are usually cut by numerous veins running in all directions. A close examination shows that whether these cherty parts follow the bedding or the schistosity, or cut the rock at random, they are secondary infiltrations.

In many places the orogenic movements have been so powerful as to shatter the rock through and through (fig. 12, p. 263, and Pl. IX, fig. 1), or even to produce breccias (fig. 13, p. 263, and Pl. IX, fig. 2), the fragments of which are in some places tolerably well rounded by dynamic action, so as to form pseudo-conglomerates. The fragments vary in size from minute ones to great blocks several feet in diameter. The shattered rocks have been cemented by vein quartz, jaspery quartz, and hematite, sometimes one and sometimes two or three together (Pl. IX, fig. 1).

PLATE IX.

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PLATE IX.—BRECCIATED WEWE SLATE.

FIG. 1. Shattered Wewe slate from the NE. ¼ sec. 21, T. 47 N., R. 26 W. (Atlas Sheet XXXII). The cherty slate was shattered by a first movement which opened cracks in various directions. These were filled with secondary quartz. The rock was again shattered, and the openings thus formed were filled by secondary quartz, limonite, and hematite. Besides this shattering there was movement between the individual mineral particles, which granulated the rock. In the interspaces between the particles chert and hematite were deposited. By observing the figure closely innumerable minute brilliant flecks of the latter may be seen. Natural size.

FIG. 2. Brecciated Wewe slate from the same locality as fig. 1. The orogenic forces locally shattered the rock into a rubble. The broken fragments were cemented by secondary quartz, which in the figure occupies as much space as the material of the original slate. In some places the slate fragments themselves are broken along two regular sets of planes inclined to each other, which doubtless in each case represent shearing planes, both sets being produced simultaneously, just as in the case of building stone crushed under the testing machine. That these sets of planes do not intersect each other at right angles is doubtless largely explained by the structure of the slate, which controlled to some extent the direction of fracture and thus prevented the breaking from always occurring along the maximum shearing planes. After the rock was brecciated and cemented as above described, a later movement again slightly shattered it. The cracks thus formed, running through slate fragments and matrix alike, are filled with secondary silica. As in fig. 1, the slate fragments are impregnated with secondary hematite. Natural size.

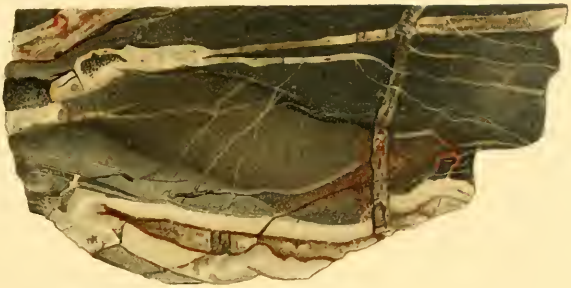

FIG 1

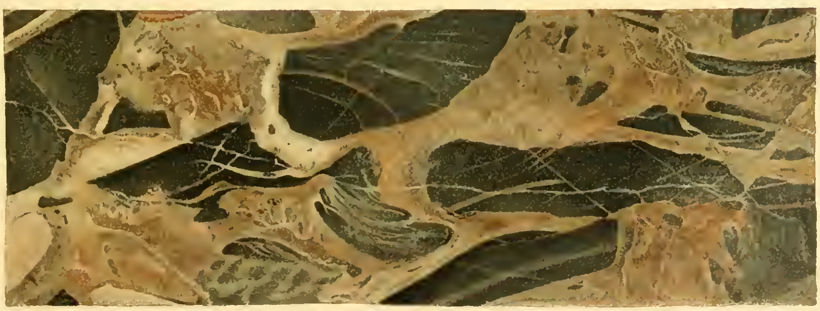

FIG. 2

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FIG 1. SHATTERED WEWE SLATE.
FIG. 2. BRECCIATED WEWE SLATE.

At one exposure the veins of hematite are later than the white quartz, and the jasper is later than the hematite; and some of the fragments have around them, in concentric parallel zones, quartz, hematite, and jasper, although even at this place the quartz entirely fills some of the spaces. Where the veins of hematite and jasper are of considerable size they can not be discriminated from the hematitic jasper of the iron-bearing formation. In places the amount of hematite is so great in the breccia that the material has been prospected for ore. The secondary character of the jasper and hematite in the case of these breccias can not be doubted, and this has a bearing upon the origin of the jasper and hematite of the iron-bearing formation. These breccias are discriminated from true

FIG. 12.—Shattered slate cemented by vein quartz, from NE. ¼ sec. 21, T. 47 N., R. 26 W.

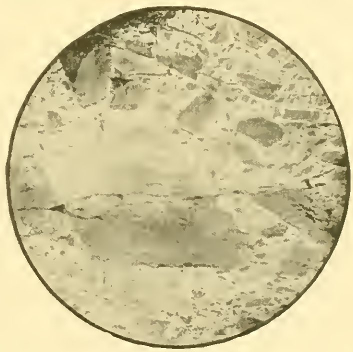

FIG. 13.—Brecciated slate cemented by vein quartz, from same locality as fig. 12.

conglomerates by the fact that all of the fragments are derived from the slate. Also, the breccias vary into slate by imperceptible stages, both along the strike and across it; and finally, while many of the fragments have been rounded so as to resemble those produced by water action, others have an irregular character which is not consonant with a water origin.

Microscopical.—The main varieties of rock discriminated in thin section are basal conglomerates and quartzites, graywackes, novaculites, slates, and slate-conglomerates.

The quartzites and conglomerates differ from each other only in that the conglomerates have large fragments. In other words, the conglomerates have a quartzite base. The complex fragments found in the conglomerates in each locality are predominantly of the particular rock immediately subjacent, but with these are fragments derived from other sources. These fragments comprise white mashed granite, described on p. 220 as sericitic quartz-schist; white mashed granite containing large crystals of feldspar; pink granite; gneissoid granite; a peculiar, very feldspathic pegmatite; fine-grained chloritic schist or gneiss; sericite-schist or gneiss; quartz pebbles; and other varieties of rock. All of these pebbles show dynamic effects. Many of them have been broken and cemented by finely crystalline and secondary quartz. Microcline cleavage is also developed in the potash-feldspars. The quartz grains uniformly show undulatory extinction; many of them are distinctly fractured, and these fractures are in some grains according to a rectangular system. The quartz pebbles are found to consist of intricately interlocking or closely fitting, roundish granules of quartz, but in no case do any of these distinctly show a fragmental character, and they are believed to have been derived from granite or from vein quartz. The chloritic and sericitic schists and gneisses have in some cases, at first glance, a fragmental appearance, but the more closely they are studied the more do they appear to be completely crystalline rocks. To describe the fragments of the conglomerates in detail would be a repetition of the description of the rocks of the Basement Complex.

The quartzite or quartzite background of the conglomerates contains an abundant, very finely crystalline groundmass of sericite, kaolin, and quartz, with a little chlorite, and is often impregnated with iron oxide. In this groundmass are simple and complex grains of quartz and less abundant grains of the various feldspars, and as the rocks become coarser-grained these pass into the complex areas composed of quartz and feldspar. The groundmass of these rocks and that of the fragments contained in them are the same, and the structure is somewhat similar to the mashed gneissoid granites or sericitic quartz-schists of the Archean. (See p. 220.) Also, many of the simple and complex quartz grains have a granitic appearance, having been but little waterworn; but some of the grains show a distinct waterworn character, and they are rarely enlarged. In the quartzites there are usually alternating layers of finer and coarser material, while in the gneissoid granite the laminæ are all alike. The recomposed rocks contain a much larger amount of secondary iron oxide than the schistose granites, and in the folding they have been more broken, thus producing distinct cracks and minute cavities, which have become filled with finely crystalline, secondary quartz. The thin section thus enables us to discriminate the recomposed rocks from the original, mashed, gneissoid granite. Many of the feldspars of the quartzites are sufficiently fresh to show distinctly their twinning, but all of them are more or less kaolinized. Frequently the feldspars have largely or wholly decomposed into a complex, interlocking, finely crystalline mass of sericite and quartz, chlorite and quartz, biotite and quartz, or combinations of these. In an intermediate stage there is with these residual feldspar. Often during or subsequent to this decomposition much secondary iron oxide has entered, and in these cases we have in place of the feldspar grains an interlocking mass of iron oxides, quartz, and sericite.

By a change in the character of the groundmass and a decrease in the size of the fragmental grains the quartzites pass into the graywackes. The same constituents are present in the groundmass of the latter as in that of the quartzites, but chlorite is abundant, and intermingled with the groundmass are very small fragmental grains of quartz and feldspar, and frequently a large amount of secondary iron oxides, chiefly hematite and magnetite, often with distinct crystal outlines. In some cases a film of oxide of iron is around each of the individual grains of quartz. In the background, as the rocks become mashed, the leaflets of sericite and biotite have a tendency to a parallel arrangement. The coarser quartz grains uniformly show undulatory extinction or fracturing, frequently according to a rectangular system. The smaller quartz grains, where buried in an abundant matrix, and therefore not pressed against one another, are freer from these pressure effects, and in some of them pressure effects are not seen at all. The quartz grains are much more frequently enlarged than in the basal quartzites. The feldspars, while often rather fresh, show all phases of decomposition to sericite, biotite, or chlorite, and to quartz with iron oxide impregnation, described in the conglomerates.

By a decrease in the size of the coarser fragmental grains the graywackes pass into the slates. In these slates the decomposition of the feldspar grains, because of their smaller size, is much more common. On account of the more plastic character of the slates, there is frequently developed in them a slaty cleavage or schistose structure, the ordinary cleaved slates passing into mica-slates, and occasionally into sericite-schists. In passing from the less mashed to the most mashed phases there is an increase in the regularity of the arrangement of the sericite leaflets in a uniform direction. As in the graywackes, the rocks are usually impregnated to a greater or less degree by iron oxide, and frequently very heavily so. The iron oxide includes limonite, hematite, and magnetite, the two latter often being in large part in well-defined crystals, and sometimes in veins. Frequently the slates consist of layers of differing degrees of coarseness, sometimes a half dozen fine and coarse laminæ being observed in a single section. In these cases the coarser bands are more likely to be heavily iron-stained, the accommodations apparently having formed cracks and crevices to a greater degree than in the interlaminated finer and more plastic layers.

The slates and graywackes at times become conglomeratic, so that whole exposures are slate-conglomerate, or else the conglomerate layers are interstratified with the ordinary slate and graywacke. These slate-conglomerates bear exactly the same relation to the slates and graywackes that the basal conglomerate does to the quartzite—that is, there are pebbles and bowlders in the slate or graywacke background. These pebbles and bowlders are identical in lithological character with those of the basal conglomerate, but, upon the whole, they are better rounded. In certain places the later movements which these slate-conglomerates have undergone have brecciated them, so that with the water-rounded fragments are apparent pebbles of slate and graywacke. A close examination of these in the field, and especially in thin section, shows that they have angular forms and are clearly produced by the brecciation of the rock itself. This occurrence was particularly confusing, as the rock is an undoubted conglomerate, and yet a conglomerate which is partly autoclastic.

The novaculites are similar to the slates and graywackes, except that they are largely composed of very small, rounded grains of quartz and fewer of feldspar, of a somewhat uniform size, with a very sparse matrix of sericite, kaolin, and ferrite. In the field these uniformly granular fine-grained rocks were not discriminated from the secondary chert veins and layers, but in thin section they are wholly different, having the grains distinctly rounded and not closely fitting, and having the sparse matrix above described. The cherty material, upon the other hand, consists of finely granular, perfectly fitting quartz, free from the clayey constituents, and where iron oxide is present, it is usually concentrated to a greater or less degree in bunches or layers, rather than uniformly disseminated between the particles, as in the novaculites.

The quartzites, interstratified with the higher members of the formation, are in all respects like the Ajibik quartzites hereafter described.

The graywackes, slates, and novaculites, as has been indicated (pp. 260–263), have frequently had developed in them a slaty cleavage or schistose structure, and have been broken through and through by dynamic action. As a result of this, crevices and cracks have formed parallel to the bedding, parallel to the secondary structures which intersect the bedding, in directions independent of either of these, and between the individual particles of the rocks themselves. These cracks and crevices have been largely cemented by finely crystalline, perfectly fitting grains of quartz, which in hand specimen has a cherty appearance. In other places coarsely crystalline vein quartz has entered. During the readjustments cracks have largely formed parallel to the bedding, and secondary cherty layers have formed in this direction. In hand specimen, in some cases, they might be regarded as truly interbedded layers, but when examined in thin section the secondary character of this vein chert is undoubted. This is shown by the fact that within it are fragments of the original slate, and also from these apparent quartz bands smaller veins of cherty quartz ramify, cutting the slate in all directions. Moreover, as examined in hand specimen, these cherty-looking layers often have a lenticular character, the oval layers lying end to end or overlapping. In one case, where the secondary coarsely crystalline quartz is present, we have the clearest evidence of two separate movements, since the crystalline quartz shows undulatory extinction and fracturing, sometimes according to the rectangular system. When the rocks have not only been broken but interior movement has occurred throughout their mass, the entering quartz has taken advantage of all of these spaces, thus recementing the rock (Pl. IX). In some cases, in the background of the slate, this secondary quartz seems to be almost as plentiful as the original material, occurring in little oval, complex areas, in minute stringers ramifying through the coarser veins, and in single individuals between the fragmental constituents. While the cementing of the shattered rock has been mainly a process of silicification, it has been indicated that a large amount of oxides of iron has also entered. In some instances these oxides of iron are the main constituents of the cementing material, but usually they are subordinate to the secondary quartz. Where both are present they are not uniformly intermingled but are more or less concentrated in irregular areas or bands. As another result of the shattering of the rocks, the layers have been faulted in a minor degree.

In an extreme stage of fracturing the rocks pass into genuine autoclastic rocks or reibungsbreccias. In some of these the angular fragments of the slate are separated by reticulating veins of coarsely crystalline quartz, finely crystalline chert or jasper, and hematite (fig. 12, p. 263, and Pl. IX, fig. 1). In other cases the secondary material makes a continuous ramifying mass, within which are complex bands and fragments of the original slate or the separated individual grains (fig. 13, p. 263, and Pl. IX, fig. 2). The extreme stages of brecciation more usually occur in the graywackes, the finer-grained phases being more plastic and yielding more readily to pressure, and thus developing into slates and schists. In some of the coarser graywackes the relief appears to have occurred along zones of irregular width, and here the grains have been loosened from one another. These zones are indicated by abundant iron impregnation, and are sharply separated from the layers at the sides, which have not suffered so much from movements.

No better case is known to me of the phenomena characteristic of the zone of combined fracture and flowage[1] than is exhibited by the Wewe

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part 1, 1896, pp. 601–603, 654–656.

slate. The softer layers were at one time certainly in the zone of flowage, and under these conditions cleavage developed in the normal planes. Later some of these slates passed into the zone of fracture for them, and a fissility secondary to the cleavage formed along shearing planes. The stronger rocks exhibit beautifully all the phenomena characteristic of deformed rocks in the zone of fracture.

RELATIONS TO ADJACENT FORMATIONS.

In all the exposures north and east of Goose Lake the inferior formation is the Kona dolomite. This dolomite generally pasess upward into the slate by a gradual disappearance of the calcareous material. The lower and central portions of the formation are pure slates or graywackes. In some cases the basal horizon of the slate, or the upper horizon of the dolomite, is a chert-breccia, undoubtedly of dynamic origin, but resembling a conglomerate (Pl. VII, fig. 2). Such breccias may be well seen at the contact between the slate and the Kona dolomite in the southeast part of sec. 13, T. 47 N., R. 26 W. (Atlas Sheet XXXIV). The slate at this particular locality becomes coarser-grained in passing toward the base, grading first into a novaculite, then into a graywacke, and then into a brecciated, cherty quartzite. The chert-breccia at the contact appears to have been produced from secondary belts of chert, which have appeared within, and perhaps have replaced calcareous layers in the quartzite. When the rock was folded the brittle cherty layers were broken into fragments. This pseudo-conglomerate might possibly be taken by a careless observer as evidence of a physical break between the Kona dolomite and the Wewe slate.

Southwest of Goose Lake (Atlas Sheet XXXV), below the slate, are islands of Archean rocks. It has been said that here conglomerates have an extensive development adjacent to the Archean cores. In sec. 23 T. 47 N., R. 26 W., and near the central part of sec. 22, T. 47 N., R. 26 W., contacts are exposed between the Archean and the conglomerates, but no contacts were seen adjacent to the area in the southern part of the SW. ¼ sec. 22, although large exposures of conglomerate were found near those of the granite.

At the west, southwest, and south of the western bluff of the Archean of sec. 23 the basal conglomerate is well exposed in direct contact with the underlying crystalline rocks. At the west foot of the hill is a solid ledge of the white, mashed, schistose Archean granite. It is in contact with and mantled on both sides by the conglomerate, which is mainly composed of material exactly like the original rock. The fragments and matrix of the conglomerate so closely resemble the granite that its recomposed character scarcely shows—so intensely mashed is the rock—except upon the weathered surface, where may be seen rounded, protruding fragments of the granite, varying in size from small ones to great blocks. In passing eastward along the south slope of the bluff the white granite of the Basement Complex takes on a different character, here being less altered, and containing pink augen of the original feldspar. In the field, as well as from microscopical study, it is plain that it is a mashed granite. Adjacent to this granite the conglomerate contains predominant pebbles of a corresponding kind. As further evidence of this unconformity, the white and pink mashed granite is cut through and through by veins of red granite, which are nowhere observed to cut the conglomerate.

The contact is again seen in the valley to the south, where the recomposed rock on a little ridge projects east as an arm into the area of the Archean. Here the conglomerate has not been so much mashed. The sparse clayey matrix is stuccoed with fragments of the red granite and the white, kaolinic quartz-schist (mashed granite) from the Archean. Many of these macroscopically closely resemble chert. The conglomerate appears also to contain fragments derived from a slate or graywacke. The upper part of the conglomerate contains, besides pebbles of granite and gneiss, many pebbles of white quartz, some of which macroscopically appear to be derived from a quartzite; also rare pebbles of chert and jasper, and many of a slaty or schistose rock. The matrix, usually white or pale-green, is ordinarily slate, graywacke, or quartzite, but oftentimes it is so fine-grained as to have a novaculitic appearance.

In sec. 22 also the actual contact between the gneissoid granite Archean axis and the conglomerate is seen. Here are magnificent exposures of great bowlder conglomerates, the granitic fragments of which, of varying sizes, are close together, so that there is but a sparse matrix. In some cases this recomposed rock so closely resembles granite that it is with difficulty that its true character is certainly determined. In cases of doubt, however, the weathered surface enables one to distinguish between the original and the recomposed rocks, as here the granite fragments protrude from the face of the conglomerate. This granite stucco varies up into slate-conglomerate of differing degrees of coarseness, and finally slate is found containing only small pebbles of granite. In some cases, in the finer conglomerate, the particles of the recomposed rock are almost wholly single grains of quartz and feldspar, or are small complex grains of granite. These show a laminated arrangement, and in the hand specimen the recomposed rock (Pl. X, fig. 1) very closely resembles the original gneissoid granite. As higher horizons are reached the slate and slate-conglomerate pass up into feldspathic quartzites, novaculites, slates, and graywackes of various hues, similar to those in sec. 23, and finally above them appear the pure vitreous quartzite of the Ajibik formation. In a number of places the actual gradations are seen, and the formation line between the two is somewhat arbitrarily drawn.

THICKNESS.

On account of the complicated character of the folding of the slates, graywackes, and conglomerates southwest of Goose Lake, it is impossible to give even an approximate estimate of the thickness of the formation. Here, adjacent to the shore-line, it is natural to expect it to have a greater thickness than to the eastward, and it is believed that the thickness is very considerable. In sec. 22 (Atlas Sheet XXXV) there are almost continuous exposures of the slate, all apparently north of the northernmost anticline, and all dipping 50° to 60° the same way for a breadth of 1,300 feet. This would correspond to a thickness of about 1,050 feet. To this would necessarily be added the thickness of the conglomerate, which should appear below the slate and graywacke. This area is, however, near the northern end of a northwest-southeast anticlinal dome, and the slate shows much brecciation, well-developed slaty cleavage, and, when studied closely, numerous minor rolls; so it is entirely possible that the real thickness of the formation is not more than a third of the above estimate. In the east part of secs. 13 and 24 (Atlas Sheets XXXIV, XXXV), where there are numerous rolls of the slate and quartzite, a close examination showed that there is probably exposed a thickness of slates not exceeding 100 feet. At the numerous exposures in secs. 5, 6, 7, and 8, T. 47 N., R. 25 W. (Atlas Sheet XXXVII), there is little opportunity for an accurate estimate of the thickness. The calculated thickness west of Goose Lake is probably a maximum, and that east of Goose Lake may be considered a minimum. The average thickness of the formation may perhaps be as much as 500 feet.

INTERESTING LOCALITIES.

Makwa Hills.—Beginning at the north and west, the first locality in which the Wewe slate may be present is in the quartzite range north and east of Teal Lake (Atlas Sheet XXX). In the center of the quartzite formation is a belt of slate, which is probably equivalent to some part of the Wewe slate to the east, but with what part it should be equated it is impossible to say. In passing from this place toward the east there are no exposures for several miles. The belt is, however, supposed to persist, but to lack exposure because of its feeble resistance.

Eastern area.—At the eastern end of the great westward-plunging syncline occur numerous outcrops of this formation (Atlas Sheets XXXVI and XXXVII). The exposures here are for the most part found along the small streams and on the Carp River, the cutting action having been sufficient to remove the overlying drift. The rocks have a slaty cleavage, but the bedding is usually determinable. In the southeast part of sec. 31 the rocks strike east and west and dip south. In the east part of sec. 5 the strikes are mostly north and south, and in sec. 6 they are again approximately east and west, thus following the folding. In the SE $\frac{1}{4}$ sec. 6, along and near the Carp River, are the best exposures. The slate south of the river is here overlain, with a slight discordance, by the Ajibik quartzite. The character of this break will be discussed later in connection with that formation. Lithologically the slates vary from very fine grained argillaceous rocks to coarse graywackes. In color the nonferruginous phases grade from gray or greenish-gray to black. Many of them are, however, heavily ferruginous, and these are dark-red, bright-red, or brown. In some cases the amount of hematite is so considerable that test-pitting has been done. In many of the coarser-grained black slates are seen numerous fragmental particles of mica, the leaflets being generally arranged parallel to the bedding. Certain of the black slates have a carbonaceous appearance, and in these is seen very abundant iron sulphide in innumerable small crystals.

West of the exposures in this vicinity none are found along the Wewe belt for 2 miles. In secs. 11 and 12, T. 47 N., R. 26 W. (Atlas Sheet XXXIV), however, occur typical exposures of the slate, separating the Kona dolomite below and the Ajibik quartzite above, and thus showing that the belt is persistent.

Goose Lake.—The next exposures of the formation are those about Goose Lake. The first locality which presents exceptional interest is in the NE. ¼ sec. 24 and the SE. ¼ sec. 13, T. 47 N., R. 26 W. (Atlas Sheets XXXIV and XXXV). At this place there are continuous exposures of the slate from the Kona dolomite below to the Ajibik quartzite above. This exposure has a large number of minor rolls, with strikes approximately east-west or south of east, and with axes plunging to the east or south of east at angles from 10° to 20°.

At the bottom of the formation, or at the top of the Kona dolomite, is a chert and novaculite breccia, many of the chert fragments being rather well rounded by movement. It was at first thought that this was a conglomerate, and that possibly there was a break between the Kona dolomite and the Wewe slate (Pl. VII, fig. 2). This breccia grades up into interlaminated fine-grained gray and felsitic-looking red novaculites and graywackes, these into red and black slates, these into black slate, and this, by numerous interstratifications, into the Ajibik quartzite. An estimate of the thickness of the various beds between the Kona dolomite and the Ajibik quartzite is as follows: Novaculite and graywacke, 30 to 50 feet; red and black slates, 25 feet; black slate, 10 feet; interstratifications of slate and quartzite, 15 feet; thus making a maximum thickness of 100 feet. On account of the complicated folding of the beds, it was difficult to make the determinations at all accurate, as the same layer is reproduced in exposure several times.

Beginning at the north and at the bottom of the exposures, the limestone plunges under the novaculite with a dip of 50° to the south. In passing toward the south, while the same layer, as has been said, may be repeated by the folding, on the whole higher and higher members appear. The whole is a part of an east-of-south-dipping stratum, which, however, is itself bent into a number of secondary folds. If one sights along the axes of the folds toward the west, he sees that the slate will rise above the Kona dolomite, the same as it does where the two are in contact to the north.

The folding of the Wewe slate and Kona dolomite in this vicinity is almost an ideal case, illustrating the types of folds and observations to be made in districts of complex folding. The use of topography, tops of anticlines, bottoms of synclines, and the pitch of one set of folds to obtain the dips of the cross set are all shown.[1]

The movements of the Wewe slate have produced a cleavage—in certain places something of a schistose structure, and in the novaculitic layers, as has been said, a breccia. The pseudo-conglomerate at the bottom of the formation was at first supposed to be a true conglomerate, and was thought to mark a possible unconformable break between the slates and the dolomite (Pl. VII, fig. 2). The strata were, however, found to be strictly conformable, and the chert and novaculite fragments dynamic rather than waterworn pebbles. Traced along the strike, the autoclastic rock gradually passes into the continuous layers. It appears probable that the fine sand at the base was interstratified with calcareous layers, that the carbonate was leached out and replaced by chert, and that when folded the rock was broken. As further evidence that this rock is a pseudo-conglomerate, the novaculites higher in the formation at many places have been broken through and through in a similar manner and changed into breccias, the fragments of which are cemented by secondary cherty quartz. In the more argillaceous rocks a slaty cleavage has everywhere developed, which sometimes passes into partial schistosity. These phenomena are

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 626-631.

particularly marked in those layers interstratified with the Ajibik quartzite, the cleavage and schistosity stopping abruptly at the quartzite beds. Many of the brecciated slates and novaculites are heavily ferruginous, the iron being largely concentrated in veins. The extensive dynamic phenomena shown by the formation about Goose Lake, and the complicated folding of the slates, would seem to indicate that in the general folding of the district the major accommodations and readjustments necessary have occurred mainly in the weak slate rather than in the strong Kona dolomite below or the Ajibik quartzite above.

An examination of the thin sections confirms the field observations. While the fragmental character of the coarse slates is perfectly distinct, the numerous roundish fragmental grains being very apparent, each individual shows undulatory extinction or fracturing, as a result of the great deformation. In proportion as the rocks are fine-grained, recrystallization has gone on, some of them becoming sericite-schists, which at first sight might not be thought to be fragmental. There is abundant evidence of extensive deposition of silica and iron oxide, these materials being present both as veins and in the background. No complete description of the slides will be given here, as they are similar to the other slides of the formation in the general area of Goose Lake, and a description of these is given at a previous place (pp. 265–269).

Wewe Hills.—West of Goose Lake (Atlas Sheets XXXII and XXXV) occur the most extensive exposures of the formation. The positions of ledges actually observed are given on the detailed sheets, but these by no means represent all of the exposures, but merely those which have been examined.

Along and adjacent to the shore of the southwest arm of Goose Lake there are almost continuous exposures of mica-slate, graywacke, and novaculite, from the old charcoal kilns nearly to the southeast end of the lake. The rocks here are slaty or schistose, brecciated and cherty—in short, in most respects are similar to those in secs. 13 and 24 above described.

The most interesting exposures of the formation are those on the Wewe Hills about the Archean islands in secs. 22 and 23. Here are found at a number of localities great basal conglomerates, which pass up into the slate and graywacke, with occasional interstratified conglomeratic phases. The first and largest of these islands is that near the center of sec. 23. This is an oval area, with its greater diameter in a northwest-southeast direction. It is almost entirely surrounded by abundant exposures of the Wewe formation, but those of the greatest interest are along the southwest border. Just north of the quarter line is a great basal conglomerate, in contact with and resting upon a white schistose granite microscopically resembling quartz-schist. The fragments and matrix of the conglomerate are almost wholly from the granite, and the rock is so firmly cemented that fresh fractures break across the matrix and pebbles, so that its recomposed character scarcely shows, except upon the weathered surface. Where weathered, there may be seen well-rounded fragments of the granite, from those of small size to great bowlders, protruding from the matrix. A thin belt of this conglomerate mantles the granite for some distance along the brow of the bluff, and here, besides the white granite, are also found fragments of granite bearing pink feldspar crystals and fragments of red granite. The matrix of the conglomerate is an ordinary quartzite. In the core area the pink feldspar-bearing granite was found associated with the white granite, and the red granite cuts both.

A short distance south of the quarter line of the section, on the southwest slope of the bluff, great exposures of conglomerate are again found in contact with and immediately adjacent to the granite. Here, on close examination, it is perfectly clear where the schistose granite ends and the schistose conglomerate begins. The latter varies from a coarse conglomerate, bearing abundant granitic débris, to a fine-grained conglomerate in which the fragmental particles are mainly single quartz and feldspar grains. This conglomerate in its upper part is interlaminated with slate and graywacke phases. As a consequence of the intense folding to which the rock has been subjected, it has become brecciated, so that with the genuine detrital fragments derived from the granite are also angular to subangular fragments of the slate and graywacke.

Farther to the southeast is a small creek, and across this to the southwest, on the slope of a great bluff, is again found the sericitic schistose granite, which is directly overlain by conglomerates containing pebbles of the underlying rock. This conglomerate is interlaminated with ferruginous slate and graywacke. Here, as at the first locality, it is difficult to determine certainly the exact point at which the recomposed rock ends and the schistose granite begins.

As has been explained above, this area is a northeastward-dipping isoclinal fold. These conglomerates and slates therefore appear to dip under the gneissoid granite on the southwest side of the area, and to dip away from it on the northeast side. Superimposed upon the major fold are minor corrugations. As a consequence of this, just south of the quarter line of sec. 23 a tongue of quartzite projects into the granite area to the southeast, so that a section here passes from the Wewe slate to the granite, then to the Wewe slate, then to the granite, and finally to the Wewe slate.

These folds are cross folded, and consequently pitch either to the southeast or to the northwest, and the gneissoid granite plunges under the slate, and is thus an isolated area. The intense mashing has produced in the original granite, as has been said, a strongly marked schistose structure, so that the original white granite has been transformed to a rock which resembles a quartz-schist. In a similar way the detrital rocks have been subjected to mashing, with a consequent development of a crystalline structure, so that it would not be surprising if the whole were regarded as a conformable series, dipping to the northeast. However, in working along the contact carefully, the conglomerates and the occasional localities in which the demarcation between the Wewe formation and the Archean is clear show that the slate is later than, and is composed of, the broken granitic material.

The Wewe slates, both to the northeast and to the southwest of the Archean area, grade upward by interlaminations into the Ajibik quartzite, just as east of Goose Lake. Here, as there, the placing of the boundary line between the two formations is somewhat arbitrary, the rock being regarded as belonging to the slate where the slaty phases are predominant. This passage of the slate into the quartzite on the southwestern part of the bluff, because of the overturning of the strata, occurs in going from apparently higher to lower members. The upper phases of the Wewe slate are peculiar iron-stained novaculites.

An examination of the thin sections enables one to discriminate with great certainty between the schistose granites which have taken on the character of kaolinic quartz-schists, and the conglomerates. In the most mashed phases of the granite, the feldspars have been entirely decomposed, the broken granitic quartzes resting in a kaolinic, sericitic, and siliceous background. In the conglomerates, while many of the complex fragmental grains have a distinct granitic appearance and are much affected by dynamic action, the waterworn character of some of them is distinct. Also the conglomerates have alternating layers of finer and coarser material, while the laminæ of the granite are all alike. Finally, the recomposed rock has allowed more secondary iron oxide to enter than the granite.

In the center of sec. 22 are a few outcrops of the Archean basement, which together form an oblong area. West of this area, making up the larger part of a considerable ridge, are great outcrops of conglomerate. The great bowlders and smaller fragments of granite and gneiss are so thickly set in a sparse matrix as to form a stucco. This conglomerate, as seen upon the glaciated surface, presents the most magnificent example of a basal conglomerate known in the district (fig. 11, p. 259). At one place in this conglomerate occurs a small exposure of the gneissoid granite which is surrounded on all sides by the conglomerate.

The fold here is again an isoclinal anticline, the strikes being about northwest-southeast and the dips to the northeast. Also the fold is cross folded, so that from the crest it plunges to the northwest and to the southeast. In going to the northeast or southwest from the center of the bluff one passes to higher horizons, although the dips are continuously to the northeast. The exposures to the southwest are more nearly continuous, and here the coarse conglomerate is seen to vary into fine conglomerate, this into coarse feldspathic graywacke, and this into slate, there being, however, various interstratifications of these materials. The coarse feldspathic graywacke—that is, the phase which is made up mainly of the constituent minerals of the granite—takes on at times a gneissoid appearance which is remarkably similar to that of the original gneissoid granite making the center of sec. 22 (Pl. X, fig. 1). In fact, at first they were not discriminated in the field. and were regarded as the same. A study of the thin sections,

PLATE X.

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PLATE X.—WEWE SLATE AND SIAMO SLATE.

FIG. 1. Recomposed rock, resembling granite, from the Wewe slate near the center of sec. 22, T. 47 N., R. 26 W. (Atlas Sheet XXXV). The specimen is taken from near the base of the formation. The underlying Archean rock is granite. The discrete mineral particles of the granite form the detritus of the figures. These, when cemented, produced a rock very similar in appearance to a gneiss. Indeed, in the hand specimen it is almost impossible to discriminate this rock from true gneissoid granite of the Archean, but in thin section the fragmental character of the specimen figured is in strong contrast with the completely crystalline character of the gneissoid granite. The recomposed rock has been somewhat broken by dynamic action, and along the cracks veins have formed. Natural size.

FIG. 2. Ferruginous Siamo slate, showing overthrust fault, from the top of the formation in sec. 35, T. 48 N., R. 27 W. (Atlas Sheet XXVII). The specimen is cut diagonally across the bedding, so that the layers appear to be wider than they really are. The finely laminated, greenish-gray portion is typical of the less altered varieties of the Siamo slate. At the bottom and top of the formation this material is frequently interlaminated with iron-stained layers, and the figure shows a typical case of this kind. Though the ferruginous bands approximately follow the bedding, they cut across it in such a way as to show that, while the percolating waters were controlled in a large way by the bedding, to some extent they went across it. A study of the thin section shows that the ferruginous layers usually develop where there was originally siderite. In one of the gray bands an overthrust fault is beautifully shown. This has sharply broken the harder, more siliceous layers and has carried with it the weaker layers between the harder ones. However, both above and below, the fault passes into a flexure. The specimen was evidently in the zone of combined fracture and flowage, the readjustment of the harder layers being by fracture and that of the softer layers by flowage. This fault, although on a minute scale, illustrates perfectly how a major fault may disappear below by passing into a flexure. Natural size.

FIG 1

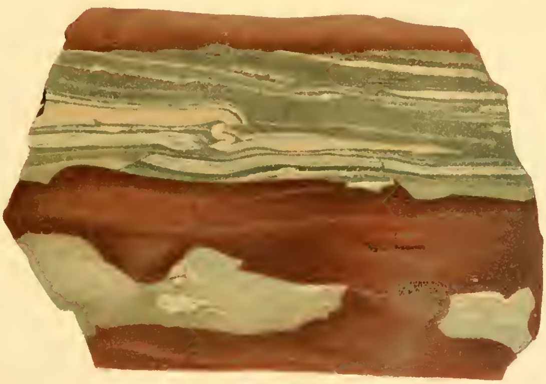

FIG 2.

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FIG 1 RECOMPOSED ROCK, RESEMBLING GRANITE, FROM WEWE SLATE
FIG. 2. FERRUGINOUS SIAMO SLATE, SHOWING OVERTHRUST FAULT

however, shows the completely crystalline character of the one and the recomposed character of the other.

Northwest of this conglomerate bluff, making another considerable set of bluffs in the northwest part of sec. 22 and the northeast part of sec. 21, are the typical cherty and brecciated Wewe slates and graywackes. Consequent upon the northwest plunge of the fold, the higher members are found on the southwest, northwest, and northeast sides of the exposures, the coarsely conglomeratic phases being limited to the southeastern hills, though distinctly conglomeratic phases occur at higher horizons. The slates, graywackes, and novaculites, their cleavage and foliation, their brecciation, silicification, and ferrugination (figs. 12 and 13, and Pl. IX) are very similar to those phenomena described in the ledges east of Goose Lake, in secs. 13 and 24. Parallel to the bedding are either cherty or novaculitic layers, which are traversed by veins of quartz. The usual strike is N. 15° W. to N. 40° W., and the dip at an angle of 50° to 60° north of east. The bedding is usually cut by a foliation, which strikes about N. 50° W. and has a vertical dip. The breccias are more extensively developed in the locality under consideration than anywhere else. Many of the ledges are traversed in all directions by veins of white quartz, but the majority of these are parallel to the schistosity. Near the northwest part of the exposures, on one of the more prominent bluffs, the extreme stage of dynamic action is represented by a remarkable reibungsbreccia. The fragments are all of the black slaty or cherty rock. They vary in size from minute ones to great blocks several feet in diameter. The whole is recemented mainly by vein quartz, but in part by hematite and jaspery quartz. The veins of the latter are later than the white quartz veins, and where of some width the bands of ore or jasper could not be discriminated from the ferruginous jasper of the Negaunee formation. This breccia differs from a true conglomerate in that the cementing material is of a vein character, the fragments all of one kind, and usually exceedingly angular. The black and gray schist, set in the quartz veins and ornamented by the specular hematite and red jasper in smaller quantity, makes the exposure a beautiful one. The fragments of schistose slate often have around them parallel zones of quartz, hematite, and jasper, although usually the quartz is alone. Between the brecciated slates and those in which there is merely a development of slatiness or schistosity, with secondary ferrugination and silicification, there are all gradations, so that there is positive proof of the brecciated character of the rocks.

About the other two Archean islands in secs. 22 and 23, are interesting exposures of conglomerate, slate, and graywacke, but as these are not very different from those already mentioned, they will not be further described. The conglomerates, slates, and graywackes are particularly well developed about the corner between secs. 21, 22, 27, and 28, and also to the east and northwest of this point.

SECTION IV.—THE AJIBIK QUARTZITE.

The formation is given the name Ajibik quartzite because the predominant rock is quartzite, and because typical exposures of it occur on the bold Ajibik Hills northeast of Palmer (Atlas Sheet XXXII).

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Beginning at the south arm of Goose Lake (Atlas Sheet IV), the formation occupies a broad belt, which narrows in sec. 23, swings south of the Wewe slate, and then gradually increases in width to sec. 28, T. 47 N., R. 26 W. From this place one arm extends to the west for nearly a mile, but the main arm swings to the north, west of the Wewe slate, and then east, north of the same formation. West of Goose Lake the belt again becomes broad, and an arm projects to the southeast between two Archean islands, being bounded on both the east and the west by the Wewe slate. The main belt, reaching Goose Lake, extends north of this area for a mile, then swings eastward, which course it follows for 2 or 3 miles, then swings to the northeast to Carp River. Here it is faulted, but, reappearing again north of the river, it continues its course east, then north, then west in sec. 6, T. 47 N., R. 25 W. It follows this western course to the quartzite range east of Teal Lake, the southern part of which it constitutes. West of Teal Lake it reappears, here being in contact with the Archean, and follows along this formation to Lake Michigamme.

South of the Negaunee formation, in sec. 35, T. 47 N., R. 26 W., there appears a quartzite, placed with the Ajibik quartzite, which extends westward almost continuously to sec. 31. The belt here swings to the north, northeast, north, and finally west again, about an anticline in the Archean, and then extends in a general westerly course to sec. 20, T. 47 N., R. 28 W.; thence northwest to near Humboldt, in sec. 12, T. 47 N., R. 29 W. Exposures of quartzite reappear at the base of the Lower Marquette series on both sides of the Republic and Western tongues. It is doubtful whether this western part of the quartzite is really the time equivalent of the remainder of the Ajibik quartzite. Throughout the district it is natural, almost inevitable, that at the base of the sedimentary series there should have been deposited a conglomeratic quartzite. It is therefore not impossible—indeed, it is probable—that the westward part of this belt of quartzite belongs, in age, with the lower part of the Siamo slate as developed to the east, rather than with the Ajibik quartzite. However, as this quartzite constitutes a continuous lithological formation, and as there is no basis upon which to make the equation, and as above it there occur the representatives of the Siamo slate, at least as far west as sec. 28, T. 47 N., R. 27 W., the whole formation is here considered.

On account of the resistant character of the quartzite, at various places it becomes one of the chief topographic features of the district. South of the southeast arm of Goose Lake the bold quartzite exposures rise steeply from the lake, and from the sand plain to the east and south. The series of ledges composing the quartzite belt are almost continuous to the westward, everywhere rising abruptly from the valley to the south, and in secs. 27, 28, and 29, T. 47 N., R. 26 W., the quartzite constitutes the Ajibik Hills, a bold east-and-west ridge, with precipitous, south-facing exposures. This ridge rises about 200 feet from the valley of Ajibik Creek. On the north side the ridge falls away less steeply to the exposures of the Siamo slate. While this ridge has the general features above given, in a smaller way it is exceedingly rough, a north-and-south traverse ascending precipitous bluffs, to almost immediately descend into a steep ravine, the other side of which must be climbed but to repeat the performance As has been said, in sec. 28 the ridge branches into two parts, one of which extends west about a mile. The main belt swings to the north into sec. 21, T. 47 N., R. 26 W. Here there are again numerous huge ledges of the quartzite. Following along the course of the belt to the northeast, between secs. 22 and 23 there are again numerous large exposures. Continuing to the north, the formation has a position between the Wewe slate and the Siamo slate. The quartzite, being the more resistant rock, occupies the higher lands, between lower lands to the south and to the north. In the valley of Carp River the outcrops are, however, less numerous than to the southwest, although sufficiently abundant to show that the belt is certainly continuous to sec. 36, T. 48 N., R. 26 W. From this point exposures are not abundant until the quartzite east of Teal Lake is reached, where again they are numerous. From this place they extend almost continuously along the ridge to sec. 33, T. 48 N., R. 27 W. From here west to Michigamme the outcrops are not abundant, but are found at a number of places close to the Archean.

Where the formation appears south of the Negaunee iron formation, in secs. 34 and 35, T. 47 N., R. 26 W., there are ledges of quartzite and conglomerate. West for some distance the topographic features are given by the Archean to the south and the jaspery iron formation to the north, so that the quartzite usually occupies a valley between these two formations, but with frequent exposures in secs. 31, 32, and 33. West of the Volunteer mine the formation appears as a conglomerate below the iron-bearing member. In sec. 30, to the north, there are a number of large and typical ledges. West of this place the quartzite is again in the valley between the Archean to the south and the iron formation to the north, there being only a few outcrops. The rock is found facing the granite near the center of sec. 28, T. 47 N., R. 27 W., and somewhat unusual slaty phases, interbedded with amygdaloids, are found near the top of the formation in secs. 27 and 28. Several exposures are found in sec. 19, west of which are no outcrops until the vicinity of Humboldt is reached, where exposures are again found south of the iron formation. The remaining outcrops are considered in Chapter IV.

FOLDING.

The topographic features and the exposures are closely dependent upon the folding to which the quartzite has been subjected. Beginning south of Goose Lake, the quartzite constitutes an eastward-plunging anticline over the Wewe slate in sec. 23 (Atlas Sheet XXXV). To the north this anticline is quickly followed by a syncline, so that the section from north to south includes a southern anticline and a northern syncline. Following the belt westward, the formation constitutes the southward slope of an anticline, the crown of which is to the north in the area of the Wewe slate and Archean islands. The belt is continuous to sec. 28, T. 47 N., R. 26 W. (Atlas Sheet XXXII), where, still constituting one side of an anticline, it swings northwest and then north. The westward-projecting arm, which runs into the NW. $\frac{1}{4}$ sec. 28 and the NE. $\frac{1}{4}$ sec. 29, is due to a subordinate anticline which springs up on the slope of the main anticline. The greater breadth of the formation in sec. 28 is due to this same cause. The westward-projecting arm is a westward-plunging anticline, so that the quartzite soon disappears under higher formations. In the center of this anticline a small area of Archean appears. The main belt of the formation (Atlas Sheet IV) swings to the northward, thence northeast, thence east to Carp River, and thence north and west to Teal Lake. This main belt is thus a part of the great westward-plunging syncline of the eastern half of the district, dipping to the north along its southern arm, to the south along its northern arm, and to the west at the eastern end of the syncline.

West of Teal Lake (Atlas Sheet XXVII) the regularly bedded, typical quartzite in the lower horizons is found to be somewhat plicated, then more plicated, and finally very closely plicated into a series of minor cross folds, with axes plunging sharply to the south, following the general dip of the formation.

In secs. 30 and 31, T. 48 N., R. 28 W., and in sec. 25, T. 48 N., R. 29 W., the quartzite swings to the north, and here the characteristic folding of the district is well illustrated (Atlas Sheets XV and XVIII). The formation is infolded in the most complicated fashion with the granite and gneiss of the Archean, the whole being a set of isoclinal overfolds with southern dips. The fragmental rock occupies the valleys and the granite the elevations. These valleys open out to the west and close to the east, the granite thus forming amphitheaters about the quartzite. This is due to the fact that the south-dipping isoclinal folds have a steep westward pitch. As a result of this complex folding, an island of granite appears surrounded by the Ajibik quartzite in sec. 30, and another island of granite occurs within the Siamo slate above the quartzite in sec. 31. Consequently, the north-south subordinate rolls are of sufficient size to form at the anticlines islands of granite within the sedimentary rocks.

Running southeast between the Archean area of sec. 23 and the Archean area of sec. 22, T. 47 N., R. 26 W. (Atlas Sheet XXXV), is a northwestward-plunging syncline of the quartzite, making an arm projecting from the main area. This belt may extend farther than mapped and connect with the belt to the south.

With the exception of a single swing about the Archean anticline in sec. 30, T. 47 N., R. 26 W. (Atlas Sheet XXXII), the southern belt of quartzite has a general northward dip away from the Archean and under the iron formation. The exposures in secs. 27 and 28, T. 47 N., R. 27 W. (Atlas Sheets XXVI and XXIX), when cursorily examined, appear to have a uniform northward dip, but when examined closely the upper members of the formation, which are here slates, are found to be pressed into a sharp set of overfolds with northern dips. These folds are not horizontal, but plunge steeply (Pl. XXXV, fig. 1). Accompanying these minor rolls are, doubtless, major rolls. This is indicated by the fact that interstratified with the slate are apparently three belts of amygdaloid; but as the rocks of these belts are all exactly alike, and as amygdaloid is absent elsewhere in the formation, it is more than probable that this is the same lava flow, reduplicated by the northward-dipping overfolds. In the Republic tongue and in the tongue to the west the Ajibik quartzite is in a closely compressed syncline.

PETROGRAPHICAL CHARACTER.

Macroscopical.—The Ajibik quartzite has two main areas—a western one, in which it rests directly upon the Archean, and an eastern one, in which it is underlain by the Wewe slate (Atlas Sheet IV). This difference is fully explained in another connection by the transgression of the sea from the east. The Ajibik area in contact with the Archean extends west from the Teal Lake quartzite range on the north, and from sec. 35, T. 47 N., R. 26 W., on the south, to the west end of the district. Also there is here included the area in sec. 29, T. 47 N., R. 26 W. The eastern area comprises the remainder of the formation.

Where the formation rests directly upon the Archean its basal part is a conglomerate or recomposed rock, the material of which is derived mainly from the immediately subjacent rocks. In short, the conditions of formation are the same as, and the phases of the basal rock identical with, those of the Mesnard quartzite, described on page 223. This is entirely natural, as the two are in fact but parts of the first deposit of the transgressing sea. The basal conglomerates, slates, and graywackes for this part of the area quickly grade up into quartzite which does not differ from that of the remainder of the formation.

In the eastern part of the district, as the Wewe slate passes into the Ajibik quartzite there is usually an intermediate phase, or interstratifications of the two. In many places the slate varies into a coarse graywacke, this into a feldspathic quartzite, and this into the ordinary quartzite. In other cases the transition phase is a white or green novaculitic quartzite. With these are sometimes red and brown iron-stained kinds. In places the nonferruginous and ferruginous varieties show the most curiously complex relations, one appearing in the other in the most indiscriminate manner, as if in extremely irregular inclusions or patches. The iron staining is evidently a secondary process, and the differing effects have been produced by the varying depths to which the solutions have penetrated. In one exceptional locality, in sec. 6, T. 47 N., R. 25 W. (Atlas Sheet XXXVII), the basal member of the quartzite is a conglomerate interstratified with slate, the fragments of the conglomerate being mainly from the Wewe slate.

The central part of the formation in its ordinary phases is a typical, rather pure, vitreous quartzite. In some places this quartzite becomes conglomeratic and bears small pebbles of white quartz or red jasper. In other places it is interstratified with belts of mica-slate or graywacke. In many places the formation was subjected to dynamic forces. In the least-marked stage of alteration the quartzites were simply broken to a greater or less amount, and the crevices thus formed were cemented with finely crystalline cherty quartz, or with oxide of iron, or both. In a further stage of the process the quartzites were fractured through and through, and in places they pass into reibungsbreccias. In the numerous ramifying, branching, and intersecting cracks, silica and iron oxide infiltrated. The silica in places took on cherty or jaspery forms, and in other places it crystallized as a vein quartz. The secondary material may locally be so abundant as to compose a large part of the rock, and rarely considerable belts of chert or vein quartz and iron oxide may be seen. In proportion as the fracturing and the amount of secondary cherty silica increase, the rocks assume a peculiar vitreous aspect. The iron oxide crystallized as hematite and magnetite, the latter now largely changed to martite.

In their very general brecciation, with consequent considerable areas of pseudo-conglomerates, in the secondary veining, both with coarsely and finely crystalline quartz, and in the large quantity of secondary hematite and magnetite, these quartzites differ from the Goodrich quartzite of the Upper Marquette series. Apparently in some cases the brecciation was produced before the rocks became thoroughly indurated, while the fragments had a sandy matrix, in which case the individual grains were broken asunder, and the whole has been indurated by secondary infiltrating silica and iron oxide. In some localities very peculiar dynamic effects are observable. As a consequence of the folding a most curious spheroidal fracturing has occurred, resulting in roundish pebble-like and bowlder-like forms. Iron oxide has infiltrated along the cracks, and has especially affected the more fractured and broken matrix, so that the spherical pieces appear like pebbles derived from a different rock. In the most brecciated phase we have a pseudo-conglomerate consisting of white spheroids of quartzite in an iron-stained quartzite matrix; a close examination shows, however, that many of the supposed pebbles are not entirely surrounded by the matrix, each being really attached at some place to it. Following along the pseudo-conglomerate belt, we pass from this most conglomeratic-looking phase to that in which there is less and less dynamic effects, and the rock by gradation passes into the ordinary quartzite of the area. In an intermediate phase, while conchoidal fractures are seen, they do not wholly separate different parts of the rock, so that what would have been separate fragments had the fractures gone further are but a half or a third separated from the quartzite background. The most extremely alterated quartzite, instead of being brecciated, was mashed throughout, and as a result passed into a biotitic or muscovitic quartz-schist, or into coarse, completely crystalline, typical chlorite-schists, biotite-schists, and muscovite-schists.

In the northern and eastern parts of the district the quartzites grade upward by interstratifications into the Siamo slate. In the southern and southwestern parts of the district the formation grades in a similar manner into the nonfragmental Negaunee iron formation. In secs. 27 and 28, T. 47 N., R. 27 W., the intermediate phases are slates like those of the Siamo formation.

Microscopical.—Where the Ajibik quartzite rests upon the Archean, and therefore has a conglomerate or feldspathic quartzite at its base, it is very similar to the basal conglomerates of the Mesnard quartzite and Wewe slate described on pages 224–227, 263–265. The basal rock in some places is a distinct conglomerate, and in others is composed mainly of the separate mineral constituents of the adjacent underlying rocks. At many places the basal horizon has been so much mashed as to pass into a crystalline schist. In these places, instead of the conglomerate, we have chloritic, sericitic, biotitic, or muscovitic schists, and in the most extreme stage of alteration the rocks pass into typical mica-schists, the leaflets of biotite and muscovite being of large size and having a parallel arrangement. In this phase the quartz grains are wholly granulated: the new quartz which has developed is similar in appearance to the granules; and the original feldspar is wholly decomposed, its place being taken by the muscovite, biotite, and secondary quartz. In certain of the schist-conglomerates, while the matrix is completely crystalline, in hand specimens the mashed and greatly elongated conglomerate pebbles may still be recognized.

Where the formation underlying the Ajibik quartzite is the Wewe slate, there are apt to be interlaminated with the lower horizons of the quartzite, biotitic and sericitic slates and graywackes which are in every respect similar to those described (pp. 265–269) under the Wewe formation.

In the purest and least mashed phase of quartzite the rocks are composed almost wholly of rounded grains of quartz of somewhat uniform size, which are beautifully enlarged, the enlargements filling the entire interspaces. But even in this quartzite the grains uniformly show undulatory extinction, and some of them are distinctly fractured. Where the dynamic effects are somewhat stronger, between and in connection with the enlargements of the quartz grains there is a fine mosaic of independent interstitial quartz, and with this there is a beginning of the arrangement of the grains with their longer axes in a common direction. Very frequently the fractures of the grains pass directly across the cores and the enlargements, showing that the fracturing occurred after the second growth of the quartz grains. Occasionally with the simple quartz grains there are finely complex grains of quartz, which appear to be derived from chert. In a phase intermediate between the quartzites and the graywackes there is present with the quartz a greater or less amount of kaolin, sericite, and chlorite. In some cases these become rather abundant, so that the rocks are chloritic or sericitic quartzites. Not infrequently the quartzites are feldspathic, and in some cases this mineral has undergone to a greater or less degree the usual decomposition into mica and quartz, or into chlorite and quartz. Where the decomposition is complete, in place of the round grains of feldspar we have an interlocking mass of sericite and quartz, biotite and quartz, or chlorite and quartz, as the case may be. At one place the feldspar grains are as distinctly enlarged as the quartz grains. The quartzites usually contain a small amount of iron oxide, which marks the cores of the original quartz grains and is intermingled with the new quartz.

In the quartzites where the dynamic forces were still stronger the individual grains of quartz are broken apart, or the rock is fractured through and through, or even changed into a reibungsbreccia. In the larger crevices and cracks is vein quartz or iron oxide—in some one alone, in others the two together, although the quartz is more abundant. These veins in some cases are coarsely crystalline quartz; in others they are finely crystalline, cherty, or jaspery quartz, and with either of these are iron oxides. These ferruginous chert and jasper veins often have the iron oxide and the quartz arranged in bands or irregularly distributed, and the veins are exactly similar to the jaspilite of the Negaunee formation. Often the vein material is mingled with fragmental quartz, the grains having been broken from the rock and fallen in the crevices. Where the individual grains of the rock were sundered, the parts were cemented by the secondary quartz and iron oxide exactly as were the larger spaces. The recognizable original grains of quartz show strong dynamic effects, all of them giving undulatory extinction, and many of them being broken into several individuals, or even wholly granulated. In some cases the cracks are in two sets at right angles to each other, the cracks of each set having a parallel arrangement. The areas in which the grains were rent asunder and those in which they were not are very irregular, and in the field the first are usually separated from the second by stains of iron oxide. In those cases in which the secondary quartz is abundant and the primary quartz was granulated, so that it no longer has a clastic appearance, we have an intricately interlocking mass of quartz grains of various sizes in which the original material can not be discriminated from that which has come in later. In some places the whole rock is composed of small, closely fitting granules of quartz. The granulated material is commonly finer or coarser than that of the interlocking and intersecting veins, and in the latter iron oxide is usually abundant. These rocks, in which the evidence of fragmental origin has disappeared, and yet which do not have a schistose structure, are called quartz-rocks. All of these phases are so similar to the jaspilite of the Negaunee formation that the two could not be separated in thin section. However, these extremely altered rocks are traced into those which are less modified, there first appearing a few distinctly clastic grains, then clusters of them, until we have an intermediate variety in which perhaps half of the section shows fragmental quartz buried in a crystalline matrix.

Resulting from the differing modifications of the original sandstone, we therefore have in the formation quartzite, cherty quartzite, ferruginous quartzite, ferruginous cherty quartzite, quartz-rocks, quartzite-breccia, vein quartz, vein chert and jasper, and other phases.

The rather peculiar autoclastic rocks which resemble quartzite-conglomerates were mentioned in the macroscopical description. The pebble-like areas, which were believed to be due to spheroidal fracturing, are clearly shown to be of this character in the thin section. Instead of having smooth exterior boundaries, as would be expected in waterworn pebbles, there are minute irregularities, such as would be produced by fracturing. The spheroids are found to be pure vitreous quartzites, which are wholly cemented by the enlargement process, or, more rarely, by this combined with finely crystalline, interstitial quartz. These pebble-like areas rest in a background composed of quartz grains, which are set in a matrix composed of finely crystalline quartz, iron oxide, and sericite. It is apparent that the individual grains of this part of the rock were broken apart, and thus allowed the secondary materials to enter, whereas in the uncrushed pebble-like areas the space was fully occupied. It is clear that before this rock was brecciated it was indurated by the enlargement process.

In the macroscopical description a locality was mentioned where the lowest horizon of the Ajibik quartzite bears slate fragments. Here the lower beds consist of interstratified slates, graywackes, and conglomerates, which quickly pass up into ferruginous quartzite, and this into the ordinary vitreous rock. The slates are composed of interstratified coarse and fine materials, which differ chiefly from each other in that the coarser layers contain numerous large fragmental grains of quartz, usually simple, but sometimes complex, and sometimes cherty. The matrix is clayey material, so fine that it is difficult to determine the constituents, but sericite, quartz, chlorite, feldspar, and ferrite are present. The conglomeratic layers also bear fragments of the underlying Wewe slate. However, these fragments when closely examined are seen not to be sharply outlined, as is usual with ordinary pebbles, but are greatly elongated and have minutely irregular borders, the projections of which fill the interspaces of the quartz grains. This suggests that the underlying slate was not much indurated at the time it yielded the fragments to the quartzite, being rather a compacted clay than a solid rock.

For those parts of the area where the Ajibik formation is overlain by the Negaunee iron formation the lower formation grades into the higher, or beds which belong lithologically in the two formations are interstratified. In passing from the lower to the higher formation; where the lowest rock of the Negaunee formation is jasper, the change takes place by the dying out of fragmental quartz and the appearance of hematite, magnetite, and finely crystalline quartz; where the overlying formation is grünerite-magnetite-schist, the minerals which appear are magnetite, grünerite, and often garnet. Occasionally the intermediate phase is a ferruginous slate, like the transition horizon of the Siamo and Negaunee formations. In the southwest part of the area—that is, in the Republic and Southwest tongues—the folding and consequent mashing were so severe as to transform the Ajibik quartzite formation into a completely crystalline schist. Even the pure quartzitic phases now show no distinctly fragmental grains of quartz, but consist mainly of coarsely crystalline interlocking quartz, in which are small amounts of grünerite, garnet, chlorite, biotite, and muscovite. In some cases the chlorite developed from the grünerite and garnet. While the quartz grains show undulatory extinction and fracturing, the dynamic effects are not so great as would be expected, and the appearance of the section strongly suggests that the rock was largely recrystallized. Where the sandstones were less pure there developed from them coarse-grained, typical biotite-schists, muscovite-schists, and chlorite-schists, often garnetiferous. In these rocks we have a somewhat uniformly granular quartzose background, through which developed the biotite, muscovite, and chlorite. There is a tendency for the micaceous minerals to be concentrated into layers, the less micaceous zones perhaps corresponding to the original, more quartzitic laminæ. Occasionally the quartzose bands have a distinct oval or lenticular character, as if each represented a greatly mashed and granulated quartz pebble. The mica bends around these areas, joining at their ends, thus presenting a mesh-like appearance, but differing from a mesh in that the leaflets of mica do not intersect. In some of the slides the biotite, muscovite, and chlorite are all in large blades with a parallel arrangement. In other cases the sericite is in part in innumerable minute leaflets. In certain of the chlorite-schists the chlorite leaflets are minutely puckered by the folding in some places, and in other places the stress has been relieved by minute faulting diagonal to the schistosity. Thus we have a cleavage in one direction parallel to the schistosity and a fissility diagonal to this. By a dying out of the micaceous element and the appearance of grünerite and magnetite these schists pass into the Negaunee formation. In some cases there are interstratified typical biotite-schists and grünerite-magnetite-schists. These biotite-schists are ordinarily, however, strongly garnetiferous. The garnet, as usual, developed in large individuals, which include very numerous granules of quartz. Where the garnet appears the biotite is very sparse, so that we have a ramifying background of biotite and quartz, in which are large garnet individuals, including quartz and a small amount of biotite. In the schist-conglomerate south of Republic the matrix is a completely crystalline mica-schist, and in their shapes and relations to the matrix the mashed granite pebbles are similar to the quartz areas just described.

RELATIONS TO ADJACENT FORMATIONS.

For the part of the belt running from Goose Lake to near Teal Lake the quartzite occupies a place between two slates. It was suggested that the mud of the Wewe slate began to deposit because by the upward building of the limestone the waters became too shallow for limestone formation. A continued shallowing of the water may have gone on by the upbuilding of the slate until it became so shallow as to permit the waves to carry coarse-grained sand, when the sandstone was deposited which was indurated later into the Ajibik quartzite. In places it may be that local elevations occurred, raising the mud above the water, so that when the waves next overrode it, it yielded fragments of compacted mud to the basal horizon of the quartzite. This is indicated by the fact—discovered by Mr. A. E. Seaman—that in sec. 6, T. 47 N., R. 25 W. (Atlas Sheet XXXVII), south of Carp River, the quartzite, with a conglomerate at its base containing slate fragments, rests with slight discordance upon the slate. Also interstratified with the quartzite for a few feet from the base are thin belts of conglomerate which bear fragments of slate identical in character with the slate below. To account for the full thickness of the sandstone, it is supposed that subsidence, if interrupted at all, soon began again. After a time it appears that the rate of subsidence was greater than the rate of upbuilding, so that following the sand deposits there was another time of mud deposits. Further indicating such a subsidence is the fact that above this shale followed the nonfragmental iron-bearing formation. In the eastern part of the district the quartzite grades above into a slate, and below it rests upon another slate.

In the area west of Goose Lake the Wewe slate, as has been said, appears to grade up into the Ajibik quartzite, in many places the boundary line between the two being somewhat arbitrarily placed.

In the quartzite range in sec. 29, T. 47 N., R. 26 W. (Atlas Sheet XXXII), the quartzite rests immediately upon the Archean, the Wewe slate not appearing between the two, as is the case to the eastward. This is explained by the fact that the transgression of the sea was from the east, but it is not impossible that the lower part of the quartzite is really the equivalent of the upper part of the Wewe slate, sand being deposited near shore at the same time that mud was being deposited offshore.

East of Teal Lake, supposing the slate belt in the middle of the quartzite to belong with the Wewe slate, there is a transition from the slate upward into the quartzite. West of Teal Lake it has been seen that the inferior formations of the Lower Marquette series were not deposited, and therefore that the quartzites rest directly upon the Archean. In the petrographical description it has been indicated that here basal conglomerates occur. North of the west end of Teal Lake, and at various places for a few miles west, the actual contacts between the quartzite and the green schists, greenstone-conglomerates, and amygdaloids of the Archean are found. One of the best localities at which to observe this contact is just north of the west end of Teal Lake (Atlas Sheet XXVII). Here the green schist strikes approximately east and west, and its schistose structure dips at a high angle—75° to 80°—to the south. However, the contact of the quartzite and schist dips but 55° to the south, so that the fibers of the schist abut against the contact plane at an acute angle (fig. 14). Above the contact plane is a genuine basal conglomerate, the pebbles of which are mainly derived from the schist, but with which are also large pebbles of quartz, some of them 8 or 9 inches in greatest diameter. Besides the green schist and quartzite pebbles, there are also present abundant pebbles of a more acid schist which is like the acidic schists occurring in the Northern Complex north of the stone quarry at Carp River. There can be no doubt that here the green schist had become foliated and was deeply truncated before the deposition of the overlying conglomerate.

At several localities for a half mile west of Carp River contacts are also found between the quartzite and the green schist. The quartzite near the contacts is intensely plicated, but wherever an opportunity could be found to get at the junction a sharp contact between the two rocks was invariably discovered. In only one place was the plicated quartzite found in any other position than on the south slope of the schist. Here it wraps around the east end of a small knob of schist, and is found on the north side with its typical characters. This occurrence is probably explained by regarding the green-schist knob as a headland projecting somewhat diagonally off from the old shore-line, and therefore giving a bay in which the detrital material could be deposited behind the schistose rock. When the two were later upturned to their present inclination the tilting would result in the distribution described.

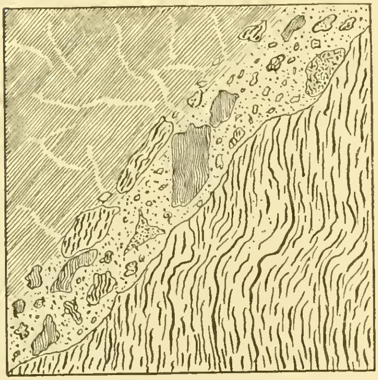


Fig. 14.—Ajibik quartzite resting unconformably upon Kitchi schist.

At various localities east of Teal Lake (Atlas Sheet XXX) the quartzite is found to be in contact with the green schist. This may be particularly well seen just west of the road running north from Negaunee and east of the gorge of the Carp River. The relations are, however, essentially the same as at the Carp and west of Teal Lake, with the exception that east of the gorge there has been such intense movement near the contact plane that the basal rock has become a schist-conglomerate which closely resembles the much mashed green schist of the Northern Complex. It is difficult to say exactly where the green schist ends and the schist-conglomerate begins. In discriminating between the fragmental and igneous rocks the microscope is frequently of considerable assistance. The igneous character of the green schist in its typical form is plain, while the fragmental character of the quartzite is equally evident; but close to the contact even the microscope fails to discriminate between the igneous rocks and the intensely metamorphosed fragmental rocks. We have, then, an apparent transition between the green schists and the clastic rocks just above, as we have an apparent gradation between the Mesnard quartzite and the granite-gneiss south of Marquette. In both cases, however, the conglomerates along the contact, in areas in which dynamic action was not so severe, reveal the true nature of the relation, and show that the downward gradation is secondary, and is not evidence of a single continuous series with downward progressing metamorphism.

The contacts east of Teal Lake may belong rather at the base of the Mesnard quartzite than at the base of the Ajibik quartzite, as has been explained above, but the connection between them and the contacts west of Teal Lake is so close that their description was deferred to this place. Whatever their correlative position, all of the contacts along this belt of conglomerate mark the advance of a shore-line, from the east toward the west.

The intricate structural relations which obtain between the quartzite and granite in secs. 30 and 31, T. 48 N., R. 28 W., and in sec. 25, T. 48 N., R. 29 W. (Atlas Sheets XV and XVIII), have already been described. Here, along the irregular dividing line, the contacts between the two rocks are found at numerous localities. In many cases the lowest horizon of the quartzite is strongly conglomeratic, the pebbles of the conglomerate being derived mainly from the immediately subjacent granite. These conglomerates at the contacts show conclusively that the granite is older than the quartzite and was deeply denuded before the deposition of the latter formation. However, at many places so close has been the folding and so great the movement along the contact plane that the quartzite has become a quartz-schist, closely resembling the mashed granite. Further, the secondary schistose structure in the granite and that in the quartzite are parallel, and this structure is particularly prominent just at the contact of the two rocks. Here again, if one considered only certain localities, the phenomena might be regarded as an indication of the downward gradation by progressive metamorphism of the quartzite into the granite, or the explanation might be given that the granite is intrusive within the quartzite. However, if the contact be followed throughout its various windings, and the phenomena carefully studied, the only conclusion which can be reached is that the quartzite is a newer formation which has derived its detritus in largest measure from the underlying formation. West of sec. 25 only one contact between the granite and quartzite has been discovered, but the latter near the granite at a number of places becomes feldspathic in character, indicating the derivation of its material largely from the subjacent granite.

The southern belt of the Ajibik quartzite rests unconformably upon the Archean south of the Cascade range, as shown by the presence of great basal conglomerates, the bowlders of which are derived from the immediately subjacent iron formation. The only actual contact here found is in sec. 35 (see p. 311). As first observed by Wadsworth, the great conglomerate adjacent to the Platt mine, sec. 32, T. 47 N., R. 26 W. (Atlas Sheet XXXII), containing pebbles of granite, basic eruptive rocks, and schists, each identical with the corresponding kind of rock in the Archean to the south, proves the existence of this unconformity. Exactly similar phenomena are found in sec. 34 (Atlas Sheet XXXV), and here the interval separating the basal conglomerate and granite is but a few paces. In sec. 28, T. 47 N., R. 27 W. (Atlas Sheet XXVI), the movements were so great that the conglomeratic quartzite which here occurs was changed into a schist.

The contact relations of the Ajibik quartzite and the Archean seen at various localities strongly suggest that in many cases which have been explained as downward gradation by metamorphism of a sedimentary into a completely crystalline rock, or as sedimentary rock intruded by granite, the phenomena may have another explanation. If the metamorphism in the Marquette district had been so severe as to obliterate the conglomerates which occur at various places, it would have been almost impossible to show that between the Lower Marquette series and the Archean there is a great unconformity.

For the southern belt the overlying formation is the Negaunee, and the Ajibik quartzite or conglomerate grades into this formation by interstratification, there being in some cases a number of distinctly interstratified beds of quartzite or conglomerate and jasper, but always in passing to higher horizons the jasper becomes predominant and the fragmental material of the Ajibik formation disappears. In the northeast part of sec. 28, T. 47 N., R. 27 W., an exceptional transition phase is a ferruginous mica-slate. The character of the usual transition may be well seen at the conglomerates occurring south of the Platt mine, east of Cascade Brook, and south of the Goodrich and Saginaw mines, in sec. 19, T. 47 N., R. 27 W. (See Section VI.)

Along the southern belt the Ajibik quartzite for much of the distance is narrow, consisting of a basal conglomerate alone, or of a basal conglomerate with a comparatively thin belt of quartzite. However, the belt is of variable thickness, this doubtless being due to irregularities of the Basement Complex at the time of the transgression of the sea. While this belt of ferruginous conglomerate or quartzite is placed with the Ajibik, it is probable that much of it really belongs in time to the Siamo slate or to the Negaunee formation, and that this part of the area was above the water during Ajibik time. This is shown to be highly probable by the occurrences in sec. 30, T. 47 N., R. 26 W. (Atlas Sheet XXXII). Here, upon opposite sides of a narrow syncline, directly below the Negaunee formation as mapped, are the Ajibik quartzite and Siamo slate, the former close to the Palmer gneiss. Near a shore was deposited a sandstone, while farther from the shore mud or sandy mud was being deposited. However, as this southern belt is lithologically like the Ajibik quartzite, and the part which belongs in time with the Siamo slate can not be determined, it is all platted as Ajibik.

THICKNESS.

As in the case of the previous formations, it is exceedingly difficult to give any accurate estimate of the thickness of the Ajibik quartzite. As the folding is very complex west of Goose Lake, where the most continuous exposures are, any computation based upon the breadth of outcrop and average dip would be sure to give conclusions far from the truth. In the belt extending north and east from this area there are no continuous exposures with well-determined dips for the entire breadth of the formation. South of Carp River, in secs. 6 and 7, T. 47 N., R. 25 W. (Atlas Sheet XXXVII), there is, perhaps, the best opportunity to make an approximate estimate. Here the breadth of the formation appears to be about 1,200 or 1,300 feet. This, with a dip of 35°, would give a thickness of about 700 to 750 feet. East of Teal Lake (Atlas Sheet XXX) it is perhaps possible to give the maximum thickness of the slate and quartzite from the base upward, but how much of these exposures belongs with the lower formations it is, as has been said, impossible to state If the slate included with the Wewe slate is correctly placed, above this is a breadth of quartzite of 1,000 feet, which, with an average dip of 65°, gives a thickness of about 900 feet.

INTERESTING LOCALITIES.

Michigamme area.—Beginning at the northwest, there are numerous exposures of quartzite just south of the Archean from the west end of the area mapped for 4 miles to the east, that is, to sec. 21, T. 48 N., R. 30 W. (Atlas Sheet V). The rocks here adjacent to the granite are at places feldspathic quartzites, but the ordinary phases are vitreous quartzites, which in some cases are sericitic, in others cherty.

North of the Michigamme mine the quartzite is found directly in contact with a wall of the granite and hanging upon it. The rock is here a coarse, feldspathic, gray or green quartzite. Three feet from the contact is a layer of conglomerate 10 to 15 inches in thickness, which contains pebbles of quartz, the larger of which are coarsely crystalline, but the smaller of which are granulated. In its upper parts the Ajibik quartzite is interlaminated with the Siamo slate, the layers of quartzite between the layers of slate being 1 to 6 inches in thickness

In thin section the quartzite at the base of the formation has a finely crystalline, sericitic, kaolinic, and quartzose background, which contains simple and complex grains of quartz, from those of small to those of large size. Numerous flakes of biotite and blades of chloritoid are present. All of the quartz grains show undulatory extinction or fracturing At high horizons, between the grains of the quartzite there is abundant chlorite and garnet, the outlines of the two minerals having a similar appearance. Certain areas consist in part of chlorite and in part of garnet. The chlorite is apparently an alteration product of the garnet, the latter being the original mineral which developed within the rock. In the layers of quartzite interstratified with the slate the dynamic effects are less marked than elsewhere in the formation of this part of the area, and here the quartz grains frequently show cores and distinct enlargements. The matrix in which the quartz grains are set is similar to that in the quartzite adjacent to the granite. For the major part of the formation in this general area the quartzites are very crystalline. Distinct cores of the original grains are found in only a few of the slides, and in these there is a sericitic background. Apparently when the original sandstones were nearly pure the grains were pressed against one another so strongly as to result in granulation. In the most crystalline phases there is a finely granular, intricately interlocking background of quartz, in which is a small amount of sericite and chlorite. In a less crystalline phase the original quartz grains still exist, but they have been mashed, so that they are arranged with their longer axes in a common direction. As usual, the rocks are cut by veins of secondary cherty quartz.

Broken bluffs.—There are numerous exposures of the Ajibik formation in secs. 30, 31, and 32, T. 48 N., R. 28 W. (Atlas Sheet XVIII). This is the locality, referred to on pages 285–286, where the peculiar infolding of the quartzite and gneissoid granite occurs, the whole series of folds having isoclinal dips and a westward pitch. At many places the quartzite formation is exposed in contact with the granite, and here a conglomerate, bearing numerous quartz pebbles, many large feldspar grains, and occasional small granitic pebbles, is found. In some places the basal rock is a fine-grained feldspathic quartzite, the granite having apparently been disintegrated and broken into its constituent mineral particles. The conglomeratic parts have a feldspathic quartzite base which is similar to the nonconglomeratic phases of the rock. In many places the movement during the folding was so great as to entirely granulate the quartz pebbles, different specimens showing all gradations between coarse, vitreous vein quartz and completely granulated, opaque, sugary quartz. In this mashed phase of the conglomerate little feldspar detritus is seen. If it was originally present it has become decomposed. However, in those phases of the rock in which the pebbles of quartz are transparent and vitreous the large detrital feldspars are abundant. In the intermediate phases the schist background contains numerous roundish but flattened areas of quartz, the rock approaching in its appearance a fine-grained augen-gneiss. Examined in thin section, the quartzites are found to be feldspathic. In the less mashed phases the feldspars have renewed their growth, and they present the best instances of feldspar enlargement in the Marquette district. The pure feldspathic quartzites pass into those which are micaceous and chloritic, the mica and chlorite having largely developed at the expense of the feldspar. These micaceous and chloritic quartzites pass by interstratification or gradation into the mica-schists and chlorite-schists. While in hand specimen these schists appear to be completely crystalline, in thin section rounded grains of quartz still show their fragmental character. The development of biotite and chlorite, with the separation of secondary quartz from the feldspar, is beautifully shown.

Area west of Teal Lake.—North and west of the west end of Teal Lake, in secs. 33, 34, and 35 (Atlas Sheets XXIV and XXVII), there are very numerous and large exposures of the quartzite for a distance of 2½ miles. The underlying rocks of the Archean here belong to the Kitchi formation, this place being, in fact, its typical locality and here occurring nearly all of its peculiar phases. At a number of localities the Ajibik quartzite is found in contact with or close to the Kitchi rocks. In some places at the contact between the two there seems to be only a minor discordance, but a close examination shows that nowhere do the two formations grade into each other. On the other hand, there is always a perfectly sharp contact between them, although Rominger describes the two formations as grading into each other.[1] This mistake is excusable, because the Kitchi formation is here a tuff closely resembling a true water-deposited conglomerate.

Near the north-south quarter line of sec. 34, in a little valley between the quartzite on the south and the green schist on the north, a contact was found between the two formations where the unconformable relations are perfectly clear. This contact has already been described on page 295.

At another locality, west of the wagon road near the west line of sec. 34, the quartzite lies on the south side of the green schist as a mere skin, and here the same unconformable relations are seen as in the center of the section. In one case the plicated quartzite described (pp. 297–298) is found wrapping around the east end and the north side of a small knob of Kitchi schist. This occurrence is believed to be explained by a headland

[1] The Marquette iron region, by C. Rominger: Geol. Surv. of Michigan, Vol. IV, Part I, 1878–1880, pp. 37–39.

projecting somewhat diagonally from the old shore-line into the Ajibik sea, thus forming a bay, and detrital material was deposited upon three sides of the schist. When the two formations were upturned to the north and eroded, the rocks assumed their present relations.

A basal conglomerate grades up quickly into a regularly bedded, southward-dipping, vitreous quartzite, which shows nearly all of the phases characteristic of the formation, including ordinary quartzite, ferruginous quartzite, veined cherty quartzite, quartz-rock, and chloritic quartzite. At one place, at the quarry just west of the Carp River, is a fine-grained conglomerate 6 or 8 inches thick, which holds very numerous fragments of bright-red jasper. These were at first thought to have been derived from the Negaunee formation of the Lower Marquette series, but probably they came from the jasper veins in the Kitchi schist.

West of the Carp River, in passing downward from the topmost layers, where the quartzite is regularly bedded, one finds them becoming somewhat plicated, then more plicated, and finally closely plicated into a series of minor cross folds, with axes plunging steeply to the south. In places near the contact with the Kitchi formation this plication is so sharp that reibungsbreccias have been produced. These are readily discriminated from the conglomerate, as no pebbles are contained in them other than the quartzite pebbles, and because the brecciated phases grade into the nonbrecciated phases along the strike. These brecciated rocks have been cemented by secondary quartz, and by a large amount of oxide of iron, so that they have a strongly ferruginous appearance. Because of their ferruginous and brecciated character they have been thought by some geologists to lie unconformably below the ordinary, regularly bedded quartzite of other parts of the formation. This locality gives, therefore, an excellent illustration of the rapid change from areas where dynamic effects are small to those where they are profound. It is to be noticed that the dynamic effects are greatest at or near the contact with the underlying Kitchi schist. This contact plane was apparently one of weakness, and therefore near it the major readjustments in the folding took place.

In thin section the conglomerate is found to have a wide variety of pebbles, derived from the Kitchi formation. The quartz pebbles in no case prove to be from a clastic rock. There are, however, pebbles of finely crystalline cherty or jaspery quartz. The background of the conglomerate is slate or graywacke, which does not differ in its character from the slates and graywackes of the Wewe formation (described on pp. 265–269), except that a large amount of chlorite has developed, and in some cases hornblende. The quartzites comprise all of the phases described in the general description (pp. 290–291), but the less mashed and nonbrecciated phases are more common, so that in most cases the fragmental character of the rocks is evident at a glance. The purer quartzites are either cemented by enlargement or by enlargement combined with interstitial independent quartz. These purer phases vary into ferruginous, sericitic, and chloritic quartzites, and these, by an increase of the sericite and chlorite, and a decrease in the size of the quartz grains, into novaculites or graywackes. In some places a small amount of interstitial hornblende developed. In places the ledges are cut by quartz veins composed of intimately intermingled and interlocking, finely and coarsely crystalline quartz. The slate and graywacke phases are largely sericite-slates, identical with those of the Wewe formation. Like them, they are in places brecciated, and veined by secondary quartz mingled in places with oxide of iron. In the background with the chlorite there is, in some specimens, a small amount of hornblende.

Area east of Teal Lake.—The largest and most continuous exposures of the formation begin north of the east end of Teal Lake and extend to the Carp River, a distance of about 3 miles (Atlas Sheet XXX). The precipitous bluffs making up this area are known as the Makwa Hills. For the central part of the area the exposures are practically continuous from the bottom of the formation to the top. In many particulars this quartzite is similar to that west of Teal Lake, but it differs from that in being much thicker and in containing many interstratified argillaceous beds. In fact, a large portion of the exposures are slate and graywacke rather than quartzite. As has been explained in the previous sections, it is probable that the lower horizons are really the time equivalent of the Wewe slate, the Kona dolomite, and the Mesnard quartzite. In the atlas sheet the ridge is apportioned between these four formations, each later formation overlapping the preceding, but the whole constitutes such a continuous series of exposures that it has been thought best to describe them together.

As west of Teal Lake, wherever the lowest member of the formation is exposed it is a conglomerate. The pebbles of this conglomerate are mainly of white quartz, but with these are some of jasper. One contact is found a short distance west of the road through the quartzite range running north from Negaunee, at about 1,425 to 1,450 steps N. and 450 to 500 steps W. of the SE. corner of sec. 31. At two places the conglomerate was seen in direct contact with the green schist of the Kitchi formation. The schistosity of the schist is here very nearly parallel to the bedding of the quartzite, and there is no apparent unconformity. At the Carp River section the lower slaty members of the formation have been so strongly mashed as to resemble the green schist below. However, there always seems to be a difference. The schists have great uniformity in appearance, their laminæ being of the same character, while the slates are composed of alternating layers of different characters. Further, the schists break about equally well throughout an entire zone, parting as though they were a mass of parallel fibers, rather than like leaves, as do the slates. Also east of the Carp River the lower parts of the slate are distinctly conglomeratic. Notwithstanding these differences, at one place it is exceedingly difficult in the field to say exactly where the schists end and the slates begin. However, when it is considered that along this same horizon, both at the State road conglomerate to the east and south of the Kitchi Hills to the west, there is the clearest sort of structural break, it can not be doubted that the same is true for this area. As is so frequently the case, the major accommodation took place along the contact plane. The fragmental rock and the Kitchi formation were so mashed that a parallel schistosity was produced in them. Fortunately, while the matrix has become crystalline in the sedimentary rocks, the white quartz pebbles were sufficiently resistant to show their fragmental character.

In a section at the widest part of the ridge, in passing to higher horizons the conglomerate usually varies quickly into a mica-slate, and this passes into the typical quartzites of the formation. South of this quartzite is a belt of red graywacke. In it slatiness and schistosity have developed. The slate is folded into minute crinkles, and in places cross-folded by east-west pressure. It is also fractured, and the cracks and veins are filled with cherty or vein quartz. This belt, on account of its uniform character and schistosity, macroscopically resembles closely the schists of the Kitchi formation. South of the belt of graywacke is a broad belt of reddish and greenish slates, interstratified with occasional beds of quartzite and cherty-looking quartz. In this part of the formation, in a single ledge, black slate, red slate, novaculite, fine-grained red quartzite, and cherty quartzite may be seen regularly interstratified. As a result of the movements, the slates in many places take on a rather crystalline aspect. The whole is usually veined with white quartz and cherty quartz, and altogether the rocks have a very crystalline aspect. At one place a stratum of slate abuts directly against the quartzite to the west, showing that there is here a minor transverse fault.

The southernmost exposures of the formation are in sec. 32, where the belt is the broadest, and they are vitreous quartzites; and here occur peculiar rocks, which at first sight were taken for conglomerates, having a quartzite matrix and quartzite pebbles, the matrix being stained by oxide of iron. When this belt was closely examined the peculiar conglomerate was found to be dynamic. Under the stress to which the rock was subjected it fractured in a spheroidal manner, each of the spheroids at first sight appearing to be a pebble, but close examination shows that many of them are attached at some place to the matrix. This conglomeratic rock, when traced along the strike, is found to become less and less fractured, and to grade into the ordinary quartzite.

The whole set of beds making up the bluffs has a rather uniform dip to the south, the dip perhaps being somewhat higher on the northern side, near the contact with the green schists, than farther south. The dips observed vary between 57° and 70° to the south. It is perhaps possible that the lower bed of conglomerate and quartzite represents the Mesnard formation; the red graywacke, the Kona dolomite; the interstratified slates, graywackes, and quartzites, the Wewe slate; and the upper quartzite, the

Ajibik. If this be true, the three lower formations must one by one die out to the west, each higher formation overlapping the one next lower.

In thin section nearly all of the more altered phases of the Ajibik quartzite, the Wewe slate, and the Mesnard quartzite are found. Their descriptions will not be here repeated.

Eastern area.—The next prominent exposures to the east are in the northern part of sec. 6 and the western part of sec. 5, T. 47 N., R. 25 W. (Atlas Sheet XXXVII). The numerous ledges are very nearly pure quartzites or ferruginous quartzites. None of them are changed into sericitic quartz-schist or into cherty quartzite. The folding to which they have been subjected has merely cracked the rocks, and along these cracks small, secondary quartz and iron oxide veins have formed.

In the southeastern part of sec. 6 and the northern part of sec. 7 there are large exposures of quartzites, which in most respects are similar to those east of Teal Lake. However, in the exposure just south of the Carp River the quartzite is found to rest upon the Wewe slate and to bear fragments of it. Apparently there is a very slight discordance between them. The basal conglomerate is only a few feet in thickness, and quickly passes up into a gray slate, which bears several thin layers of conglomerate. The interstratified slate and conglomerate in turn pass up into interlaminated slate and ferruginous quartzite, and this into the ordinary quartzite. So far as the structural evidence is concerned, the discordance is so slight as to have little significance. The phenomena could be explained by the mud rising above the water for a short time, becoming slightly compacted, and then, when buried beneath the water, furnishing fragments to the overlying formation. Such an occurrence might be extremely local On the west side of this exposure the Wewe slate is found to be faulted against the quartzite. This fault, or another running northwest and southeast, has displaced the quartzite and a small part of the underlying Wewe slate to the southward for a distance of about an eighth of a mile, thus making the quartzites of the south side of the river stand directly opposite large exposures of the Wewe slates of the north side of the river. Apparently the river follows approximately the fault line. An examination of the thin sections of the basal conglomerates, described on page 292, confirms the conclusion that the mud was but slightly compacted at the time it yielded fragments to the Ajibik quartzite. The outlines of the pebbles are minutely irregular, the projections filling the spaces between adjacent fragmental quartz grains and thus contrasting with the clean-cut forms of well-indurated waterworn pebbles.

Large exposures of the Ajibik formation occur in secs. 11 and 12, T. 47 N., R. 26 W., and on both sides of the northwest arm of Goose Lake (Atlas Sheet XXXIV). These ledges are all rather pure, fresh-looking quartzites.

The foregoing series of ledges connecting Goose Lake and Teal Lake are all in the eastern part of the great westward-plunging syncline, where the minor plications are slight. Corresponding with this in thin section, we find the normal phase of quartzite to be the pure enlargement kind, although secondary independent quartz was also deposited in the interstices. While the dynamic effects are slight, nearly all of the quartz grains show undulatory extinction, and many of them are distinctly fractured.

Wewe Hills.—The next large bunch of exposures is in secs. 22 and 23, T. 47 N., R. 26 W. (Atlas Sheet XXXV). The northernmost of these ledges are similar to those just described. The large exposures in the southeastern part of this area constitute a westward-plunging, isoclinal, synclinal fold, and, as a consequence of this, many of the quartzites become sericitic, cherty, and vitreous, and some of them schistose. At certain places along the south border of this set of ledges the rock is a distinct reibungsbreccia which closely simulates a conglomerate. Indeed, this breccia was at first taken for a basal conglomerate resting upon an older rock. A closer examination, however, showed that while many of the fragments have been shattered in a spheroidal manner, many others are angular or subangular, and all are similar to the adjacent phases of quartzite. As usual, these breccias are cemented with vein quartz, cherty quartz, and the oxides of iron. The latter are naturally more abundant in the matrix than in the fragments, thus giving to the former a dark color in which the fragments stand out sharply.

Ajibik Hills.—The next great ledges, mainly in secs. 27, 28, and 29, T. 47 N., R. 26 W. (Atlas Sheets XXXII and XXXV), are the Ajibik Hills, upon which occur the typical exposures of the formation. These are exceedingly precipitous ridges, very rough in detail, the different ledges breaking off with vertical cliffs or with very steep slopes, and each large ridge is made up of many smaller ones. The roughness would hardly be exceeded if the ridges were made by piling up at random a vast number of gigantic blocks, except that the bluffs are somewhat rounded by glacial abrasion. It is difficult to find ridges more fatiguing to cross than these. One is not able to keep his elevation, but after climbing one ridge he is obliged to descend into a steep ravine, only to climb another precipitous slope which rises somewhat higher than the first, to again descend a sharp declivity.

As the formation is directly in contact with the Archean in sec. 29 and rests upon the Wewe slates in secs. 27 and 28, and the folding was locally severe, nearly all phases of the formation are found. In sec. 29 the basal conglomerate is made up of Archean débris. In secs. 27 and 28 we have the transitional variety between the Wewe slate and the Ajibik quartzite. Here in the quartzite are interstratified novaculites, slates, and graywackes. Certain of the quartzites in areas of relief were but little affected by dynamic forces, being ordinary fresh quartzites. Others were fractured extensively in both a major and a minor way, thus producing the veined cherty quartzites. In other places the fracturing went so far as to produce a dynamic breccia exactly similar to breccias in sec. 22 (p. 308). In a number of places also the fracturing resulted in the production of spheroidal-looking fragments, which are set in an iron-stained matrix, thus giving a very conglomeratic appearance. At numerous places in the graywacke-like phases a schistosity developed as a result of the mashing, while in the overlying beds of purer quartzite the pseudo-conglomerates or breccias were produced. We thus have at first sight a vertical schistose rock overlain by a conglomerate which occasionally bears fragments of the schist. The appearance of a structural break was so great that at a first, and even a second, examination it was confidently believed that there was here a great unconformity between a schist series and a quartzite-conglomerate series; but a detailed and close examination left no doubt that the peculiar phenomena were the different effects of dynamic forces in an argillaceous and a nonargillaceous rock—in the first, flowage and schistosity resulting; in the second, shattering. These phenomena are best seen in the NW. ¼ sec. 28, especially along the southwestern slopes of the bluffs; and a still further complication is here found, since apparently the true Archean schist does appear at one place below the quartzite-conglomerate.

It is possible that in the Ajibik Hills there are small areas of the Goodrich quartzite which, as a consequence of the removal by erosion of the Negaunee formation, were deposited upon the Ajibik quartzite. This is suggested by certain little-mashed quartzite exposures, which contain jasper pebbles. But in no case could such suspected later quartzite be certainly discriminated from the Ajibik quartzite; so all are mapped as belonging to the older formation.

To give the microscopical characters of the different phases of rocks on the Ajibik Hills would be practically to repeat the general description (pp. 289–294), as nearly all phases of the formation are here found.

Goose Lake.—Eastward along this belt the next bunch of ledges found is south of the southeast arm of Goose Lake, in secs. 23 and 24 (Atlas Sheet XXXV). The quartzites are underlain by the Wewe slates, and between are the transition forms. The quartzites suffered great deformation, and consequently little-altered quartzites are rare, and the cherty quartzites, quartz-rocks, and quartzite-breccias are particularly abundant. The veins in this area are unusually large and numerous, and they are filled to more than a usual degree by secondary hematite and magnetite. The larger of these veins and the most brecciated phases of the quartzites simulate ferruginous chert or jasper, and the abundance of iron oxide has led to prospecting in a number of localities.

In the northeast part of sec. 24, surrounded on three sides by the Wewe slates, is a great ledge of quartzite, precisely similar to the ledges southwest of Goose Lake. Here, however, are particularly well seen the interstratifications of the slate and quartzite and the different manners in which the folding affected the vitreous rock and the slates. The folded Wewe rocks passed into mica-slates, with a nearly vertical cleavage, which stops abruptly upon reaching the quartzite layers. These quartzites were shattered and cemented by quartz and iron oxide.

Cascade area.—Passing to the southern belt of the Ajibik quartzite, we find numerous exposures at various points from the northwest part of sec. 35 to the west part of sec. 32, T. 47 N., R. 26 W. (Atlas Sheets XXXII and XXXV).

Hanging on the west face of the great ledges in the NW. ¼ sec. 35 is a coarse conglomerate. This conglomerate passes up into the pure vitreous quartzite. The Palmer formation is here a white sericite-schist, cut by granite veins, brecciated, and cemented with coarse vein quartz, cherty quartz, and ferruginous chert or jasper. All of these materials are abundantly found in the conglomerate, and that they are derived from the underlying formation can not be doubted. Farther west along the contact between the Palmer gneiss and the Ajibik formation, in the northeast part of sec. 34 is a great bluff of conglomerate, containing huge bowlders of the white sericitic quartz-schist and chert, and also irregular masses of jasper. A short distance to the south are found huge ledges of the Palmer gneiss. This conglomerate appears clearly to be the basal conglomerate of the Ajibik quartzite. However, it is not positively certain that the conglomerate in sec. 35 may not be the Goodrich quartzite resting upon the Basement Complex, as a consequence of the removal of the Lower Marquette series in the erosion interval between Lower and Upper Marquette time.

Near the line between secs. 32 and 33 a conglomerate again occurs, which grades up into quartzite. South and a little west of the Platt mine, in sec. 32, is found a great conglomerate near the base of the formation, which has been described by Wadsworth. This conglomerate occurs in a precipitous southward-facing bluff, and is a mass of well-rounded pebbles and bowlders cemented by a sparse matrix. About 50 steps south of the conglomerate is a dense, nearly massive, green rock, which is cut through and through by granite veins. In the vicinity other varieties of the Palmer gneiss occur. In the conglomerate the predominant pebbles and bowlders are of rocks identical in character with those found in the Palmer formation just to the south. In the conglomerate there are also quartz pebbles, and its upper parts alternate with layers which approach jasper. In passing to higher horizons the jasper layers become more and more prevalent, until they are predominant. In the conglomerate are no undoubted jasper pebbles, but there are roundish areas of jasper or chert which appear to be secondary concentrations.

A short distance east of the Cascade Brook, in the valley between the Negaunee formation and the Palmer gneiss, is a conglomerate which contains pebbles of many kinds from the Basement Complex, including green schist and sericite-schist, precisely similar to rocks in the Palmer formation at the Brook section. This conglomerate quickly grades up into jasper, there being, however, at many places several alternations of conglomerate or quartzite and jasper before the typical banded jasper is reached. On the west side of the old open pit of the Volunteer or old Cascade mine is a conglomerate which again contains detritus from the Palmer gneiss, but it is rather probable that this conglomerate belongs to the Ishpeming formation, and that the entire Lower Marquette series has been removed by erosion. Adjacent to the center of sec. 30 and to the westward are large exposures of the Ajibik quartzite, and at one place this becomes conglomeratic.

Secs. 27 and 28, T. 47 N., R. 27 W.—A short distance northwest of the center of sec. 28, T. 47 N., R. 27 W. (Atlas Sheet XXVI), on the north side of the exposures, is a knob of quartzite-conglomerate, and south of this, a little farther up the hill, is a white mashed gneiss, which at so many places is the uppermost member of the Palmer formation. In the NW. $\frac{1}{4}$ sec. 27 and in the NE. $\frac{1}{4}$ sec. 28 are ferruginous mica-slates interstratified with amygdaloids. As platted on the ground, there are three belts of amygdaloid. These slates when first examined were thought to have a regular east-west strike and a uniform northern dip. When the ledges were closely examined the slates were seen to be intricately folded into a series of northern-dipping isoclinal folds, the axes of which plunge steeply to the east. A specimen from one of the more open of these folds shows a difference of dip of only 32° between the two legs (Pl. XXXV, fig. 1). While there is everywhere a northern dip and an east-west strike, the same belt of slate is repeated many times, and the question arises whether the three apparent belts of amygdaloid are not really one, being repeated by isoclinal folding.

When studied in thin section, these slates are found to be exactly like the heavily hematitic and magnetitic slates which occur at the transition horizon of the Siamo slate and the Negaunee formation. These are described on a subsequent page.

Republic and Southwest tongues.—The rather unusual phases of the Ajibik quartzite occurring in the southwestern part of the area, along the Republic and Southwest tongues, are described in the general description (pp. 287, 289, 293) and in Chapter VI, upon the Republic trough. Near Republic occurs one of the best basal conglomerates in contact with the Archean in the district. Also the coarse quartzite just above this conglomerate is worthy of mention. It is gray, massive, crystalline-looking, and appears in hand specimen to contain grünerite. When examined in thin section it is found to be composed mainly of coarsely crystalline, interlocking quartz. The particles show undulatory extinction, but no granulation. Some of them have a roundish appearance, but no distinct cores are observable. Between these grains and included in some of them are clusters of grünerite, garnet, chlorite, and magnetite crystals. Some of the garnet crystals are so large as to inclose a number of grains of quartz. The grünerite in radiating blades penetrates the quartz grains in all directions. Apparently the chlorite is a secondary product, which has developed in part from the garnet and in part from the grünerite. The relations of these minerals, and particularly the grünerite, to the quartz strongly suggest that the rock has largely recrystallized.

Secs. 29 and 30, T. 48 N., R. 27 W.—More than a mile north of the main northern belt of the Ajibik quartzite is an isolated quartzite ridge about a half mile long, bounded on the north by peridotite and on the south by the Kitchi schist. The rock strikes northeast-southwest and dips to the southeast at an angle of 25°. This ridge in places is conglomeratic. Both the quartzite and quartzite-conglomerate are similar macroscopically and microscopically to the rocks west of Teal Lake, and are placed with the Ajibik formation on lithological grounds. The exceptional position of the area is probably due either to overfolding or to faulting.

SECTION V.—THE SIAMO SLATE.

The Siamo slate is so called because abundant exposures occur between the Ajibik quartzite and the Negaunee formation on the Siamo Hills, just south of the west part of Teal Lake (Atlas Sheet XXVII), and because the most typical rock of the formation is a slate, although locally it passes into a graywacke, or into a rock approaching a quartzite.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Beginning at the north and west (Atlas Sheet IV), the first exposures of this rock occur between the Ajibik quartzite and the Negaunee formation north of the Michigamme mine. From this place the formation stretches in a general easterly course for a number of miles to sec. 33, T. 48 N., R. 26 W., east of Teal Lake. East of sec. 33 is a broad area of the formation, extending to sec. 5, T. 47 N., R. 25 W., the slate being the topmost member of the great westward-plunging syncline. On the south side of this area the formation divides into two parts. The eastern arm swings to the south and southwest, past the northwest arm of Goose Lake; thence west, southwest, and south to sec. 29, T. 47 N., R. 26 W.; thence south about the west end of the anticline made by the Ajibik quartzite; and thence east to the sand plain in sec. 23, T. 47 N., R. 26 W. The western area extends west through sec. 3, and in secs. 4, 5, 8, and 9, T. 47 N., R. 26 W., constitutes a broad dome with minor folds. From sec. 9 an arm extends southwest, terminating as a plunging anticlinal dome in sec. 20. Farther southwest, in secs. 19 and 30, is another area, which was probably originally continuous with the area terminating in sec. 20.

The slate, being a soft formation, is not well exposed throughout, but at various localities where it is a mica-slate or a coarse graywacke the ledges are numerous. Upon the whole, however, the formation occupies the lowlands between the more resistant Ajibik quartzite and Negaunee formation. North of the Michigamme mine there are a number of exposures; from this place to Teal Lake there are few. However, south of the west arm of Teal Lake are the Siamo Hills, which give the name to the formation and upon which outcrops are abundant. The iron formation is here soft, and occupies even lower ground than the slate. East of Teal Lake there are many exposures of the formation south of the quartzite range. The exposures become more and more sparse in passing east, but they are still frequent to sec. 35, T. 48 N., R. 26 W. From this place southward there are no more natural outcrops until the Carp River is reached, south of which a number of exposures occur, but with long intervals between them. As the belt swings to the west, following the western arm, the outcrops in secs. 3, 4, 5, 8, and 9, T. 47 N., R. 26 W., are very numerous. The formation here contains much graywacke, and is therefore resistant, and we have a rough and elevated area surrounded by the less resistant iron formation. In the southwesterly extension of the belt prominent exposures occur in the center of sec. 20. In the arm which swings southwesterly from sec. 2, around the Ajibik quartzite, to the sand plain, the outcrops are few, and the land occupied by the belt is low. In secs. 19 and 30 there are numerous exposures, and the area, as a whole, is one of elevation.

FOLDING.

Beginning at the west, the northern belt of the formation has, upon the whole, a southern dip. However, when the ledges are examined in

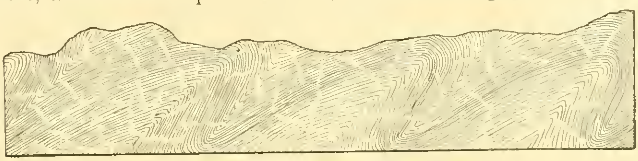


FIG. 15.—Minor overturned folds in Siamo slate

detail, it is found that the rocks are in a set of minor rolls, the dips sometimes being to the north, sometimes to the south. The latter are more persistent because of the general south dip of the formation, and therefore more conspicuous (fig. 15). Also, in places where the folds are overturned, the horizontal or northern dips upon the tops of the anticlines and the

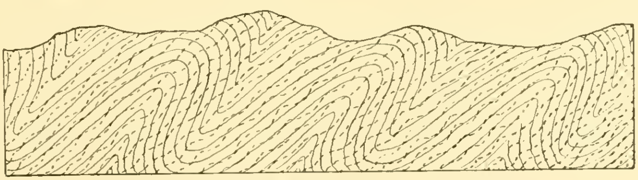


FIG. 16.—Relations of schistosity and bedding in Siamo slate.

bottoms of the synclines turn so quickly to the general southwest direction as to be easily overlooked. This is especially true where there is a schistosity parallel to the prevalent dip (fig. 16). To the subordinate folding is doubtless due the very greatly varying width of the formation. These minor rolls may be particularly well seen south of the west end of Teal

Lake (Atlas Sheet XXVII). The broad eastern area is a gently westward-plunging syncline with minor folds. In the eastern arm, which swings to the south in sec. 2, T. 47 N., R. 26 W. (Atlas Sheet XXXIV), the dips are always away from the Ajibik quartzite and under the Negaunee formation. Following the main belt from sec. 3, T. 47 N., R. 26 W., into secs. 4, 5, 8, and 9 (Atlas Sheet XXXI), the slates, upon the whole, constitute a great anticlinal dome. There the folding is complex. The pressure was more severe in a north-south than in an east-west direction, so that on the northern side of the area the dips are, in general, to the south, and upon the southern side to the north. This, however, is by no means a simple fold, but an anticlinorium with a large number of minor rolls with east-west axes. The north-south major cross fold causes these minor plications to plunge under the iron formation to the west, and the contact line between the formations curves outward and inward in a number of reentrants and salients. The salients correspond to anticlines in the slates, the reentrants to synclines. The same irregularity is probable upon the east side of the area, but here a swamp prevents a close delimitation of the Siamo slate and the Negaunee formation. Following the belt to the southwest, the southwestern termination of the fold occurs in sec. 20 (Atlas Sheet XXXII), where the iron formation appears in a semicircular belt about the plunging anticline. The Siamo slate, thus plunging beneath the iron formation, reappears as an anticlinal dome in secs. 19 and 30, T. 47 N., R. 26 W. On a smaller scale, the phenomena of folding are here the same as in the large exposures of this formation to the northeast.

PETROGRAPHICAL CHARACTER.

Macroscopical.—The Siamo slate varies from a coarse-grained feldspathic graywacke approaching a quartzite, through typical, massive graywacke, to a very fine grained, slaty rock. The slate and fine-grained graywackes are more abundant than the coarse, feldspathic graywackes.

The finer-grained phases are very generally affected by a slaty cleavage, which in places approximately corresponds with the bedding, but which also at other places cuts across the bedding at various angles. As explained on a previous page, the slate in many places is folded into a series of minor, isoclinal folds. Usually the slaty cleavage nearly corresponds with the longer limbs of these folds, and cuts across the bedding of the shorter limbs. Nowhere is the slaty cleavage so regular as to furnish roofing slates. At some places when the rocks were in the zone of fracture there was so much movement along the cleavage planes and between the beds as to develop distinct slickensides, the rock parting into irregular blocks with sides parallel to the bedding and to the cleavage. Each block was smoothed by movement along two sets of shearing planes. The cleavage therefore passes into a fissility.[1] In the most extreme stage of alteration the rock is a crystalline mica-schist, with well-developed mica folia. In proportion as the rocks are coarse-grained, slaty cleavage is not developed in them, and it is entirely absent in the coarser-grained graywackes. In general, the rocks of the formation have yielded to the forces to which they have been subjected by folding and mashing, but occasionally the coarser phases are brecciated, and rarely they become reibungs-breccias. This indicates that the formation is more plastic than the other Lower Marquette formations, in which autoclastic rocks are very common.

The normal varieties of the formation are not heavily ferruginous, but at the upper and lower horizons the slates contain a great deal of iron oxide and, locally, interlaminated layers of chert and ferruginous chert, or even grüneritic schist. The contact plane between the Siamo slate and the Ajibik formation seems to have been one of the major planes of differential movement, and thus numerous cracks and crevices have formed, which have been taken advantage of by iron-bearing solutions from above. The concentration of ferruginous masses at this horizon, although occurring on a comparatively small scale, is analogous to the concentration of the ore bodies on impervious basements in pitching troughs, as explained in Section VI. At the upper horizon the slate changes by gradation or by interlamination into rocks belonging to the Negaunee formation. The ferruginous phases are usually hematitic or magnetitic slates, but occasionally interlaminated or intermingled with the slates are layers of chert or

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 654-656.

ferruginous chert which are identical with the similar rocks of the iron formation. In color the nonferruginous varieties of the rocks are usually dark-gray or greenish-gray, but some of the coarser kinds are light-gray. In these the naked eye distinctly sees the well-rounded grains of quartz and feldspar. Also, in many of them there appear to be large fragmental grains of mica. In general, the iron oxide staining the slates is hematite, but in some cases it is magnetite. The fine and coarse varieties of the rock are interlaminated at many places, a layer of coarse graywacke being between two fine-grained, slaty layers, and these bands being composed of still finer bands of different degrees of coarseness.

Microscopical.—The least altered and coarsest graywackes are composed mainly of large, well-rounded grains of quartz, a few of them finely complex and cherty-looking, and of grains of feldspar, between which is a sparse matrix consisting of chlorite, biotite, muscovite, finely crystalline quartz, and more or less ferrite. Usually the chlorite is predominant, but in some cases the biotite and muscovite are equally abundant. Frequently the quartz grains are distinctly enlarged. In most cases they show pressure effects by undulatory extinction and fracturing, the latter sometimes being in a rectangular system. The feldspar grains comprise orthoclase, microcline, and plagioclase. They show beautifully their metasomatic change into chlorite and quartz, biotite and quartz, or muscovite and quartz. In any one case the alteration of individual grains may result in only one of the micaceous minerals, more often chlorite than any other; very frequently the alteration is into chlorite and biotite, or into biotite and sericite, although chlorite may also be a simultaneous product. All stages of the change may be seen, from those cases where the outer borders of the feldspar grains are surrounded by a film of the chlorite and mica, through those in which the grains are interlocking masses of the chlorite, mica, quartz, and feldspar, to those where the feldspar grains have entirely disappeared, their places being taken by a roundish, complex mass of the secondary materials. This alteration of the large feldspar grains is so general that it strongly suggests that the most of the chlorite, biotite, and sericite in the matrix developed from a feldspathic background.

In the least mashed phases of the graywackes there appears to be no arrangement of the secondary leaflets of chlorite, muscovite, and sericite in any definite direction. Where the dynamic action was somewhat greater there is a suggestion of the arrangement of the leaflets of these minerals in a parallel direction; also the original grains of quartz and feldspar are mashed or somewhat rotated, so as to have a similar arrangement. Further, finely crystalline secondary quartz begins to appear prominently in the background, and chlorite, which was predominant in the less mashed phases, becomes less prominent, being replaced by biotite and sericite or muscovite. Where the dynamic action was somewhat more severe the slides show distinct evidence of minor fault-slipping along two sets of diagonal planes, the somewhat irregular, connecting, and mesh-like slip-planes being marked by continuous bands of chlorite and mica, mingled with oxide of iron.

The chloritic and micaceous slates differ from the graywackes only in that the distinctly recognizable fragmental quartz and feldspar are much less abundant and the matrix much more abundant. As the quartz and feldspar grains become of very small size they are less rounded, apparently being below the limit of magnitude affected by water action. Out of the feldspar there formed chlorite, biotite, sericite, muscovite, and quartz, exactly as in the graywackes, and the same minerals also developed in the matrix. On account of the more plastic character of these rocks the evidence of interior movement is much greater than in the graywackes, the intersecting slip-planes being more numerous and approximately parallel, like a drawn-out net.

In a more advanced stage of alteration the slip-planes increase in number and are more nearly parallel, until there are several or many in the breadth of a single millimeter, and here we have typical fissility. The chlorite and mica developed or were arranged parallel to the fissility. The slip-cleavage very often corresponds with bedding. It appears as though different layers had been pushed forward over one another, somewhat as are particles of dough under the roller, the elongation being greater in the direction of the movement of the roller and less at right angles to this in the plane of movement. Sometimes there are present large flakes of mica or of chlorite, which are often bent or contorted, but these appear to be fragmental.

In a still more advanced stage of metamorphism the larger quartz grains are partly granulated, secondary quartz is present, the whole of the feldspar is decomposed, and we have a fine-grained mica-slate. In many places these mica-slates are interlaminated with coarser-grained layers, which distinctly show the clastic origin of the rock. In a single section there may be a number of alterations of mica-slate and micaceous graywacke. Sometimes the fissility is well developed in the mica-slate, and abuts diagonally against the laminæ of graywacke, in which it is less prominent or absent altogether. In the most extreme stage of metamorphism the coarse, fragmental grains of quartz, if there were any, were granulated, and the secondary quartz is as coarsely crystalline as this original quartz. The grains of varying sizes fit closely or interlock. The mica and chlorite are in well-developed parallel blades of considerable size, and thus the rock is a mica-schist. In one phase of the mica-schist are numerous large crystals of chlorite, which have their cleavage transverse to the schistosity. They include numerous grains of quartz. These have probably developed under static conditions after the dynamic action had ceased. In some of the mica-schists is a considerable amount of clear feldspar, which looks as though it were in part a secondary development, and thus the rock approaches a mica-gneiss. Although the Siamo formation thus locally becomes a completely crystalline schist, in that it no longer shows in itself any distinct evidence of original fragmental character, the gradation phases enable one to determine its manner of development as above given.

Where the slates and graywackes pass into the ferruginous varieties there appears in the matrix more and more of iron oxide, generally hematite, but in many cases magnetite also. These increase in quantity until there are more or less continuous, nearly solid layers of iron oxide, and in the extreme stage of ferrugination the matrix is so heavily iron-stained that little else can be discriminated. Where the iron oxide is magnetite, this is apt to take definite crystal outlines. In most cases it is plain that the oxides of iron are secondary infiltrations, being in part in crystals, and in part included in the enlarged borders of the quartz grains. These ferruginous slates have interlaminated layers of material which in all respects, except that an occasional fragmental grain of quartz may be seen, are like the ferruginous and sideritic slates and cherts and grünerite-magnetite-schists of the Negaunee iron formation. These are subsequently described in connection with that formation. In many instances the ferruginous chert belts cut across the layers in a minor way, and thus show that they are certainly a secondary product which formed by the alteration or replacement of some original constituent. In other instances they are along cracks which formed as a consequence of movement. Many of these belts are probably replacements of original sideritic layers, which were interlaminated with the fragmental sediments at the basal and topmost horizons. From the siderite the other minerals developed, just as in the Negaunee formation. In other cases the ferruginous and cherty materials which fill the cracks are probably from an extraneous source.

RELATIONS TO ADJACENT FORMATIONS.

It has already been said that the Ajibik quartzite grades upward into the Siamo slate. The transition rocks are usually feldspathic quartzites and graywackes. The best locality at which to observe all the phases of this gradation is east of Teal Lake, in sec. 32, T. 48 N., R. 26 W. (Atlas Sheet XXX). For the most part along the contact there are no conspicuous exposures which show the exact manner of transition.

Above, the slate is overlain conformably by the Negaunee iron formation. In many places the transition is gradual: in others, rather abrupt. Near the center of sec. 20, T. 47 N., R. 26 W. (Atlas Sheet XXXII), the formation is a coarse graywacke, and even approaches a quartzite, which grades upward into the iron-bearing formation. There are various interlaminations of fragmental and nonfragmental material, until finally the latter becomes predominant. Within this gradation zone the slate contains more or less of nonfragmental material, and after the iron formation becomes practically continuous it includes some fragmental material. The interlaminated beds were closely infolded, and consequently brecciation and minor faulting occurred. As a result, blocks of Negaunee jasper are found in the graywacke. At one place the lamination of the jasper abuts against the bedding of the graywacke. In sec. 35, T. 48 N., R. 27 W. (Atlas Sheet XXVII), south of the west end of Teal Lake, the change is somewhat abrupt. Here the top of the slate seems to have been a shear zone, and the iron-stained slates are semicrystalline. Resting upon these, with scarcely any gradation zone, are the iron-ore deposits. The above localities are the best found for showing the transition zone between the Siamo slate and the Negaunee iron formation. For most of the district exposures are not found along the contact zone.

THICKNESS.

To give an estimate of the thickness of the underlying formations has been difficult, and to determine the thickness of the Siamo slate is even more difficult, because of its close minor plications. In the broad area of Siamo slate in secs. 3, 4, 5, 8, and 9, T. 47 N., R. 26 W. (Atlas Sheets XXXI and XXXIV), the folding is so complicated that it is impossible to make any estimate of the thickness. The area perhaps most favorable is that west and east of Teal Lake (Atlas Sheets XXVII and XXX), where the belt has a width varying from a quarter of a mile to a half mile, or even more. This great variation in width is undoubtedly due to minor rolls in the formation, and taking the smallest width, 1,300 feet, with a dip of 75°, we would have a thickness of about 1,250 feet. However, it is known that slaty cleavage and subordinate rolls are here developed, so that it is probable that this thickness should be reduced by one-half, and perhaps by more.

INTERESTING LOCALITIES.

Michigamme area.—Beginning at the north and west, the first numerous exposures of the Siamo slate are north of the Michigamme mine, in secs. 19 and 20, T. 48 N., R. 30 W. (Atlas Sheet V), occupying for the most part a valley between the greenstone range and the granites. This is the locality in which all of the mica-schists are found. As examined in the field, they vary from a biotitic and chloritic quartz-schist to a finely laminated, chloritic biotite-schist which often contains large crystals of chlorite and sometimes large crystals of hornblende. The rock, while distinctly schistose, is not strongly foliated. In general the schistosity dips to the south, but there are in many cases minor crinkles, and for short distances a northern dip. Just north of the main ridge of greenstones the schists are cut at a number of places by dikes of greenstone, varying in width from minute ones to those 15 feet across. The larger dikes usually cut across the schistosity, but some of the smaller ones were intruded almost exactly parallel to the schistosity. At one place an earlier, coarse greenstone is cut by a later dike. At one exposure the schistosity has a dome structure, apparently occasioned by intrusive greenstone, which just reaches the surface of the ground. Adjacent to the dikes the minor crinklings of the schist are often prominent. At various places the greenstone dikes and the schists are so firmly welded that the rock breaks elsewhere rather than along the contact, and there appears to be a gradation zone a fraction of an inch across between the two, but in general the contact is rather sharp. In and upon the main ridge of greenstone to the south are considerable areas of the Siamo slate, which have apparently been caught in the eruptive mass. Near the base of the formation there is seen at one place a continuous exposure from the Ajibik quartzite to the typical mica-slate, and in the passage from one to the other there are a number of interlaminations of the quartzite and mica-slate, some of the beds being so thin that a hand specimen shows several of each of the two formations. Here the schistosity developed parallel to the bedding, as shown by its relation to the coarse and fine layers. At one or two places near the base of the formation there are also thin interlaminated belts of garnetiferous grünerite-magnetite-schist.

As examined in thin section, the most altered phases of the rocks are typical, regularly laminated, chloritic and sericitic biotite-schists, but, as explained in the general description, there are less altered phases in this area which distinctly show the fragmental character of the rock and the manner of transition from one to the other. The mica-schists are found adjacent to the intrusive greenstone, but the mica-slate also has as close relations. The contact between the two rocks, as seen in thin section, is very sharp, both in the case of slate or schist cut by dikes and in the case of included blocks in the main mass of greenstone. Near the contact, within the biotite-schist there are found large crystals of hornblende, which include numerous granules of quartz. Large crystals of chlorite, including grains of quartz, with folia transverse to the schistosity, are plentiful in the coarser schists. These and the hornblende crystals appear to be the latest minerals of the rock. Probably they developed under static conditions after the folding and after the intrusion of the greenstone. It appears highly probable that the unusually crystalline character of the Siamo slate in this neighborhood is partly due to the later intrusives.

The garnetiferous grünerite-magnetite-schists near the base of the Siamo formation at Michigamme are identical with similar transition rocks near the base of the Negaunee, and are described in connection with that formation.

Nonpareil mine.—The next exposures of interest are at and south of the Nonpareil mine, west of Lake Cooper (Atlas Sheet XXV). Here the rock is a regularly laminated ferruginous slate, which contains layers of ferruginous chert and graywacke. In the less ferruginous layers is seen a fissility which dips to the south 70° or 75°, but the more ferruginous layers on the south or hanging wall of an open pit dip south about 45°, and these probably follow the true bedding. Farther south the exposures of the formation are ordinary ferruginous slate. When examined in thin section the ferruginous chert differs from that of the Negaunee formation only in that it contains scattered, distinctly fragmental grains of quartz and layers which contain a great deal of fragmental material. In some of these cherty phases there is present a small amount of siderite. This occurrence, taken in connection with the known origin of the similar rocks in the iron formation, suggests that at the Nonpareil mine the lowest horizon of the Siamo slate contained interlaminated sideritic phases.

Siamo Hills.—The next important set of exposures is southwest of Teal Lake, on the Siamo Hills (Atlas Sheet XXVII), and these are taken as the type outcrops of the formation. The exposures, besides being numerous and large, give a nearly complete section from the Ajibik quartzite below to the Negaunee formation above. At the base of the formation, as at the Nonpareil mine, as shown by test-pitting, there is ferruginous chert. The central large exposures of the formation comprise all varieties of slate and graywacke, both ferruginous and nonferruginous, from the finest-grained phases to coarse rocks which approach a quartzite. The uppermost horizons, by interlamination or gradation, pass into or are overlain by the typical rocks of the Negaunee formation (Pl. X, fig. 2). The Siamo formation here constitutes the foot-wall of the iron-ore deposits. In some places it is a ferruginous quartzite, but at most places it is a slate, the alternate beds of which are ferruginous and nonferruginous. These have a southern dip at an angle of about 45°. These beds are cut at many places by a cleavage which at various points passes into fissility, and which dips at a steeper angle to the south, and hence cuts diagonally across the bedding. It appears probable, therefore, that the ferruginous layers were originally of a different character from the nonferruginous ones. The central parts of the formation show that the slate is folded in a series of minor rolls. There is a uniform secondary structure, with a high dip to the south, which corresponds in a general way to one set of legs of the series of folds.

As examined in thin section, the basal ferruginous chert is again found to contain a great deal of fragmental quartz, and also a large amount of siderite, out of which the hematite plainly developed. Many of the larger areas of siderite are surrounded by zones of hematite. The hematite decreases in amount, and the siderite increases, in passing inward. In other cases through the siderite everywhere are crystals of hematite and magnetite. In the upper part of the formation the Negaunee ferruginous chert in some cases appears somewhat suddenly upon the ferruginous Siamo slate; and in other cases there are interlaminations of the two, and it is apparent in these latter that the ferruginous chert is secondary material, as it does not follow the fragmental layers closely, but cuts across them minutely and irregularly. One of the slides from the central part of the belt shows beautifully the development of the finer-grained rock into a mica-slate, the fissility of which is very uniformly parallel, and which comes abruptly against a graywacke layer at an angle of about 30°. Here the planes of fissility die out or become extremely irregular, but reappear upon the other side of the narrow graywacke band. In some of the graywacke belts irregular fragments of slate are found which are plainly autoclastic, having been rent from the slate in the folding. In these phases the rock approaches a breccia, but the breccias occur only adjacent to the contact plane between the slate and graywacke.

Area east of Teal Lake.—East of Teal Lake, in secs. 31, 32, 33, and 34 (Atlas Sheets XXX and XXXIII), there are again very large exposures of slate and graywacke, but these need not be especially described, as in all particulars they are similar to the central mass of slate and graywacke of the Siamo Hills.

In the southern part of sec. 35 (Atlas Sheet XXXIII), about three-fourths of a mile southeast of Eagle Mills, are numerous exposures of slate and graywacke, which are in most respects similar to those of the Siamo Hills. At one place the slates are sharply folded into a minor anticline, which plunges to the west at an angle of 15°. At the middle of the ledge is a band of reibungsbreccia, about 4 or 5 feet broad, composed mainly of cemented slate fragments, but containing areas of quartz and ferruginous chert. These latter are apparently secondary. Iron oxide is one of the abundant cementing materials, and many of the slate fragments are heavily impregnated with this material.

Eastern area.—The next important exposures are at the east end of the great westward-plunging syncline in sec. 31, T. 48 N., R. 25 W., in sec. 1, T. 47 N., R. 26 W., and in sec. 6, T. 47 N., R. 25 W. (Atlas Sheets XXXVI and XXXVII). Here, at the bottom of the formation, especially in secs. 1 and 6, the slate and graywackes are very ferruginous, and they contain considerable belts of material which approaches very closely to a ferruginous chert. In some cases, for narrow zones, this chert is in all respects similar to the ferruginous chert of the Negaunee formation. As in the previous localities, the bands of pure chert or ferruginous chert are minutely interlaminated with belts which are largely fragmental. The unusual abundance and persistence of the ferruginous slates at this locality have already been explained as due to the fact that they are at the bottom of a westward-plunging syncline and rest upon a quartzite; that is, they are at a place where there has been extensive readjustment between the two formations, and also where percolating waters would be converged. In passing to higher horizons these ferruginous slates grade into the ordinary slates and graywackes of the formation.

When examined in thin section, the purest phases of the ferruginous chert are found to contain a certain amount of plainly fragmental quartz. Siderite is also found. This suggests, as at the Nonpareil mine and Siamo Hills, that this mineral was a partial source, at least, of the iron oxides.

In the NW. ¼ sec. 2 and in sec. 3, T. 47 N., R. 26 W. (Atlas Sheet XXXIV), there are large exposures of typical slate and graywacke. These show minor rolls and transition phases into the Negaunee formation.

West half of T. 47 N., R. 26 W.—The most extensive area of the exposures of the formation occurs in secs. 4, 5, 8, and 9, T. 47 N., R. 26 W. (Atlas Sheet XXXI). Here, as on the Siamo Hills, are nearly all phases of the formation. On the irregular west side of the area the transition phases between the Siamo slate and the Negaunee formation are well shown. In going east from the Buffalo mine embayment, one sees at various places in the slates and graywackes unusually ferruginous phases and often ferruginous chert. These are probably near the top of the formation. As examined in thin section, the rocks of this area are less modified than those of the Siamo Hills area, and therefore show particularly well the feldspar decomposition into chlorite, biotite, and muscovite, especially the first.

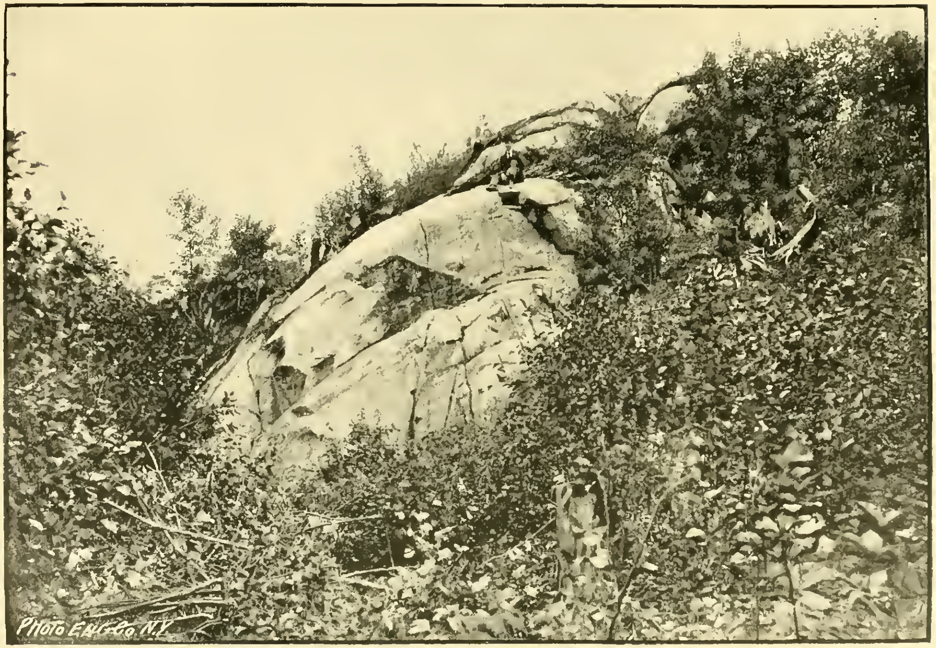
About the center and north of the center of sec. 20 of the same township (Atlas Sheet XXXII) are other large exposures of the Siamo formation. These are chiefly of the feldspathic graywacke phases, which approach a quartzite. On the west side of the exposures the interlaminations and gradations between the Siamo slate and the Negaunee formation are particularly well seen. In some cases there are numerous interlaminations of the fragmental and nonfragmental rock before the pure iron formation material is reached. The relations are still further complicated by the fact that both the graywacke and the jasper are rolled into a series of minor isoclinal, westward-dipping folds, and these subordinate folds are not simple but are each composed of several anticlines and synclines of the third order. Moreover, the axes of these folds are inclined. Thus, the apparent number of interstratifications of graywacke and jasper is far greater than is really the case, as the same beds reappear at the surface several times. In places the folding went to such an extreme as to brecciate the rocks, so that great blocks of the jasper were broken off and are contained in the graywacke. At one place minor faulting occurred, and as a result of this the lamination of the jasper abuts directly against that of the graywacke. These phenomena at first sight led to the belief that there is here an unconformable contact between the jasper and the graywacke, and that the whole series is overturned; but a closer study showed this conclusion to be erroneous, and that the phenomena are explained, as above, by interstratification of the graywacke and jasper, by the isoclinal folding, brecciation, and minor faulting. As would be expected, there results an extremely irregular boundary line between the two formations, which is placed so that upon the whole the jasper is predominant upon one side and the quartzite upon the other.

The last important set of exposures of the Siamo formation is in secs. 19 and 30 of the same atlas sheet. Here the rock is a coarse graywacke, which at times contains very large grains of quartz and feldspar, becoming almost conglomeratic in narrow belts. These are, however, minutely interstratified with finer material. In the northeastern part of the area, near the top of the formation, the usual interlaminations of the graywacke and iron-bearing formation occur.

As examined in thin section, these rocks again beautifully exhibit all stages of the alteration of the fragmental feldspar into biotite, chlorite, sericite, and quartz. In many cases in an intermediate stage we have these different minerals interlocking, and residual feldspar also present. Such a section, viewed with a high power, looks like a crystalline schist, but with a lower power the fragmental character of the whole is at once apparent, and so many transition phases are found between such areas and those in which the feldspar is but slightly affected as to show conclusively that the complex areas were originally feldspar.

SECTION VI.—THE NEGAUNEE FORMATION.

The Lower Marquette iron-bearing formation is given the distinctive name Negaunee because in the town of that name and to the southward are extensive typical exposures of the formation (Atlas Sheets XXVIII and



DOME STRUCTURE OF GRUNERITE-MAGNETITE-SCHIST, CAUSED BY INTRUSIVE GREENSTONE.

XXXI). It is called the iron-bearing formation because within it occur many of the Marquette iron-ore deposits.

RELATIONS TO ERUPTIVES.

Vast quantities of greenstone are associated with the iron-bearing formation. This greenstone includes both intrusives and extrusives, the former being much the more abundant. The intrusive rocks are diabases and their altered equivalents. The most conspicuous of these intrusives are in the form of bosses, varying from those of small size to those 2 miles or more long and a half mile wide. The bosses are of exceedingly irregular shapes, and from them radiate numerous dikes, varying from small ones to those many feet in diameter. These dikes usually do not outcrop, but mining shows that they frequently connect one boss with another, and thus unite into one mass several apparently detached areas of greenstone. In many cases the greenstone intruded the sedimentary series in a laccolitic fashion, so that the iron formation has a quaquaversal dip about the greenstone masses (Pl. XI). In some places fragments of the Negaunee formation are included in the intrusives (Pl. XII.) In other places the greenstone breaks across the iron formation, and at these the latter beds may dip against the greenstone, although in many cases the dip of Negaunee beds may be locally modified (figs. 17, 24, and 25).

The intrusives particularly affect the iron formation, the bosses of this rock found in the underlying and overlying formations being relatively few and of small size. This is illustrated by the fact that a map including the greenstone areas about Ishpeming and Negaunee would approximately cover the distribution of the iron-bearing formation. Large and abundant masses of intrusives are also found in the central-eastern arm of the iron formation, are very conspicuous in the masses of grünerite-magnetite-schist constituting Mount Humboldt (fig. 27), and are abundant in the great outcrops of iron formation at Republic and at Michigamme. At the latter place fragments of the Negaunee formation are included within the intrusives (Pl. XII). While this general relation is very marked, the greenstone not infrequently penetrates the superior formation (Pl. XXX), and is also found in the inferior formation. A possible explanation of this relation between the intrusives and the iron formation may lie in the exceeding brittleness of the latter. When the series was folded this formation was fractured at innumerable places, thus allowing the wedges of igneous material to enter.

At a few places the tuffaceous igneous rocks occur, giving evidence of contemporaneous volcanic activity.

In the mapping only those areas are colored as greenstone which are shown by visible exposure or by underground working to be igneous. There can be no doubt that greenstone, in the forms of bosses and dikes, occupies a considerable area which is given the color of the Negaunee iron

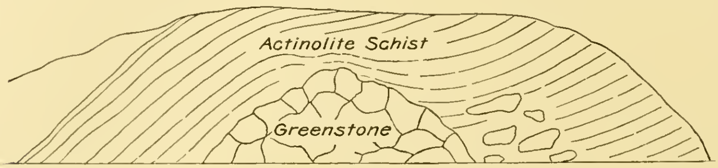
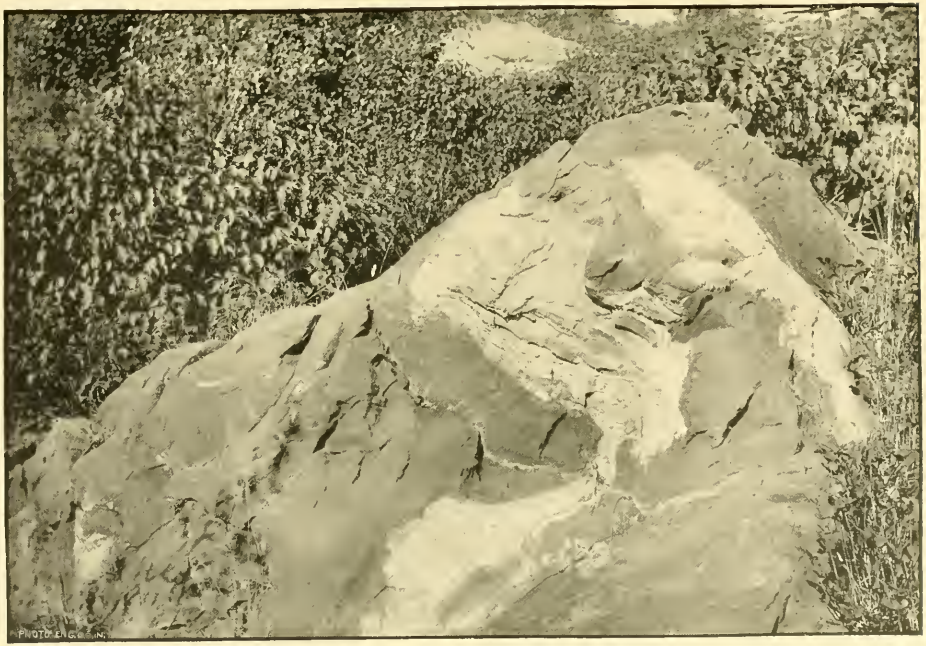


Fig. 17.—Intrusive greenstone in grünerite-magnetite-schist, from near center of sec. 12, T. 47 N., R. 29 W.

formation, but the positions of such greenstones are undetermined. Therefore the iron-formation color covers both the iron formation proper and unknown areas of included greenstones.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The largest area of the iron formation (Atlas Sheet IV) occupies the major part of the E. ½ of T. 47 N., R. 27 W., and the W. ½ of T. 47 N., R. 26 W., extending from near Teal Lake on the north to the village of Palmer and to Summit Mountain on the south. From the southern part of this broad central area two arms project to the northeast and east. The first arm runs in a northeast direction from Palmer, spreads out into a broad area in secs. 10 and 15, T. 47 N., R. 26 W., and terminates in sec. 3; the second arm, a half to three-quarters of a mile wide, extends east from Palmer to the sand plain in sec. 27, T. 47 N., R. 26 W. Its course after reaching the sand plain is undetermined. From the broad Ishpeming-Negaunee area two arms pass to the west, one near the south side of the Marquette series and the other near the north side. The southern belt has



INCLUSIONS OF GRÜNERITE-MAGNETITE-SCHIST IN INTRUSIVE GREENSTONE, EAST OF SPURR MINE

a considerable width in secs. 20 and 21, T. 47 N., R. 27 W., but farther west, as a consequence of the inter-Marquette erosion, it occupies but a narrow zone until Humboldt is reached, and it is not even certain that for a part of this distance the entire formation is not cut out. However this may be, in sec. 18, T. 47 N., R. 28 W., the formation reappears with a considerable width, and has a breadth of half a mile south of Humboldt. West of Humboldt for some distance the formation may be entirely cut off by the Upper Marquette transgression, but exposures reappear at Champion. From Champion to the eastern side of the Republic tongue the formation is cut out. At the southeast end of the Republic tongue it swings to the south, west, and northwest, to the western side of the trough, being again cut out at intervals. Thus in the Republic tongue the two belts are in a syncline which is independent of the main Marquette area. West of Republic is another similar tongue.

From the main area the northern belt extends west from Ishpeming, with frequent exposures, to sec. 6, T. 47 N., R. 27 W. West of this place it is known only by occasional outcrops to near Michigamme. At Michigamme and Spurr the iron formation has a considerable width, and from the latter place it extends to the west for an undetermined distance. It is wholly possible that in the area between Michigamme and sec. 4, T. 47 N., R. 28 W., the Upper Marquette transgression entirely cut out the Negaunee formation for a greater or less part of the distance, but in the absence of evidence of this it is mapped as continuous.

As has been seen, throughout much of the extent of the Negaunee formation there are abundant masses of intrusives, and these, rather than the iron-bearing formation itself, usually give the prominent topographic features. In the broad Ishpeming-Negaunee area this is particularly the case, nearly all of the bluffs being composed of greenstone, the iron formation occupying the valleys between the numerous greenstone knobs and ridges (Pls. XIII and XIV). For much of this part of the district the 1,400-foot contour is approximately the boundary line between the greenstone and the iron formation. However, where the Negaunee formation is a jasper or a grünerite-magnetite-schist, it is likely to be hard and resistant, and so to make important topographic features. Large outcrops

FIG. 18.—Minor plications in ferruginous slate interlaminated with schistose greenstones, on Chicago and Northwestern Railway east of Negaunee.

of the jasper may be seen about Ishpeming and Negaunee, southt east of Palmer, and at Republic. The magnetite-grünerite-schis- makes prominent exposures southeast of the Goodrich mine, at Mount Humboldt, at Champion, and at Republic. In general, where the Goodrich quartzite is in contact with the iron-bearing formation the former is the more resistant rock. The same is true of the Ajibik quartzite along the Cascade range, and where graywackes are abundant at the upper part of the Siamo slate this occupies the higher lands. Hence, upon the whole, the iron formation is not well exposed, and occupies depressions, either between intrusives within the iron formation or between the underlying and overlying formations.

FOLDING.

Beginning at the east, the two long arms of the iron formation constitute two synclinal troughs. As a result of the general westward pitch of the series, the northern tongue is known to terminate to the east, but the termination of the southern trough is undetermined because of its disappearance below the Pleistocene sands. As another consequence of the westward pitch, these two tongues and other shorter ones unite into the broad Ishpeming and Negaunee synclinorium. The continued westerly pitch of the series brings the quartzite of the Upper Marquette to the surface at Ishpeming, and this divides the Negaunee formation into two arms, one of which extends along the south side of the Marquette district and the other along the north side. Therefore, west of Ishpeming the formation appears in two belts on opposite sides of the great synclinorium. At Lake Michigamme an intermediate anticline becomes prominent, and as a result of it a synclinal arm extending southeast, terminating at Republic, is produced. West of the Republic fold is another very similar one. In the large Ishpeming-Negaunee area the secondary folding of the formation, combined with the distortions of the intrusions, produces extremely complicated contact lines, both

GENERAL VIEW OF LAKE ANGELINE FROM THE EAST, SHOWING BLUFFS OF GREENSTONE, AND LOWLANDS UNDERLAIN BY THE NEGAUNEE FORMATION.

with the underlying Siamo slate and the overlying Goodrich quartzite. By studying these lines it is seen that the formation is in a number of east-west secondary folds, which produce several large reentrants and salients, each of which is composed of smaller reentrants and salients, due to folds of the third order (Pl. XV). The eastern swings of the contact lines mark synclines, and the western swings anticlines. Putting it in another way, in going west the iron formation first appears above the Siamo slate in several fingers, each being a syncline. These to the west unite to form the broad area. Farther to the west the Goodrich quartzite appears, and hides the iron formation in a manner exactly similar. The secondary folds are still further modified and complicated by the intrusion of the igneous masses, about which the iron formation in some places has a quaquaversal dip. At other places the dip is but little modified by the intrusives (fig. 17). The western arms of the iron formation also have minor overfolds, which are more easily discernible when infolded with the Goodrich quartzite, but for the most part the belts are not sufficiently well exposed to indicate the minor folding.

A few localities in which such subordinate folds appear may, however, be mentioned. East of Palmer the general syncline of the iron formation has near its center a subordinate anticline, which causes the belt of Goodrich quartzite at Volunteer to split just south of Palmer into two arms (Atlas Sheet XXXII). As a result of this anticline the lower members of the formation are exposed near the railroad track east of Palmer, in the center of the iron belt. At Humboldt the grünerite-magnetite-schist has a subordinate anticline, which causes the Goodrich quartzite to be distributed about the great mass of grünerite-magnetite-schist in a quaquaversal fashion.

Upon the secondary folds are superimposed those of the third order (Pls. XV and XVI and figs. 18 and 19), and on these those of a still higher order, and so on to microscopic plications.

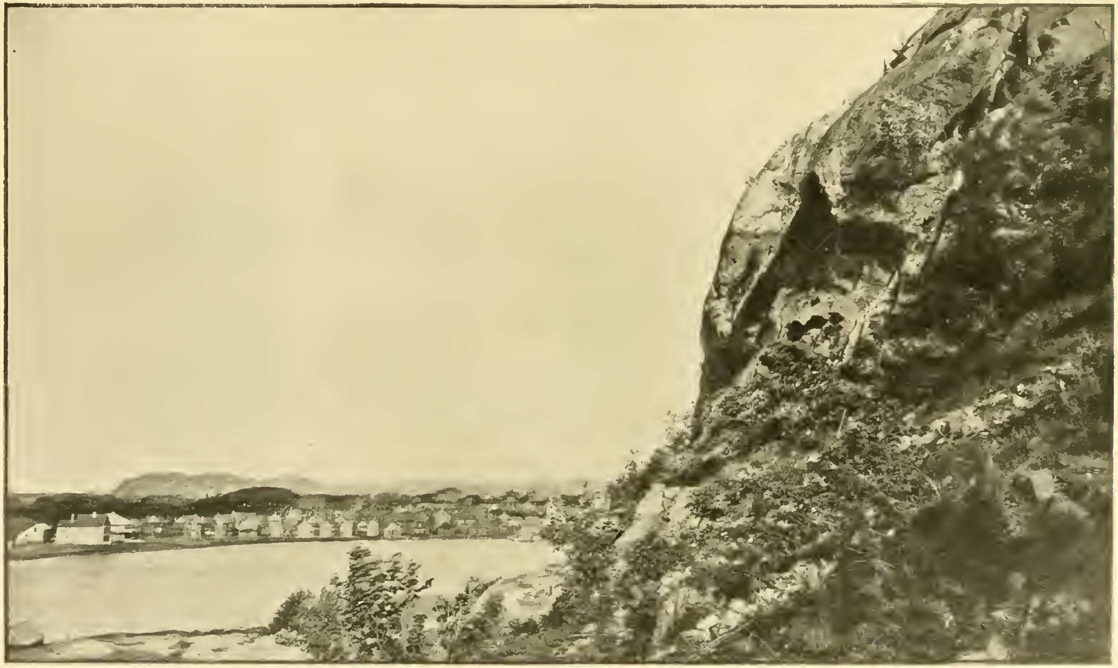
RELATIONS TO UNDERLYING AND OVERLYING FORMATIONS.

The iron-bearing formation rests conformably upon the Siamo slate or the Ajibik quartzite, and grades downward into one or the other of these formations. In passing upward within the fragmental formation nonfragmental material begins to appear and the slate or quartzite becomes more or less ferruginous, and by an increase of the ferruginous constituent it grades up into the iron-bearing formation. This gradation may occur within a comparatively few feet, or it may require a thickness of 100 or more feet. More often than not the gradation is not a regular transition, but is accomplished by interlaminations of material which is mainly fragmental and

Fig. 19.—Folded ferruginous chert of Starwest mine.

material which is mainly nonfragmental. These interstratifications are particularly well shown at the top of the Ajibik quartzite south of Palmer and at the top of the Siamo slate east of Negaunee. In different places the lowest horizon of the Negaunee formation may be the sideritic slate, the grünerite-magnetic-schist, the ferruginous chert, or the jasper.

The overlying formation is the Ishpeming formation of the Upper Marquette series. The relations between the two are those of unconformity, there having been considerable orogenic movement and deep erosion after



VIEW SOUTHWEST FROM LAKE BANCROFT, SHOWING ON THE RIGHT A GREENSTONE BLUFF, AND IN THE DISTANCE GREENSTONE HILLS AND LOWLANDS. UNDERLAIN BY THE NEGAUNEE FORMATION

the deposition of the Negaunee formation, before the Ishpeming formation began to be deposited. The degree of folding and the amount of erosion are different in different parts of the district. At most places the discordance is not more than 5° to 15°, but locally, as at the Goodrich mine (Atlas

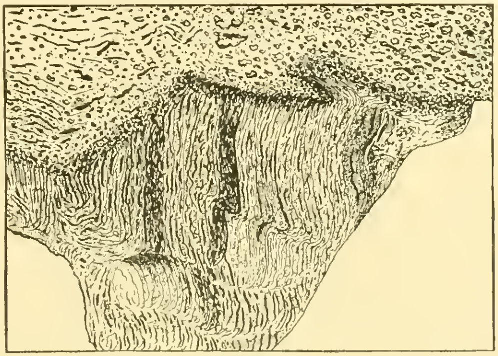


FIG. 20.—Horizontal plan of contact of Goodrich quartzite on plicated Negaunee jaspilite.

Sheet XXVI), the Goodrich quartzite cuts vertically across the plicated jasper (figs. 20 and 21). In some places the erosion has cut so deep as to have entirely removed the Negaunee formation, and in other places the

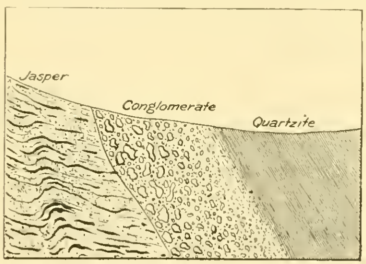


FIG. 21.—Cross-section of contact of Goodrich quartzite on plicated Negaunee jaspilite.

formation has a very considerable thickness. It thus follows that the contact line between the two formations is now at one horizon of the iron-bearing formation and now at another, varying from the highest known horizon of the formation to its lowest.

THICKNESS.

The average original thickness of the Negaunee iron formation may have been greater than its present maximum thickness, for we have no means of ascertaining what part of it and of overlying formations was removed by erosion.

If subordinate foldings are not considered, the interstratified eruptives are neglected, and the maximum breadth of outcrop is multiplied by the sine of the angle of dip, this gives a thickness of about 1,500 feet; but the subordinate folding and eruptives certainly reduce this thickness somewhat—probably as much as one-third. In the broad area of Ishpeming and Negaunee it is impossible to determine the thickness, for nowhere have diamond drills penetrated the underlying Siamo slate. The folding is here so complicated that an accurate estimate of the thickness can not be given, even of the part of the formation which is exposed and explored. It is, however, certain that the thickness is considerable, and it may be more than 1,000 feet. From what has been said in reference to erosion it is evident that the formation varies from its maximum thickness to disappearance.

PETROGRAPHICAL CHARACTER.

Macroscopical.—Petrographically the iron-bearing formation comprises sideritic slates, which may be grüneritic, magnetitic, hematitic, or limonitic; grünerite-magnetite-schists; ferruginous slates; ferruginous cherts; jaspilite; and iron ores. The ferruginous cherts and jaspilite are frequently brecciated; the other kinds less frequently.

The *sideritic slates* are most abundantly found in the valleys between the greenstone masses in the large area south of Ishpeming and Negaunee, although they occur at other localities. These rocks are regularly laminated, fine-grained, and when unaltered are of a dull-gray color (Pl. XVII). The purest phases of them are approximately cherty iron carbonate, as shown by two analyses made by George Steiger in the laboratory of the Survey.

OPEN PIT OF CLEVELAND HARD-ORE MINE, LOOKING WEST, SHOWING MINOR FOLDS IN JASPER

Analyses of cherty siderites.

	Per cent.
FIRST ANALYSIS.	
SiO_2	42.37
Fe_2O_3	1.09
FeO	31.41
CaO	.50
MgO	2.48
CO_2	21.80
Total	99.65
SECOND ANALYSIS.	
Insoluble in HCl:	
SiO_2	26.67
Al_2O_3	.12
Fe_2O_3	.16
MgO	.10
Soluble in HCl:	
SiO_2	.30
Al_2O_3	1.18
Fe_2O_3	2.15
FeO	39.77
MnO	.29
CaO	.66
MgO	1.84
$(KNa)_2O$	.09
P_2O_5	.03
CO_2	26.20
Water below 100° C.[1]	.10
Water above 100° C.[1]	.51
Total	100.17

[1] The above determinations of water were made on the original sample.

It is unusual to find exposures of the cherty siderite-slates which have not been more or less affected by deep-seated alteration or by weathering processes. As a consequence, the iron carbonates pass by gradations, on the one hand into grünerite-magnetite-schists, and on the other into ferruginous slates, ferruginous chert, jasper, or iron ore.

The *grünerite-magnetite-schists* consist of alternating bands composed of varying proportions of the minerals grünerite and magnetite and quartz (Pl. XVIII). Where least modified they have a structure precisely like the sideritic slates from which they grade, the grünerite-magnetite belts having taken the place of the carbonate bands. In some places the grünerite-magnetite-schists are minutely banded, the alternate bands consisting of dense, green grünerite and of white or gray chert, with but a small quantity of magnetite. Certain important kinds appear to be composed almost altogether of grünerite, with a little magnetite. In general, the grünerite-magnetite-schists are found at low horizons, below the ferruginous chert and jaspilite, i. e., at or near the same horizon as the sideritic slates. Frequently, also, they are below intrusive masses of greenstone.

Analyses of four of the typical grünerite-magnetite-schists were made in the chemical laboratory of the Geological Survey, the first by George Steiger, the second and third by W. H. Melville, and the fourth by H. M. Stokes. The material for the first analysis (specimen 21146, 1,200 steps N., 985 W., sec. 12, T. 47 N., R. 27 W.) was from the broad area of iron formation southeast of Ishpeming; that for the second (specimen 16149, 1,475 steps N., 150 W., sec. 11, T. 47 N., R. 27 W.), from Humboldt; that for the third (specimen 16566, 1,555 steps N., 1,375 W., sec. 18, T. 47 N., R. 28 W.), from a mile or two east of Humboldt Mountain; and that for the fourth (specimen 18938, 900 steps N., 50 W., sec. 20, T. 46 N., R. 30 W.), from the Magnetic mine, at the northwest end of the Republic trough.

Analyses of grünerite-magnetite-schists.

	(1)	(2)	(3)	(4)
Loss	....	0.67	1.40	....
SiO_2	59.26	46.94	49.70	46.25
Al_2O_3	....	.66	1.35	.92
Fe_2O_3	2.42	4.51	3.10	30.62
FeO	26.49	33.72	37.19	16.92
MnO	....	.31	.93	1.01
CaO	5.03	3.22	.68	1.69
MgO	2.17	6.64	5.72	2.13
CuO	....	....	....	Trace.
Na_2O	....	.16	Trace.	....
P_2O_5	....	.07	.12	.07
CO_2	.35	2.79	....	....
H_2O (above 110°)	....	....	....	.42
	95.72	99.69	100.19	100.03

VIEW OF WESTWARD-PITCHING FOLD IN No. 1 PIT, LAKE SUPERIOR IRON COMPANY. LOOKING WEST.

The rocks in the center of the figure are the Goodrich quartzite and these are underlain by the Negaunee jasper

PLATE XVII.

PLATE XVII.—BANDED, CHERTY SIDERITE.

FIG. 1. Cherty siderite from sec. 19, T. 47 N., R. 27 W. (Atlas Sheet XXVI). This is one of the purest cherty siderites found in the Marquette district. The gray material consists almost wholly of very finely crystalline and opaline silica and of siderite. The bluish-gray layers contain some silica, the greenish layers some siderite. On the weathered surface the siderite is entirely decomposed and in place of it is hematite and limonite. The beginning of the same kind of alteration may be seen to affect some of the siderite belts quite to the center of the specimen. As examined in thin section the secondary limonite is found to be in pseudomorphous areas after the siderite. Between the unaltered siderite and that which is completely decomposed there is every gradation, different granules showing all stages of the transformation. Natural size.

FIG. 2. Cherty siderite from the Penokee district, sec. 13, T. 47 N., R. 46 W. (See Pl. XXI, fig. 4, Mon. U. S. Geol. Survey, Vol. XIX.) The original cherty siderite of the Penokee district is represented perfectly by the grayish-green material. Its very close similarity to that of the Marquette siderite represented in the previous figure is noticeable. The beginning of the transformation of the siderite to limonite and hematite is beautifully shown The transitions between the two are clearer than in the previous figure. The processes of change begin along the bedding planes and along intersecting veins. These two together make two sets of nearly right-angle planes, which doubtless are shearing planes. The veins are entirely filled with limonite and hematite, and therefore are minute layers of ore. The changes along the bedding illustrate the beginning of the process which results in the formation of the iron-ore deposits. It is noticeable that, as a result of the alterations, the original banding of the rock is emphasized, although the emphasizing bands are not so regular as the original sedimentary laminæ. This emphasizing of the original banding of the iron-bearing rocks by metasomatic changes is a general law for the iron formations of the entire Lake Superior region. Natural size.

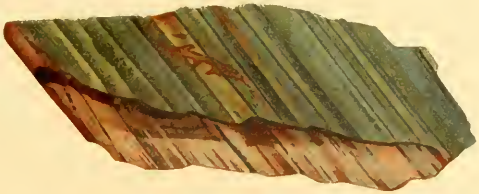


FIG 1

FIG. 2

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FIG 1 CHERTY SIDERITE, FROM THE MARQUETTE DISTRICT
FIG. 2. CHERTY SIDERITE, FROM THE PENOKEE DISTRICT.

PLATE XVIII.

PLATE XVIII.—MAGNETITE-GRÜNERITE-SCHISTS.

FIG. 1. Magnetite-grünerite-schist from Republic mine (Atlas Sheet XI). This is one of the coarsest varieties of the grünerite-magnetite-schists. In place of the siderite of Plate XVII we have grünerite and to some extent limonite, hematite, and magnetite. The grünerite is caused by the decomposition of siderite into iron protoxide and carbon dioxide and the union of the former with silica. The iron oxides, and especially the magnetite associated with the grünerite, are in part the direct results of the oxidation of the original siderite. Some of the limonite and hematite are due to the decomposition of the grünerite. Finally, a part of each of the iron oxides is a secondary concentration. This is shown by their appearance in veins cutting the bedding. Natural size.

FIG. 2. Sideritic magnetite-grünerite-schist from sec. 13, T. 47 N., R. 27 W. (Atlas Sheet XXVIII). The different bands consist mainly of grünerite, hematite, magnetite, and quartz, in varying proportions. The darker-colored bands contain much of the iron oxide. In the lighter bands grünerite is abundant. In all of the layers there is a sufficient amount of residual siderite to show that from this mineral and silica the grünerite formed, and from it, with partial or complete oxidation, the magnetite and hematite developed. The most of the hematite is of the specular variety, but in places blood-red flecks of hematite may be seen, and parts of the specimens are stained by limonite. This is doubtless the result of weathering. Natural size.

FIG 1

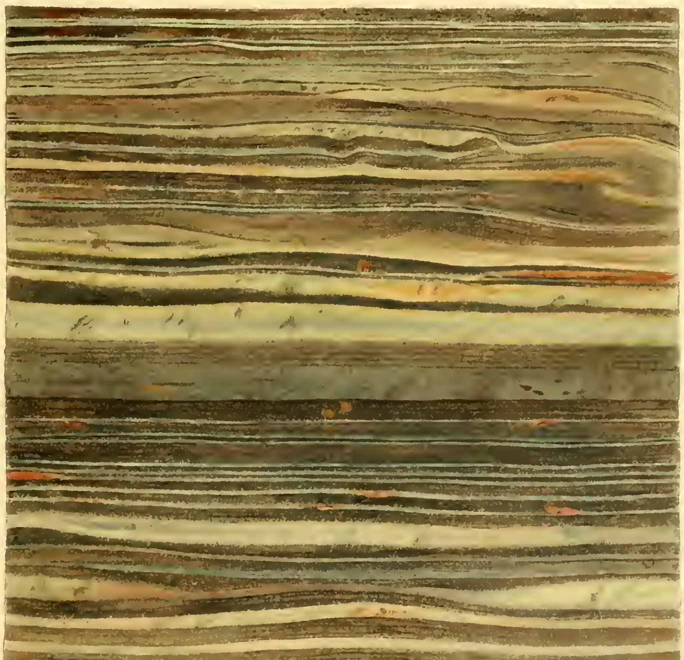

FIG. 2

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FIG 1 MAGNETITE GRÜNERITE SCHIST.

FIG. 2 SIDERITIC MAGNETITE-GRÜNERITE SCHIST

PLATE XIX.

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PLATE XIX.—GRÜNERITIC MAGNETITE-SCHIST AND FERRUGINOUS SLATE.

FIG. 1. Grünerític magnetite-schist from Republic mine. The lighter-colored bands are strongly quartzose. The darker bands are heavily ferruginous, but contain a great deal of quartz. The iron oxide is largely magnetite, but with this is much hematite. The grünerite is scattered throughout the rock, but is more prevalent in the heavily ferruginous bands. In its regular banding the rock is very similar to the original cherty sideritic slates represented by Pl. XVII, fig. 2.

FIG. 2. Ferruginous slate from sec. 7, T. 47 N., R. 26 W. (Atlas Sheet XXXI). The bluish-gray bands are largely chert, but in them iron oxide is contained. The reddish-brown bands are largely limonite and hematite, but contain much chert. This rock is evidently exactly what would be produced by the complete oxidation of the cherty siderite shown in fig. 1, Pl. XVII. The chert bands of the two are almost absolutely of the same color and composition. In place of the siderite bands of the latter are the limonite and hematite bands. The change emphasizes the structure as indicated in the description of fig. 2, Pl. XVII. Also, as in that figure, the ferruginous layers are not so regular as the original siderite layers. In the rearrangement the iron-bearing solutions have penetrated to a greater or less degree into the cherty layers. At a number of places the rock was fractured across the layers. At such places the iron oxide has been leached out to some extent, and the belts of chert connect different layers of that material. Last of all, along one vein secondary iron oxide has formed. Natural size.

FIG. 3. Ferruginous slate or jasper from sec. 7, T. 47 N., R. 26 W. (Atlas sheet XXXI). This figure represents a somewhat more advanced stage of alteration. The iron oxide is largely concentrated in the red and black bands and the silica is largely concentrated in the yellowish-red layers. The illustration might perhaps as well have been placed with the jaspers as with the ferruginous slates. It is, in fact, a transition variety. If the chert were somewhat more stained with brilliant-red hematite it would be called jasper.

The specimen beautifully illustrates deformation in the zone of combined fracture and flowage. The rigid cherty layer is fractured and faulted. The fault is normal. The more plastic ferruginous layers accommodated themselves to the changed position of the siliceous layer by flexure. The specimen looks as though black hematite material had flowed in between the broken siliceous bands, like dough. The specimen illustrates in miniature how a fault may pass into a flexure either above or below. Natural size.

FIG 1

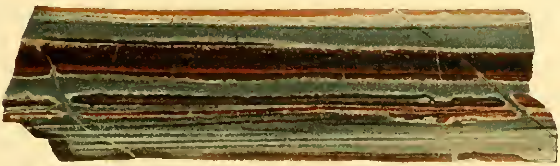

FIG. 2.

FIG. 3

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FIG 1 GRÜNERITIC MAGNETITE SCHIST

FIG. 2. FERRUGINOUS SLATE.

FIG 3. FERRUGINOUS SLATE

PLATE XX.

PLATE XX.—FERRUGINOUS CHERT.

FIG. 1. Ferruginous chert from Taylor mine sec. 9, T. 49 N., R. 33 W. This specimen illustrates a somewhat different stage of alteration from Pl. XIX. The silica has been almost perfectly concentrated into bands. The same is true of iron oxides. Movement has fractured the siliceous bands, and along these the removal of silica has begun. If nearly all of the silica were replaced by hematite, iron ore would be formed. In fig. 1 of Pl. XIX the reverse process is seen—that is, the solution of ore and the deposition of silica. It is a general law of the Lake Superior region that the solution of silica and the deposition of iron oxides occur at places where abundant percolating waters are concentrated. It will be shown later (see Pls. XXVIII and XXIX) that these favorable conditions are just above impervious formations which occur in pitching troughs. This figure, from a specimen obtained from the Upper Marquette series outside of the district mapped, is here inserted for comparison with the ferruginous cherts of the Negaunee formation. Natural size.

FIG. 2. Ferruginous chert from south of Jackson mine, sec. 1, T. 47 N., R. 27 W. (Atlas Sheet XXVIII). The iron oxide and chert were largely concentrated into bands before the last folding. At the time of the folding radial cracks were formed, especially in the chert layers, due to the position of the rock on the crown of an anticline. Along these cracks the silica has to some extent been leached out and iron oxide introduced. One light-colored area of chert appears to be a secondary infiltration, but it was apparently present before the last folding, as it is fractured the same as the other layers. Natural size.

FIG 1

FIG 2

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FIG 1 FERRUGINOUS CHERT

FIG. 2 FERRUGINOUS CHERT

PLATE XXI.

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Plate XXI.—Hematitic Chert from Negaunee.

The plate shows a somewhat different stage of alteration from Pl. XX. The bands of chert are so broken by movement that they are in some places difficult to follow. Many of the fragments have roundish outlines, due to their partial solution and replacement by iron oxide. In the field there may be found every phase of transition between the rock represented by fig. 1 of Pl. XVII, through the rocks represented by the figures of Pl. XIX, to the rock represented by fig. 2 of Pl. XX and to the varieties represented by Pl. XXI. Fig. 2 represents a somewhat more advanced stage of alteration than fig. 1. The material illustrated is frequently found very close to the ore bodies. If a portion of the remaining silica were removed and iron oxides introduced in its place, it would become iron ore. The hematite is soft, and the material illustrated is therefore called soft-ore jasper by the miners.

FIG 1

FIG. 2

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HEMATITIC CHERT.

PLATE XXII.

Plate XXII.—HEMATITIC CHERT FROM NEGAUNEE.

This plate represents the same phenomena as Pl. XXI, but in a more satisfactory way. The folding has shattered the chert layers throughout. Along all the openings between the chert fragments hematite has formed or has been forced in by pressure. A later folding has slightly shattered the rock, and in the cracks minute veins of magnetite have formed. The specimen beautifully illustrates the action of material when folded in the zone of combined fracture and flowage. The regularity of the fracturing of the chert layers in a direction almost transverse to their length is noticeable. This suggests that the cracks formed in tensile planes when the chert belts were being bent.

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HEMATITIC CHERT, FROM NEGAUNEE.

PLATE XXIII.

PLATE XXIII.—MAGNETITIC CHERT FROM THE MICHIGAMME MINE.

The bluish-gray bands are rather coarsely crystalline quartz. This kind of quartz is characteristic of the west end of the district. The dark material is hematite, and the lustrous material is magnetite. The hematite was present before the last folding, and is in brilliant flecks, due to accommodations along the beds. The magnetite entered after the last folding. In fig. 1 the abundance of the magnetite is seen to be in direct ratio to the fracturing. On the left-hand side of the figure, where the rock is much broken, there is little quartz. The peculiar magnetitic chert represented by this plate is found closely associated with the ore at the Michigamme and Spurr mines.

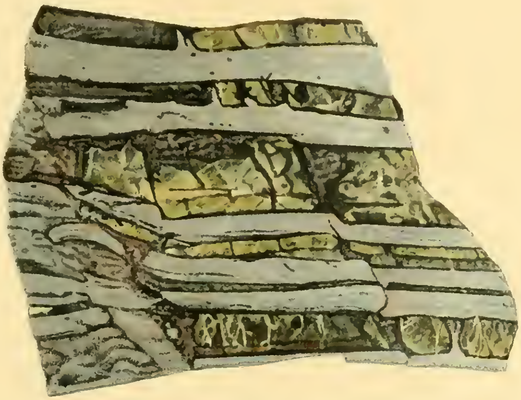

FIG 1

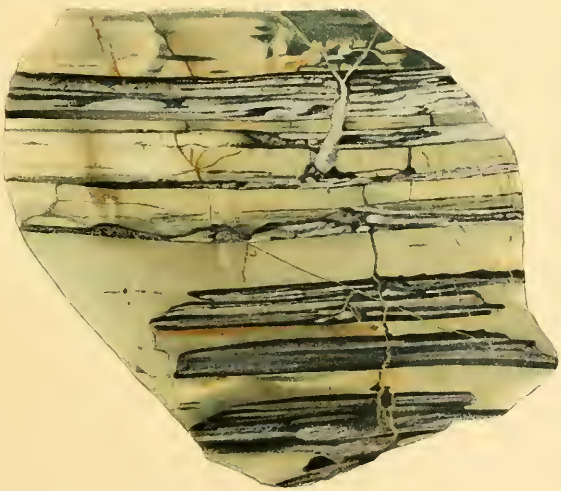

FIG. 2

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MAGNETITIC CHERT.

PLATE XXIV.

PLATE XXIV.—JASPILITE.

This rock is from the Grand Rapids mine, Negaunee (Atlas Sheet XXVIII). The dark bands are mainly hematite. The brown bands consist mainly of minute grains of quartz, but each grain is stained with hematite. The red jasper belts do not continue indefinitely, but layers die out after extending a greater or less distance, with oval terminations. This is beautifully shown in one of the bands. The rock illustrated by this plate is allied to that of fig. 3, Pl. XIX. In the change from the original rock there was almost complete oxidation of the siderite, little or no hydration of iron oxide, and but little of the iron oxide united with silica to form grünerite. In the rock of fig. 2 no grünerite is present, but some occurs in the upper part of fig. 1.

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JASPILITE FROM GRAND RAPIDS MINE, NEGAUNEE

PLATE XXV.

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PLATE XXV.—JASPILITE FROM JASPER BLUFF, ISHPEMING.

This is a representation of a typical piece of the brilliant jaspilite which occurs associated with the hard ores of the Marquette district. The rock was folded in the zone of combined fracture and flowage. The jasper bands bent for a certain time without macroscopic fracture, but later were broken through and through. During the time of folding the rock may have been more deeply buried than during the time of fracturing. At both periods the hematite accommodated itself to its new position without apparent fracture. However, the laminæ moved over one another, giving them a brilliant specular appearance. To some extent it flowed in between the broken jasper fragments. Between the leaflets of hematite there were minute spaces. The spaces, large and small, were occupied by subsequently infiltrated hematite and magnetite, which in thin section may be discriminated by its crystal outlines from the hematite present before the folding.

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JASPILITE

PLATE XXVI.

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PLATE XXVI.—JASPILITE.

FIG. 1. Folded jaspilite, from Jasper Bluff, Ishpeming. The illustration beautifully shows the secondary infiltration of iron oxide and deformation by combined fracture and flow. By close observation iron oxide of three different ages may be seen. The oldest is the dark-gray hematite. Intersecting this is the more brilliant steel-gray hematite and magnetite, and cutting both of the former are other veins of brilliant hematite and magnetite. The history of the rock seems to be briefly as follows: Banded hematite and jasper was bent by folding, probably while the rock was deep-seated. During this folding the hematite was mashed. In a later stage, when the rock was more rapidly deformed near the surface, fracturing occurred. This gave the conditions for the first infiltration of iron oxide, and later, when the rock was perhaps still nearer the surface, further deformation resulted in new fractures. Finally, the crevices thus formed were filled with the latest iron oxide.

FIG. 2. Brecciated jaspilite, from Jasper Bluff, Ishpeming. The illustration gives evidence of the history as shown by fig. 1. However, during the final process the layers of jasper, which were bent at the earlier stage, were broken through and through, producing a breccia. The same evidences are seen of three stages of iron oxide as in fig. 1. The less brilliant gray is the earliest-mashed hematite; the intermediate gray represents a first infiltration; after this there was shattering, and finally the breccia was cemented by brilliant steel-gray hematite and magnetite.

FIG 1

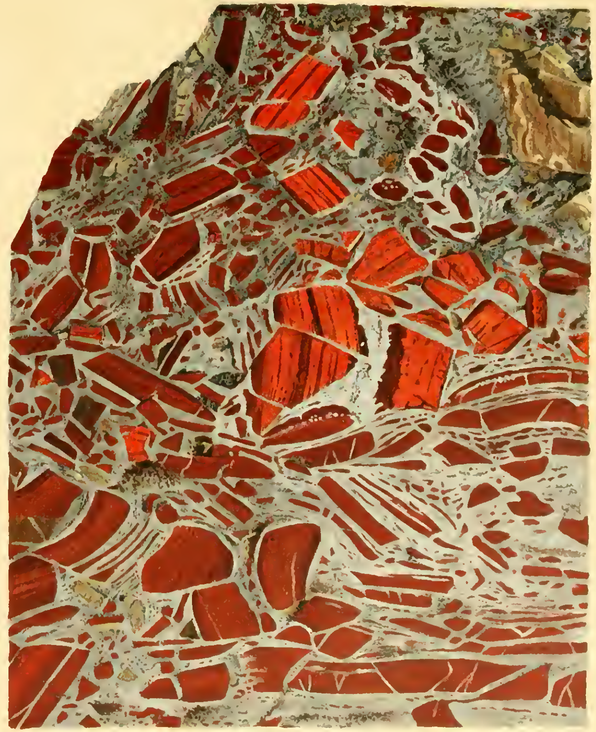

FIG. 2

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FIG 1. FOLDED JASPILITE

FIG 2. BRECCIATED JASPILITE

PLATE XXVII.

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PLATE XXVII.—JASPILITE, AND ORE AND JASPER CONGLOMERATE.

FIG. 1. Jaspilite from the Jackson mine, Negaunee (Atlas Sheet XXVIII). This figure represents a typical piece of the regularly banded jaspilite. The bluish-gray bands are brilliant specular hematite. In the red bands each granule of quartz contains innumerable particles of translucent blood-red hematite. The lenticular character of the jasper bands is well illustrated, the specimen being selected especially to show this. The transverse fracturing of the jasper and other bands and the secondary infiltration of iron oxides are shown.

FIG. 2. Ore and jasper conglomerate from Saginaw range (Atlas Sheet XXVI). This is a typical basal conglomerate of the Goodrich quartzite of the Upper Marquette series. The detritus consists almost wholly of various materials derived from the Negaunee formation, including jasper, chert, and ore. There is present, however, some quartz derived from the Archean. A close examination of the illustration shows that secondary hematite and magnetite have largely formed in the spaces between the grains about many of the jasper fragments, and, indeed, have partly replaced the jasper fragments themselves. This is beautifully shown at the lower left-hand corner of the figure. In those places where the basal conglomerate is fine-grained these replacements by iron oxide may be almost complete, in which case an iron-ore deposit is formed. Of such an origin is the iron ore of the Volunteer and some other mines.

FIG 1

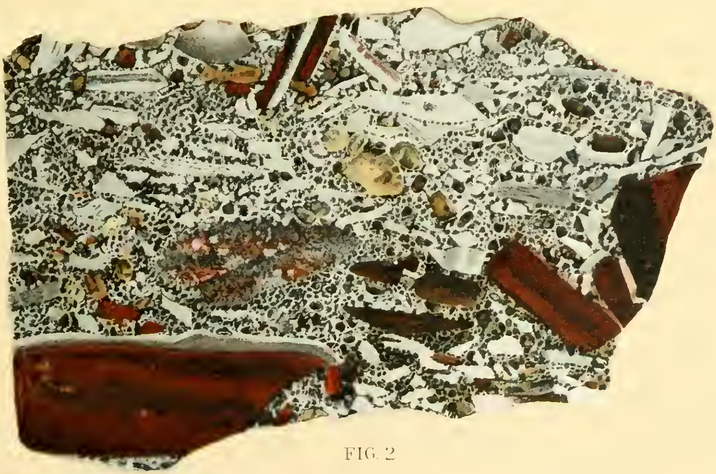

FIG. 2

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FIG 1 JASPILITE.

FIG 2 ORE AND JASPER CONGLOMERATE.

The analyses on page 338 show that the rocks are composed mainly of impure grünerite, magnetite, and quartz. The analyses indicate that the amphibole is intermediate between grünerite and actinolite, but upon the whole is much nearer the former than the latter.

By oxidation of the iron carbonate the sideritic slates pass into the *ferruginous slates*, the iron oxide being hematite or limonite, or both. These rocks, in regularity of lamination and in structure, are similar to the sideritic slates, differing from them mainly in the fact that the iron is present in another combination (Pl. XIX). In the different ledges may be seen every possible stage of change from the sideritic slates to the ferruginous slates. The only necessary change is a loss of carbon dioxide and peroxidation of the iron. In Pl. XVII the beginning of the process is beautifully shown. On weathered surfaces, along veins, and along some of the bedding planes the transformation is complete. Between this transformed material and the original rock there is complete gradation. Pl. XIX illustrates different ferruginous slates in which the siderite is partly or wholly decomposed.

The *ferruginous cherts* are rocks consisting mainly of alternating layers of chert and iron oxide, although in the iron-oxide bands chert is contained, and also in the chert bands iron oxide is found (Pls. XX–XXII). This iron oxide is mainly hematite, but both limonite and magnetite are sometimes present. Rarely magnetite is the predominant oxide of iron (Pl. XXIII). In such cases the silica is usually coarsely crystallized. In the field the ferruginous slates are found to grade step by step into the ferruginous cherts, and it is manifest that they were produced from them by a rearrangement of the iron oxide and silica, with a possible introduction of extraneous silica and iron oxide. The rocks are folded in a complicated fashion, as a result of which the layers present an extremely contorted appearance. The folded layers frequently show minor faulting. On account of the exceedingly brittle character of these rocks, they are very often broken through and through, and sometimes they pass into reibungs-breccias. Sometimes the shearing of the fragments over one another has been so severe as to produce a conglomeratic aspect. The ferruginous cherts are particularly abundant at the middle and lower parts of the iron-bearing formation, just above or in contact with the greenstone masses.

They thus occupy a horizon within the iron-bearing formation, and in a number of cases they are between the grünerite-magnetite-schists or sideritic slates below and the jaspilite above. The rocks here named ferruginous chert are called by the miners "soft-ore jasper," discriminating them from the hard-ore jasper, or jaspilite. This material is so called because within or associated with it are found the soft ores of the district.

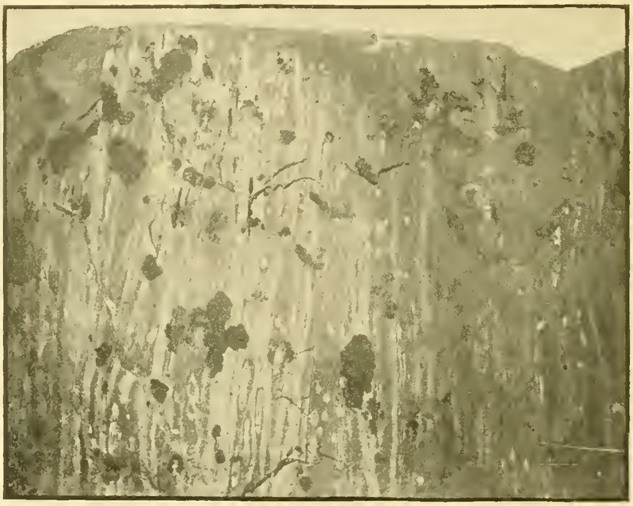


Fig. 22.—Jaspilite of Republic mine, showing white areas of chert in the red jasper.

The *jaspilites* are rocks consisting of alternate bands composed mainly of finely crystalline, iron-stained quartz and iron oxide (Pls. XXIV–XXVII, and fig. 22). The exposures present a brilliant appearance, due to the interlamination of the bright-red jasper and the dark-red or black iron oxides. The iron oxide is mainly hematite, and includes both red and specular varieties, but magnetite is frequently present. The jasper bands often have oval terminations, or die out in an irregular manner. The folding, faulting, and brecciation of the jaspilites are precisely like those of the ferruginous chert, except that in the jaspilite they are more severe. The interstices produced by the dynamic action are largely cemented with crystalline hematite, but magnetite is present in subordinate quantity.

In the folding of the rock the readjustment has occurred mainly in the iron oxide between the jasper bands. As a result of this, the iron oxide has been sheared, and when a specimen is cleaved along a layer, it presents a brilliant micaceous appearance, and such ore has been called micaceous hematite. This sheared lustrous hematite, present as some form of iron oxide before the dynamic movement, is discriminated with the naked eye or with the lens from the later crystal-outlined hematite and magnetite which fills the cracks in the jasper bands and the spaces between the sheared laminæ of hematite. The jaspilite differs mainly from the ferruginous chert, with which it is closely associated, in that the siliceous bands of the former are stained a bright red by hematite, and the bands of ore between them are mainly specular hematite, while in the cherts the iron oxide is earthy hematite. The jaspilite in its typical form, whenever present, always occupies one horizon—the present top of the iron-bearing formation, just below the Goodrich quartzite. In different parts of the district it has a varying thickness. With this jasper, or just above it, are the hard iron ores of the district; hence it has been called "hard-ore jasper" by the miners, to discriminate it from the ferruginous chert, or "soft-ore jasper."

An analysis of one of the typical jaspilites, made by George Steiger, in the laboratory of the Survey, is as follows:

Analysis of jaspilite.

	Per cent.
Soluble matter, chiefly iron oxide	62.36
Insoluble matter	37.64
Total	100.00

The insoluble matter contains—

	Per cent.
SiO_2	98.91
Al_2O_3	.53
Fe_2O_3	.10
MgO	.20
Alkali oxides	.10
Total	100.14

This analysis shows that the rock is composed almost wholly of silica and iron oxides.

The *iron ores* in the Marquette district comprise many varieties, among which the more prominent are hematitic, granular magnetite; magnetitic, specular hematite, and soft, red hematite, which is very often limonitic; and all gradation phases. The magnetites and specular hematites are called hard ores by the miners, and the red hematites are called soft ores.

The hematitic magnetites vary from very coarsely granular magnetite to finely granular magnetite. With the magnetite there is always more or less of hematite, in many cases a large part of this resulting from the alteration of the magnetite. The hematite varies from a subordinate to an important amount. Also, at many places, with the magnetite are varying quantities of pyrite and garnet, and the alteration product of the latter, chlorite. The magnetites vary in color from pure black to gray.

By an increase in the quantity of the hematite the magnetites pass into specular hematites. The specular hematites vary in texture from very coarse to aphanitic. In the coarse hematites each individual of hematite resembles a flake of mica. Such ores are frequently called micaceous hematites. The flakes are largely arranged with their greater dimensions parallel, thus giving the ore a marked schistosity or rift. The coarse hematites are usually strongly magnetitic, there being between the flakes of hematite many crystals of magnetite. In the finer-grained specular hematites the particles are so small that the eye does not easily discriminate them. In many cases such ore cleaves like slate or schist, giving a smooth, brilliant surface. These ores are frequently called slate ores. While magnetitic, they are usually less strongly so than the so-called micaceous ores, although in them in many cases may be seen numerous small crystals of magnetite. Another variety of the fine-grained, specular hematite is steel-gray, dense, very hard, and breaks with a conchoidal fracture.

Many of the specular ores contain a greater or less quantity of red hematite, which gives them a mottled appearance. This class of ores, which is abundant, is either very slightly magnetitic or not at all so. These ores are gradation phases between the pure specular hard ores and the soft red hematites.

The reddish specular ores pass gradually into the soft hematites. The majority of the soft ores have a distinct lamination. Many of them on freshly broken surfaces have a finely crystalline appearance. All give a brilliant cherry-red streak. In hand specimen the pure hematites are bright-red. The limonitic hematites differ from the red hematites in having a brown color, due to the presence of hydrated iron oxide.

While a laminated or banded appearance of the ores is very general, locally they are entirely without any such structure. Oftentimes the massive varieties contain numerous cavities, varying from those of minute size to those of considerable magnitude. These cavities are commonly lined with crystals of hematite or magnetite, or by radiating needles of hematite or the hydrated oxides of iron. Very often the interiors of these cavities have a botryoidal appearance. In a few of the soft hematite mines oxides of manganese occur in various forms, and in some places this material is so concentrated as to furnish manganese ore.

The magnetites and coarse specular hematites are confined to the upper horizon of the Negaunee formation or to the basal horizon of the overlying Ishpeming formation, and largely to the western part of the district. The most common rock associated with these ores is jaspilite, although in places it is a coarse, white, ferruginous chert. The fine-grained specular ores are confined to the upper horizon of the iron formation, and mainly to the eastern part of the district. The soft hematites are found at middle or lower horizons of the Negaunee formation, associated with the ferruginous slates or ferruginous cherts.

It appears that the ferruginous slates, ferruginous cherts, jasper, and ore form in the zone of weathering, and that the grünerite-magnetite-schists develop in the zone of deep-seated alteration. The different characters are then due to original position within the formation and to subsequent environment, rather than to difference in the original rock.

In fullest section the Negaunee formation exhibits, therefore, the following stratigraphy: At the bottom are the sideritic slate and grünerite-magnetite-slate; above these, ferruginous slate; above this, ferruginous chert; and at the top of the formation, jaspilite. The iron ore may occur at any horizon. While this is the common order, in a given locality one or more of these members may be absent.

For instance, at Republic (Atlas Sheet XI) only the grünerite-magnetite-schists, the ferruginous chert, and the jaspilite are found. South of the Saginaw mine (Atlas Sheet XXVI), at the base, is the grünerite-magnetite-schist; at the intermediate horizons, the ferruginous chert; and at the top, the jaspilite. South of Palmer (Atlas Sheet XXXII) the jaspilite occupies the whole breadth of the formation between the Goodrich quartzite and the Ajibik quartzite. Farther to the east, however, where the formation has a greater thickness, the ferruginous chert occurs below the jaspilite. At and south of Negaunee (Atlas Sheets XXVIII and XXXI) the full succession is found. Beginning at the Jackson mine and passing southward, we find at the top of the formation magnificent exposures of jaspilite; below this are numerous open pits, which give typical exposures of the ferruginous chert. This grades down into the ferruginous slate of the Grand Rapids mine, and continuing southward, we find within the valleys between the greenstones the grünerite-magnetite-schists and the very little altered sideritic slate.

Microscopical.—The kinds of rocks found in the iron-bearing member of the Lower Marquette series and their relations to one another are very similar to those of the iron-bearing member of the Penokee and Animikie series, which have been described in great detail. Also, the microscopical characters of the different phases of rocks are similar to those of the Penokee series. In fact, so remarkable is the likeness that, with a restatement of localities, what has been written in reference to the Penokee and Animikie iron formations might be applied almost verbatim to the Marquette iron-bearing formation. Therefore, for a detailed description of the different phases of the iron-bearing formation and the manner in which the original rock grades into the other phases, reference is made to Mon. U. S. Geol. Survey, Vol. XIX, Chapter V, pages 182–268.

A very brief description will, however, be given of the general character of the different phases of the iron-bearing formation, and a more detailed statement will be made in reference to those points in which there are differences between the Lower Marquette and the Penokee iron-bearing formations.

In the purest phases of *cherty siderite-slate* (Pl. XVII) there is a continuous mass of siderite, which contains separate granules or irregular, complex areas of cherty silica, small crystals of magnetite, and needles of actinolite or grünerite. The silica is rarely partly amorphous, being in minute opaline droplets, but is more commonly completely individualized quartz, the grains varying in the different slides from 0.01 to 0.03 mm. in diameter. The siderite is in closely packed, small rhombohedra. Upon the weathered surfaces the siderite is entirely oxidized, being changed into hematite or limonite, with pseudomorphous forms. In this iron oxide is contained cherty silica, identical with that in the unaltered part of the rocks. Between the two there is a transition zone, in which are seen the various stages of alteration from the unchanged siderite to the secondary hematite. In one of the finest instances the transition band is broad, and there are seen many rhombohedra of siderite surrounded by bands of beautiful, blood-red, translucent hematite. These borders vary from mere films to those so broad that but a minute speck of the siderite remains. If the oxidized portion of the slide were seen by itself it would be regarded as a ferruginous slate, with which it is in every respect identical; but in this case it can not be doubted that the siderite is the original source of the hematite. Where the siderite is less abundant and the chert more plentiful, the rhombohedra of siderite are set in a matrix of chert, which may consist wholly of individualized quartz, but which sometimes apparently contains some opaline silica. Oftentimes bands consisting largely of silica alternate with bands consisting largely of siderite. In the less pure phases, near the base of the Negaunee formation, the cherty siderite in some cases alternates with strata of an impure clayey rock, approaching the Siamo ferruginous clay-slates; in other cases, mingled with the siderite itself is fragmental material, including both quartz and feldspar, and their alteration products. Not infrequently within these semifragmental rocks, along cracks and joints, all transitions between the impure siderite and a ferriferous or cherty slate, partly fragmental and partly nonfragmental, may be seen.

Where the sideritic slates are altered, not by weathering, but by deep-seated metasomatic action, there develop abundant magnetite and a light amphibole, nonpleochroic in thin section, which will be called grünerite. There is thus produced a magnetite-grünerite-siderite-slate, intermediate between the sideritic slates and the typical magnetite-grünerite-schists. It appears, as in the cases of the Penokee and Animikie series, that when the siderite decomposed there was an abundance of silica present, and conditions not favorable to oxidation, so that the silica united with the iron oxide alone, producing grünerite, or with the iron, calcium, and magnesium oxide, producing a mineral intermediate between grünerite and actinolite. The iron which does not combine with the silica, not being completely oxidized, is in the form of magnetite. This is the first stage of the development of the magnetite-grünerite-schists from the sideritic slates.

The *grüneritic* and *magnetitic schists* (Pl. XVIII) may vary from nearly pure grünerite-schists to nearly pure magnetite-schists. However, the more common phase is the grünerite-magnetite-schist. Grünerite, magnetite, and quartz are the three important constituents, but in some areas quartz is in subordinate quantity. The minerals are usually concentrated to some extent into bands, although a layer composed chiefly of any one of the three always includes a greater or less quantity of the other two. In many cases within a felted mass of grünerite or magnetite are found many rhombohedra of siderite, and this siderite has such relations to the grünerite and magnetite as to suggest that these minerals developed from the siderite. We thus have evidence of the transition of the sideritic slates into a grünerite-magnetite-schist. When the transformation is complete there remains no evidence of the change, as the rock then consists of a completely interlocking crystalline mass of the three minerals, grünerite, magnetite, and quartz.

Not infrequently with the magnetite is a variable quantity of hematite. In some cases this appears to have been an early development, simultaneous with the magnetite, and in other cases it has resulted from the weathering of the rock, developing either from the magnetite or from the grünerite. Less frequently limonite is found in similar relations. A common hornblende appears in some cases to be separable from the grünerite by a decided pleochroism, and the two often occur in the same section or intergrown in the same individual. Not infrequently the quartz grains have a peculiar parallel arrangement, with their longer axes in a common direction, and with this an undulatory extinction. This is taken as indicating that these rocks have been subjected to stress during or subsequent to the time the quartz developed. The grünerite and magnetite are closely associated, often penetrating each other, and are also found within and penetrating the quartz, showing that the minerals developed to some extent simultaneously, although the quartz appears on the whole to be somewhat later than the grünerite and magnetite. In the finer-grained phases opaline silica is also present. As in the case of the sideritic slates, some of the grüneritic schists contain interstratified or intermingled fragmental material, and the rock by transition passes downward into the fragmental Siamo slate. In these kinds ordinary hornblende has abundantly developed, and chlorite and biotite are important secondary products. Sometimes associated or included in the magnetite-grünerite-schists is a great deal of secondary garnet, and this is particularly abundant adjacent to greenstones, showing that its development is related to the intrusives (see pp. 513–514).

The development of the grünerite-magnetite-schists, in contrast with the ferruginous slates, cherts, and jaspers, seems to have been favored by deep-seated metasomatic changes, rather than by weathering processes. This is indicated by the following facts: Where weathering has been active, the ferruginous slates and cherts are found rather than the grünerite-magnetite-schists; the grünerite-magnetite-schists where weathered have been partly transformed into the ferruginous slates or cherts; the grünerite-magnetite-schists are usually closely associated with the greenstones. This suggests that the heat of these intrusives increased the activity of percolating waters; possibly also the heat helped to decompose the iron carbonate; and the greenstones may also have furnished alkalis to assist in the solution of silica. The silica in solution united with the protoxides present to produce the grünerite and other amphiboles, the excess of iron oxide, not completely oxidized, remaining as magnetite.

The *ferruginous slates* (Pl. XIX) consist of cherty silica, like that of the sideritic slates, and of hematite and limonite, the latter minerals occupying the place of the siderite in the sideritic slates. Where the iron oxides are abundant the slides consist of a continuous, ramifying mass of hematite and limonite, within which the numerous patches or particles of cherty silica are set. Where the silica is abundant the reverse relations obtain. The manner in which this phase of rock developed from the sideritic slate has already been indicated.

The *ferruginous cherts* (Pls. XX–XXIII) differ from the ferruginous slates chiefly in that the silica has been more extensively rearranged. As a consequence of this the chert and iron oxides are more or less concentrated in alternating bands, instead of being uniformly mingled in a mass, as in the ferruginous slates. However, the chert bands are never free from the iron oxide, nor are the iron-oxide bands ever free from the chert. Between almost pure iron oxide and almost pure chert bands there are all gradations. The silica of the chert is usually completely individualized, but in different sections varies from partly amorphous through finely crystalline to rather coarsely crystalline. The quartz which does not show evidence of much rearrangement is very like in size of granules and in appearance to the quartz of the sideritic slates, but that in veins and filled areas is much more coarsely crystalline. In arrangement the particles of iron oxide appear to be wholly independent of the quartz. There is no apparent concentration of the iron oxides between the quartz grains, but they occur concentrated in laminæ or as separate flecks included in the grains of quartz, just as though they were all in their present positions before the silica began to crystallize. In the ferruginous cherts which are near the ore bodies cavities are very common, due to the solution of the quartz. These cavities have often been subsequently partly or wholly filled by hematite. In all these particulars these ferruginous cherts are similar to those from the Penokee and Animikie districts, but they differ from them in not showing extensively the somewhat remarkable concretionary structure characteristic of those districts, although in a few places this is well developed.

The Marquette ferruginous cherts have been subjected to profound dynamic action, and the brittle rock has become shattered through and through, producing innumerable cracks and fissures, and not infrequently reibungsbreccias (Pls. XXI–XXIII). Within the spaces thus produced secondary hematite and magnetite in well-defined crystals have formed. By the crystal outlines the secondary iron oxide can frequently be discriminated from that present before the mashing occurred. The metamorphosing processes were so long continued within the ferruginous cherts that it could not be expected that residual siderite should occur, yet in one or two cases a small quantity is found. However, in the field the gradations are so complete that one can not doubt that these rocks were produced by the alteration of an original sideritic chert, combined with secondary infiltration. It is highly probable that much of the iron oxide and much of the silica now present were derived from an iron carbonate once above the ferruginous cherts, but now removed by erosion. The ferruginous slates represent the kinds of rock produced by the simple oxidation in place of the original sideritic slates, and from them, by the secondary actions described, are produced the ferruginous cherts As in the case of the sideritic slates and the grünerite-magnetite-schists, fragmental material is occasionally recognized.

In thin section the *jaspilites* (Pls. XXIV–XXVII) have a minutely laminated character, each of the coarser bands, as seen in hand specimen, being composed of many laminæ, due to the irregular concentration of the iron oxide. These laminæ are of greatly varying width. They unite and part in a most irregular fashion, producing a mesh-like appearance, and frequently laminæ disappear, as do the coarser bands. The complex, bright-red jasper bands are composed mainly of finely crystalline cherty quartz, but they are everywhere stained with minute particles of blood-red hematite. The particles of quartz average less rather than more than 0.01 mm. in diameter, and each of these minute grains contains one or more particles of hematite. These are concentrated in laminæ or are separate flecks included in the quartz grains. In some cases the hematite appears to be somewhat concentrated between the grains, but in general it is arranged in entire independence of them, as though it were present before the silica had crystallized. The most ferruginous bands contain a predominant amount of iron oxide, but in them is included much quartz, exactly similar to that of the jasper bands. The original, translucent, red, mashed hematite is easily discriminated from the secondary, crystal-outlined hematite and magnetite.

The folding, faulting, fracturing, and brecciation, spoken of in hand specimen (Pls. XXV and XXVI), are beautifully shown under the microscope. The resultant cracks and crevices are filled with secondary quartz and crystalline hematite and magnetite. This quartz is much more coarsely crystalline than the older quartz, the grains oftentimes averaging from 0.05 to 0.1 mm. in diameter. While much of this secondary quartz occurs in veins which cut across the original lamination of the rock, a great deal of it was deposited parallel to the lamination. Its likeness to the vein quartz and its coarseness readily discriminate it from the earlier quartz. The crystal-outlined hematite and magnetite also help to fill the veins and the spaces between the micaceous hematite laminæ between which accommodation took place. The secondary material usually fills the spaces entirely, thus completely healing the rock, and because much of the material is arranged parallel to the original lamination the structure is emphasized by the secondary impregnations.

It has been noted that the jaspilite is characteristic of the uppermost horizon of the iron-bearing formation—that is, it is immediately below the next overlying series. This contact zone was one of the great planes of accommodation, and thus the dynamic effects upon the jasper are explained. Between the jasper horizon and that at which the ferruginous cherts occur is a transition zone. In this the layers of siliceous material sometimes have borders of red, iron-stained quartz. It has been explained that the chief differences between the jaspilites and ferruginous cherts are the blood-red character of the minute hematite particles and the micaceous character of the ferruginous layers of the former. It appears highly probable, therefore, that dynamic action transformed the ferruginous chert into the jasper, the layers of earthy hematite being sheared into micaceous hematite, and the inclusions of earthy hematite being changed into the blood-red variety.

The foregoing general description is of the rocks as they occur in the eastern part of the district. At the west end of the district the predominant varieties of the Negaunee formation are the grünerite-magnetite-schists and the jasper. There are also subordinate amounts of ferruginous chert. In this part of the area the rocks are much more coarsely crystalline than in the eastern part of the district (Pl. XXIII). The quartz grains in the extreme western end of the district have diameters averaging from 0.10 to 0.15 mm., and in the southwest arm they average about 0.20 to 0.40 mm., and run as high as 1 mm. It will be seen that the size of the grains is many times greater than in the Ishpeming-Negaunee area, where the average diameters vary from less than 0.01 mm. to 0.03 mm. The quartz grains of the western area are of sufficient size to show distinctly undulatory extinction and fracturing, the latter rarely in a rectangular manner. In the more mashed varieties they are arranged, to some extent, with their axes in a common direction. The grünerite is also coarsely crystallized. Exact comparison with the grünerite of the Ishpeming area is, however, difficult. The jaspers of the western end of the district afford a good opportunity to observe the relations of the included particles of hematite and the grains of quartz. The former appear just as if they were in their present positions before the silica had taken the remaining space and crystallized. There is no tendency to concentration of this hematite at the borders of the quartz grains or in the cracks formed by their fracturing. In the jaspers and in some of the more quartzose grünerite-magnetite-schists is also a beautiful concretionary structure, exactly similar to that of the ferruginous cherts of the Penokee district. The concentric zones of red hematite, separated by a greater or less distance, appear as if painted upon the quartzose background, the grains of which seem in no way to be affected by the hematite. The crystals of hematite and magnetite formed still earlier, or else developed where the red hematite and the quartz have been dissolved, for they are scattered at random through the section, interrupting the concentric zones of hematite at many places. In some slides the concretions are decidedly flattened by pressure.

The foregoing facts show that in these jaspers the minerals, with the possible exception of the crystals of hematite and magnetite, had assumed their present relations before the last orogenic movement. The concretions, the coarsely crystalline character of the rocks, and the absence of the sideritic and ferruginous slates imply a much more nearly complete recrystallization of the entire formation than has taken place in the eastern part of the district. If the original rocks in the western part of the district were of the same character as about Ishpeming and Negaunee, the silica must have entirely recrystallized. It is to be noted that in this part of the district the other formations of the Marquette series are also much more profoundly metamorphosed than they are farther east. Therefore the unusually modified character of the rocks of the Negaunee formation accords with what would be expected from a study of the other formations.

On account of the opacity of the *iron ores*, comparatively little is learned by a study of their thin sections.

The magnetites are perfectly opaque in transmitted light, and in reflected light give the characteristic spotty appearance of that mineral. Where not pure the usual minerals contained in the iron formation appear with their ordinary relations. Those most plentifully seen are quartz, grünerite, muscovite, and biotite. Occasionally garnet, and chlorite as an alteration product, are abundant. Bordering the included material, the magnetite invariably shows crystal outlines. As a result, each area of included minerals has a serrated form.

The coarse specular hematites are made up mainly of large, closely fitting flakes of hematite, the majority of which take an imperfect polish, and have, therefore, a gray, sheeny, spotted appearance. The flakes which are parted along the cleavage reflect the light like a mirror. The large number of individuals of this kind is appreciated only by rotating the sections. This brings successively different flakes of hematite into favorable positions to reflect the light into the microscope tube. In some sections cut transverse to the cleavage the schistose character of the rock is apparent in reflected light, innumerable laminæ of hematite giving fine, narrow, parallel, dark and light bands, which are comparable in appearance to the polysynthetic twinning bands of feldspar. As both the magnetite and the hematite are usually opaque, the two minerals in general can not be discriminated, although in some cases the crystal forms of magnetite are seen, and a small part of the hematite, much of it in little crystals, shows the characteristic blood-red color. The important accessory minerals are quartz, grünerite, feldspar, and muscovite. Some of the small, detached areas of quartz and feldspar appear to be fragmental. The muscovite occurs mainly in small, independent flakes, but some of it is apparently secondary to the feldspar.

The fine-grained specular hematites differ from the so-called micaceous hematites chiefly in that much more of the hematite is translucent, and hence at the edges and various places through the centers of the slides is a brilliant red color. The slate ores in reflected light show the laminated character of the rock, while the massive ores give the peculiar spotty reflections, exactly the same as magnetite.

The mottled red and black specular ores in reflected light present a peculiar appearance, the true specular material giving the usual brilliant, spotty reflections, while the soft hematite has a brownish-red color.

The soft hematites in transmitted light, in many slides, show the characteristic blood-red color of hematite, although for the most part the sections are so thick as to give a brownish appearance or are opaque. In the softest ores in reflected light a dark brownish-red color is everywhere seen, which is much less brilliant than that presented by the same mineral in transmitted light. In some of the soft hematites, however, within the mass of red material are many small areas which reflect the light in the same manner as the specular ores. The limonitic hematites differ from the pure hematites only in that, in both transmitted and reflected light, in many places, the reddish colors are not so bright.

The foregoing description shows that there are gradations from the coarsest magnetite to the softest limonitic hematite.

INTERESTING LOCALITIES.

The localities where the Negaunee formation is exposed are so numerous that only more important areas of exposures will be here mentioned.

Michigamme and Spurr.—At Michigamme and Spurr mines (Atlas Sheet V), and in the area connecting them, are very good exposures of the Negaunee formation of a somewhat exceptional character. At the lowest horizon, adjacent to or underlying a great greenstone ridge, are typical exposures of magnetite-grünerite-rock and magnetite-grünerite-schist. Locally the schist mantles areas of intrusive greenstone (Pl. XI), and the latter in other places includes many fragments of the schist (Pl. XII). The grünerite-magnetite-schists are overlain by coarse typical red jaspilite, which at several places is just above the greenstone. The jaspilite of this locality differs from that of most of the district in that the pure jasper bands are of unusual width, sometimes reaching a thickness of 6 to 8 inches. Between these jasper layers are belts of specular micaceous hematite, the laminæ of which show slickensides, indicating that readjustment has occurred between them. The jaspilite varies upward into a banded rock consisting of alternate layers of pure, white, finely crystalline quartz and dark bands composed of hematite and magnetite (Pl. XXIII). Intermediate layers show the transition between the rocks having bands of white and of red quartz. The grains of the jasper and white quartz belts are larger than those of the ordinary varieties of jasper, and are to a large degree crystal-faced, as shown by the innumerable reflecting facets when held in the sun. At the top of the formation is a thin belt of ore, making up a part of the ore body of the Michigamme mine. The remainder belongs with the Ishpeming formation. The bands of white chert and red jasper have frequently a lenticular character. The rocks are often folded and fractured in a minor way. The cracks are filled with secondary magnetite, and more rarely grünerite. In some places the folding was so severe as to make genuine breccias. At one place, a short distance east of the Spurr mine, the inter-Marquette erosion cut away all of the jasper, and here the grünerite-magnetite-schist is at the top of the formation. A minor fold here occurs, so that in a single exposure the strike may be seen to vary from an east-west direction to a northwest and finally to a north direction. North of the Spurr mine minor corrugations are seen, which give local northern dips in the general southward-dipping formation.

In thin section much of the Michigamme and Spurr jaspilite shows a concretionary arrangement of the iron oxide, many of the concretions being made up of a large number of concentric rows of hematite and magnetite particles. While much of the hematite is in small particles or areas in these concretions, in many of them are large crystals, which look like later infiltrations. The quartz is much more coarsely crystallized than the quartz of the formation in the main area about Ishpeming and Negaunee and to the south and east of these towns, the average grains being from 0.10 to 0.15 mm. in diameter. Each of these quartz grains contains a large number of the smaller crystals and flecks of hematite. Also included in these quartzes are numerous long, minute, curved needles of rutile. The grünerite of the jaspers has usually a distinct pleochroism, giving yellow and greenish colors. As usual, the grünerite has a tendency to be associated with the magnetite and hematite. In one case an opaque crystal of hematite or magnetite was found to be surrounded by blades of grünerite, each blade being parallel to one of the sides of the crystal. Where the concretionary jasper is mashed, the concretions have an oval form, the longer axes being in a common direction. In the banded ferruginous rock containing white quartz layers (Pl. XXIII) the quartz grains contain very little oxide of iron. Why this material is absent here and present in the jasper is not apparent. The grains of quartz in both the red and white siliceous layers in many slides have crystal outlines, appearing in thin section as closely fitting polygonal areas.

By an increase of magnetite and grünerite and a decrease of hematite the jaspilites pass into typical grünerite-magnetite-schists. Each quartz grain includes hematite and magnetite crystals, and often blades of grünerite. A concretionary arrangement of iron oxide occurs in the transition phases. Pleochroic hornblende is absent. In the most strongly grüneritic rock, which is prevalent near the base of the formation, the quartz almost disappears, and there is a background composed of interlocking blades of grünerite which include a large amount of magnetite, and thus they become grünerite-magnetite-rocks. The iron ores are magnetites.

Boston and Dexter areas.—East of the Michigamme mine the exposures of the Negaunee formation are rare for nearly 15 miles. However, in the SW. ¼ sec. 32, T. 48 N., R. 28 W., is the Boston mine (Atlas Sheet XVIII). In secs. 3 and 4, T. 47 N., R. 28 W., are a number of exposures of the formation (Atlas Sheets XIX and XXII), and north of the center of sec. 3 is the Dexter mine. On the line between secs. 3 and 4 is the contact between the Negaunee formation and the Goodrich quartzite. The unconformity between the two formations is here not marked. The two are slightly overturned, so that the quartzite appears to lie under the Negaunee jasper. A short distance to the northeast is a hill composed largely of the Negaunee formation, but at the foot of its northern slope is found the Siamo slate, so that at this place we have the Negaunee formation accurately delimited above and below.

Excelsior area.—East of the Dexter mine there are again no exposures of the formation for 2½ miles. However, in secs. 4, 5, and 6, T. 47 N., R. 27 W. (Atlas Sheet XXV), the Negaunee belt is exposed at very numerous localities. The formation here has usually a somewhat regular east-west strike and a southern dip. In a few places, especially in sec. 4, minor folds and brecciation were observed. At the old Excelsior mine, just west of the east line of sec. 6, the contact is again exposed between the Negaunee formation and the Goodrich quartzite, and here the evidence of unconformity is strong, the quartzite and slate appearing to mount upon and mantle around the Negaunee strata on the east side of the pit. In these exposures the rock is mainly ferruginous chert. In thin section the quartz is of the finely crystallized kind of the Ishpeming-Negaunee area, and thus contrasts with that of the Michigamme and Spurr area.

Lake Bancroft area.—Upon the south slope of the bluff north of Lake Bancroft (Atlas Sheet XXVIII), and at various places in the little valley separating the two ridges of greenstone north of this lake, are found exposures of hematitic, magnetitic, grüneritic schists. These appear to have been caught in the intrusive rocks. It is interesting to note that all of the rocks here found are of the grünerite-magnetite-schist variety, while the ordinary phases of the formation, both to the west and to the east, are the ferruginous cherts and jaspers, except the grüneritic and sideritic slates adjacent to a greenstone a short distance east of Lake Bancroft, in the north part of the city of Ishpeming. In thin section the Lake Bancroft rocks show a peculiarly finely crystalline or partly amorphous siliceous background. Also, the larger part of the iron oxide is in the form of hematite, this being due to weathering. The grünerite is stained deep-red by hematite.

Teal Lake area.—The next important exposures to the east are those of the Teal Lake iron range, just south of Teal Lake (Atlas Sheets XXVII and XXVIII). The interest in this locality lies in the fact that the ferruginous chert of the Negaunee formation rests directly upon the Siamo slate. As has been said, the uppermost horizon of the latter formation is here a slaty graywacke, or a rock approaching a ferruginous quartzite. At many places the change from the slate to the iron formation is sudden, the clean ore or the ferruginous chert resting upon the ferruginous slate or graywacke with no transition horizon. At other places there are minor interlaminations of the two. The ferruginous chert of the iron formation has a very regular strike and dip, being remarkably free from the minor folding which is so prominent in the iron formation to the southward.

As examined in thin section, the ferruginous slates and cherts of this locality differ from those of other places only in that the lower horizons show a certain amount of fragmental quartz mingled with, or in layers interbedded with, the nonfragmental material. This clastic quartz is often enlarged. Also mica is occasionally seen.

Negaunee-Ishpeming area.—South of the Teal Lake range are numerous exposures adjacent to the mines of Negaunee-Ishpeming and vicinity (Atlas Sheets XXV and XXVIII). Here, as has been explained, the iron formation occupies the lower lands, usually those below the 1,400-foot contour (Pls. XIII and XIV). The exposures are in a series of bay-like areas, which open out to the west, but are surrounded and overtopped to the north, east, and south by amphitheaters of greenstone (Pl. XIII). In these bays are found some of the great mines of the area, such as the Cleveland Cliffs, Lake Superior, Lake Angeline, and Salisbury. At or close to the contact with the Goodrich quartzite the rock is always typical banded ore and jasper or jaspilite (Pls. XVI, XXIV–XXVII), and at the lower horizons it is the typical ferruginous chert (Pls. XX–XXXII). Between the two there are often gradations, but often also they are separated by a dike of altered greenstone. Mining has shown that the masses of greenstone not only border but underlie the bays of iron formation, being, however, deeper below the surface in passing west, thus making westward-plunging basins of greenstone in which the Negaunee formation material rests (Pl. XIII). At the bottoms of these basins are the great ore deposits of the district.

Thus in this area are found the largest ore deposits and the most numerous varieties of the ferruginous chert and jasper. The strike of the formation is generally east and west, corresponding to the close north-south folds; but as the folding is highly complex, this probably being in part due to the intrusive greenstones, strikes in all directions may be found. The ferruginous chert and jasper are most intricately crumpled, and are broken and faulted in a minor way. The brilliant appearance of the crumpled and sometimes brecciated jasper may be particularly well seen on the so-called jasper bluff southeast of Ishpeming (Pls. XXV and XXVI). In the exposures, and particularly in the open pits and waste-dump material of the mine, may be seen all stages of the processes of replacement of the siliceous bands of the ferruginous chert and jasper by iron ore.

At Negaunee a section from the Jackson mine to the southeast (Atlas Sheets XXVIII and XXXI) gives the fullest known succession from the jasper above to the comparatively little altered grünerite-siderite-slate below. At the Jackson open pits exposures of the Negaunee formation is beautiful typical banded jaspilite (Pls. XXIV and XXVII, fig. 1). To the south the red quartz is somewhat suddenly replaced by the white quartz, and in place of the jasper we have the ferruginous chert (Pls. XXI and XXII). This jasper and ferruginous chert, while having a general northward dip, shows minor crenulations, faulting, and brecciation, becoming not infrequently a genuine reibungsbreccia. As the ridge of greenstone is neared in the southeast part of sec. 1, the rocks of the iron formation change gradually from the typical broken ferruginous chert to a somewhat regularly laminated ferruginous slate, in which a large part of the oxide of iron is limonite. The change from this ferruginous slate to the ore is very beautifully shown at the Grand Rapids mine. To the south of the greenstone ridge there at once appears the sideritic grünerite-magnetite slate. While the section is not complete, no one can study this locality without becoming convinced that the evenly banded sideritic slate (Pl. XVII, fig. 1) to the south is the rock from which the regularly laminated ferruginous slates and grüneritic slates have developed, and that from these the ferruginous chert, jasper, and ore bodies have been formed by combined dynamic action, metasomatic change, and infiltration. In thin section the rocks of the Ishpeming and Negaunee area include all phases of the ferruginous cherts and jaspers found in the eastern part of the district. To describe them would be but to repeat the general description of these rocks.

Area southeast of Ishpeming.—In the broad area south of Negaunee and east of Ishpeming (Atlas Sheets XXVIII, XXIX, XXXI, and XXXII), very largely composed of greenstone, there are everywhere found, in the valleys between the greenstones, exposures of sideritic slates, sideritic grünerite-magnetite-slates, grünerite-magnetite-schists, ferruginous slate, and occasionally ferruginous chert. The widespread distribution of the grüneritic and magnetitic phases of the formation, in connection with these greenstones, at once suggests that the intrusive rocks are the cause of the development of these varieties of the Negaunee formation from the sideritic slates, rather than the ferruginous cherts and jaspers. How this alteration occurred has already been explained in the general description of the grünerite-magnetite-schists (pp. 359–361, 368–369). The presence of much residual siderite in this area is doubtless partly explained, at least, by the protective influence of the greenstones, and possibly also by the relatively impervious character of the secondary grünerite-magnetite-schist as compared with the broken ferruginous cherts and jaspers.

In thin section all the varieties of rocks described under the general description (pp. 358–375) as cherty siderites, magnetitic, grüneritic, and sideritic slates, magnetitic and grüneritic schists, and ferruginous slates, are found, with all of their transition varieties. To give a description here would be substantially to repeat that already given, and a few only of the peculiar features will be mentioned.

It is in this area that the very finely crystalline and apparently partly amorphous forms of silica are found. In some cases the siliceous background seems to be almost nonpolarizing. In a more advanced stage of alteration, minute opaline droplets or granules, averaging perhaps 0.01 mm. in diameter, and surrounded by films of iron oxide, constitute the background. These droplets or granules are rather characteristic of the early stages of the rearrangement of the silica. The silica is, however, ordinarily completely individualized, and occurs either in granules similar to the droplets or in ordinary chert, the grains averaging in some sections as much as 0.03 mm. in diameter. The hematite in the ferruginous slates, even where the siderite has wholly disappeared, has a decided tendency to occur in rhombohedra. At the lower horizons of the formation, where fragmental material begins to appear, certain peculiar varieties are found. In some cases there are seen large feldspathic areas, which appear to be partly altered into or replaced by the magnetite, grünerite, and quartz. Small, distinctly fragmental grains of quartz are plentiful. Not infrequently the quartz grains have their greatest diameters in the same direction and have a common extinction. In some slides these parallel-arranged individuals cut almost at right angles across the belts of magnetite and actinolite. These facts suggest that the quartz is a secondary material, which has arranged itself as demanded by the differential pressure. In other slides the quartz has a peculiar irregular extinction, which reminds one of half-individualized material. It appears unlike truly cherty or chalcedonic quartz, and yet is unlike granulated, coarse-grained quartz. Where these peculiar varieties of quartz occur the iron oxide is very largely magnetite, mostly in the form of small crystals. In many slides the amphibole is decidedly pleochroic, and in some of them it gives beautiful blue and violet colors. The particles are so small that they could not be isolated, but it is thought that this amphibole developed at the lower horizons because in the mingled nonclastic and clastic material a wide variety of chemical elements were available. In passing from this area toward the Ishpeming and Negaunee area the quartz shows more and more of rearrangement and becomes more coarsely crystalline, grading into the irregularly laminated varieties which have been denominated ferruginous chert.

Cascade range.—Passing now to the east end of the southern belt, at the Cascade range, in secs. 28, 29, 30, 31, 32, and 33, T. 47 N., R. 26 W. (Atlas Sheet XXXII), we find the most extensive exposures of ferruginous chert and jaspilite in the district. Also there are here complete sections from the Ajibik quartzite below to the Goodrich quartzite above. Where the formation has considerable width, as in sec. 28, the lower horizons of the formation are the typical ferruginous chert, but as the Goodrich quartzite is approached the rock, as usual, becomes typical jasper. In the W. ½ secs. 29 and 32, and in secs. 30 and 31, where there is only a comparatively narrow belt of the Negaunee formation between the Ajibik quartzite and the Goodrich quartzite, the whole of the formation is typical banded jasper. It is this locality which strongly suggests that the position of the iron-formation rocks with reference to the overlying Goodrich quartzite, rather than the particular horizon of the formation, determines whether the rock is mainly ferruginous chert or jaspilite; for in secs. 28 and 33 the same horizon is ferruginous chert which a mile or two to the west is typical banded jasper.

In the great exposures in secs. 29, 30, 31, and 32, the folding, brecciation, and minor faulting of the formation are particularly well shown. At many places between the Platt mine and Cascade Brook are seen the transition phases between the Negaunee jasper and the Ajibik quartzite.

In thin section the ferruginous chert and jasper of the Cascade area are in no respect different from those of the Ishpeming-Negaunee area except that in the lower horizons fragmental quartz appears in the slides as disseminated grains and in minute layers.

Foster-Lowthian area.—Passing to the west, there are again great exposures of the ferruginous chert in secs. 21, 22, 23, 26, and 27, T. 47 N., R. 27 W. (Atlas Sheets XXVI and XXIX). In the northeast part of sec. 20 is a bluff consisting of massive greenstone, greenstone-schist, and greenstone-conglomerate. On the south side of this knob the greenstone-schist and grünerite-magnetite-slates appear to be interbanded, the layers varying from a few inches to several feet across. There are also several exposures of grünerite-magnetite-schist on top of the bluff. Whether the greenstone is an intrusive which has caught fragments of the Negaunee formation, or whether it was a contemporaneous volcanic, was not positively determined, but the latter is perhaps the more probable. The occurrences here again strongly suggest that the igneous rock is the cause of the development of the grüneritic and magnetitic kinds of the Negaunee formation. Just to the north of the greenstone, at the open pits of the Lowthian mine, are typical exposures of ferruginous chert.

Saginaw-Goodrich area.—In the neighborhood of the Saginaw and Goodrich mines, in sec. 19, T. 47 N., R. 27 W. (Atlas Sheet XXVI), are again nearly continuous exposures from the Ajibik quartzite below to the Goodrich quartzite above. This locality, however, differs from the Cascade range in that the southern exposures of the Negaunee formation are the typical grüneritic and magnetitic slates. These are, however, cut through by greenstones, which again suggests that the grüneritic and magnetitic character is due to intrusive rocks. At the bottom of the formation are found ferruginous quartzites, which stand as a transition horizon between the Ajibik quartzite and the Negaunee formation. For the most part the grünerite-magnetite-slates have a somewhat uniform strike and dip, but in places they are folded into a series of minor isoclinal folds, the axes of which pitch to the north with about the general dip of the formation. In horizontal plan the beds of one of the folds are shown by fig. 23. On the north slope of the ridge of the grünerite-magnetite-schists this material grades rapidly into the ferruginous chert. A number of subordinate folds are observable at the open pits of the Saginaw mine. These have superimposed isoclinal folds of the third order. As a result of the many minor foldings and crinklings, the rocks are much broken. The strata of these minor folds were truncated by the inter-Marquette erosion, and consequently the Goodrich quartzite cuts across the bedding of the Negaunee formation at various angles. For instance, at the old Goodrich mine, at one place the strike of the jasper is almost parallel to that of the overlying Goodrich quartzite, but a little distance to the east abuts perpendicularly against it (figs. 20 and 21, p. 335).

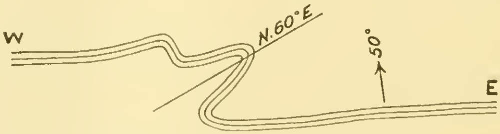


FIG. 23.—Horizontal plan of one of the minor pitching isoclinal folds in the grünerite magnetite-schist.

Escanaba River area.—West of the Fitch mine, sec. 24, T. 47 N., R. 28 W., there are no exposures of the iron-bearing formation for more than 4 miles. However, in sec. 20, just north of the Escanaba River, and in sec. 21, T. 47 N., R. 28 W. (Atlas Sheet XX), are exposures of grünerite-magnetite-schist, which grade below into a novaculitic rock or into a biotite-slate. These are apparently transition varieties between the Negaunee formation and the Ajibik quartzite. These biotite-slates are very similar to the transition rocks between the Negaunee formation and the Siamo slate at Michigamme.

In thin section the grünerite-magnetite-schists are in all respects similar to the far more extensive exposures of Mount Humboldt, described immediately below. The biotite-slates are identical with those near the top of the Siamo formation at Michigamme, even in the matter of the development of a certain amount of hornblende and garnet. The novaculite, which occurs at one place, has a fine-grained quartzose background, and between the particles are innumerable minute flakes of sericite. Coarser bands between the finer-grained ones distinctly show the clastic character of the quartz grains.

Humboldt area.—West of sec. 20 there are no exposures for a mile or more, but in sec. 18 appears the southeastern end of the Mount Humboldt ridge (Atlas Sheets XVI and XIX). This is of minor importance in sec. 18, but in secs. 11 and 12, T. 47 N., R. 29 W., south of Humboldt, becomes an important bluff, with steep-faced sides and an uneven top. Everywhere upon the ridge are large and numerous exposures of the Negaunee formation. Except upon the north and west borders, the rocks of the Negaunee formation are all dense, fine-grained, but distinctly banded grünerite-magnetite-schists. The strike generally corresponds with the trend of the formation. In the ledges in sec. 18, southeast of the road, the schistosity is nearly east and west, while the true bedding, as shown by the minor folds, is southeast and northwest. The axes of these minor folds plunge to the southeast. On the north and west faces of the bluff the strikes vary with its form, being parallel to its face—that is, in passing from the north face of the bluff toward the west the strikes gradually change to the southwest, then to the south, and in the southwestern part even to the southeast. The dips are very generally to the north or northeast, but in the southwestern part of the area there are, for short distances, reverse or southern dips. Between the ledges having a north and those having a south dip there is a little valley, which is therefore on the crown of the anticline. This strongly suggests for this part of the area a quaquaversal or dome structure, although it is thought that the anticline spoken of is of a second order, being a subordinate bend in the general northward-dipping beds. The secondary fold shows superimposed folds of the third order, and these again those of the fourth order, and so on, until microscopic plications are reached. Where the change of strike is the most rapid—that is, at the northwest and southwest corners of the bluff—the plications are closest, and in some places the rocks are brecciated. Throughout the central part of the bluff the exposures of greenstone are almost as abundant and numerous as those of the grünerite-magnetite-schist (Pl. XXXIII). The very considerable width of the belt of grünerite-magnetite-schist in secs. 11 and 12, as compared with its breadth to the southeast, may be in part due to the large amount of intrusive greenstone, the formation having been spread out, as it were, by the entering material. As seen in cross-section, the greenstone occurs in dome-like forms under the schists, or as masses cutting across or between the layers. In some cases the dip of the schists is comparatively little affected by the intrusive greenstone (fig. 17, p. 330), but in other cases the schist to some extent mantles over the greenstone, although the schistosity is cut across on one

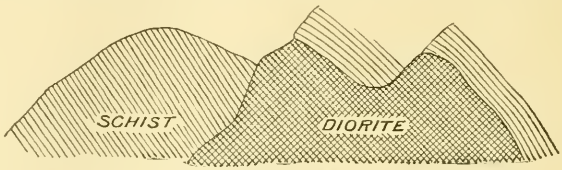


FIG. 24.—Section showing relations of grünerite-magnetite-schist and intrusive diorite on Mount Humboldt.

side, and the dips remain prevailingly to the north (fig. 24). As seen in plan, the greenstone often appears as oval areas surrounded by the schists, the latter curving about the intrusive areas, as if bent by it (fig. 25).

The grüneritic and magnetitic rocks of Mount Humboldt rest upon the Ajibik quartzite below, and are overlain upon the north and west slopes of the bluff by a thin belt of jaspilite, connecting the row of mining pits which

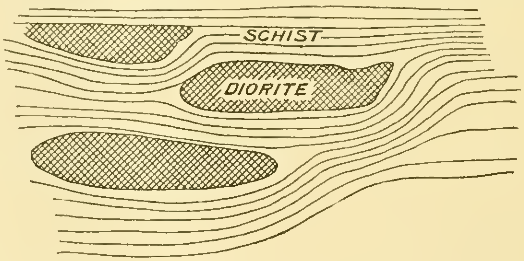


FIG. 25.—Plat showing relations between grünerite-magnetite-schist and intrusive diorite on Mount Humboldt.

extend from the old Humboldt to the Barron mine. This jaspilite is in most respects like that at Michigamme, different places showing beautifully the white and red siliceous bands and varieties intermediate between the two. However, at Mount Humboldt the jasper is extremely plicated, often brecciated, and the ferruginous bands are most brilliant, coarse-grained, micaceous hematite. As is usual, the crevices formed by the folding, both parallel and transverse to the lamination, are healed by crystalline magnetite. No transition varieties between the jasper and the grüneritic rocks were here seen. The annular area where such rocks would occur, if they exist, shows no exposures.

At the south end of the Barron mine, at the southwest end of the bluff, it is said that a diamond-drill passed at once from the jasper to the granite. If this be true, the Ajibik quartzite is here very thin, and it is not impossible that the whole of the Lower Marquette series for some distance west of Mount Humboldt was cut out by the inter-Marquette erosion.

Under the microscope the grüneritic rocks on Mount Humboldt for the most part prove to be but slightly quartzitic, being composed almost wholly of grünerite and iron oxides. Many of the slides consist of a nearly solid mass of grünerite, in which is contained comparatively little iron oxide. While the blades to some extent are in various directions, there is a distinct tendency for the longer axes to have a parallel arrangement. These grünerite rocks grade into those in which the magnetite and hematite are plentiful. Of the iron oxides, magnetite is predominant, and the hematite seems to be, in part at least, an oxidation product of the magnetite. Much of the magnetite is in crystals or clusters of crystals. Where the iron oxides are abundant they are usually more or less concentrated into bands. Sometimes the parallel blades of grünerite, following the schistosity, are diagonal or perpendicular to the bands of iron oxide. Not infrequently the magnetite-grünerite-rocks are garnetiferous. The garnets include a large amount of grünerite in the grünerite-rocks, and of magnetite and grünerite in the magnetite-grünerite-rocks. The grünerite needles may be seen penetrating the garnets in all directions. The garnets appear to have been the latest development and to have included or absorbed the previously existing minerals. These garnetiferous varieties are particularly abundant adjacent to the greenstone masses and at low horizons. In some cases between an intrusive greenstone and a grünerite-magnetite-rock there is an almost solid layer of garnet. In a number of cases associated with the grünerite is a pleochroic green hornblende. This green hornblende occurs as independent blades and as parts of blades. In the latter case a blade of amphibole consists in part of grünerite and in part of green hornblende. The cleavage runs from one to the other, showing that both are parts of the same crystal individual. The two are discriminated by the color and pleochroism of the green hornblende, and by a slight difference in the extinction. The grünerite-rocks and the grünerite-magnetite-rocks are associated with a small quantity of grünerite-magnetite-schist. In the passage to the latter rock the quartz first appears as small oval areas, and finally as distinct bands. The quartz grains are penetrated through and through by the grünerite blades. They include numerous crystals of magnetite, and, except garnet, therefore appear to be the last mineral to develop. At the bottom of the formation in the southeastern part of the area mica and quartz appear, and the grünerite-magnetite-schists grade into ferruginous mica-slates belonging to the upper part of the Ajibik quartzite, or more probably the equivalent in age of the Siamo slate. These transition varieties are frequently garnetiferous.

In thin section the jaspilites of Mount Humboldt are similar to those of Michigamme. A small amount of pleochroic amphibole is present, as at that locality, and in one case this has partly altered to chlorite. The slides show remarkably well the difference between the original sheared hematite and the secondary magnetite. The former, in reflected light, may be seen in a series of extremely close microscopic folds, the laminæ of which are often broken at the more acute bends. The crystals of magnetite take a nearly perfect polish and give brilliant reflections. These are found to be largely concentrated at the places of fracturing and at the turns of the folds As is well known, these are places where spaces are naturally formed by the folding process. So marked is the difference between the reflecting power of the original sheared hematite and the magnetite that the two may be discriminated with the naked eye in section or on the polished surface. The slides of the mashed breccias, looked at with the naked eye, very closely resemble the mashed conglomerates of the overlying Ishpeming formation. The broken fragments of jasper are flattened in a common direction, the different areas overlap, and the rock has a very strongly conglomeratic appearance. However, when examined under the microscope, the fragmental quartz, almost invariably present in the true Ishpeming conglomerates, is entirely absent.

Champion area.—Passing west from Mount Humboldt, we find no exposures of the Negaunee formation for about 3 miles. Adjacent to and southeast of Champion (Atlas Sheets XII and XIII) there again appear numerous exposures of grünerite-magnetite-schist, constituting a high ridge running northwest and southeast. The rocks are very dense and refractory, retaining their glacial forms almost perfectly. They consist of alternate bands which vary in the amount of contained quartz. The strongly grüneritic bands are light-green; those with little grünerite are dull-white. While the rocks have a strike corresponding in a general way with that of the formation, they are influenced by the great masses of intrusive greenstone. This is well shown by the exposures of grünerite-schist in the SE. ¼ sec. 31, where the strike curves about the intrusive mass of greenstone. West of this intrusive is another, of less magnitude, and again the grünerite-schists have a strike parallel to it. North of the grüneritic rocks, constituting the foot-wall of some of the mining pits, is magnetitic chert similar to that of the Michigamme mine. The quartz bands are of the white variety; the ferruginous bands are largely crystallized magnetite. In thin section the grüneritic rocks of Champion are very similar to those of Mount Humboldt. They are, perhaps, somewhat coarser grained, and quartz is rather more abundant. The slides of the magnetitic jaspilite are in all respects similar to those of the foot-walls of the Michigamme and Spurr mines. The quartz is rarely coarsely crystalline. Each grain includes crystals of magnetite. Also the magnetite is in nearly solid bands between the siliceous layers. The crystals of magnetite at the borders of the bands project into the quartz. The amphibole is all of the pleochroic variety, giving blue, green, and yellow colors.

Republic area.—The remaining important exposures of the district are those adjacent to the town of Republic (Atlas Sheet XI). These are subsequently described in a separate chapter devoted to the Republic trough, but it will here be remarked that the lower part of the Negaunee formation is grünerite-magnetite-schist, while the upper part is typical coarse jasper. The lower part of the formation is much intruded by greenstones, which seem to follow the bedding of the rock in a general way for short distances, the same as at Humboldt, although the beds are also crossed. It is to be noticed, however, that, as in previous cases where the greenstones appear, the Negaunee rock is the grünerite-magnetite-schist. There are transition varieties between the grünerite rocks and the jaspilite. In certain of these the layers of grünerite-schist have outer zones or borders of jasper, suggesting that the latter developed from the same original rock under conditions more favorable for oxidation. There are at Republic excellent transition phases and interlaminated beds between the grünerite-magnetite-schist and the Ajibik quartzite. These have already been described in connection with that quartzite. (See pp. 292–294.) Between the grünerite-magnetite-schist and the red jasper, which occupies the upper horizon of the formation, there is a rock the siliceous bands of which are white and similar to those which occur at the topmost horizon at Michigamme and Spurr. In a phase intermediate between this rock and the jaspilite the white bands or oval areas of quartz have a jasper border (fig. 22, p. 362). The relations are here, therefore, just the reverse of those at Michigamme, in the latter place the red jasper being below the rock with white bands, while at Republic the jasper is above.

In thin section the jaspilites and grünerite-magnetite-schists are in nearly every respect similar to those of Michigamme and Spurr, but a concretionary arrangement of the quartz is less common. While the grünerite generally has the usual radiating arrangement, in one case it has a parallel one, resembling that of muscovite in a perfectly laminated mica-schist. At low horizons beautiful intergrowths of grünerite and green hornblende are found. In one case the amphibole of alternate bands consists predominantly of grünerite and of hornblende, but in some bands intergrowths of the two occur. As usual, garnet is plentiful, especially adjacent to the intrusive greenstones and at low horizons. At the transition horizons to the Ajibik quartzite muscovite and chlorite also appear.

Magnetic mine area.—In the southwest tongue, at the Magnetic mine, and at various places to the south (Atlas Sheet VII), the Negaunee formation consists of a coarsely banded grünerite-magnetite-schist. The amphibole, unlike that of the major part of the formation, has a decided green color. The quartz of the siliceous bands is also more coarsely crystallized than anywhere else in the formation. The magnetite occurs to a great extent in crystals large enough to be distinct to the naked eye. Many bands are composed almost wholly of grünerite and magnetite, and these are interlaminated with those in which the quartz is equally abundant with the other minerals, or becomes predominant, serving as a matrix for them.

In thin section these grünerite-magnetite-schists are seen to represent the extreme phase of metamorphism of the rocks of the Negaunee formation. The quartz is more coarsely crystallized than in any of the previously described rocks, the grains averaging from 0.2 to 0.4 mm. in diameter, and in one of the coarser varieties averaging about 1 mm. The amphibole is of two kinds, the ordinary white, slightly pleochroic grünerite, and a green amphibole. The grünerite occurs in the ordinary blades and crystals, but in some cases has a very uniformly parallel arrangement of its fibers, which is rather unusual, the ordinary varieties in other parts of the Marquette district having a radiating, sheaf-like arrangement. This may indicate that dynamic metamorphism was more severe in the area of the Magnetic mine than elsewhere. The colored amphibole has a tendency to occur in idiomorphic crystals. It gives beautiful pleochroism: $\mathfrak{c}$ is light pea-green, $\mathfrak{b}$ is dark greenish-yellow, $\mathfrak{a}$ is light transparent yellow. The absorption formula is $\mathfrak{b} > \mathfrak{c} > \mathfrak{a}$. In one case the angle $C:\mathfrak{c}$ was found to be 16°. In the same slides different bands are composed predominantly of each of the varieties of amphibole, but also in these and in other slides there are beautiful and complicated intergrowths of the two, as at Michigamme. In some cases the green variety constitutes the outer bands of the crystals; in other cases the reverse is true. In some instances nuclei of the colored amphibole are entirely surrounded by the fibrous grünerite, as though it were an added growth, and in other instances the opposite occurs. The magnetite in its occurrence is the same as in the previously described grünerite-magnetite-schists. In the gradation phases to the Ajibik quartzite, biotite, chlorite, and garnet are abundantly associated with the green amphibole.

THE IRON-ORE DEPOSITS.

THE ORE HORIZONS.

The ore deposits may be divided, according to position, into three classes, (1) those at the bottom of the iron-bearing formation, (2) those within the iron-bearing formation, and (3) those at the top of the iron-bearing formation. (Pl. XXVIII, fig. 1.) By the last is meant the horizon immediately below the next overlying formation, the Goodrich quartzite. The ore deposits of the second class frequently reach the surface, but are not at the uppermost horizon of the formation. The first two classes of ores are generally soft, and the adjacent rock is ferruginous chert or "soft-ore jasper" (Pls. XX–XXII), while those at the top of the iron-bearing formations are hard specular ores or magnetite, and the adjacent rock is jaspilite, also called "specular jasper" and "hard-ore jasper" (Pls. XXIII–XXVII). This last class of deposit frequently runs up, past the unconformity, into the Upper Marquette Goodrich quartzite, and sometimes some of these ore bodies are almost wholly in this position. Stratigraphically the consideration of these deposits ought to be deferred until the Goodrich quartzite is treated, but they are so closely connected genetically and in position with the Lower Marquette ore deposits that they are here treated.

While the larger number of ore bodies can be referred to one or another of these three classes, it not infrequently happens that the same ore deposit belongs partly in one and partly in another. To illustrate: The inter-Marquette erosion may have cut so nearly through the iron formation that an ore deposit may extend from the bottom of the formation to the top. However, in these cases the ore bodies are usually hard, and, upon the whole, are more closely allied to the third class than to the first. In many places, also, the upper part of an ore deposit may be at the topmost horizon of the iron-bearing formation, and be a specular ore, while the lower part is wholly within the iron-bearing formation and is soft ore. In some places there is a gradation between the two phases of such a deposit, but in more instances the two bodies are separated by a dike, now changed to soapstone or paint-rock.

(1) The ore deposits at the bottom horizon (Pl. XXIX, figs. 3 and 4) can occur only where the lowest horizon of the formation is present; that is, they are confined to that part of the formation resting upon the Siamo slate or the Ajibik quartzite. Hence they are found along the outer borders of the formation, and do not occur in the broad Ishpeming-Negaunee

PLATE XXVIII.

Plate XXVIII.—THE ORE DEPOSITS.

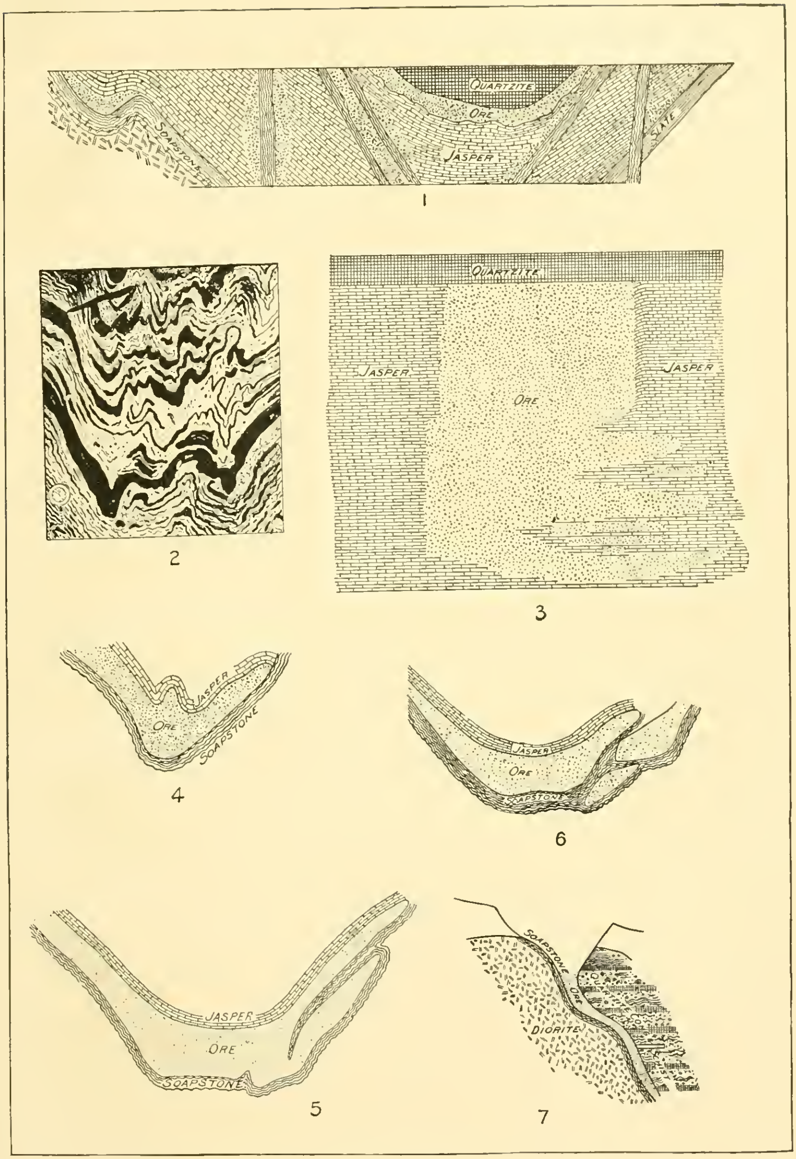
Fig. 1. Generalized section showing relations of all classes of ore deposits to associated formations. On the right is soft ore resting in a V-shaped trough between the Siamo slate and a dike of soapstone. In the lower central part of the figure the more common relations of soft ore to vertical and inclined dikes cutting the jasper are shown. The ore may rest upon an inclined dike, between two inclined dikes and upon the upper of the two, or be on both sides of a nearly vertical dike. In the upper central part of the figure are seen the relations of the hard ore to the Negaunee formation and the Goodrich quartzite. At the left is soft ore resting in a trough of soapstone which grades downward into greenstone.

Fig. 2. Sharply plicated jasper (black belts) and ore (white areas), showing shattering of the jasper and concentration of the ore. The ore is proportionally greater where the folding has been sharpest. Drawn from photograph from southeast corner of Republic horseshoe.

Fig. 3. Horizontal section of chimney of ore on east side of Republic horseshoe. The left side of the ore is bounded by cross-joints. The right side is bounded in part by a sharp flexure passing into a joint, and in part grades into the lean banded jasper and ore. Scale: 20′ = 1″.

Figs. 4, 5, and 6. Three cross-sections of ore in trough of soapstone grading downward into greenstone. In fig. 4 the ore deposit is solid. In fig. 5 a dike offshoots and nearly separates this ore body into two parts. In fig. 6 the two dikes divide the same ore body into three parts. Scale: 200′ = 1″.

Fig. 7. Cross-section of National mine. On the left is soapstone grading into greenstone. Above this is hard ore, and overlying the hard ore are interstratified conglomerate, quartzite, and schist. The ore is here plainly due to a replacement of the silica of the different sedimentary bands by ore, although the original conglomerate was heavily ferruginous. Scale: 200′ = 1″.



THE ORE DEPOSITS.

area. The best examples of these deposits are those occurring at the Teal Lake range and east of Negaunee (Atlas Sheets XXVII and XXXI). Here are situated the Cleveland Hematite, the Cambria, the Buffalo, the Blue, and other mines. These ore deposits have as their foot-wall the Siamo slate. A striking fact about these deposits is that all of those mentioned, and all of those known, occur at places where the Siamo slate is folded so as to form a trough. By reference to the maps (Atlas Sheets IV and XXVII) it is seen that all the Teal Lake mines occupy a place where the iron formation curves to the north and then swings back to its original course, the ore deposits thus resting upon a southward-pitching trough of the slate. Still more striking is the occurrence east of Negaunee. Here the ore bodies occur at places where the slate is folded so as to furnish sharply pitching synclinal troughs, which plunge to the west. (Pl. XXIX, figs. 3 and 4.) It is further found, by an examination of the workings, that the iron-bearing formation is often cut by a set of steep or vertical dikes, and that the conjunction of these dikes with the foot-wall slate forms sharp V-shaped troughs. This is particularly clear in the case of the Cleveland Hematite mine, where, between a series of vertical dikes and the Siamo slate, the ore bodies are found. By comparing this occurrence with the ore deposits of the Penokee range,[1] it will be seen that they are almost identical, in each case there being on one side of the formation an impervious slate and quartzite, and upon the other an impervious dike, the two uniting to form a pitching trough.

(2) The typical area for the soft-ore bodies within the iron formation is that of Ishpeming and Negaunee. Here belonging are such deposits as the Cleveland Lake, the Lake Angeline, the Lake Superior Hematite, the Salisbury, and many others. When these deposits are examined in detail it is found that the large deposits always rest upon a pitching trough composed wholly of a single mass of greenstone (Pl. XXVIII, figs. 4–6), or on a pitching trough one side of which is a mass of greenstone and the other side of which is a dike joining the greenstone mass. The underlying rock is called greenstone, although immediately in contact with the ore it is known as paint-rock or soapstone by the miners.

[1] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey, Vol. XIX, 1892, pp. 268–294.

However, a close examination of numerous localities shows that the greenstone changes by minute gradations into the schistose soapstone, and this into the paint-rock, and that therefore these phases are merely parts of the greenstone which have been profoundly altered by mashing and leaching processes and which have been strongly impregnated by iron oxide. Many of the thinner dikes are wholly changed to paint-rock or soapstone, or to the two combined. The larger number of these troughs are found along the western third of the Ishpeming-Negaunee area. By examining the maps (Atlas Sheets IV, XXV, and XXVIII), the masses of greenstone may be seen partly inclosing several westward-opening bays, which are occupied by the iron formation. (See also Pl. XIII.) Conspicuous among these are the Ishpeming basin, the northern Lake Angeline basin, the southern Lake Angeline basin, and the Salisbury basin. In each of these cases the greenstone forms an amphitheater about the rocks of the iron-bearing formation. Areas of iron formation open out to the west into the main area, and thus the troughs have a westward pitch. In the case of Lake Angeline, an east-and-west dike cuts across the basin south of the center, and this, combined with the greenstone bluffs to the north and to the south, forms two westward-pitching troughs. The northernmost of these has the greatest ore deposits of the Marquette district, containing many millions of tons of ore.

(3) The hard-ore bodies, mainly specular hematite, but in some deposits including much magnetite, occur, as has been said, at the top of the iron-bearing formation, immediately below the Goodrich quartzite and within the lower horizons of the Goodrich quartzite. (Pls. XVI, XXVIII, figs. 1, 3, and 7, and XXIX, fig. 2.) As typical examples of mines of this class may be mentioned the Jackson mine, the Lake Superior Specular, the Volunteer, the Michigamme, the Riverside, the Champion, the Republic, and the Barnum. Also, as interesting deposits, giving the history of the ore, may be mentioned the Kloman and the Goodrich. In all of these deposits the associated rock of the iron formation is jaspilite or grünerite-magnetite-schist, usually the former. These ore deposits, bridging two different geological series, can not be separated in description, for frequently they weld together the Upper Marquette Goodrich quartzite

PLATE XXIX.

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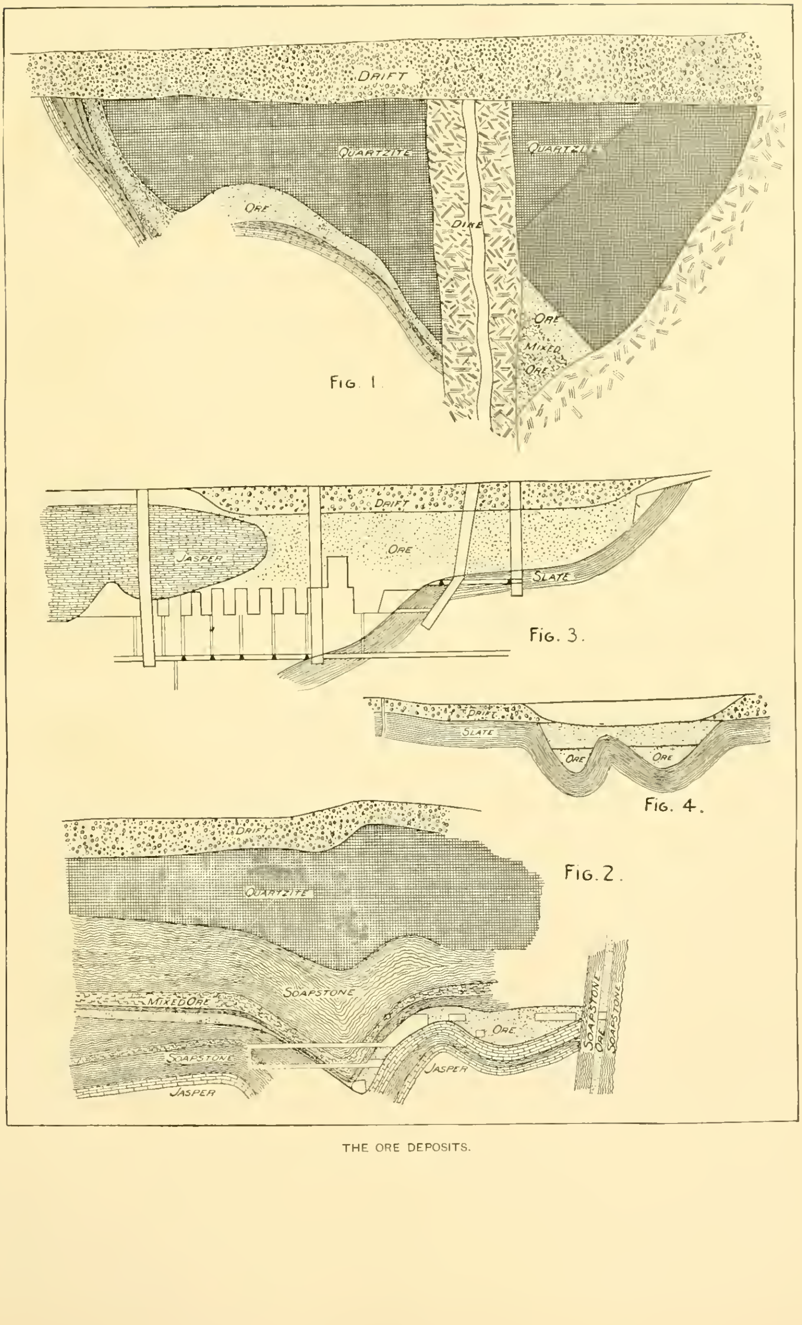
PLATE XXIX.—THE ORE DEPOSITS.

FIG. 1. Cross-section of Section 16 mine, Lake Superior Iron Company. On the right is a V-shaped trough made by the junction of a greenstone mass and a dike. The hard ore is between these and below the Goodrich quartzite. On the left the hard ore again rests on soapstone, which is upon and interstratified with jasper, and is overlain by the Goodrich quartzite. Scale: 200′ = 1″.

FIG. 2. Cross-section of the Barnum mine, showing hard ore resting either upon folded soapstone or upon jasper, and overlain by soapstone. At the right of the figure is seen a layer of ore between two soapstone dikes. Scale: 200′ = 1″.

FIG. 3. Longitudinal section of the mines operated by the Buffalo Mining Company, showing the soft ore resting upon an impervious foot-wall of Siamo slate and grading upward into jasper. Scale: 200′ = 1″.

FIG. 4. Cross-section of same, showing the slate folded into two troughs, which are shown by the longitudinal section (fig. 3) to have a western pitch.



THE ORE DEPOSITS.

formation and the Lower Marquette Negaunee formation. As in the cases of (1) and (2), all of the large ore deposits belonging to this third class have at their bases soapstone or paint-rock. (Pl. XXIX, fig. 2, and Pl. XXXIV, fig. 1.) In those cases in which the soapstone is within the Negaunee formation it is a modified diabase, or a greenstone mass in conjunction with a dike or dikes. Where the ore deposits are largely or mainly in the Goodrich quartzite the basement rock may again be a greenstone, but also it may be a layer of sedimentary slate belonging to the Goodrich quartzite. These different classes of rocks are, however, not discriminated by the miners, but are lumped together as soapstone or paint-rock. Also, as in the cases of (1) and (2), wherever the deposits are of any considerable size the basement rock is folded into the form of a pitching trough, or else, by a union of a mass of greenstone with a dike, or by a union of either one of these with a sedimentary slate, an impervious pitching trough is formed. Perhaps the most conspicuous example of this is at the Republic mine (Pl. XXXIV), but it is scarcely less evident in the other large deposits. However, a few small deposits—chimneys and shoots—of ore occur at the contact of the Negaunee and Ishpeming formations (Pl. XXVIII, fig. 3), where no soapstone has been found. As examples of ore deposits which are largely or wholly within the Upper Marquette may be mentioned the Volunteer, Michigamme, Champion, and Riverside. These are partly recomposed ores, and differ in appearance from the specular hematite or magnetite of the Lower Marquette in having a peculiar gray color and in containing small fragmental particles of quartz and complex fragmental pieces of jasper, and frequently also sericite and chlorite are discovered with the microscope.

In any of these classes the deposits may be cut into a number of bodies by a combination of greenstone dikes or masses. A deposit which in one part of the mine is continuous, in another part of the mine, by a gradually projecting mass of greenstone which passes into a dike, may be cut into two deposits, and each of these may be again dissevered, so that the deposit may be cut up into a number of ore bodies separated by soapstone or paint-rock. (Pl. XXVIII, figs. 4–6.) In some cases the ore deposits have a somewhat regular form from level to level, but the shape of the deposit at the next lower level can never be certainly predicted from that of the level above. Horses of "jasper" may appear along the dikes or within an ore body at almost any place. The ore bodies grade above and at the sides into the jasper in a variable manner. As a result of the combination of these uncertain factors, most of the ore bodies have extraordinarily irregular and curious forms when examined in detail, although in general shape they conform to the above descriptions.

While these different classes of ore bodies have the distinctive features indicated above, they have important features in common. They are confined to the iron-bearing formation. They occur upon impervious basements in pitching troughs. The impervious basement may be a sedimentary or igneous rock, or a combination of the two. Where the ore deposits are of considerable size the plication and brecciation of the chert and jasper are usual phenomena. (Pls. XX–XXIII and XXV–XXVII.) Frequently this shattering was concomitant with the folding into troughs or with the intrusion of the igneous rocks. When the passage of the ore bodies into the chert or jasper is examined in detail, it is found that a siliceous band, if followed toward the ore, instead of remaining solid, becomes porous and frequently contains considerable cavities. These places in the transition zone are lined with ore. In passing toward the ore deposit more and more of the silica is found to have been removed, and the ore has replaced it to a corresponding degree. (Pl. XXIII, fig. 1.) An examination at many localities shows this transition from the banded ore and jasper to take place as a consequence of the removal of the silica and the substitution of iron oxide. In such instances the fine-grained part of the ore is often that of the original rock, while the coarser crystalline material is a secondary infiltration. (Pls. XXIII and XXVI.) It is not infrequently the case, however, that the ore deposits abruptly terminate along a joint crack or fracture. (Pl. XXVIII, fig. 3.)

ORIGIN OF THE ORES.

The facts given in the foregoing pages in reference to the iron-bearing formation and its origin, combined with the peculiar occurrence of the ores, indicate with certainty the main features of the origin of the ore deposits.

While the ore deposits of the Lower Marquette series have a greater variety of form and relations than those of the Penokee district,[1] it is evident

[1] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey, Vol. XIX, 1892, pp. 280-290.

that the conditions governing their formation are much the same. In both districts the material immediately underlying the ore is relatively impervious to water. In the cases of the deposits resting upon soaprock this lack of porosity is nearly complete. Most of the ore bodies are in troughs in both districts; the ore bodies in both, in longitudinal section, have a pitch; in both the many phases of material found in the iron bearing formation are nearly the same; and in both is found plentiful residual iron carbonate. It is therefore thought that the explanation of the origin of the ores in the Penokee district is applicable, with a few modifications, to those of the Marquette district, although the larger number of the deposits of the latter belong to an older series.

The forms, attitudes, and relations of the ore deposits render it evident that they are not eruptives. (Pls. XXVIII and XXIX.) No eruptive would be found in such strange shapes and relations. It is equally certain that these irregular masses of ore are not altogether formed by direct sedimentation, although a considerable part of the iron oxide in an ore body may be an oxidation product in place of a sedimentary iron carbonate.

All these facts bear toward the conclusion that the ore was secondarily enriched by the action of downward-percolating water, since the ore deposits occur at places where percolating waters are sure to have been concentrated The soaprock accommodated itself to folding without fracture, and, while probably allowing more or less water to pass through, acted as a practically impervious stratum along which water was deflected when it came in contact with it. It is a common opinion among miners that a few inches of soaprock is more effective in keeping out water than many feet of the iron-bearing formation. On the other hand, the brittle, siliceous ore-bearing formation was fractured by the folding to which it was subjected, so that where this process was extreme water passes through it like a sieve. That the tilted bodies of greenstone or soaprock, especially when in pitching synclines or forming pitching troughs by the union of dikes and masses of greenstone, must have converged downward-flowing waters is self-evident. It is also clear that the weak contact plane between the Goodrich quartzite and the Negaunee formation was one of accommodation and shattering.

Therefore the plane of unconformity between the Upper Marquette and Lower Marquette series must have been a great horizon for downward-flowing waters.

It has been seen that the whole of the iron-bearing formation was probably originally a lean, cherty carbonate of iron, with perhaps some calcium and magnesium, and that from this rock the ferruginous cherts and jaspers developed. If we now go no further back than the ferruginous cherts and jaspers, in order to produce the ore two things must have occurred: first, the further concentration of iron oxide in the places where the ore bodies are found; and second, the removal of silica from these places.

The final concentration of the ores occurring at the contact of the Upper Marquette and Lower Marquette series must have taken place later than Upper Marquette time. This is indicated by the fact that the unconformable formations are welded together by the iron ore at many places. The relations of the ore bodies within the ore formation to the greenstone masses and dikes give evidence that the concentration of this ore occurred subsequently to the intrusion of these rocks. It is certain that some of these igneous rocks were intruded during or later than Upper Marquette time, since they cut across the Goodrich quartzite. Others of them appear to have yielded fragments to the Upper Marquette series, and therefore antedate these rocks. Finally, if the ore bodies were concentrated before the Upper Marquette folding and erosion their invariable positions above the impervious formations would be inexplicable. The folding would perhaps have left them as often below as above these formations. Taking all the facts together, it is highly probable that the final concentration of all the ores occurred during and later than the folding and erosion subsequent to Upper Marquette time.

Surface waters bearing oxygen, passing downward through the Upper Marquette series or the iron-bearing formation of the Lower Marquette series, would decompose the iron carbonates with which they came in contact and thus become carbonated. These carbonated waters would then be capable of taking other iron carbonates into solution. What proportion of the original iron carbonate still remained in the ore-bearing formation at the beginning of the concentration of the ore deposits is uncertain, but since it is still found in places sheltered from percolating waters, such as the deeper horizons of the iron formation, adjacent to and probably protected by greenstone masses, it is probable that the quantity was very considerable. The oxides or carbonates of iron may also have been taken into solution through the agency of organic acids. The downward-moving waters passed along and through the beds of the iron-bearing formation until they came in contact with an impervious substance. Here were also converged oxygen-bearing waters more directly from the surface. The union of these two currents precipitated the iron oxide. The abundant waters traversing these ore-bearing localities slowly dissolved the silica, its place being taken by the ore. That this interchange actually did occur is known of the localities in which a detailed examination has been made, as, for instance, at Republic. It is probable that in the ore deposits associated with the soaprocks the removal of silica was due in part to them. Originally diabases, they must have contained alkalis. The alkaline waters produced by their alteration thus furnished a menstruum capable of taking the silica into solution. This desilicification of the iron-bearing formation by alkaline waters was many years ago suggested by Brooks[1] for a part of the Marquette district. Rominger[2] not only made the same suggestion in reference to the Jackson mine, but further held that the siliceous matter removed was replaced by oxide of iron carried by water solutions.

The percolating waters which carried material along the readiest paths to form the ore bodies, and which removed the silica, also helped to jasperize the upper part of the Negaunee formation, although this may have been partly done before Upper Marquette time. Whatever the time at which the work was done, the process seems to have been as follows: The quartz grains of the ferruginous chert were separated by mashing. The upper part of the ore formation was more extensively traversed by solutions than the deeper-lying portions. It naturally followed that the ferruginous material was in part deposited about and through the minute particles of

[1] Geol. of Michigan, Vol. I, p. 134. [2] Ibid., Vol. IV, p. 75.

quartz, reddening them and changing the material from white chert to red jasper. In some places this jasperization extended deeper than in others, and, as already said, at other places it abruptly stopped at an impervious mass of soaprock.

One or two questions remain to be considered: first, why the ore is so frequently hard and specular along the contact horizon or in the jasper and is usually soft within the ferruginous chert; second, why the magnetites, when present, occur at the contact horizon.

An examination of the jasper associated with the hard ores shows tnat crystallized hematite and magnetite occur in many cavities formed by the removal of silica. In such geodal cavities these materials were deposited in a granular crystalline condition. In the continuation of the process the silica was wholly removed and its place taken by the crystalline hematite and magnetite. The adjacent jasper also shows numerous cracks and fissures filled with hematite or magnetite. The manner in which these veins of coarser crystallized material frequently cut across the finer-grained substances, which represent the iron oxides present before the final concentration of the ore, shows conclusively that they are secondary infiltrations later than the last orogenic movement. The formation of the coarsely crystalline granular hematite and magnetite thus appears to have been connected with the abundance of iron-bearing solutions along the contact plane.

In many places, however, the hard ores are of the brilliant micaceous or specular variety. This is sometimes called slate ore. In the hand specimen of jaspilite, composed of minute alternating layers of hematite and quartz, where the folding has been severe micaceous ore is found between the rigid bands of quartz. Along the ferruginous laminæ is seen all the evidence of slickensides. The micaceous character of the ore is in this case plainly due to the accommodation and consequent shearing which took place between the layers.

The micaceous ore from the large deposits, as first suggested by Pumpelly, gives the same evidence of shearing. When it is remembered that in the folding of thick formations readjustments must occur, it is natural to suppose that they took place more largely at the contact between the

Upper Marquette and Lower Marquette series than at any other one horizon, for this is emphatically the plane of weakness. Thus would be explained the finely laminated micaceous variety of ore. The specular hematite may have been soft ore, for it is not impossible that shearing along the contact plane, with the heat developed, was sufficient to cause this transformation.

A close examination of the slate ores shows that they are composed of two parts, one of which was mashed, the other being granular or crystal-outlined hematite and magnetite. The latter material fills the cracks left as a result of the mashing, perhaps occupies the place of residual silica, and welds the micaceous leaves together. Thus this granular ore was certainly deposited after the folding. How much was introduced during the folding it is impossible to say, for this part can not be separated from that present before the folding.

That it is easy to reduce hematite to magnetite is well known, and it is probable that the production of the granular infiltrated variety of this ore is due to the reducing character of some of the solutions which passed down along the great contact plane of percolation, where the magnetites are extensively found. Reducing power could readily be imparted by organic acids, and that some kind of reducing agent was present is indicated by the veins of pyrite which are frequently associated with the magnetic ores.

The magnetite of the grünerite-magnetite-schist has been seen to be partly due to an imperfect oxidation of the original iron carbonate. It is, however, doubtful whether any considerable quantity of the magnetite of the greater number of worked ore bodies is directly of this derivation, although some of the lesser magnetite deposits appear to be an enriched grünerite-magnetite-schist. In these cases there is no particular difficulty in accounting for the larger part of the magnetite, but the same difficulty exists in explaining the imperfect oxidation of the infiltrated material as in the other instances.

PROSPECTING.

In considering the advisability of prospecting in any particular locality the foregoing conclusions as to the relations of the iron ores may be of assistance. These may be briefly summarized as follows: The iron ores are always confined to the iron-bearing formation. They always rest upon a relatively impervious basement. This may be a shale, a slate, a greenstone mass, a dike, or two or more of these combined. Adjacent to the ores all of these formations are apt to be modified and impregnated with iron oxide, and are hence called soapstone or paint-rock. The large ore bodies are found only when the impervious basements are in the forms of pitching troughs. These pitching troughs are particularly likely to bear unusually large ore bodies when the iron-bearing formation is much shattered by folding.

In prospecting for the first class of ores, those that rest upon the Siamo slate, a trough in the slate should be sought. A plunging synclinal trough may be formed by a swing of the boundary line between this formation and the iron-bearing formation; or a trough may be formed by a combination of the slate with a cutting dike or mass of greenstone; or a trough in the slate may be supplemented by an intersecting greenstone.

In the second class of deposits—those within the formation—the pitching troughs are wholly formed by the intrusives. Here valleys of the iron-bearing formation, when nearly surrounded by an amphitheater of greenstone, furnish a particularly favorable area. Where the iron-bearing formation in the valley is the ferruginous chert, rather than the grünerite-magnetite-schist, the conditions are more favorable. Pitching troughs bottomed by soapstone may exist underground which can not be discovered at the surface, since, where an intersecting intrusive is of small size and has been transformed to soapstone, it is eroded as rapidly as the iron formation, and thus its existence is not discovered by outcrop or any topographic feature.

The third class of deposits, the hard ores, must always be prospected for near the contact of the Negaunee iron formation and the Goodrich quartzite. As in the previous cases, the ore bodies are particularly likely to exist if the two are folded so that the contact forms a pitching trough, and if this be bottomed by soapstone the conditions are still more favorable for the formation of large deposits.

The general map (Atlas Sheet IV) shows several extensions of the iron-bearing formation which have not been prospected. The arm running east of Palmer has been prospected along its south side, but as yet almost no work has been done along the north side. The exposures here are not sufficient to indicate the minor bends of the iron-bearing formation, but the break across the quartzite in sec. 28, T. 47 N., R. 26 W., suggests that there may be a north swing of the formation at this place; and if so, this would be a favorable point for exploration. Other favorable places may exist along the northern side of this syncline, but their exact positions can not be pointed out. The second synclinal arm, running from the southeast corner of sec. 20, T. 47 N., R. 26 W., in a northeasterly direction, has not been explored at all. West of this arm is the great anticlinal dome of Siamo slate. This dome is folded by minor rolls in an east-west direction, thus furnishing on the west side of the iron formation a number of westward-pitching synclinal troughs, in which are large deposits of ore. Doubtless the same folded condition prevails on the eastern side, producing eastward-pitching troughs, although here outcrops are not sufficient to accurately delineate the boundary lines; but while the existence of a swamp in secs. 3, 4, 9, and 10 makes the area difficult to prospect, the sides of the arm are worthy of exploration. In the south part of sec. 3, near the north-south quarter line of the section, there is a ridge of greenstone. This is also the end of the syncline, which here plunges to the south. The junction of this greenstone with the contact line between the Siamo slate and the Negaunee iron formation is a favorable point. Within the iron formation in secs. 10 and 15 a great mass of greenstone forms a westward-facing amphitheater, and here in the southwest quarter of sec. 10 would seem to be a favorable place for exploration.

It is not impossible that a close magnetic survey with a dial compass and dip needle across the approximate boundary lines of the Siamo slate and the Negaunee formation, for these eastern arms, would enable the explorer to more accurately delimit the iron-bearing formation and to determine the probable positions of pitching troughs, if they exist, and thus point out the more favorable points. This attempt ought certainly to be made before money is spent in actual underground work. Exposures of these eastern arms are so infrequent that it is not certainly known that the iron-bearing formation maintains its pure nonfragmental character. If it contains interstratified or intermingled clayey material, this would be unfavorable to the development of merchantable ore deposits.

In the foregoing paragraphs it is not meant to imply that workable iron-ore deposits will surely be found in these eastern arms, but merely that the conditions are sufficiently favorable to warrant a search for them.

CHAPTER IV.

THE UPPER MARQUETTE SERIES.

INTRODUCTION.

By C. R. Van Hise.

The general statement has been made that the Upper Marquette series appears at Negaunee and at Palmer in two detached areas, reappears at Ishpeming, and from this place toward the west rapidly widens out into a broad belt, occupying the greater part of the area of Marquette rocks. It has also been said that this general distribution is due to the great north-south transverse anticline east of Negaunee.

Broadly considered, the Upper Marquette series was predominantly a great shale formation, which was subsequently modified to a greater or less degree. The lowest horizon of the series is, however, a conglomerate and quartzite, which marks the transgression of the sea. Replacing this in part in the west end of the area is a grünerite-magnetite-schist horizon. Following above this is the great slate formation, and in it is a horizon which originally bore a considerable quantity of iron carbonate, from which various ferruginous rocks have developed, and also small ore bodies. Finally, during Upper Marquette time, in parts of the district there was contemporaneous volcanic action, so that associated with the modified shales of the series is a belt of volcanics a number of miles long. As in the case of the Lower Marquette, later intrusives penetrated the series at various places.

The Upper Marquette series is, then, structurally divisible into a lower belt of conglomerate, quartzite, grünerite-magnetite-schist, and associated rocks; a slate formation; and a belt of volcanics. The first will be called the Ishpeming formation, the second the Michigamme formation, and the last the Clarksburg formation.

SECTION I.—THE ISHPEMING FORMATION.

By C. R. Van Hise.

The Ishpeming formation is so named because typical exposures of this formation surround the city of Ishpeming and underlie it. For the eastern part of the district, and including the Ishpeming area, the predominant rocks are conglomeratic quartzites and quartzites. These are finely exposed at and adjacent to the Goodrich mine (Atlas Sheet XXVI), and this rock will therefore be called the Goodrich quartzite. In the western part of the district, while quartzites are present, a peculiar schist, which is typically exposed at the lower part of the Bijiki River (Atlas Sheet VIII) and will therefore be called the Bijiki schist, occupies a large part of the horizon of the Goodrich quartzite and is equivalent to it in age.

THE GOODRICH QUARTZITE.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The easternmost occurrence of the Goodrich quartzite is the Palmer area (Atlas Sheet IV). From the village of Palmer it extends east and west about $1\frac{1}{2}$ miles, making a belt 3 miles long. From near its center, as a consequence of subordinate folding, a short belt projects to the southeast. Small isolated patches may also occur capping the Ajibik quartzite of the Ajibik Hills. The second subordinate area is near the town of Negaunee, north of the Jackson mine. On account of the close folding the boundary line of this area is very irregular. The chief area, as has been said, begins at Ishpeming. From this area a rather narrow belt extends, in a course nearly due west, to west of Michigamme. Another arm, of irregular width, swings to the south and southwest, then follows a general westerly course to sec. 20, T. 47 N., R. 28 W., where it swings to the northwest to Humboldt and Champion; thence it extends west, southwest, and south to the end of the Republic tongue, in sec. 7, T. 46 N., R. 29 W., passes around the end of this tongue, and again swings to the northwest to sec. 20, T. 47 N., R. 30 W.; thence it swings to the west and south, beyond the limits of the district. West of this belt is still another.

The prominent exposures of the formation are usually near its base. The rocks are here conglomerates. These grade into quartzites. At many places in passing upward the quartzite approaches a graywacke, is consequently softer, and therefore not so frequently seen. Exposures are particularly abundant in the Palmer and Negaunee areas, about the Ishpeming basin, and as far west on the southern belt as the Fitch mine, sec. 24, T. 47 N., R. 28 W. For the last 3 miles of this distance it constitutes a rather prominent range. West of this place exposures are infrequent until Humboldt is reached. Here are numerous outcrops north of Mount Humboldt. At Republic are large and fine exposures. Many outcrops are found in the northern belt south of the Michigamme and Spurr mines.

FOLDING.

Broadly considered, the Goodrich quartzite is folded into a great westward-plunging synclinorium, the eastern end of the U extending from Ishpeming southward. This eastern border of the formation comprises a series of reentrants and salients—reentrants where there are minor synclines, and salients where there are minor anticlines. On account of the flat dip, corresponding to the westward plunge of the syncline, the formation here occupies a broad belt. On the south side of the formation at one place the Goodrich quartzite and Negaunee iron formation are infolded and overturned, having northward dips (Atlas Sheet XXVI). At this point the Goodrich quartzite has a tongue running east into the iron formation, being bounded both to the north and to the south by the rocks of the Negaunee formation, which dip in the same direction as the quartzite. The area at Negaunee is in general an east-west oval synclinal basin. Here again there is minor folding, so that the formation terminates both to the east and west in a number of fingers. At the west end of the Jackson mine the Goodrich quartzite and the Negaunee iron formation are folded into a set of isoclinal overfolds, so that a north-south section passes three times from one formation to the other. The Palmer belt is another east-west synclinal basin, with a short arm extending to the southeast at one place, due to the appearance of a central anticline. The Republic tongue and that to the west are two closely compressed isoclinal synclines.

GOODRICH QUARTZITE WITH MINOR FOLD CUT BY DIKE, MICHIGAMME MINE.

At Michigamme the minor folding of the quartzite is beautifully shown. (Pl. XXX.)

RELATIONS TO ADJACENT FORMATIONS.

The details of the relations of the Goodrich quartzite to the underlying Negaunee formation are so fully stated in connection with the latter and the general geology that they need not be repeated here. Generally stated, they are those of unconformity, the advancing sea having formed a conglomerate at the base of the quartzite As a consequence of mining development and the resistant character of this part of the formation, the conglomerate may be seen at scores of localities lying upon and cutting across the bedding of the underlying formation at a greater or less angle (figs 20 and 21).

Where erosion cut through the Negaunee formation the basal conglomerate rests upon the Ajibik quartzite, and derives the majority of its fragments from it. Where the latter formation is also cut through, as apparently it is south of Palmer, the material is largely derived from the Basement Complex This fact, that the Goodrich quartzite thus comes in contact not only with the Negaunee formation but with inferior formations, shows that the unconformity between the Upper and Lower Marquette series must be very considerable

For much of the district, by a dying out of the coarse fragmental quartz and the appearance of clayey material the quartzite gradually passes into the Michigamme formation. This gradation is usually not rapid, and hence the location of the boundary line between the two is somewhat arbitrary. At the western end of the district the quartzite is very thin, and the formation passes quickly upward into the grünerite-magnetite-schists of the Bijiki horizon. (Pl XXXI.)

PETROGRAPHICAL CHARACTER.

Macroscopical.—A conglomerate is usually at the base of the Goodrich quartzite. The character of the conglomerate depends upon the subjacent formation, the larger portion of the detritus in each case being derived from it. As has been stated, this inferior rock is usually the Negaunee formation, and at the base of the Goodrich quartzite is ore, recomposed ore, or ore, chert, jasper, and quartz conglomerate. At a few places the subjacent rocks belong to the Archean, and at these the great variety of materials constituting this complex are predominant in the conglomerate. At various places—as, for instance, in the great conglomerate at and immediately south of the village of Palmer—there are abundant quartzitic, granitic, and schistose bowlders, derived from the Archean, and also abundant jaspilite detritus from the Negaunee formation.

The basal conglomerate, of varying thickness, grades up into quartzites, which are apt to contain much of chert and jasper in minute fragments. The higher horizons of the quartzite are usually feldspathic. Frequently the mashing due to the folding was so severe as to partly or wholly destroy the fragments of ore and jasper, making the rock a schist-conglomerate or schistose quartzite. This change is complete at the places where the close infolding which has been spoken of occurs, as at the Jackson mine, at Humboldt, and in the Republic trough. In the most extreme stage of alteration it is difficult to discriminate the mashed recomposed ore and jasper conglomerates from the original jaspilite. In passing from the least altered to the most altered phases we find, first, flattened pebbles, then those which are elongated into layers, and finally those in which are alternating layers of different thickness, which simulate original lamination in a remarkable degree.

In the case of the nonconglomeratic recomposed jaspers the rocks are not unlike the original formation, although a close examination usually shows a difference. Ordinarily, large fragmental grains of quartz are seen; flakes of mica are often present; and the banding is less distinct than in the original jasper.

Under the subject "Negaunee Iron Formation" the development of ore bodies within the Goodrich quartzite has been mentioned. The ore usually occurs at places where the detritus was rather fine grained, and thus contained no large fragments of chert and jasper. As conspicuous localities for the occurrence of these recomposed ore bodies may be mentioned the Volunteer mine, the Barron, the Humboldt, the Champion, part of the Jackson, and part of the Michigamme and Spurr. As a consequence of the intense mashing which the formation underwent, numerous cracks developed and minute spaces formed between the laminæ and between the individual particles. Where the rock was enriched so as to become an ore,

CONFORMABLE EXPOSURE OF GOODRICH QUARTZITE AND BIJIKI SCHIST, WITH GRADATION ZONE BETWEEN, NEAR MICHIGAMME.

as has been before explained, secondary magnetite formed. The detrital micaceous hematite is usually easily discriminated from the crystal-outlined secondary magnetite. While a considerable percentage of the iron oxide of the ore was present as detritus, in no case does it appear that the material was rich enough for merchantable ore before the secondary concentration, and often the secondary magnetite and its alteration product, martite, are the predominant constituents of the ore.

Microscopical.—With the microscope, the basal conglomerate resting on the Ajibik quartzite is found to have a background consisting of quartz grains set in a more or less abundant sericitic, cherty, and iron-impregnated matrix This matrix may be so abundant as to separate the fragmental grains, or may be sparse. In this background are found complex fragments of quartzite the individual grains of which are rounded, and fragments of sericite-slate and sericite-schist, all identical with these rocks in the Ajibik quartzite.

In the Republic trough, where the Goodrich quartzite in part rests directly upon the Archean, the schist-conglomerate found at the bottom of the detrital formation has as a matrix a micaceous quartz-schist. In certain varieties feldspar is abundant in the background, and it becomes a mica-gneiss. In this background are oval or ribbon-like areas of quartz or of feldspar, which represent the mashed pebbles of the conglomerate. Occasionally these pebbles contain both quartz and feldspar, and represent complex fragments derived from the granite. The quartz is always and the feldspar is usually shattered, and along the crevices of the feldspar mica and quartz have developed. Frequently the residual feldspar and the secondary quartz and mica form an interlocking mass. Were it not for the pebble-like areas these rocks would be regarded as completely crystalline schists.

Where the Goodrich quartzite rests upon the Negaunee formation there are three main phases of material: (1) Chert and jasper conglomerate, (2) recomposed jasper, and (3) ore.

The chert and jasper conglomerate may have a sparse or an abundant matrix. In the first case the matrix consists of small, simple, fragmental grains of quartz, complex particles of ferruginous chert and jasper, and iron oxide. In passing to the less strongly conglomeratic phases the matrix is a continuous ramifying mass which contains the separate pebbles and bowlders. This matrix may be composed chiefly of any one of the substances, iron oxide, chert, jasper, or quartz, or of any combination of them. Not infrequently some secondary muscovite has also developed. Often the quartz grains are enlarged. In all cases the simple quartzes show undulatory extinction and fracturing. In the resultant and other crevices secondary hematite and magnetite were deposited. Where the mashing was great the fragments of chert, jasper, and quartz were flattened into thin, layer-like areas, and in this case a slide of the recomposed rock differs but little in its appearance from the original jaspilite. Accompanying the granulation of the ore, chert, and jasper, the hematite was sheared into brilliant, finely laminated, micaceous, or silky fibrous hematite. Flakes of muscovite are usually seen. The secondary magnetite and hematite are easily discriminated from the sheared micaceous hematite by having crystal outlines. This infiltrated material is frequently present in very large proportion, filling all the interspaces between the original particles and the cracks formed within the fragments. In some cases the secondary hematite and magnetite have such relations to the quartz grains as to show that the silica was actually dissolved and replaced by the iron oxide. To what extent this occurred where the rocks are much mashed it is difficult to say, but in the little-altered phases we find crystals of hematite and magnetite which not only pass to the borders of the cores of the enlarged grains but into them. There seems to be some relation between the solution of quartz and the deposition of magnetite; that is, when the conditions are favorable for the deposition of magnetite they are also favorable for the solution of quartz.

The most mashed phases of recomposed jaspers have very much the same appearance as those of the original jasper formation, but when examined with a low power the overlapping lenticular leaflets of the mashed chert and jasper fragments are seen, and a high power shows in some cases a micaceous mineral which is almost invariably absent in the original formation. In the less mashed phases of the recomposed jaspers their genesis is more plainly indicated by the presence of coarse-grained quartzose material, not derivable from the immediately subjacent formation;

but even in such cases these quartzes were often granulated into jasper-like material.

By disappearance of the siliceous element and increase of the secondary hematite and magnetite the recomposed rocks pass into magnetic or specular ore. Macroscopically these ores often show a peculiar gray color, and in thin section they are usually easily separated from the ores of the Negaunee formation by the presence of brilliantly polarizing flakes of muscovite and of occasional particles of fragmental quartz.

The conglomerates, recomposed jaspers, or recomposed ores, by a lessening of the amount of chert, jasper, and iron oxide, grade upward into the quartzites. In the purer phases these quartzites consist mainly of well-rounded, simple fragments of quartz, many of which are enlarged, but with these are usually complex particles of chert and jasper. The quartz grains generally show strong pressure effects, such as undulatory extinction or fracturing in a complex manner. This fracturing is in certain cases in a rectangular system corresponding to the shearing planes. In other phases there is an abundant matrix composed of finely crystalline quartz, with sericite, biotite, and chlorite, in which the large fragmental grains of quartz are set. By an introduction of feldspar the quartzites pass into feldspathic quartzites, and from these to the graywackes of the Michigamme formation. In the less pure quartzites, sericite, biotite, and chlorite frequently developed abundantly from the clayey background.

In the more mashed phases of the quartzite, and particularly in the Republic trough, the rocks are micaceous quartz-schists. Feldspar is plentifully associated with the quartz in a number of cases. Usually the grains of quartz still show a roundish appearance, but they interlock intricately, and show no evidence of original cores. In the finer-grained, most mashed kinds the background is a finely granular, interlocking mass of quartz. Between and wrapping around the larger grains abundant muscovite is found. In some of the rocks muscovite is a chief constituent, and these may be called muscovite-schists. Muscovite-biotite-schists and biotite-schists are also associated with the quartz-schists. These are, in nearly all aspects, like the more metamorphosed rocks of the Michigamme formation. In a few places feldspar is a chief constituent of the background, and the rocks become mica-gneisses. Various accessory minerals, such as chlorite, epidote, and zoisite, are found in the quartz-schists, mica-schists, and mica-gneisses.

At various localities there are exceptional varieties of rocks which belong to the Goodrich quartzite, but these will not be considered here. They are described later in connection with the localities at which they occur.

THICKNESS.

The thickness of the Goodrich quartzite is variable, and no average estimate can be given, as it is not sharply delimited above. The best-known locality to determine its thickness is north of the Saginaw mine, where it has a surface width of about 1,800 feet and an average dip of probably not less than 60°. This would give a thickness of about 1,550 feet. Since the transgression horizon here rapidly cuts across the iron formation, which a short distance to the west is reduced to a narrow belt, it is probable that this thickness is much beyond the average of the formation, even for the Ishpeming area, and that it is several times as great as in the western part of the district.

THE BIJIKI SCHIST.

The second division of the Ishpeming formation is the Bijiki schist. The rock is given this name because typical exposures of it occur near the mouth of Bijiki River. They were regarded by Brooks as anthophyllitic schists.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

This schist has three narrow belts. The northernmost one extends, with frequent exposures, from the west end of the district, just south of the Goodrich quartzite, to sec. 28, T. 48 N., R. 29 W. (Atlas Sheets V, VIII, and XII). The belt may extend somewhat farther to the east than this, but there are no exposures. The second belt is a short distance south of the first. It runs along the northern side of Michigamme Lake to a point northeast of Champion. The third belt extends from the southern extremity of Michigamme Lake to Champion, and is north of the southern belt of Goodrich quartzite. The Bijiki schist thus appears to be confined to the west end of the district. In the time scale it must be equivalent to a part of the Goodrich quartzite to the east. Where the Bijiki formation appears the Goodrich quartzite becomes an exceedingly narrow belt, too small to be shown on the atlas sheets; hence the two are mapped together as the Ishpeming formation.

The rock is of a resistant character, and for the areas outlined there are numerous exposures. South of Michigamme and Spurr it makes conspicuous east-and-west ridges just north of the railroad For most of the length of Lake Michigamme the southern border of the central resistant belt forms the northern lake boundary. However, at two or three places the schist was cut through and the lake shore follows the softer formation to the north In two of these cases the Bijiki schist constitutes headlands lapped on three sides by water In the same way the southeastern shore of Lake Michigamme is limited by the southern belt of this schist At various places erosion encroached upon the belt, but the rock is so resistant that the lake nowhere cuts entirely across the formation.

FOLDING.

The belts adjacent to the Goodrich quartzite owe their position to their being the next higher horizon in the general synclinorium of the district. The central belt is due to a subordinate anticline which rises high enough to expose the Bijiki schist, but erosion has not reached a lower horizon, and thus a section across the area, including the three formations, shows two synclines with a central anticline.

PETROGRAPHICAL CHARACTER.

Macroscopical.—The Bijiki schist is a banded grünerite-magnetite-schist. Associated with this rock are also phases which approach the Michigamme slate above and the Goodrich quartzite below. These are usually gradation phases, and occur upon the outer parts of the belt. (Pl. XXXI) The grünerite-magnetite-schists consist of bands composed mainly of the three minerals, quartz, grünerite, and magnetite, and while in any single band one of these minerals may be predominant, the other two are usually present. The rocks are gray or green, and in their nearly pure phases they differ from the grünerite-magnetite-schist of the Negaunee formation chiefly in their exceeding toughness. It is with great difficulty that the rock is broken into pieces parallel to the stratification, so firmly are the different plates bound together by the long grünerite needles; but it is comparatively easy to break the rock across the bedding. This peculiar toughness and the more coarsely crystalline character of the grünerite are the chief points which distinguish it from the similar rock of the Negaunee formation.

An analysis of the typical Bijiki schist (Specimen 25446, sec 19, T. 48 N., R. 30 W.) north of Michigamme was made by George Steiger, in the chemical laboratory of the United States Geological Survey, with the following result:

Analysis of typical Bijiki schist.

	Per cent
SiO_2	65.42
Fe_2O_3	1.64
FeO	27.08
CaO	.31
MgO	3.12
Total	97.57

This analysis indicates that the essential constituents of the rock are grünerite and quartz. A comparison of the analysis of this rock with the analyses of the grünerite-magnetite-schists of the Negaunee formation (p. 338) shows how very similar they are. The first analysis given of the Negaunee grünerite-schist is very similar indeed to that of the Bijiki schist, and the others differ from the latter mainly in containing more magnetite. Other specimens of the Bijiki schist might have been selected which are also rich in magnetite.

Microscopical.—The kinds of the schist free from clastic material consist of intricately interlocking grünerite, magnetite, and quartz, with more or less hematite. The different materials may be uniformly intermingled, but more commonly each is alternately predominant, and this gives the rock a banded appearance. Occasionally the amphibole has a green color, and with this a decided pleochroism, perhaps indicating that it is common hornblende. Not infrequently the same amphibole individual is composed in part of the hornblende and in part of the grünerite. In different individuals and slides the two show the greatest variety of intergrowths. In one or two instances, near the top of the member, siderite is an important constituent, constituting a matrix in which the other constituents are set. In other cases, at lower horizons, a little residual siderite is seen, which is surrounded and penetrated by grünerite or hornblende and magnetite, strongly suggesting that these minerals, with the addition of silica, developed from the siderite. Near the base of the Bijiki schist rounded and enlarged grains of fragmental quartz appear within the completely crystalline interlocking grünerite, magnetite, and quartz. Still nearer the Goodrich quartzite we have a fragmental quartzose background, in the matrix of which grünerite and magnetite have developed. In both the pure and the impure phases a great deal of garnet appears. It is possible that a part of the grünerite and magnetite is detritus derived from the Negaunee formation, but the extraordinary likeness of the Bijiki schist to the grünerite-magnetite-schist produced by metasomatic processes from iron carbonate, the presence of siderite in the formation itself, the relations of this siderite to the grünerite and magnetite, the absence of any fragmental appearance, all suggest that the rock developed out of an original sideritic slate, similar to that of the Negaunee formation. It is not improbable that the development of the grünerite-magnetite-schist, both in the Upper Marquette and Lower Marquette series, was a simultaneous process, occurring during and after the Upper Marquette folding.

RELATIONS TO ADJACENT FORMATIONS.

It has been said that the Goodrich quartzite grades rapidly upward into the Bijiki schist. The Bijiki schist in turn grades into the Michigamme formation, the intermediate zone again being half fragmental. Belonging with or immediately above the grünerite-magnetite-schists, in the western part of the district, are the ore deposits of the Upper Marquette series. These ore bodies appear, however, to be rather within the slates than to belong with the grünerite-magnetite-schist; but if exposures were sufficiently numerous it might be possible to map in the Upper Marquette series a continuous iron-bearing formation which would include these ore bodies and the grünerite-magnetite-schists, thus making the latter rocks the lowest horizon of this ore-bearing formation.

THICKNESS.

The formation varies from a considerable thickness to disappearance, and, as in the previous cases, it is impossible to give an accurate estimate of its thickness at any place. At some places it apparently has a surface width of 600 feet, with a dip varying somewhat, but perhaps averaging 60°. This would indicate a maximum thickness of about 520 feet.

INTERESTING LOCALITIES OF THE ISHPEMING FORMATION.

Michigamme and Spurr.—Beginning at the northwest part of the district, there are large and typical exposures of the Goodrich quartzite and Bijiki schist from the Spurr mine to east of the Michigamme mine (Atlas Sheet V). At these mines a considerable part of the magnetic ore apparently belongs to the

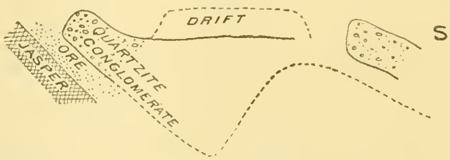


FIG. 26.—Section showing relations of jaspilite, ore, conglomerate, and quartzite at Michigamme mine.

basal horizon of the Ishpeming formation. The ore deposits weld together the unconformable Ishpeming and Negaunee formations. The hanging wall of the ore deposits is a conglomerate, the pebbles of which are mainly from the underlying Negaunee jasper, and the matrix of which is mainly magnetite. At the Spurr mine the pebbles are of the white, cherty rock; at the Michigamme mine they are of the red jasper, the larger ones being 6 to 8 inches in diameter. This suggests that the underlying Negaunee rock had assumed its present form before it was broken up, and yielded detritus to the Ishpeming formation. It is, however, possible that at each place subsequent changes have altered the upper part of the siliceous rock of the Negaunee formation and the overlying conglomerate in a similar manner. At the Michigamme mine the conglomerate is in places at least 20 feet thick, and in other places is absent, the quartzite directly overlying the ore. The relations of the Negaunee jasper, the ore, and the conglomerate are shown by fig. 26. At the Spurr mine the conglomerate is at least 40 feet thick. The conglomerate at both mines passes up rather abruptly into a greenish or grayish, massive quartzite. This quartzite in turn varies by interstratification into the grünerite-magnetite-schist which has been called the Bijiki schist. (Pl. XXXI.) An intermediate variety is a fine-grained biotitic and grüneritic graywacke. Not more than 50 feet south of the interlaminated beds are typical exposures of the Bijiki schist. This quartzite at the Michigamme mine is folded into a series of minor rolls, which are cut by dikes. (Pl. XXX.) At the Spurr and Michigamme mines, on the south or hanging-wall side of the pits, are dikes of chlorite-schist, which are taken to be modified eruptives, as they cut the other rocks like dikes. It is in and adjacent to the chlorite-schists that the large garnets and chlorite pseudomorphs after garnets described by Pumpelly are obtained. The entire thickness of the Goodrich rock is perhaps not more than 100 feet. The Bijiki schist occurs in very numerous exposures on the hills between the mines and the railroad track, and particularly on a prominent ridge just north of the railroad track between the two mines. The boundary between the Ishpeming formation and the Negaunee formation follows a low and sometimes swampy area. In all respects the Bijiki schist of this locality corresponds to the general description (pp. 417–418). The rock is minutely crenulated, and, while having a general southward dip, has many minor, often isoclinal folds.

As seen in thin section the majority of the quartzites are composed of rather well-rounded grains of quartz having a matrix of chlorite or of chlorite with biotite and magnetite. With the fragmental grains of quartz at the Spurr mine are also fragmental grains of feldspar and small granitic pebbles. Most of the grains of quartz are so large that they could not have been derived from the Negaunee formation, and they very probably come from the granite of the Basement Complex. That this is their source is indicated by the feldspar and the granitic fragments. Little or no fragmental material from the Negaunee formation was detected. It thus appears that shortly after the Goodrich quartzite began to form, the thin bed of conglomerate buried the Negaunee formation in the immediate vicinity, and the fragmental material for the quartzite was transported by the waves from the Basement Complex, which at some not distant point was above the water. The grains of quartz all show pressure effects by undulatory extinction and fracturing, and they do not commonly show distinct enlargement, although minute irregularities, which indicate that they have probably grown, are seen. In some cases the enlargements are distinct. The feldspars, where present, show partial decomposition into interlocking chlorite, muscovite, biotite, and quartz. The chlorite in the interstices of the grains is usually in aggregates of minute leaflets, but rarely it occurs in blades of considerable size. Hornblende is found in some slides between the grains of the quartzite. Garnet is occasionally present.

In the variety of rock intermediate between the quartzite and the Bijiki schist the coarse-grained fragmental quartz is clearly discriminated from the fine-grained quartz, which developed in another way. These rocks may be described as hornblendic and magnetitic schists which contain numerous clastic grains of quartz. In some of them there remains a considerable amount of siderite, and out of this siderite, joined with silicification, the magnetite, hornblende, and quartz have developed, exactly as from the sideritic slates of the Negaunee formation. In the half-fragmental phases, wherever the siderite is found, grünerite and magnetite appear; where fragmental quartz is abundant they are not prominent. It therefore appears that the original transition rock was here a siderite which contained a certain amount of fragmental material. By comparison (pp. 321–322, 333–334) it will be seen that the rock is analogous to the transition form between the Ajibik quartzite and the Negaunee formation. Another analogy between this transition rock and that of the Negaunee formation is the fact that the amphibole which develops is pleochroic rather than nonpleochroic. The cause is doubtless the same in both cases—the presence of a great variety of chemical elements in a mingled clastic and nonclastic sediment from which material could be drawn.

By disappearance of the fragmental quartz and replacement of the pleochroic amphibole by the nonpleochroic grünerite the rock passes into the typical Bijiki schist, which is either a grünerite-magnetite-rock or a grünerite-magnetite-schist. In these rocks there are still found varieties which are largely composed of siderite, and out of this siderite the grünerite and magnetite may be seen developing. The description of the grünerite-magnetite-rocks and grünerite-magnetite-schists given in the general description (pp. 417–419) applies to the Spurr and Michigamme area. They are in all respects like similar rocks from the Negaunee formation, with the exception that the grünerite is in coarser blades and crystals, and that frequently there are numerous minute black particles throughout the rock which have a carbonaceous appearance, but which may be flecks of iron oxide. The quartz of the grünerite-magnetite-schists is very similar to that of the Negaunee formation of the Michigamme area. Upon the whole, however, it is somewhat more finely crystalline, the grains averaging, in the different sections, from 0.03 to 0.1 mm. in diameter. In certain slides the nonpleochroic grünerite and the pleochroic amphibole are intergrown, exactly as they are in the Negaunee formation in this area. Where the rocks are exposed to weathering the grünerite is more or less altered into biotite and chlorite, and where these minerals occur there is also seen brilliant blood-red hematite, which has doubtless developed by oxidation from the magnetite. Not infrequently the grüneritic and magnetitic rocks are garnetiferous. The garnets include the various other minerals, and it is apparently the last mineral to develop.

Lake Michigamme area.—Upon the anticlinal ridge bordering the north side of Lake Michigamme and constituting the headlands of this body of water are numerous exposures of typical Bijiki schist (Atlas Sheets V and VIII). In fact, it is from the exposures adjacent to the mouth of the Bijiki River that this formation is given its name. The rocks are here grünerite-magnetite-rocks and grünerite-magnetite-schists, in all respects like those constituting the ridge north of the railroad track between Michigamme and Spurr. In thin section, also, they are identical. The ordinary hornblende is the nonpleochroic grünerite, but at the northwest point of the westward-projecting headland in sec. 28 there are beautiful intergrowths of the nonpleochroic and pleochroic amphiboles, the latter giving blue, green, and yellow colors. It is possible that the phenomena are due to combinations, of varying proportions, of the actinolite and grünerite molecules.

East of Lake Michigamme (Atlas Sheet XII) this anticline is represented by a prominent ridge of the Bijiki formation, running from the

NE. ¼ sec. 31, in a course somewhat south of east, into the SW. ¼ sec. 33, a distance of about 2 miles. This ridge for the most of the distance has an abrupt southward-facing slope, which overlooks swampy land to the south. The north side of the ridge is distinctly but not so sharply marked. For the most part this ridge is composed of typical grünerite-magnetite-schists and grünerite-magnetite-rocks of the Bijiki horizon. However, where the ridge breaks down upon its west end, in the SE. ¼ sec. 31, adjacent to the road, at the bottom and central parts of the exposure are conglomerates containing fragments of chert, coarse quartzites, and fine-grained novaculites; and schistose and dolomitic graywackes and shales intermediate between the foregoing and the Bijiki schists. The change from the fragmental rocks to the Bijiki schist takes place very quickly. The clastics are in most respects like those at the bottom of the Bijiki schist at the Spurr and Michigamme mines, and they doubtless mark the lowest stratum found in this anticlinal ridge. The quartzites and novaculites are much brecciated by the sharp folding. To the south of the fragmental rocks are typical grünerite-magnetite-schists. To the north the Bijiki rocks are very quartzose, and grünerite is subordinate. Both north and south they show extreme plication, and occasionally brecciation. In places the schistosity does not correspond with the bedding.

In thin section the rocks of this ridge are in almost every respect identical with those of Spurr and Michigamme. The siliceous layers between the grünerite-magnetite layers are very often composed of crystal-outlined grains similar to those of the Negaunee formation at the Spurr and Michigamme mines. In coarseness of crystallization the quartz of the two formations is identical. On account of their crystal outlines the grains do not interlock, and the rocks are therefore rather friable. In some sections films of hematite occur everywhere between the grains, thus giving a continuous net-like area of translucent red hematite, the spaces between being occupied by the pellucid quartz. This is best seen in the sections from the north side of the ridge, where the grünerite is rather sparse and quartz is the predominant constituent.

Boston and Dexter area.—In passing to the east, the next exposures found are those in the neighborhood of the Boston and Dexter mines and at intermediate points (Atlas Sheets XVIII and XXII). Here the rocks are for the most part typical quartzites, although at one place interstratified graywacke is seen. The basal portion of the quartzite is a conglomerate, bearing detritus from the Negaunee formation.

Lake Corning area.—The next set of exposures, in secs. 4, 5, and 6, T. 47 N., R. 27 W., occur at intervals west of the Excelsior mine to a point about 2 miles east (Atlas Sheets XXV and XXVIII). At the basal horizon there is here again a conglomerate, the débris of which is chiefly from the Negaunee formation; the ordinary varieties of the formation, however, are the typical quartzites, but with these are slaty phases.

Ishpeming area.—The next important localities are those at Ishpeming and in the various basins south of Ishpeming. At nearly all of the mines adjacent to this city the contact between the Negaunee formation and the Goodrich quartzite is seen. East of Ishpeming the conglomerate at the contact is found at the large open pit of the Lake Superior mine and in open pits in the bays both to the north and south. At the first of these the contact between the Ishpeming formation and the Negaunee formation makes the so-called Lake Superior "W." (Pl. XVI.)

South of Ishpeming, the conglomerate is again seen in the large open pit near the east quarter post of sec. 9, at open pits north of the greenstone bluff in the SE. $\frac{1}{4}$ of the section, and at numerous localities at the large open pits in the SW. $\frac{1}{4}$ sec. 16. In the localities nearest the city of Ishpeming the conglomerate usually rests upon the Negaunee formation, but on the south slope of the greenstone bluff, adjacent to the section line between secs. 3 and 10, the conglomerate rests upon the greenstone. The same relations are seen in the southeast part of sec. 16, in the large open pit just south of the east-west quarter line.

South of this locality, in the SW. $\frac{1}{4}$ sec. 16, are the handsomest exposures of this conglomerate in the Ishpeming area. The rock occupies a well-marked ridge parallel to the railroad. Upon its smooth glaciated surface it presents a beautiful appearance, due to the pebbles of brilliant red jasper.

The basal phase of the conglomerate for the Ishpeming area is usually very ferruginous (Pl. XXVII, fig. 2), and where it is fine-grained it may become an iron ore. These iron ores usually have a grayish or greenish color, and are known to the miners as the hard gray ores. As looked at in hand specimen, the detrital hematite and the heavily ferruginous fragments have a micaceous appearance, due to mashing. The larger part of the ore is, however, magnetite in crystals, or its alteration product, martite. Associated with the latter is a great deal of a green mineral. As these ores become impure there are observed in them fragments of jasper and grains of quartz, which increase in quantity until the rock is no longer an ore, but a heavily ferruginous quartzite, or ore and jasper conglomerate. There are all gradations between a conglomerate which consists almost wholly of fragments derived from the Negaunee formation and one in which the detrital material is mainly grains of quartz, in which case the rock becomes a ferruginous quartzite.

In thin section the general description of the jasper-conglomerate given on pages 413–415 applies fully to the conglomerate of the area. In different localities the dynamic effects vary greatly. At some places the jasper pebbles are greatly flattened and the ore pebbles are changed to hematitic slate. In other places the dynamic effects are slight, the rock consisting of rounded or angular ore and jasper pebbles, cemented by finer detritus of the same kind and by iron oxide. There is present in nearly all of the conglomerates a small amount of plainly fragmental quartz not derived from the Negaunee formation; and also a small amount of sericite and chlorite have developed, the former especially in the mashed varieties. The gray ore is found to consist of the original mashed hematite, and of crystals and clusters of crystals of magnetite, between which is chlorite. In the impure ores there is a certain amount of fragmental quartz, which is plainly partly replaced by magnetite. Crystals of magnetite project into the roundish quartz grains, just as though notches had been filed out of the clastic grains to give place to the magnetite. Also numerous crystals of magnetite are wholly included within the quartz grains. It thus appears perfectly clear that by some reaction quartz was dissolved and the magnetite took its place. What relation there is between the disappearance of the quartz and the appearance of the magnetite is not clear, but one seems to be, to some extent at least, conditioned on the other; for if this were not the case the quartz would be irregularly dissolved and the magnetite take the vacant space. It is in the rocks which are half way between ore and ferruginous quartzite or conglomerate that this process of replacement is best seen.

For most of the Ishpeming area only the belt of ore and ore and jasper conglomerate is exposed. However, in the center of the city of Ishpeming typical quartzite is seen. Also in sec. 16 the exposures are found at intervals from the basal conglomerate to the top of the formation. The conglomerate, by a disappearance of the ore and jasper fragments varies up into ferruginous quartzite and ferruginous slate, and this into ordinary quartzite, which is, however, interstratified with graywacke. In thin section, taken in the same order there is a steady lessening of the chert and jasper fragments, and in the ferruginous quartzite there is a very considerable amount of complex material derived from the Negaunee formation. Above the lower 200 feet the material was derived mainly from some other than the Negaunee formation.

Negaunee area.—West of Negaunee and north of the Jackson mine is a basin of the Goodrich quartzite (Atlas Sheet XXVIII). As explained in another place, the Negaunee formation and the Goodrich quartzite at the main Jackson pits are infolded. As a consequence of this, both have apparently the same dip, nearly vertical, and at the west end of the open pit the two are infolded several times, so that a horizontal section from the south toward the north passes from the Negaunee formation to the Goodrich quartzite, thence to the Negaunee formation, thence to the Goodrich quartzite, thence to the Negaunee, and finally to the Goodrich quartzite; that is, there are two tongues of the Negaunee formation between the exposures of the Goodrich quartzite. The basal horizon of the Goodrich quartzite here, as at Ishpeming, was composed almost wholly of the fine and coarse detritus of the Negaunee formation. As a consequence of the close infolding, the detrital rock was so closely mashed that it is difficult to discriminate it from the original Negaunee formation. Especially where the detritus was fine, the rock simulates to a remarkable degree the typical jaspilite, and even where fragments of jasper were present these have been mashed until they resemble jasper laminæ, or, where not so much altered, they have an appearance which resembles that of the brecciated jasper of the Negaunee formation. However, a close examination discloses differences between the two rocks. The jasper laminæ in the conglomerate have not the continuity that they have in the true jasper. Some of the flattened areas have a roundish appearance, and slightly different colored jaspers occur close together, whereas in the brecciated jaspers, while the layers may be broken apart, there is usually a suggestion of former continuity and a likeness of character in the fragments. The cracks in the broken pebbles and in the matrix are cemented by magnetite in crystals, which is readily discriminated from the detrital, mashed, lustrous, micaceous hematite.

A short distance to the north of the main pits of the Jackson mine the relation of the Negaunee formation and Goodrich quartzite is much clearer. The Negaunee jasper is folded into a number of westerly pitching rolls, the strike of the axis of the central fold being nearly N. 75° W. The dip of the jasper or the dip of the axes is 45° W. The overlying quartzite has a north-south strike, and dips to the west at an angle of 20°. At this locality the unconformity between the two formations is apparent, but at the main Jackson pit the severe folding obliterated evidence of this. The conglomerate and recomposed ferruginous schist pass upward quickly into the plainly fragmental ferruginous quartzite.

As examined in thin section, the mashed conglomerates simulate to a remarkable degree the mashed and brecciated original jasper. Many of the pebbles were broken by the pressure into a number of angular fragments, which are cemented by secondary iron oxide. Other pebbles, where the mashing was most severe, are flattened until they approach the jasper bands in appearance. In the recomposed rock in which all of the material is derived from the Negaunee formation, it would be impossible to state from the thin sections that the rock is clastic, but in many of them there appears a subordinate quantity of small, roundish grains of distinctly fragmental quartz, larger than the quartz grains of the Negaunee formation, and evidently derived from some other source, probably from the Basement Complex. These quartz grains show undulatory extinction and fracturing. By an increase of the clastic quartz the rocks pass into the ferruginous quartzites, the fragments of which are derived almost wholly from a distant source, but with which are a few chert and jasper fragments. The whole is cemented by oxide of iron. The fragmental quartz grains all show undulatory extinction and fracturing, and many are arranged with their longer axes in a common direction.

The presence of a quartzite above but a moderate thickness of the chert and jasper conglomerate shows that the Negaunee formation in this vicinity was quickly buried by the Goodrich deposits, and that the major portion of the material for the Goodrich quartzite was derived from the Basement Complex or from the lower part of the Lower Marquette series.

Cascade area.—South of Palmer there are a number of localities in which the Goodrich quartzite is well exposed (Atlas Sheet XXXII). The whole area is a basin, like that at Negaunee, with a subordinate fold, which produces a short arm or basin running southeast from the main area and separated from the latter by the Negaunee formation. At the west end of the Palmer area is the Volunteer mine. This is an eastward-plunging syncline at the bottom of the Goodrich quartzite. The ore belongs wholly to the Goodrich quartzite, a part of it being the gray granular ore, but much of it being similar to the ore of the Goodrich mine, subsequently described. The latter is a micaceous hematite, in which are seen numerous little eyes of fragmental quartz. The ore grades up into ordinary ore, jasper, and quartz conglomerate, and this into a finer-grained chert and quartz conglomerate. In thin section, in the gradation varieties between the ore and conglomerate the partial replacement of the fragmental quartz by the magnetite may be seen. Much of the iron oxide was detrital, and this has been changed to lustrous hematite, and the secondary impregnation, as usual, is represented by the magnetite in crystals and by its alteration product, martite.

The village of Palmer is itself upon the area of the Goodrich quartzite. If we go directly south, the westward-plunging anticline of the Negaunee jasper is crossed, and we reach the south arm or basin of the Goodrich quartzite. Along the southern side of the basin at a number of points may be seen magnificent exposures of the great basal conglomerate, resting directly and unconformably upon the Negaunee jasper. Large, well-glaciated areas are perfectly bare, in which the great variety of brilliantly colored pebbles and bowlders presents a beautiful appearance. At no fewer than four places the actual contacts between the Negaunee and Goodrich formations are seen. In places the dip of the conglomerate is low, and on the south slope of the hills truncated banded jasper may be seen, overlain, with slight discordance, by the conglomerate. While the conglomerate is studded with waterworn bowlders of the Negaunee formation, it also contains very numerous pebbles and bowlders derived from the Basement Complex. Immediately adjacent to the Negaunee formation fragments of it are predominant, but a little higher up those from the Basement Complex are equally abundant. The conglomerate grades up in the central and northern part of the basin into a quartzite, but on the north side, adjacent to the Negaunee formation, the fine-grained conglomerate is again found. A short distance east of the village of Palmer, again, the basal conglomerates and contacts between the Goodrich quartzite and the Negaunee formation may be seen. Here the phenomena are the same as at the contact in the basin just described. About a mile east of Palmer, on an elevation surrounded by a swamp, are large exposures of quartzite and a fine-grained conglomerate, which constitute the eastern extremity of the Palmer basin.

Goodrich-Saginaw area.—To the west, numerous exposures of the Goodrich quartzite constitute a marked ridge, running from about one-fourth of a mile north of the center of sec. 21, T. 47 N., R. 27 W., to the Fitch mine, in the SE. ¼ sec. 24, T. 47 N., R. 28 W. (Atlas Sheets XXIII and XXVI). South of this ridge are the Lowthian, Saginaw, and Goodrich mines. At all of these mines, and at the Fitch, the contacts between the Negaunee and Goodrich formations may be seen. At all of them the unconformity between the two is perfectly clear, and great basal conglomerates are present, the débris of which is derived chiefly from the Negaunee formation. For the most part the discrepancy in the folding between the Negaunee and Goodrich formations is but slight, so that the break is indicated by minor differences in strike and dip; but the quartzite is deposited in the depressions of the irregularly eroded Negaunee formation. At the Goodrich mine the Negaunee jasper is plicated, and it abuts at various angles, up to perpendicularity, against the beds of the conglomerate (figs. 20 and

21, p. 335). The greater portion of the ore taken from the Goodrich mine is the recomposed material of the Goodrich quartzite. In all respects this is like that at the Volunteer mine, except that the detritus mingled with the ore is coarser, and therefore the replacement of the siliceous ingredients by the iron oxide is very incomplete. The ore presents the appearance of extreme mashing, being composed of thin plates and fibers of micaceous hematite, the thinnest of which have slickensided faces, showing that there has been shearing between them. The conglomerate above shows the same dynamic effects, the laminæ of micaceous hematite wrapping around the more resistant quartz and jasper pebbles. As usual, in places between the laminæ of sheared hematite and in cracks a great deal of magnetite in crystals has been formed. The exposures of the basal conglomerate at the Saginaw, Goodrich, and Lowthian mines are scarcely less beautiful than those in sec. 16 (see p. 425) and at Palmer. The conglomerate, composed mainly of the Negaunee formation material, contains pebbles of white, coarsely crystalline quartz, and is in places at least 300 feet thick. It grades gradually upward into a fine-grained conglomerate, in which the ore and jasper are still prominent, but in which coarse-grained quartz is abundant. This passes up into the coarse-grained quartzite, in which there is comparatively little of the chert and jasper, and this into ordinary quartzite, which in the higher horizons is interstratified with graywacke.

At the east end of the ridge, about one-fourth mile north of the center of sec. 21, the conglomerate is infolded with the Negaunee formation in an isoclinal manner, the Goodrich rock making a westward-plunging tongue. A section from south to north passes from the Negaunee formation to the Goodrich and then to the Negaunee, the dip being continuously at a high angle to the north. At this locality the Goodrich conglomerate is very much mashed. The pebbles of jasper are flattened, and in the plane of flattening are elongated unequally in two directions at right angles to each other. The finer detritus shows slickensiding effects. Some of the finer-grained varieties of the rock are gray, siliceous or ferruginous slates or schists, the more ferruginous approaching in appearance the so-called slate ore.

In thin section the conglomerates of the Saginaw range do not differ from those of the Ishpeming area. In the varieties which are most mashed, and therefore most closely resemble the original jasper, the presence of small, distinctly rounded, and often enlarged fragmental grains of quartz and secondary sericite shows the recomposed character of the rock. It therefore appears that while nearly all of the detritus came from the subjacent Negaunee formation, the sea brought in fragmental material from a more distant source. In the fine-grained quartz-conglomerates and the coarser quartzites much chert and jasper are seen, and a large amount of secondary iron oxide is in the matrix. Certain nonferruginous quartzites are strongly feldspathic. These grains and those of the quartz are of large size, some of them almost pebble-like. It therefore appears that in the shallow sea of this time, after the Negaunee formation was buried to a depth of a few hundred feet, most of the detritus came from the gneissoid granites of the Archean. The slides of the slate ores and hematitic schists of the Goodrich mine show the silky, fibrous appearance of the mashed hematite and the crystals of secondary magnetite. The recomposed character of the ore is indicated by occasional small grains of plainly fragmental quartz and by flakes of secondary sericite. The latter mineral is rarely, if ever, present in the ore belonging to the Negaunee formation.

Mount Humboldt area.—West of the Fitch mine there are no known exposures of the Ishpeming formation until north of the Mount Humboldt ridge, in sec. 18, T. 47 N., R. 28 W. From this place outcrops of the formation are found at frequent intervals to some distance west of the Barron mine (Atlas Sheets XVI and XIX). The oval Humboldt ridge is therefore surrounded, except on the south, by concentric layers of the Goodrich quartzite. The lowest horizon of the quartzite is represented by a quartz, jasper, and ore conglomerate similar to that at the Goodrich mine. This may be seen in a cut on and adjacent to the Republic branch of the Duluth, South Shore and Atlantic Railway, and at the various open pits. This conglomerate, in common with that at the Goodrich and at Palmer, differs from that of the Ishpeming area in containing more material derived from the Archean, and particularly large pebbles of white, coarsely crystalline quartz. The mashing phenomena spoken of as occurring at the Goodrich are even more prominent here. At the Barron mine the basal recomposed rock so closely resembles the original jasper that it is difficult, if not impossible, to exactly locate the place at which the Negaunee formation ends and the Goodrich quartzite begins. The two have been mashed into apparent conformity, and at the contact plane is the ore deposit which welds them together; but upon the east side of the ore deposits it is plain that we have the Negaunee jasper, and upon the west side the Goodrich quartzite. At this mine and at the west end of the Jackson mine are the two places in the main area of the district where it is most difficult to discriminate between the two formations. A short distance from the Barron, at the old Humboldt mine, north of Mount Humboldt, there is no difficulty in making the discrimination between the formations, as the mashing was less severe. The Humboldt conglomerate grades up into a coarse graywacke or into a feldspathic quartzite. At one or two of the open pits the finer-grained detritus has been mashed into a perfect, finely laminated mica-schist.

In thin section the mashed conglomerates closely resemble the mashed jasper of the Negaunee formation, but the small, distinctly fragmental grains of quartz of larger size than the granules of jasper, and flakes of sericite, mark the difference. The finer-grained conglomerate has become a ferruginous sericite-schist. The large clastic grains of quartz are broken, elongated, and often wholly granulated. Around these areas the mashed hematite and lustrous sericite wrap in the usual manner in such rocks. As these conglomerates pass up into those in which no coarse detritus was present, we have the sericite-schists. In one case the rock consists almost wholly of flakes of sericite having a minutely crenulated, parallel arrangement of a majority of the blades. There are present a few larger blades of muscovite which are arranged transverse to the others, or at a large angle to them. These are doubtless original clastic flakes. The quartzose mica-schists differ from the pure micaceous rock only in that between the leaflets of sericite are very numerous small particles of quartz, either single or clustered, about which the sericite passes, like the meshes of a stretched net. The quartzite close to Humboldt has largely recrystallized, and approaches a quartz-schist. Many of the original fragmental grains have been granulated, and the new quartz which has developed sometimes approximates in coarseness to the granulated quartz, and between the grains much sericite and chlorite has developed. Where the fragmental grains were large their granulation resulted in distinct flattening. These granulated areas free from the mica still indicate the fragmental character of the rock. At the localities southeast of Humboldt, in sec. 18, where there are a number of exposures of quartzite, the rock is sericitic, less crystalline than that near Humboldt, and more nearly like the normal Goodrich quartzites.

Champion area.—In the vicinity of Champion, at the various mining pits, the lowest horizon of the Ishpeming formation is represented by the granular magnetic ore and the magnetitic hematite-schist of the mines (Atlas Sheet XII). The impure phases of the ore contain jaspery quartz and green chlorite. These grade up into hematitic and magnetitic quartzites and quartz-schists. These latter are associated with or overlain by biotitic graywackes, biotite-slates, or biotite-schists, many of which are garnetiferous, and in some cases are grüneritic. Rarely the rock approaches in appearance the grünerite-magnetite-schist as developed at Bijiki River, as, for instance, southeast of Champion, north of the road, a short distance east of the west quarter post of sec. 4. These schists in places are acutely folded in a minor way. On the road just east of the Champion mine the schist becomes conglomeratic. The matrix of the conglomerate is garnetiferous mica-schist. It holds very numerous pebbles and bowlders of many varieties, including schistose granite, quartzite, quartz-schists, etc. Some of the bowlder-like areas are several feet in diameter. The question arose at the locality as to whether they could be parts of folded or broken layers, rather than true bowlders, but this seemed hardly possible. This rock is one of the most crystalline schist-conglomerates of the Marquette district.

In places the mica-schist is almost immediately north of the rocks of the Negaunee formation. The presence of biotite in the mica-schist, the different character of its banding, and an irregular weathering, due to certain constituents dissolving out, thus giving the rock a ridgy appearance, enable one to discriminate the Ishpeming rock from the Negaunee. In the presence of the mica-schists and schist-conglomerates, and in the absence of any considerable quantity of pure quartzite, the rocks of the Ishpeming formation at Champion are different from those at any other locality. It is to be noted that just north of the Ishpeming formation in this vicinity occur mingled sedimentary and volcanic rocks of the Clarksburg formation, and further, one of the volcanic centers was probably just east of Champion. It is doubtless due to this volcano that the absence of pure quartzites is to be attributed. The peculiar conglomerate above mentioned may perhaps be really volcanic rather than sedimentary.

In thin section certain of the impure ores have a background consisting of small granules of quartz between which are leaflets of biotite, sericite, and chlorite, and in which are very numerous crystals and clusters of crystals of magnetite. Where the quantity of the micaceous minerals is small and the granules of quartz are almost wholly derived from the Negaunee jasper, the recomposed rock simulates to a remarkable degree the original formation. Where the chlorite becomes very abundant, as it sometimes does, the background is predominantly of this mineral, but it still contains clastic grains of quartz derived from the Negaunee jasper, and the whole is studded with crystals of magnetite. There are also present large crystals of chloritoid. As usual, the micaceous hematite is easily discriminated from the brightly reflecting, secondary, crystal-outlined magnetite. As the ore body at the Champion mine is so largely magnetite, it appears that the secondary replacement, after dynamic action had ceased, was the most important process in the production of the ore deposits.

By the appearance of coarse-grained fragmental quartz from the Basement Complex, the rocks at the bottom of the formation grade up into biotitic, sericitic, and chloritic quartzites or quartz-schists, which contain much iron oxide as a secondary impregnation. In the more mashed phases the quartz grains are flattened so that their longer axes are in a common direction. Accompanying the flattening is granulation. Sericite is the predominant mica, and this secondary mineral wraps around the particles of quartz in the usual mesh-like fashion. In certain of the rocks many feldspars are seen, and these are partly decomposed, the mica and quartz forming from them. The mica-slates and mica-schists are in all respects like similar rocks of the Michigamme formation, described on pages 449–450, and they will therefore not be here fully considered.

The different phases include black garnetiferous mica-slates and coarse-grained chlorite-slates and biotite-slates. The finer-grained varieties are strongly garnetiferous and andalusitic. The garnet contains few inclusions, but the andalusite, as usual, is full of the other minerals of the rock. The grüneritic rocks differ from the biotite-slates only in that in place of part of the mica grünerite has developed. Garnet is also abundant.

Lake Michigamme area.—West of Champion, south of the center of sec. 36, and at several places near the water's edge on the south arm of Lake Michigamme, occur grüneritic schists (Atlas Sheets VI, VIII, and IX). In sec 36 the rocks are nearly pure grünerite-magnetite-schists, very closely resembling those of the Bijiki formation at Michigamme. At the remaining places to the southeast the schists are biotitic or are interlaminated with bands of biotite-schist. In thin section the nearly pure grüneritic schists do not differ from those of Michigamme. The quartzose background is finely crystalline, but in it are seen occasional larger fragmental grains of quartz. With the grünerite is a certain amount of pleochroic amphibole, and the usual intergrowths of the two occur. In certain slides the chloritic decomposition of the grünerite is seen. The rocks are usually garnetiferous. As the rocks become less pure, biotite is found with the grünerite between the particles of quartz. In an intermediate variety the biotite and grünerite are about equally abundant. By a lessening of the amount of grünerite and an increase of the chlorite and biotite the rocks pass into the ordinary mica-slates and mica-schists of the Michigamme formation.

Republic area.—At the south end of the Republic trough there are numerous large exposures of the Ishpeming formation (Atlas Sheet XI). The predominant variety is white quartzite. This passes downward into a conglomerate at the base of the formation, and it grades upward into the mica-schist of the Michigamme formation. Beginning with the basal members of the formation at the southwest angle of the Republic horseshoe, there is the usual recomposed specular and magnetic ore, often "micaceous," which bears clastic grains of quartz and complex fragments from the Negaunee formation. At the same horizon or above this are magnificent exposures of conglomerate. The predominant pebbles and bowlders are from the Negaunee formation, but with these are found bowlders of quartz as large as 2 feet in diameter. Also, there are present a few pebbles which appear to be derived from the gneissoid granite of the Basement Complex. At the exposure nearest the jasper is seen a distinct cleavage parallel to the side of the Republic tongue, while the pebbles and bowlders are concentrated into bands which cut across this cleavage, although the longer diameters of the flattened pebbles are in the plane of cleavage. In all probability these pebbles were deposited with their longer axes parallel to the bedding. They have, therefore, been rotated to their present position, or have been flattened by pressure, or both have occurred. A close examination of the jasper below shows that rotation has probably taken place to some extent. Here the folding was so sharp as to bend the once regular belts of jasper into zigzag bands, more nearly parallel to the cleavage than to their original bedding. We therefore conclude that the pebbles of the conglomerate have been revolved as well as flattened. The quartzite and conglomerate are also found at various places from the Republic mine to the village of Republic, along the west side of Republic Mountain. Wherever the contact is found between the Ishpeming and Negaunee formations the latter is eroded, the former is a conglomerate bearing numerous fragments of the latter, and there is a slight discordance between the two formations. At one place on the east side of the trough, as a result of faulting, the contact is a double one, a quartzite tongue appearing within the jasper. The nature of the contact between the two formations and the origin of this tongue are fully discussed by H. L. Smyth in another place. (See pp. 542–547.)

The conglomerate grades up into a gray quartzite or quartz-schist. This is in some places sufficiently coarse grained to show distinctly the fragmental character, but at certain places it becomes novaculitic in appearance, being apparently composed mainly of the individual grains derived from the Negaunee jasper. The quartzite is more or less impregnated with magnetite. The quantity of this mineral lessens, upon the whole, in the higher horizons. Also, in the quartzite at one place is a considerable quantity of epidote, which in some specimens is sufficiently abundant to give a distinct greenish tint to the rock. The quartzite in its upper part passes into a fine-grained, micaceous quartz-schist, and this into the mica-schist of the Michigamme formation.

In thin section the recomposed ore has a hematite and magnetite background. In this are included many flakes of muscovite, broken grains of coarse quartz, and simple and complex particles from the jasper. The matrix of the less ferruginous conglomerate is essentially the same as the quartzites, except that a considerable quantity of feldspar, including both orthoclase and plagioclase, is contained in it. At some places this feldspar has partly altered into quartz, muscovite, and biotite, many of the roundish grains being now an interlocking mass of these minerals and the residual feldspar. The quartzites show the effects of extreme pressure; all of the grains show undulatory extinction or fracturing, or even granulation. While many of the grains have a general roundish appearance, they rarely show the original cores, and are minutely angular upon their exteriors. These larger grains intricately interlock, and in part finely crystalline quartz has developed between them. In the rocks in which the dynamic effects are least the coarse-grained original quartz is discriminated from the finer-grained secondary quartz, but in the more mashed phases of the rock the two are similar and the quartz grains interlock in an intricate way, giving no positive evidence of their original fragmental character. Between the grains considerable muscovite has developed, making the rocks sericitic quartzites, and where most mashed sericitic quartz-schists. At one place on the east side of the trough, in a coarsely crystalline quartzite, epidote and amphibole are so abundant as to become chief constituents. The quartzite is coarsely crystalline, and the roundish forms of the quartz grains still show the fragmental origin of the rock. The epidote occurs in small and large, distinctly pleochroic, irregular grains, some of which show a tendency toward crystal outlines. In the upper part of the Ishpeming formation the quartzite is fine-grained, and here the background consists of small granules of quartz, similar in appearance to those making up the Negaunee jasper, and this is doubtless their source. The rock, however, differs from the Negaunee jasper in that, everywhere between the grains, flakes of biotite, chlorite, and sericite have developed. In some sections the biotite is predominant, in others the sericite. In the conglomerates, quartzites, and quartz-schists alike, numerous crystals of magnetite are seen, which are included indiscriminately in all of the other minerals present.

Kloman area.—To the northwest of Republic, along the east side of the Republic trough, at the Kloman mine the contact between the Negaunee formation and the conglomerate of the Ishpeming formation is beautifully exposed (Atlas Sheet XI). The Negaunee formation has its typical characters. Resting upon this is recomposed ore. The recomposed material near the base of the Ishpeming formation very closely simulates the Negaunee jasper in appearance. However, minute roundish granules of quartz and pebbles of jasper show the character of the rock when closely examined. At one place, where the ore welds the two formations together, it is impossible to state where the Ishpeming formation ends and the Negaunee formation begins. The ore taken from the mine seems to occur about equally in the two formations. As usual, in the ore two kinds of iron oxide are discriminated, the original, detrital, mashed hematite and the secondary crystalline magnetite. In cross fracture the latter is more evident; in specimens parallel to the lamination the micaceous hematite appears to be predominant, presenting its usual lustrous, slickensided surfaces. The heavily ferruginous material passes up into a quartzite containing numerous fragments of ore and jasper. Layers of conglomerate and of quartzite, comparatively free from jasper pebbles, are interstratified. This rock passes up into a fine-grained gray quartzite, like that at Republic. In thin section the rocks do not differ from the similar rocks at Republic, except that the dynamic effects are less severe. In the quartzose ore the coarse, well-rounded, little-distorted grains of fragmental quartz derived from the Archean show distinct enlargements. All, however, show undulatory extinction, and many are fractured.

Northern Republic and Western troughs.—At a number of places between the Kloman mine and the northwest end of the Republic trough there are exposures of the Ishpeming formation. The majority of these are at the mines along the trough, but at various other places important outcrops occur. The more important localities are as follows: the S. ½ sec. 1, T. 46 N., R. 30 W., the Metropolitan mine, the Chippewa mine, the Riverside mine, the Standard mine, the Cannon mine, the Erie mine, the Magnetic mine, and various places to the east and west in sec. 20, T. 47 N., R. 30 W. In the Western tongue there are exposures of the Ishpeming formation in sec. 30, T. 47 N.,

R. 30 W., and in sec. 18, T. 46 N., R. 30 W. (Atlas Sheets VII and X.) To describe in detail each of these localities would require too much space. They are therefore treated together.

At the various mines the basal horizon is a coarse magnetic ore, associated with considerable chlorite, and in some places with pyrite. As this ore becomes lean it contains quartzose bands, which show large clear grains or pebbles of quartz that appear to be fragmental. These white quartz bands never very closely simulate the red or white jasper of the Negaunee formation, and there is usually no sharp differentiation between the ferruginous and nonferruginous bands, as is the case with the jasper. They are therefore discriminated in hand specimen from the true jaspilite of the Negaunee formation. If there were conglomerates deposited at the base of the formation, at most places these have been wholly destroyed by the dynamic action. In some cases the bands of quartz have a lenticular appearance, as if they were greatly flattened quartz pebbles.

At two places, where erosion has cut away the Lower Marquette series, the rocks of the Ishpeming formation are found close to the granite. The first of these localities is southeast of the Erie mine, in the NE. ¼ sec. 28, and the latter northwest of the same mine, in the SE. ¼ sec. 20. At the first of these localities the rock is a coarse-grained, foliated, micaceous quartz-schist, which at one place contains distinct quartz pebbles. At the second locality the rock is of a similar appearance, and it contains distinct pebbles of white quartz and of jasper. This rock is associated with a massive, greenish-gray, hornblendic quartzite. These coarse rocks pass up into fine-grained, micaceous quartz-schists.

The heavily ferriferous rocks of the mines are closely associated with or grade into muscovitic quartz-schists; these grade into completely crystalline, thoroughly foliated mica-schists, like those of the Michigamme formation.

Associated with the mica-schists, grüneritic and magnetitic schists are found. These may be particularly well observed west of the Kloman mine, adjacent to and south of the road. This grünerite-magnetite-schist contrasts with that of the Negaunee formation in having a rough appearance upon the weathered surface, and in having a peculiar toughness which prevents it from being cleaved parallel to the banding, while the similar rock of the Negaunee formation has a regular lamination, is brittle, and parts readily along the lamination; also, the layers of the former are thicker, and many of them have more of the appearance of a crystalline schist than the similar rock of the Negaunee formation. The schist is folded in a most complicated fashion. On the horizontal exposure the layers are seen to turn back upon themselves in repeated sharp V folds.

Upon the whole, the rocks of the Ishpeming formation in this area are the most extremely metamorphosed of all in the district. While occasional conglomeratic schists have been discovered and the coarser quartz-schists are not completely crystalline, the finer-grained rocks have been changed to completely crystalline schists. The evidence of unconformity between the Negaunee and Ishpeming formations, which is so marked at Republic and other localities in the district, is wholly obliterated. From the proximity to these places one can not doubt that the two are here unconformable, and that there was an irregular erosion contact between them; but if this be true, the mashing was so severe as to wholly destroy the evidence of this. The schistosity of the Ishpeming formation and the bedding of the Negaunee formation are in apparent conformity. Where the Ishpeming formation is in contact with the Archean, somewhat similar relations obtain. The basal horizon of the Ishpeming formation is a coarse micaceous quartz-schist. It is not always possible to tell exactly where this recomposed rock begins and the mashed granite ends. At two localities only, one between the Erie and Magnetic mines and the other southeast of the former, does this basal rock distinctly show by pebbles its fragmental character.

Under the microscope a few of the slides of the recomposed materials at the mines so closely resemble the original Negaunee jasper that the two could not be discriminated. However, there is usually present muscovite in small or large flakes, and biotite and chlorite are found, in some places abundantly. In certain cases lenticular areas of jasper suggest that the lenticules represent mashed pebbles. While the quartz of the siliceous layers varies considerably in coarseness, there is usually no such range in size as at Republic, where each of the coarse grains derived from the granite can be readily discriminated from the small grains derived from the Negaunee jasper. If coarse grains were originally present they have been granulated by the mashing. Toward the southeast end of the area, near the Kloman and Republic mines, the mashing was not so severe, and here two classes of quartz are discriminated. Although no grains show cores and enlargements, in some cases the coarser grains are cemented by a fine mosaic, as in ordinary quartzites; in others the coarse and fine grains are in alternate layers; while in a third case they are indiscriminately mingled.

Where the Goodrich quartzite rests upon the Archean, the basal rock is entirely different from the above, being in two places a conglomerate composed chiefly of material derived from the Basement Complex. The pebbles of the conglomerate were simple and complex fragments of quartz, large grains of feldspar, and granitic pebbles composed of both. These have been so intensely mashed that they are usually in elongated oval or ribbon-like areas. Much of the coarsely crystalline quartz is granulated, so that the quartzose pebbles consist of finely granular interlocking quartz. The feldspar fragments are usually much shattered. Along the cracks quartz and muscovite have largely developed. In one case the stresses have produced an unusually strongly marked fissility in two directions, which in section resembles the double cleavage of calcite. Where the decomposition went far enough the areas once occupied by feldspar consist of interlocking crystalline masses of quartz, muscovite, and residual feldspar. In the pebbles which consisted of quartz and feldspar together the effects upon the latter mineral were the same as in the pebbles which consisted of feldspar alone. The matrix of the conglomerate is a muscovitic and feldspathic quartz-schist. The feldspar comprises both orthoclase and plagioclase, the latter including much microcline. In some of the sections this feldspar is so abundant as to be a principal constituent. In a number of slides the matrix is completely crystalline, thus becoming mica-schist or mica-gneiss. If it were not for the conglomeratic character of these rocks their sedimentary origin could not be asserted from evidence shown by the thin section. As accessories in the conglomeratic schist and gneiss, magnetite, biotite, chlorite, and epidote are found.

By a lessening of the amount of magnetite the recomposed ore-bearing rocks at the mines pass up into muscovitic quartz-schists. Also by the disappearance of the larger fragments the conglomerates resting upon the Archean pass up into like rocks. The dynamic forces were not severe enough to entirely destroy the large original rounded fragmental grains of quartz. These are represented by roundish or oval areas, which may show only undulatory extinction or fracturing, or may be oblong granulated areas. But the latter differ from the finer-grained background in the absence of muscovite. However, the quartz grains never show cores with enlargements. They completely interlock. Their fragmental character is therefore indicated mainly by the general shapes of the complex areas. In the finer-grained varieties of the quartz-schist no distinction is to be made out between detrital and nondetrital grains. The rock is a completely crystalline, muscovitic quartz-schist. As in the case of the conglomerates, a greater or less amount of feldspar is present

By an increase in the amount of muscovite the quartz-schists pass into typical crystalline muscovite-schists. In many of the rocks biotite also is a principal constituent, and they become muscovite-biotite-schists. By a further replacement of the muscovite by biotite the rocks pass into biotite-schists. In some cases the folia of muscovite are arranged transversely to those of biotite, as though one of these minerals had developed as a consequence of one dynamic movement and the other of a later one. In a few instances the amount of feldspar in the background is so great as to be a principal constituent, and the rocks are muscovite-biotite-gneisses. The feldspar includes orthoclase and plagioclase, the major portion of the latter being microcline. The completely crystalline gneiss occurs in association with an intrusive greenstone.

A portion of the feldspar in the background of the conglomerates, quartz-schists, and mica-schists appears to be detrital, but a large part is apparently a new development, as much of it is perfectly clear, showing no decomposition, and including magnetite and other minerals. In the quartz-schists and mica-schists, magnetite, epidote, and zoisite are often abundant accessories, and in the mica-schists garnet also is plentiful. The mica-schists of the Ishpeming formation are the same in their general characters as those in the Michigamme formation (pp. 447, 449–450), and they will therefore not be here described in detail.

At the Magnetic mine, and east and west of it, a coarse-grained gray quartzite is associated with the ordinary phases of quartzites. In this quartzite, hornblende and epidote occur as chief constituents between the grains. These rocks are in all respects like those which have been described in the quartzite tongue at Republic. In some of the micaceous schists of the same area a large amount of garnet, chlorite, and chloritoid is present.

By the replacement of mica by grünerite and green hornblende in the mica-schists these rocks grade into the grüneritic rocks which have been described under the name Bijiki schist. The transition varieties and the grüneritic rocks which are free from mica are not different from those which occur northwest of Champion (pp. 434, 436). As usual, garnet is abundant.

SECTION II.—THE MICHIGAMME FORMATION.

By C. R. Van Hise.

The name Michigamme is given to the upper slate and mica-schist because on the islands of Lake Michigamme and on the mainland adjacent to the shore occur extensive exposures of this formation.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The Michigamme formation is mainly in a single great area (Atlas Sheet IV). Beginning west of Ishpeming, it sweeps westward as a broad belt to near Humboldt; here it becomes somewhat contracted, and east of Lake Michigamme it is divided into two belts, a narrow northern belt between two zones of Bijiki schist, and a broader southern belt which includes the greater part of Michigamme Lake and the country to the westward. This belt widens out over a broad area and occupies a great expanse of country in the large area of Algonkian rocks at the west and south part of the district covered by the present report. From this broad area two arms project, forming the centers of the Republic and Western tongues. At and east and west of Humboldt is a southern lenticular area about 6 miles long.

As this formation was originally a shale or grit, where it has not been much altered the exposures are not prominent, and the area as a whole is one of rather feeble relief, occupying lowlands between the ridgy country of the formations both to the north and south. This is particularly the case from the eastern extremity of the area to Lake Michigamme. At Lake Michigamme and to the south and west the formation was much more metamorphosed, becoming a mica-slate, a mica-schist, or a mica-gneiss, and here, on account of the increased resistant power, the exposures are numerous and conspicuous, especially on the southern side of the west arm of the lake and upon the islands to the east. In the Republic tongue the schist, being softer than the lower formations, is followed by the Michigamme River.

FOLDING.

Broadly considered, for most of the area the Michigamme formation is in a great syncline. This syncline is, however, very complex, and there are many subordinate anticlines and synclines. East of Lake Michigamme one of these anticlines is of sufficient importance to bring the Bijiki schist to the surface, and thus to divide the Michigamme formation into two synclines, the southern one of which is the more important. Another probable anticline is indicated by the iron-ore pits in secs. 29 and 35, T. 48 N., R. 29 W., as it is thought that the ferruginous horizon belongs near the base of the formation (Atlas Sheets XII and XV). The Republic and Western tongues are both isoclinal synclines. If the exposures are examined in detail, it is found that many of the secondary anticlines and synclines have upon them tertiary folds, and upon these are folds of the fourth order, and so on to microscopic plications; so that in many places the rocks are minutely implicated. This is particularly well seen in the schist at Lake Michigamme.

PETROGRAPHICAL CHARACTER.

Macroscopical.—The rocks of the formation comprise two main varieties—little-altered slates and graywackes, and mica-schists and mica-gneisses. Each of these comprises both ferruginous and nonferruginous kinds. The first class occurs chiefly in the area east of Lake Michigamme and the second in the Lake Michigamme area, although representatives of the first are found along the northern side of the Michigamme formation to the western limit of the district considered. The mica-schists are also found along the southern part of the belt, several miles east of Clarksburg. It can not be said that these divisions are in any way stratigraphical, unless it be true of the ferruginous phases, which appear to occupy a somewhat persistent horizon; but these latter rocks are not so well defined that they can be mapped as a separate formation.

The *slates* and *graywackes* differ from each other chiefly in coarseness of grain, the two often being interlaminated in the same exposure or ridge. There are all gradations, from the aphanitic, black shales or slates to a graywacke so coarse as to approach a quartzite, or, in one case, a conglomerate. The rocks vary in color from gray to black. Where they are fine-grained they usually have a well-developed slaty cleavage, and are often carbonaceous, ferruginous, and pyritiferous. In some places the amount of carbon is so great as to give a black streak. When broken apart parallel to the cleavage the graphite is frequently in a lustrous form, due to movements parallel to the parting. An examination of two specimens (16671 and 16678) of the most carbonaceous rocks, by H. M. Stokes, in the chemical laboratory of the United States Geological Survey, showed that they contain respectively 18.92 and 15.69 per cent of carbon, but no hydrocarbons. A portion of the carbon appears to be in the form of anthracitic, coaly substance, but much of it has been transformed to graphite. The pyrite is in detached crystals, and in laminæ parallel to the parting. The least altered of these rocks could properly be called shales or grits. In places where they are more altered the shales pass into mica-slates, and by more extreme alteration into the mica-schists.

The ferruginous slates and graywackes contain much iron. In the least-altered phases the iron compound is largely siderite, and thus the rock is a sideritic slate. Rarely the siderite becomes the predominating constituent, and in this case the rock is similar to the sideritic slates of the Negaunee formation. As a consequence of weathering and metasomatic changes, ferruginous slates, ferruginous cherts, and grünerite-magnetite-schists have developed from these sideritic slates. In the few localities where the ferruginous material was very abundant small ore bodies also have formed. Such are known at three places north of Champion and at one south of Spurr. Pits also occur in the south halves of secs. 29 and 35, T. 48 N.,

R. 29 W. (Atlas Sheets XII and XV) These ores differ from the soft ores of the Negaunee formation in that the iron oxide is largely limonite and in that the associated rocks contain much carbonaceous and graphitic material. The ferruginous phases are particularly prevalent just above the Clarksburg volcanics and the Ishpeming formation—i. e., a short distance above the formations which are immediately subjacent to the Michigamme formation. All of the pits may and probably do belong to the same horizon. If this be true, the central belt is near the crest of an anticline which rises high enough to bring this low ferruginous horizon of the formation to the surface. The foot-wall of the ore bodies is, so far as observed, the impervious fragmental Michigamme slate. The ores and peculiar associated rocks therefore appear to be in bunches or in lenses in the carbonaceous slates, strongly suggesting that the abundant organic material had to do with the deposition of the iron compounds.

The ferruginous and nonferruginous slates and graywackes, by an increase in metamorphism, pass into the *mica-schists* and *mica-gneisses.* At Lake Michigamme, it has been said, mica-schist is abundantly developed in its typical form. This mica-schist, while a completely crystalline rock having well-developed schistosity, still shows in places, when closely examined, the original bedding and an alternation of coarse and fine material such as occurs in the slates and graywackes to the east. The schistosity varies from parallel to perpendicular to the bedding, usually being at some intermediate angle Where the schists are completely crystalline, garnet, staurolite, chloritoid, and andalusite are often plentifully present.

In the most coarsely crystalline kind the rock is in places veined throughout with a granitic-looking material, and feldspar has abundantly developed within the rock, forming a gneiss. The gneiss is pegmatized through and through, as though the material, either as a magma or in the form of a water solution, had penetrated the joints, the partings parallel to the laminæ, and also the interspaces between the constituent particles, and had in these places produced quartz and feldspar. A close examination shows that many of the apparently granitic veins are but the coarser beds strongly pegmatized. The pegmatized areas grade into the ordinary mica-schist. It is concluded that the pegmatization was not the result of an igneous injection from an extraneous source, particularly as there are no known granite intrusives within the Upper Marquette series. The facts seem rather to be explained by water action. The whole rock must have been permeated by hot solutions, from which the new minerals separated in the interspaces left by the folding.

If this explanation be correct, the rock is one to which the term "metamorphism" is applicable. Why the rocks of this part of the formation are so thoroughly metamorphosed and those to the east comparatively little affected has not been certainly determined. The beds are intensely plicated. Such plication involves a large amount of readjustment of the layers over one another and within the layers themselves—that is, the mashing was exceedingly severe. During this time of folding, by the decomposition of fragmental feldspar into quartz and mica, the development of new feldspars in some places, and the granulation of the coarser crystalline quartz, the rock changed into a mica-schist or a mica-gneiss.

Microscopical.—The *slates* and *graywackes* consist mainly of fragmental quartz and feldspar set in a clayey and micaceous matrix. Occasionally other fragmental constituents, and especially mica, are found. In the cases of the finer-grained slates the clayey matrix is predominant. In the coarser-grained graywackes the plainly fragmental material is predominant. In the latter we often have closely fitting grains of quartz, some of them well rounded and enlarged, with a few of feldspar, set in a sparse matrix. This rock approaches a quartzite. The fragmental constituents generally show pressure effects, the larger grains being broken into two or more fragments, or cut by fine cracks, sometimes in a rectangular manner, which cause undulatory extinction. The fragmental grains of feldspar have largely decomposed, and quartz, biotite, and chlorite have developed from them. In the clayey background there have developed many minute flakes of biotite, sericite, leaflets of chlorite, and sometimes needles of actinolite. These usually do not have a parallel arrangement. More frequently than not there is also present a greater or less quantity of ferrite. Sometimes crystals of tourmaline also occur.

In proportion as the feldspar is decomposed and the quartz is granulated, the rocks approach the *mica-schists*, an intermediate phase being represented by the *mica-slates*. These still show evidence of their fragmental origin, occasional fragmental grains of quartz being seen, some of which are enlarged. Many of these fragmental grains are easily separable from the newly developed quartz, showing as they do undulatory extinction or fracturing. The quartz grains show an imperfect arrangement, with their longer diameters in a common direction. The folia of biotite also have a parallel arrangement. In a further stage much of the quartz has been granulated, and the feldspar is largely replaced by secondary mica and quartz.

These mica-slates on the one hand grade into the ordinary slates and graywackes step by step, and on the other hand, by greater alteration, they pass into mica-schists. Where the process of metamorphism is complete, the fragmental quartz grains are wholly granulated by the mashing, which has kneaded the rock throughout. In many slides each folium moved differentially in reference to those above and below it. The fragmental feldspar is wholly changed into quartz, mica, and chlorite. The folia of new mica developed with their longer axes in a common direction. In proportion as the deformation is greater, sericite and muscovite become prominent with the biotite. Thus in place of the fragmental rock a completely crystalline mica-schist is produced.

The details of the processes of development of these schists will not be here described, but they are similar to those given for the development of the mica-schists in the Penokee series.[1] There has, however, been the difference explained above, that mashing has played a much more important part in the case of the mica-schists of the Marquette district. As a consequence, some of the schists are strongly foliated. In the crystalline schists a large amount of garnet, staurolite, andalusite, and chloritoid has developed. These minerals include large quantities of the prior quartz. They show no evidence of strain, and they are believed to have developed

[1] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey, Vol. XIX, 1892, pp. 332–343.

in the quiescent stage after dynamic action had ceased, but while the heat still produced hot solutions which bore abundant mineral material.

By the formation of the secondary feldspar, probably by the same process both within and between the grains, quartz-mica-feldspar-rocks or mica-gneisses have developed. These mica-gneisses have an interlocking, granitic-appearing background, composed of quartz and feldspar in about equal abundance. That the rock was originally fragmental is indicated only by occasional roundish grains of quartz and feldspar, but it is always difficult to determine certainly what part of the quartz and feldspar is original and what part a secondary development. Both the original and secondary feldspars are stained with limonite and are decomposed to a greater or less degree into chlorite, biotite, and quartz. Biotite is the predominant micaceous mineral, but muscovite is present, and chlorite is abundant. Magnetite is also present in numerous crystals, and a small amount of hornblende is found. The veins cutting the gneisses are composed mainly of iron-stained feldspar, with, however, much chlorite and quartz. This feldspar, which is beyond all question secondary, is identical in its appearance with that contained throughout the rock. In the mica-gneiss are curious black concretionary-looking areas, which in thin section are seen to be essentially the same as the remainder of the rock, except that they contain numerous large crystals of hornblende and much zoisite. Each of the hornblende individuals includes many of the other mineral particles, and in their development they appear to be analogous to the staurolite and garnet.

The occurrence of these mica-gneisses within the Michigamme formation is of great interest as proving the development of this kind of rock from a clastic. In almost every respect the coarsest of these mica-gneisses are similar to many mica-gneisses of the Basement Complex. The only difference between the two is that in the Michigamme formation these crystalline forms may be traced by gradations to phases in which the fragmental characters are clearly apparent.

The purest and least-altered phase of the *ferruginous rocks* is sideritic slate. This is a fine-grained gray rock, composed almost wholly of siderite, which upon the weathered surface, where the carbonate passes into iron oxide, exhibits a reddish-brown color. From these ferriferous carbonates there have developed ferruginous slate, ferruginous chert, jasper, grünerite-magnetite-schist, and iron ore, the processes and results being identical with similar rocks from similar materials in the Negaunee formation. (See pp. 336–375.) The description of these processes will therefore not be here repeated.

Certain minor differences separate these rocks from those of the Negaunee formation—the grüneritic rocks are finer-grained, the iron oxide is largely limonite, and in all phases of them carbonaceous material is abundant.

The amount of pure nonfragmental material is subordinate, but because iron ore develops from it, it is not unimportant. There is in the Michigamme formation a much larger quantity of material intermediate between clastic and nonclastic sediments. In some places the fragmental and nonfragmental material is largely concentrated in alternate bands. In other places the two are intermingled. Where least altered, these intermediate rocks may have a background consisting of siderite and cherty quartz, with some ferrite, which contains numerous well-rounded fragmental grains of quartz and feldspar. As the metamorphosing processes set in, the siderite goes through the same set of transformations as where it is alone, and the same is true of the fragmental material, so that there results a great variety of rocks. Where the processes are chiefly metasomatic the siderite changes to ferrite, and ferruginous graywackes, ferruginous slates, cherty graywackes, and cherty slates are produced. In a common variety a ferrite background contains the clastic constituents. If at the same time the feldspar alters to biotite and chlorite, the slates are biotitic and chloritic. Where the dynamic effects are stronger, grünerite and magnetite develop from the siderite, the secondary mica has a parallel arrangement of its folia, and the quartzes are arranged with their longer axes in a common direction, or are granulated, so that there result hematitic and magnetitic mica-schists, grüneritic mica-schists, etc. At different places there are all gradations from the least to the most metamorphosed varieties, and from those which originally consisted wholly of nonfragmental material to those which consisted wholly of fragmental material. In the first case the peculiar rocks of the iron formation were produced; in the second case the mica-schists and mica-gneisses were formed. Between one extreme and the other there is every gradation.

RELATIONS TO THE UNDERLYING FORMATION.

It has already been said that the Michigamme formation grades slowly down into the Goodrich quartzite or into the Bijiki schist, and that therefore the line of separation between them is more or less arbitrary. The relations to the Clarksburg formation are considered on pages 461–463.

THICKNESS.

The thickness of the formation must be considerable, as it covers a wide area, but it is impossible, on account of the subordinate folding to which it has been subjected and the extensive development of slaty cleavage or fissility which cuts across the bedding, to make even an approximately accurate estimate. It is possible that within the area described its thickness is not more than 1,000 to 2,000 feet, but it may be much more.

INTERESTING LOCALITIES.

Spurr, Michigamme, and Champion area.—Beginning at the northwest part of the area (Atlas Sheets V, VIII, and XII), about three-fourths of a mile south of the Spurr mine are open pits of soft limonite in the slate. Exposures occur in the valley separating the two belts of the Bijiki schist along the north side of Lake Michigamme at only one or two localities. These are on the north side of East Point. Passing to the eastward, north of Champion, in secs. 29, 30, 31, and 32, there are very numerous exposures of the less altered kinds of the Michigamme formation. The larger and better-exposed area is a rough elevated plateau north of the Bijiki schist. The rocks of the area comprise fine-grained, black, carbonaceous, graphitic, and pyritiferous slates; coarser-grained slates of the same varieties; ordinary black slates; fine-grained, dark-colored graywackes; coarse-grained graywackes; occasionally rocks which approach a quartzite; and, at one place, a conglomerate. Between the different varieties of rock there are all sorts of gradations and interlaminations.

The conglomerate contains small pebbles of chert and quartz, and larger pebbles of what appears to be dense black slate. On the exposed surface these weather out, giving the rock a pitted appearance. The finer-grained and more carbonaceous rocks stain the fingers, and are so soft as to readily give a black mark. When parted along the cleavage, many of them show lustrous graphite. In all of the carbonaceous varieties of rock pyrite and marcasite are very plentiful Even the fine-grained graywackes have a dark color, due to the contained carbon. For the most part the rocks show comparatively feeble dynamic effects. To the majority of the rocks the term shales and grits would almost be applicable. Slaty cleavage is present only in the fine-grained varieties. As has been explained, occasionally the movements have been sufficient to develop lustrous graphite between the laminæ of the slates. In places, as a result of the movements, the slates were broken, and the cracks filled with vein quartz, the veins varying from minute seams to those several inches across.

In thin section the rocks correspond in their characters, in most respects, to the general description of them given on pages 448, 450–451. The coarser-grained graywackes contain comparatively little feldspar and a small amount of interstitial material. They are largely cemented by enlargement. They therefore approach quartzites. They are, however, always discriminated from the quartzites of the Ishpeming formation by the presence of black carbonaceous material between the grains. The dynamic effects observable under the microscope are usually slight, the grains only occasionally being arranged with their longer axes in a common direction, although they commonly show undulatory extinction and fracturing, sometimes in a rectangular manner. In the few slides in which the quartz grains have a parallel arrangement sericite is abundant, this appearing to be developed in proportion to the other dynamic effects. In both the slates and graywackes mica and quartz have developed by the decomposition of the feldspar in the interstices. Biotite is the predominant mica, although chlorite is rather plentiful. This process is of far greater importance in the slates than in the quartzites. The carbonaceous material is so abundant in many of the black slates as to make it difficult to determine the minerals present, and especially the amount of iron oxides. In a few of the slates the movements have been sufficient to develop folia of biotite in a parallel direction, and thus make them mica-slates. In the transverse sections of the graphitic slates the contorted laminæ of graphite are beautifully shown.

At several places within the area under consideration mining has been done on a small scale. These places are located as follows: In sec. 29 a number of pits are a short distance north of the center of the section; others are about one-fourth mile south of the center; and still others something less than one-half mile to the east. In sec. 30 only one small pit is known, and this is about one-fourth mile south of the center of the section. In the south part of sec. 31 is the North Champion mine. At all of these places the country rock is the black carbonaceous and pyritiferous slate. The ores are strongly limonitic. Associated with these ores are sideritic slates, ferruginous cherts, and grüneritic slates. The grüneritic slates are usually finer-grained than those of the Negaunee formation, and most of them appear to contain a considerable amount of carbonaceous material. The majority of the ferruginous cherts also have a somewhat different appearance from those of the Negaunee formation, and the amount of this material is small. Where the small ore bodies occur the original carbonaceous formation appears to have been sideritic. By its oxidation and the concentration of iron oxide grüneritic rocks and ferruginous cherts developed, by processes analogous to those by which similar rocks formed in the Negaunee formation.

The thin sections of the ferruginous rocks of the mines are, in all essential particulars, the same as the similar rocks in the Negaunee formation, described on pages 366–375. Like them, they show the development of the different varieties of the rock from a sideritic slate. However, there are minor differences, as follows: The chert is usually very finely crystalline, and sometimes has a semiamorphous appearance. The grünerite is at most places finely crystalline. The iron oxide is very largely limonite, and all of the minerals are everywhere impregnated with black carbonaceous material. At the mines the amount of mingled fragmental material is small.

Eastern area.—(Atlas Sheets XV, XVI, XIX, XXII, and XXV.)—In sec. 35 are pits which contain iron-bearing rocks similar to those in the pits north of Champion. Adjacent to these pits there are the usual black carbonaceous and pyritiferous slates.

To the east, between Mount Humboldt and the Clarksburg formation slates are found at various localities. However, north of the belt of Clarksburg formation, in sec. 1, T. 47 N., R. 29 W., and in secs. 5, 6, and 7, T. 47 N., R. 28 W., there is a complex ridge along which are very numerous exposures of the slates, novaculites, and graywackes of the Michigamme formation. The different varieties of these rocks are particularly well seen adjacent to and north of Clarksburg. The rocks of this area differ in a number of particulars from those north of Champion. The coarse-grained graywackes are only rarely found, but in their place there is present a considerable quantity of fine-grained, banded novaculite. The slates near Clarksburg are not so carbonaceous as north of Champion, and, finally, they are somewhat more crystalline, a strongly developed slaty cleavage being prevalent and many of the rocks being biotite-slates. This slaty cleavage varies from parallelism to the bedding to right angles to it. The cleavage is in general approximately east and west, and its dip is usually nearly vertical.

In thin section, the semicrystalline appearance observed macroscopically is borne out. The mica-slates, which are rare north of Champion, are the usual rocks north of Clarksburg. With the biotite there is abundant chlorite. In some slides one is predominant, in others the other. In a number of slides the original bedding is recognized by alternating layers of different degrees of coarseness, and across the bedding the cleavage cuts, as indicated by the parallel folia of mica. The novaculites have a fine-grained background, consisting of small, closely-fitting grains of quartz. Between these quartz grains more or less of sericite, biotite, and chlorite have developed, and also occasionally grünerite. The pure nonfragmental rocks of the iron formation are only rarely found in this area, but many of the rocks are half fragmental—that is, mingled with the clastic material are much siderite and its alteration products. The alteration of the siderite usually results in the production of needles of grünerite and crystals of magnetite, although the other oxides of iron occur. Commonly in the strongly grüneritic rocks chlorite, rather than biotite, is found.

In the broad belt of the Michigamme formation running from Clarksburg to Ishpeming the area is low and swampy, with only occasional outcrops. The most important cluster of these extends north of the Clarksburg formation, through secs. 9, 10, 11, 12, T. 47 N., R. 28 W., and sec. 18,

T. 47 N., R. 27 W. These exposures mark a moderate ridge, which, however, is not continuous. Both macroscopically and microscopically these rocks are in all respects like those north of Clarksburg, and they therefore need no further description.

Lake Michigamme area.—Returning now to the Lake Michigamme area (Atlas Sheets V, VI, and VIII), at the east end of the lake mica-slates are found. On the islands in the center of the lake and on the mainland adjacent there are very numerous exposures of mica-schist. These appear to be completely crystalline rocks. For the most part they have a moderately strong foliation. In many places they are thickly studded with crystals of garnet and staurolite. These are especially prominent upon the weathered surface, as the background has dissolved and left these crystals projecting. At most places the schistosity is the only structure observable, but in some places alternating bands of coarse and fine material, cutting across the schistosity, indicate the probable original bedding. It will be remembered that adjacent to Champion the rocks of the Michigamme formation are but little-altered shales and graywackes. At the east end of the lake the rocks are intermediate in their crystallization, being mica-slates. We therefore have a progressive increase in the metamorphism of the rocks from their little-altered condition to completely crystalline schists, the change occurring in a distance along the strike of about 4 miles.

West of the islands, and probably a continuation of the same horizon, running through secs. 32 and 33, T. 48 N., R. 30 W., is a ridge upon which are very numerous exposures, in all respects like those of the islands and the shore. The exposures also extend to the water's edge in secs. 28 and 29. For the most part the ledges are of the same general character, but in some places coarser layers are interstratified with finer ones. These apparent beds are in a series of rolls which are cut across by the schistosity. In the southwest part of sec. 29 in this area are the peculiar pegmatized exposures of mica-schist, which, on account of their exceptional characters, are fully described in the general characterization on pages 447–448, 450.

Toward the western end of the lake, in sec. 30, T. 48 N., R. 30 W., and in secs. 25 and 36, T. 48 N., R. 31 W., there are occasional exposures, and here the rocks are somewhat less crystalline, containing little or no staurolite and garnet. Just west of the west end of the lake the rock is so coarse and quartzose as to become a micaceous quartzite.

Along the southwest arm of the lake, in secs. 5, 7, 8, 17, and 20, T. 47 N., R. 30 W., at various places mica-schists are found. The rocks of this area are very similar to those on the islands and those to the west on the mainland, but upon the whole they are more strongly foliated and coarsely crystalline, being rather coarse-grained, typical, foliated mica-schists. The crystals of garnet and staurolite are very abundant, and are of larger size than in the area to the north. At one place in sec. 17 the rock has a strongly feldspathic appearance, and is apparently a garnetiferous mica-gneiss.

The mica-schists of the Lake Michigamme area are very similar to those of the Penokee district.[1] The most important difference between the two areas is that mashing has played a more important rôle in the Marquette than in the Penokee district. There has evidently been movement throughout the rock, each particle having been rearranged with reference to the surrounding particles, and where the rock becomes strongly foliated the slickensided surfaces between the folia show that these had differential movements with respect to one another. Accompanying this more strongly crystalline character are abundant garnet and staurolite, and a less quantity of chloritoid.

In thin section, by using the gradation varieties, the processes of transformation of the fragmental rocks to the completely crystalline schists is made out with great clearness. The processes are almost identical with those which have been described as taking place in the mica-schists which occupy a similar horizon in the Upper Huronian series of the Penokee district and in the Black Hills. A full description of these processes will therefore not be here given, but a few supplementary notes may be made.

The ordinary mica-schists of the area have a quartzose background, in which biotite is very abundant. Frequently a large amount of chlorite is associated with the biotite, and very often also muscovite is present. In

[1] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey, Vol. XIX, 1892, pp. 332–343.

The pre-Cambrian rocks of the Black Hills, by C. R. Van Hise: Bull. Geol. Soc. America, Vol. 1, 1890, pp. 222–229.

many cases much feldspar occurs with the quartz, so that technically the rocks are mica-gneisses. As the rock becomes more foliated the muscovite is relatively more important, and occasionally it is predominant. Oxide of iron, and especially magnetite, is found as minute specks and as crystals included within all of the foregoing minerals. The amount varies greatly; some slides are comparatively free from iron oxide; in others all of the minerals have a blotched appearance throughout, due to the inclusion of innumerable minute flecks of iron oxide, and perhaps also of carbonaceous or graphitic material. Between the two extremes there are all gradations.

In the coarse-grained micaceous graywackes adjacent to the border of the lake, where metamorphism is partial, the processes of development of the mica-schists are best made out. Here the decomposition of the coarse fragmental feldspar into interlocking secondary chlorite, biotite, muscovite, and quartz may be beautifully seen. Also the original roundish fragmental grains of quartz are recognizable. They show undulatory extinction, and oftentimes fracturing into two or more individuals, whereas the secondary quartz is in small granules which do not show pressure effects. In a coarse variety of the ordinary biotite-schist, not of the completely crystalline type, two classes of quartz are still recognizable. There are coarser grains, which have a distinct roundish appearance, averaging from 0.15 to 0.20 mm. in diameter. Some of these have their longer axes transverse to the schistosity. These larger particles are taken to be clastic. They are associated with much more abundant, finer-grained quartz, averaging from 0.04 to 0.05 mm. in diameter. Much of this quartz is plainly a secondary development, but also a part of it may be original fragmental material. In both the micaceous graywackes and the fine-grained biotite-slates the mica has in general a parallel arrangement, is in small flakes, and is of secondary origin.

In passing to the completely crystalline biotite-schists the recognizable coarser grains of quartz gradually disappear by granulation, and we have a background of quartz grains of approximately the same size, generally arranged with their longer axes in a common direction. The mica also becomes more coarsely crystalline and has a greater uniformity in its parallel arrangement. In this variety of the rock it is evident that the mineral particles have been flattened or moved differentially, or both, and thus were adjusted to one another. In many of the slides a great deal of feldspar is found mingled with the quartzose background. In those which show an intermediate degree of alteration a portion of this feldspar is clearly clastic. In the rocks which are nearly completely crystalline, what part is clastic and what part a secondary development is very difficult to determine. In the most coarsely crystalline mica-gneisses found, orthoclase, microcline, and plagioclase are all seen. The individuals for the most part average about the same size as those of the quartz. Certain of the larger feldspar areas have a fragmental appearance, but the finer-grained background has clearly recrystallized.

In the more metamorphosed varieties of the schists garnet and staurolite are abundant. The garnets often have very well developed crystal outlines. As they grow they seem to be able to absorb or push aside nearly all of the other constituents, as they are comparatively free from inclusions, although oftentimes a considerable amount of quartz and feldspar is contained The staurolite occurs in the ordinary twinned forms. Very often their outlines are ragged; at other times they have sharp crystal boundaries. As the staurolites have developed, they have grown around the quartz and feldspar, so that these minerals within the staurolite crystals are nearly as abundant as in the remainder of the section. However, in the growth the staurolite has absorbed or pushed aside the muscovite, biotite, and chlorite, as these are rarely included in it. The staurolite shows no evidence of strain. Occasionally large blades of chloritoid are seen. These, like the staurolite, include the quartz and feldspar, but exclude the mica. These blades are in general arranged with their longer diameters and cleavage transverse or at a large angle to the foliation of the rock. It is believed that the lack of dynamic effects in the staurolite and the transverse arrangement of the chloritoid are evidence that these minerals and the garnet developed under static conditions, after movements ceased. If this be true, it is probable that the micas and chlorite had largely developed at an earlier time, and if so the chloritoid, garnet, and staurolite must have grown by absorbing the micas and chlorite.

SECTION III.—THE CLARKSBURG FORMATION.

By W. S. Bayley.

The Clarksburg formation differs from the other formations of the Marquette Algonkian in that it embraces a large quantity of volcanic material interbedded with sediments as regularly as the beds of an ordinary clastic series. The series embraces surface flows of basic lava, beds of tuff, conglomerates, and breccias, interleaved with well-banded layers of graywacke, slate, or quartzite. These are cut by dikes and irregularly shaped intrusive masses of "greenstone" similar in macroscopic appearance to the "diorites" cutting the iron formation. No acid igneous rocks have been discovered anywhere in the formation, either as lava flows or as pebbles inclosed in the conglomerates.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The rocks of the formation form a belt extending westward from the high bluffs north of Stoneville Station, on the Duluth, South Shore and Atlantic Railway, in sec. 18, T. 47 N., R. 27 W., to the center of sec. 31, T. 48 N., R. 29 W., a distance of about 12 miles (Atlas Sheet IV). Passing east from its western end, near Champion the belt grows wider for several miles; then it narrows, and again widens as it swings southeastward toward Clarksburg, to the southeast of which village the formation reaches its greatest width of about 1¼ miles. From this point the belt swings to the east again, and becomes gradually narrower until it disappears in sec. 18.

It is noticeable that where the belt has its maximum width the underlying formations swing southward, and that as the belt narrows to the east and west of Clarksburg they reassume their normal courses.

The formation is a local one in the sense that it occurs on one side only of the syncline in the Upper Marquette series. The central vent from which most of the lavas and tuffs were erupted is thought to have been in the widest portion of the belt, a little to the southeast of Clarksburg. Here the tuffs and sedimentary rocks are rare and the intrusive boss-like knobs of "greenstone" are most numerous. But east and west of this place other similar knobs are found, and these are taken to indicate that there were a number of vents from which the lavas were extruded. From these vents as centers the lavas and tuffs were sent out over the surrounding country, but not to great distances, for the coarser materials did not span the width of the basin in which the Michigamme slates were deposited. The supposition of the existence of a number of vents situated along a line parallel to the axis of greatest folding of the Marquette series, but to the south of it, together with the north-south compression to which the Clarksburg beds were subjected, in company with all of the other Algonkian formations of the region, will explain satisfactorily the occurrence of the beds as a belt on one side only of the Marquette synclinorium.

The topography of the area underlain by the Clarksburg rocks is not essentially different from that of other portions of the Marquette range where greenstones are prominent. It is characterized by the occurrence of numerous small and large rounded knobs and long narrow ridges, often bare at their summits, and separated from one another by stretches of swamp land or by sand plains. Where the bedded rocks are in excess of the intrusive ones the hills often possess precipitous southern exposures, but this feature of the topography is not sufficiently striking to be characteristic.

RELATIONS TO ADJACENT FORMATIONS.

The relations of the Clarksburg rocks to the surrounding formations are often difficult to interpret. In a few cases where contacts are plainly visible the interpretation is clear. On the south the volcanic series is bounded by grünerite-magnetite-schists of the Negaunee formation and by Goodrich quartzites and Michigamme slates. Southeast of Champion the volcanics appear to rest for a short distance upon grünerite-schists. Although actual contacts of the two formations have not been seen, well-characterized ledges of the schists and of the volcanics are met with, separated by covered intervals of but a few feet in width. The schists appear to strike directly into hills composed of the Clarksburg rocks, and, what is more significant, great bowlders of the schists, some sharped-edged and others rounded, are found thickly strewn through the lower beds of the volcanic series.

With respect to the relations with the Goodrich quartzite and the Michigamme slate there is somewhat greater obscurity. In the NW. ¼ sec. 18, T. 47 N., R. 27 W. (Atlas Sheet XXV), for instance, the volcanic conglomerates are in contact with graywackes or with arenaceous slates. The exact locality of the contact in question is the east end of the top of the hills north of Stoneville station. The Clarksburg rocks at this place consist principally of conglomerates with a green schistose matrix and of tuffs. The pebbles of these conglomerates are fine-grained diabases, quartzites, slates, and granites. The south side of the hill, which is composed principally of the greenstone-conglomerates, is faced with the graywackes, which, near the top of the hill, appear to be beneath the conglomerates unconformably. At the east end of the hill again are other arenaceous slates, and these apparently strike directly into the hill. Here the volcanics again appear unconformably upon the graywackes.

A little farther west, however, near the center of sec. 13, T. 47 N., R. 28 W. (Atlas Sheet XXV), at the base of the large hills on the north side of the railroad track, are graywackes like those in sec. 18, but at this place they seem to grade up into tuffs, which are interbedded with the greenstone-conglomerates. At many other localities the same relations are observed between tuffaceous and lava beds and graywackes. The latter are interleaved with the former, and are much more abundant among the lower beds than among the higher ones of the formation.

On its northern side the belt of Clarksburg rocks is everywhere bordered by the Michigamme slate, the relations between the two formations being very similar to those between the volcanic formation and the formations to the south. At Clarksburg (Atlas Sheet XIX) these relations are plainly seen. In the little dome-like hill north of the railroad track and east of the station sedimentary, graywacke-like beds and conglomeratic greenstones are regularly interbedded. On the hills northwest of the village are slaty, tuffaceous rocks, in which the included fragments become smaller and smaller as we pass northward into the Michigamme slates, until at a short distance northward typical slates are met with. No sharp line of demarcation between the tuffs and the slates can be detected, the former apparently grading into the latter by a gradual diminution in the amount of tuffaceous material intermingled with the sedimentary substance.

Wherever the bedded volcanics are studied the same relations are found to exist between them and the sedimentary beds beneath and above them. The volcanic formation appears to be, in general, either between the Goodrich and the Michigamme formations or near the base of the latter. At its eastern and its extreme western ends it seems to be a little above the base of the lowermost members of the Michigamme slates, while toward the center of the belt beds belonging with the Goodrich quartzites are interleaved with undoubted volcanic conglomerates. The probable explanation of these seemingly contradictory phenomena is that the rocks of the eastern and western ends of the formation are a little younger than those in the central portions of the belt, where the greatest volcanic activity was exhibited, or, in other words, the volcanic energy first found vent in the central portions of the area now occupied by the formation, and from here traveled both eastward and westward.

THICKNESS AND FOLDING.

The thickness of the volcanic formation does not admit of accurate measurement, although it must amount, in places, to several thousands of feet. The individual beds in the center of the belt can not be certainly separated from one another. In other places, east and west, the bedding is more definite, but even here no single bed can be traced for any great distance. In the western portion of the area the layers are much contorted, large and small folds crowding one another in an almost endless succession. The strikes of these small folds point in all directions, though the prevailing one seems to be toward the east and west. Generally the beds dip at high angles toward the north or northeast. The series is much more highly contorted than the Ishpeming formation, a result probably due to the fact that a set of mixed volcanic ash beds, lavas, and sediments was less resistant to pressure than the quartzites.

PETROGRAPHICAL CHARACTER.

A general survey of the entire formation presents a good illustration of a series of deposits formed by submarine volcanoes. The most important vents of the volcanoes were near Clarksburg, though minor vents existed also east and west of this place. Around these, lava flows and a few tuff beds accumulated. As one passes away from the center along the belt compact sheets of lava become less and less noticeable, while well-bedded tuffs and eruptive conglomerates and breccias become more abundant, and sedimentary layers are interleaved with them. Toward the edges of the belt the latter rocks increase in importance and the well-characterized tuffs diminish in quantity. The volcanic activity continued from the later portion of Ishpeming time into the earlier portion of Michigamme time, beginning and ending gradually. The volcanoes were evidently submarine, or at any rate their products were deposited in water, even if the apices of some of them were above the water's surface for a part of the time. The submarine character of the volcanoes explains not only the interbedding of tuffs and sediments and the formation of true conglomerates containing pebbles of the underlying rocks, but it also explains the existence of bedded breccias composed of fragments of volcanic origin in a tuffaceous base and the presence of conglomerates formed of volcanic fragments in a sedimentary groundmass.

The sediments, tuffs, conglomerates, breccias, lavas, and coarse greenstones have all suffered a great amount of alteration, but in many cases their original nature can still be made out. The recognition of the true character of the tuffs depends mainly upon their field relations and field habits, but a pyroclastic structure can be detected in many of their sections. Almost all the rocks, except the best-preserved sediments, are now partly or wholly crystalline. This condition has been brought about mainly by the development within them of hornblende, biotite, and quartz. The change from the fragmental to the crystalline texture is most nearly complete in the groundmass of some of the conglomerates. This groundmass is a biotite-schist, not very unlike the biotite-schists of the Southern Complex.

THE MASSIVE GREENSTONES.

The coarse crystalline greenstones that occur so frequently as knobs in the area southeast of Clarksburg and farther east have the same composition as the "diorites" of the Negaunee and other pre-Clarksburg formations, but a somewhat different structure. A few specimens show evidences of the diabasic structure, while many of them appear to have been porphyritic.

In the hand specimens these rocks resemble in many respects the greenstones north of Lake Michigamme (see pp. 500–503). They are principally massive rocks of a dark-green, almost black color, which vary in grain from very fine to very coarse. On freshly fractured surfaces the finer-grained phases have a more or less fibrous appearance, due to the presence in them of abundant acicular hornblende and plagioclase crystals. The fresh surfaces of the coarser rocks seem to be made up almost exclusively of large areas of black or dark-green hornblende.

Under the microscope some of the thin slices of the finer-grained rocks show numerous square or quadratic sections of an altered idiomorphic plagioclase in a groundmass composed of quartz, chlorite, hornblende, calcite, biotite, and a little newly formed feldspar. The quartz and calcite are often present in largest quantity, the former as little interlocking grains, forming a matrix in which the other silicate components lie, and the calcite filling little interstices between these. The amphibole is a yellowish-green variety in spicules, and the biotite a reddish-brown variety in small plates. These same minerals are also found embedded in the altered plagioclase, by whose decomposition they were probably formed. All the components of the groundmass of these rocks are apparently new products in their present positions. They were probably derived by secondary processes from a very fine grained or possibly a glassy groundmass of a basaltic porphyrite.

In other sections there are mottlings of a brown color on a white background when the sections are viewed against white paper. The brown areas contain a great deal of biotite, while the colorless areas are free from this mineral. The latter consist of aggregates of quartz, a little feldspar, and a few hornblende needles, and the former of the same minerals with an abundance of biotite flakes and large masses of spongy magnetite. The light areas surround the brown ones as the matrix surrounds the phenocrysts in a porphyrite.

All the original structures, except the porphyritic, have disappeared from these rocks, so that it is impossible to learn much concerning their original character. It is believed, however, that they were basic porphyrites which occurred either in volcanic necks or as moderately thick lava flows.

The coarse-grained greenstones are the fillings of volcanic orifices, or they constitute great dikes cutting through the bedded members of the Clarksburg series. In these the green amphibole is sometimes in large, well-characterized, ophitic areas, between which are the alteration products of plagioclase. The interior of the hornblende, which is more or less chloritized, is of a yellowish-green color, and around this is a periphery of dark-green amphibole, more particularly where the mineral is in contact with undoubted remnants of plagioclase. The color of both nucleal and peripheral amphibole is bluish-green in a direction approximately parallel to the cleavage, but the peripheral hornblende is darker than the nucleus. Around the borders the plates are all fringed with long needles of the green-blue amphibole, and similar needles penetrate in all directions the materials of the light interstitial substance between the amphibole plates. This interstitial mass is an aggregate of the decomposition products of plagioclase, among the more prominent of which are biotite, calcite, epidote, and quartz. In addition to the long spicules of green-blue amphibole that cut this aggregate, others with the characteristics of actinolite also penetrate it.

In a very few cases a typical diabasic structure is noticed on weathered surfaces of ledges. In the thin section of these rocks, however, a porphyritic structure is also observable. Decomposed feldspars with quadratic cross-sections are embedded in the usual plexus of hornblende, biotite, altered plagioclase, quartz, and magnetite, to which is often added kaolin. The plexus may be in areas with an ophitic outline, but the lines between the porphyritic crystals and the matrix in which they lie are rendered so obscure by the many secondary substances that have arisen from the alteration of the feldspars that it is difficult, and in many cases impossible, to make them out. The larger crystals of plagioclase, of whose feldspathic nature there can be no doubt, are so filled with kaolin, sericite, quartz, biotite, and hornblende that it would seem probable that many of the same minerals in the matrix must have likewise been derived from feldspar.

Certain compact hornblendic rocks differ from the specimens just described simply in the possession of a great quantity of amphibole. The mineral is of the same nature as that in the other greenstones, but is in much larger quantity. It occurs as compact anhedra,[1] fringed with long acicular crystals that form a network, in whose meshes are areas of altered plagioclase and leucoxene.

From the above rapid survey of the coarse greenstones in the Clarksburg series it will be seen that these rocks do not differ essentially from the "greenstones" subsequently described as intrusive in the pre-Clarksburg beds. They are strikingly similar to those in the western portion of the district (see pp. 499–506). They were originally of the same composition as these, and they have suffered similar alterations. Their structure, where it can be detected, was a little different from that of the lower intrusive greenstones in that there was a tendency to the production of porphyritic feldspars. This difference may be due to the fact that the Clarksburg rocks were cooled in the ducts of volcanoes or in dike fissures that were near the surface, while the lower greenstones were cooled at greater depths. In this connection it is interesting to note that rocks like these greenstones are not found intrusive in horizons higher than the Clarksburg.

THE LAVAS.

The lavas that are interbedded with the sediments and tuffs of the formation are not very abundant. Some of the finer-grained greenstones already described may be portions of lava flows, but that this is certainly the case has by no means been shown. A few layers identical with the former in structure and composition are unquestionably sheets.

The clearest evidence that genuine lava flows were laid down among the more abundant tuff beds of the old Clarksburg volcano is afforded by the amygdaloids. These have been found in a few widely separated localities within the limits of the Clarksburg belt, but they are not at all common. The rocks are fine-grained, light-gray, and often schistose. They contain few or many amygdules filled with calcite or chlorite, and these are often flattened as though by flowage. Under the microscope they present no peculiar features. Small laths of plagioclase, with forked extremities, are

[1] This term has recently been proposed by Pirsson to designate those crystalline constituents of rocks that do not possess crystal outlines. Bull. Geol. Soc. Am., vol. 7, 1896, p. 492.

scattered through a groundmass composed of numerous microlites of feldspar in an altered basic glass. The various phases of the amygdaloids are so similar to one another, and so like diabasic lavas elsewhere, that they demand no special description.

THE SEDIMENTS AND TUFFS.

The sediments.—Petrographically most removed from the lavas are the sediments, which grade imperceptibly into the tuffs. Pure sediments are found only along the borders of the Clarksburg belt, beyond the horizon at which the volcanic series is regarded as beginning and ending. They consist of quartzites, graywackes, and slates, many of which are much mashed. The sediments interbedded with the tuffs, conglomerates, etc., are composed principally of the waste of preexisting rocks, but intermingled with this débris is a greater or smaller quantity of basic material which is supposed to be of volcanic origin. Many of the beds are now thoroughly crystalline, so that an accurate separation of their sedimentary and volcanic components is not possible. Often some of the thicker beds consist of alternating layers containing respectively large and small quantities of basic material, and these pass into others in which the volcanic substance can scarcely be detected. In some of the former beds a well-marked tuffaceous structure is recognizable, but in the majority of cases all evidences of a well-characterized original structure have been obscured by recrystallization. As a rule the structure of the more purely sedimentary rocks is much better preserved than is that of the tuffaceous ones.

The nearly pure sedimentary rocks are dark-gray or light-gray and fine-grained, with an even or a contorted bedding, marked by parallel bands of different shades of color. The coarser bands exhibit very plainly their fragmental character on the weathered surface. Little eyes of quartz can be seen against a background which has the appearance of a graywacke.

The least altered of the sedimentary rocks consist principally of rounded quartzes, altered feldspar grains, and a few flakes of a dirty, greenish-brown biotite. In the finer-grained bands biotite is probably more abundant than it is in the coarser ones, but with this exception there is little difference between them. The lighter and darker shades noticed

PLATE XXXII.

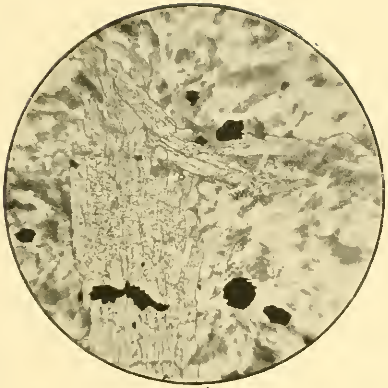
PLATE XXXII.—THIN SECTIONS FROM CLARKSBURG FORMATION AND REPUBLIC GREENSTONE.

FIG. 1. Thin section of sedimentary bed from Clarksburg formation, showing secondary hornblende crystals. No. 17640, from 200 steps N., 1,800 steps W., of SE. corner of sec. 17, T. 47 N., R. 28 W. From one of the beds constituting the Clarksburg formation. The large anhedra are of yellowish-green amphibole, idiomorphic in cross-section, but very irregular in outline in longitudinal section. The groundmass consists of biotite flakes between which is a cryptocrystalline aggregate of quartz. The black mineral is magnetite. Natural light. X 50.

FIG. 2. Thin section of fragmental rock from near base of Clarksburg formation. No. 14785, from SW. ¼ sec. 32, T. 48 N., R. 29 W. In ordinary light the fragmental structure is plainly revealed. Between crossed nicols the quartz grains (one of which is indicated by the dotted line in the figure) break up into differently orientated portions, so that the section appears like that of a very quartzose gneiss. Polarized light. X 22.

FIG. 3. Thin section of banded tuff from Clarksburg formation, SE. ¼ sec. 4, T. 47 N., R. 29 W. The figure shows a large Carlsbad twin of plagioclase in a fine-grained crystalline groundmass composed mainly of quartz, biotite, and magnetite, with a little green hornblende. The "streaming" of the biotite around the upper end of the feldspar crystal may be seen upon close inspection. In polarized light. X 22.

FIG. 4. Thin section of greenstone from Republic, showing secondary hornblende crystals. No. 16485, from SE. corner of Republic Mountain, SE. ¼ of SE. ¼ sec. 8, T. 46 N., R. 29 W. The rock is associated with the members of the iron formation. The section shows the typical structure of the secondary amphibole in many of the western greenstones. To the right is the cross-section of a small idiomorphic grain. The greater portion of the hornblende exhibits the cellular structure, which has been regarded as the characteristic structure of contact minerals. The clear white areas represent quartz grains and the cloudy areas altered plagioclase. The large light areas at the top and toward the lower right-hand edge of the figure represent spaces in the section. Natural light. X 55.



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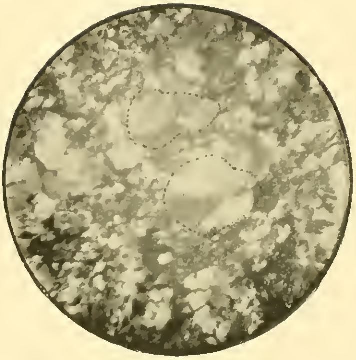

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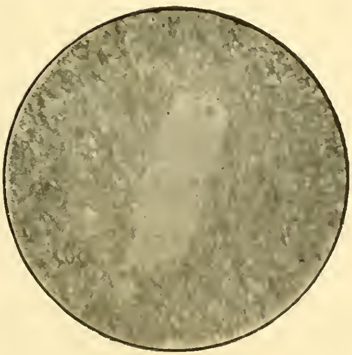

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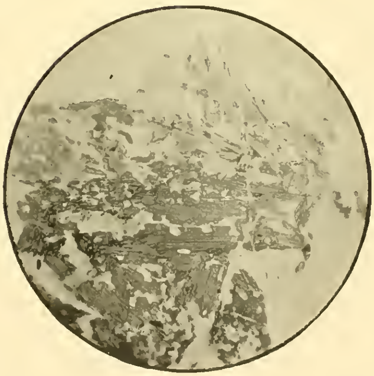

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FIG. 1.—THIN SECTION OF SEDIMENTARY BED, FROM CLARKSBURG FORMATION, SHOWING SECONDARY HORNBLENDE CRYSTALS.
FIG. 2.—THIN SECTION OF FRAGMENTAL ROCK, FROM NEAR BASE OF CLARKSBURG FORMATION.
FIG. 3. THIN SECTION OF BANDED TUFF, FROM CLARKSBURG FORMATION.
FIG. 4. THIN SECTION OF GREENSTONE, FROM REPUBLIC, SHOWING SECONDARY HORNBLENDE CRYSTALS.

in contiguous bands are due mainly to differences in the quantity of magnetite, biotite, and certain indefinite dust particles present. In all these rocks the plagioclase is altered, and among its alteration products are found biotite, quartz, and occasionally a little muscovite.

The greater number of the sedimentary beds are characterized by the presence of amphibole. They comprise rocks whose difference in degree of crystallization is dependent apparently upon the proportion of amphibole present in them. This amphibole is certainly not a product of the decomposition of the usual constituents of a sedimentary rock; on the other hand, it is the most common product of the alteration of the igneous rocks associated with the fragmental ones. For this reason largely, and because certain rocks interleaved with the sediments are composed almost exclusively of amphibole, while at the same time they are unquestionably marked by bedding lines, and further, because the hornblende rocks, by the gradual loss of their hornblende, pass into the sediments, the material from which the hornblende in the sediments was formed is believed to have been tuffaceous.

On the weathered surface the majority of the hornblendic sediments present a very rough aspect, a consequence of the projection of the hornblende crystals beyond the general surface of weathering. The rocks are dark-green on a fresh fracture, where they look like massive crystallines.

The thin sections show a groundmass which surrounds the hornblendes. The amphibole itself is in large, cellular, green plates, filled with inclusions of the rock's components. In cross-section many of the plates have the idiomorphic outlines of crystals, but in longitudinal section they are more or less irregularly shaped (see Pl. XXXII, fig. 1), the ends especially fraying out into long needles which penetrate the groundmass.

The groundmass is composed of quartz, altered plagioclase, biotite, chlorite, and magnetite, with, sometimes, light-colored garnets in little dodecahedra. Where the rock is massive the garnets are less plentiful than they are in the schistose phases.

This groundmass has a coarse and a fine part, the latter serving as a matrix to the former. The coarser part is composed of quartz and biotite. Some of the quartz grains show the rock to be fragmental, since a few rounded ones are observed that have been built out by the addition of quartz, and so have preserved the proof of their clastic origin. Other grains resemble ordinary sand grains until they are examined in polarized light, when they break up into many interlocking areas, so that often a section which in ordinary light has the typical clastic structure (Pl. XXXII, fig. 2) presents the appearance of a typical schist between crossed nicols. The foliation of the rock is due principally to the arrangement of the biotite in laminæ that wind in and out between the larger quartz grains. The biotite appears to have originated mainly in the sedimentary material between the larger quartz grains. The large plates of amphibole that lie in the groundmass, on the other hand, were formed after the rock became schistose. They probably originated in greater part from the basic material added to the sediments by the tuffs, either directly or through solutions passing into the sediments from the tuff beds interstratified with them.

The fine-grained material of the groundmass is composed principally of quartz, chlorite, altered plagioclase, and magnetite dust. It has been so completely recrystallized that all traces of its original structure have disappeared. It was probably originally the finer-grained matrix between the coarser components of a graywacke or slate.

The most hornblendic of the fragmental rocks have already been referred to as looking like massive crystalline rocks. Upon close examination, however, it is observed that even in the most crystalline of the beds there is a distinct banding, which is emphasized by the different quantities of biotite, magnetite, and hornblende in the different layers. Where the hornblende is in great excess the bands look very much like an amphibolite. Where the other components exceed the amphibole in quantity the bands resemble more closely basic tuffs. A few bands are actinolitic. These contain fairly large plates and groups of actinolite needles, identical with the grünerite in the grünerite-slates of the Negaunee formation, scattered through a groundmass of fragmental quartz grains and occasional garnets embedded in a matrix of chlorite, hornblende, biotite, magnetite, and limonite, closely aggregated and without any well-defined structure.

Gradation varieties between sediments and tuffs.—Between the rocks just described as consisting largely of sedimentary material and others that are composed almost exclusively of tuffaceous material there exists a large series of intermediate rocks that are mixtures of sedimentary and pyroclastic material in varying proportions. On the one hand they pass directly into well-defined sedimentaries, and on the other hand into typical tuffs. In macroscopic appearance they resemble the amphibole-bearing clastics described in the last paragraph.

In thin section the gradation varieties differ from the hornblendic fragmental rocks simply in the absence of any great quantity of quartz grains. Only occasionally is the tuffaceous character of some of their constituents revealed by their structure. Usually the rocks have been recrystallized, so that their original components have entirely disappeared. Now and then a quartz grain is observable in the midst of an aggregate of green hornblende and brown biotite, but the characteristic clastic structure, as well as the characteristic tuffaceous structure, is wanting.

The tuffs.—The tuffs, like the mixed tuffs and sediments, are usually largely recrystallized. Quite frequently, however, beds of them are found in which the tuffaceous structure has been well preserved. In the hand specimens these rocks, where fresh, present the usual aspect of a hornblendic tuff; where altered they closely resemble the "Schalsteins." In almost all of them more or less calcite may be observed. In a few, as, for instance, in the rock at the crossing of the Chicago and Northwestern and the Milwaukee and Northern railroads, just east of Champion, the calcite is present in such large quantities that the rock becomes practically a limestone. Even in these much altered forms, however, the tuffaceous character of the beds may often be recognized in the hand specimen, as fragments of minerals and rocks of all shapes may be seen crowding the calcareous mass in which they lie. Many of the fragments have been completely altered to calcite, which nevertheless has preserved their outlines by forming from them perfect pseudomorphs.

The less altered tuffs are more interesting from a petrographical standpoint, since they often present excellent proofs of their original character. In general the fine-grained, pure tuffs are more frequently found interbedded with volcanic conglomerates and breccias than with sedimentary layers, although alternations of the tuffs with the sediments are not uncommon.

All of them are well banded, even where their substance has been entirely recrystallized, and most of them are schistose.

In thin section the crystallized tuffs are seen to be made up of a crystalline aggregate of quartz, cloudy feldspar, small greenish-yellow biotite flakes, occasional anhedra of green hornblende, and little irregular grains of magnetite. The biotite is so arranged as to give a foliated structure to the section, while at the same time it is more abundant in certain bands than elsewhere, thus producing the banding noticed in the hand specimen. In the midst of this groundmass there are often embedded broken fragments of an altered plagioclase, or even entire crystals of this mineral. (Pl. XXXII, fig. 3.) These rocks still show evidence of their tuffaceous character, though some of them contain small quantities of sediments. Their decomposition, recrystallization, and the changes that have been effected in them by dynamic processes have effaced most of the marks of their original nature, but here and there, where a larger fragment or a complete crystal of plagioclase has resisted alteration, the marks of tuffaceous origin are still clearly legible. Most of the quartz and of the biotite in the rocks was derived most probably from a strongly feldspathic, tuffaceous dust, though a small quantity of the former mineral may originally have been present as a sediment.

In the nonschistose tuffs the tuffaceous structure is too evident to be mistaken. In these rocks large anhedra of green amphibole are scattered through a matrix which is composed of broken crystals of plagioclase in a groundmass of smaller fragments of the same mineral, little wisps of brown biotite, nests of chlorite and calcite, and a still finer matrix of the same substances, cemented together by a mass of crypto-crystalline quartz. The biotite seems to have come from chlorite on the one hand and from plagioclase on the other. The chlorite, in turn, appears to have come from a basic glass, or possibly from augite, since it often contains within its mass "divergent radial" plagioclase microlites.

In addition to the fragments of feldspar mentioned above, there may be noticed in a few specimens an occasional fragment that resembles a piece of an altered glassy rock. These fragments now consist of little flakes of muscovite, a very few of biotite, and grains and crystals of magnetite, all embedded in a faintly polarizing aggregate that is apparently made up of quartz and plagioclase in very fine grains, like the aggregate produced by the devitrification of a glass. Under high powers, in addition to the magnetite grains there are detected certain small purplish plates resembling those formerly so well known under the name of "Eisenglimmer." The magnetite of the fragments is nontitaniferous, while that in the inclosing rock is often strongly titaniferous, if we may judge from the great quantities of leucoxene and sphene in the latter and its absence from the former.

In the above descriptions detailed reference is made only to the sediments and to the tuffs, as though these rocks were the more important members of the Clarksburg formation. As a matter of fact, the well-defined sediments and the typical tuffs constitute a much smaller aggregate in the series than do the mixed sediments and tuffs. They are described in some detail because they have retained their original characteristics better than have the mixed rocks, and so afford better evidence as to the nature of the formation than do the latter. The variety of the mixed rocks is great. They well deserve close study; but to describe them in detail would unduly enlarge this monograph. It is enough for the present to reiterate the statement that the mixed rocks are intermediate in their characters between the types of rocks that are above described.

From the facts already related it is clear that we have in the Clarksburg formation a series of typical tuffs, together with a series of mixed sediments and tuffs, formed by the accumulation of volcanic dust and ashes in a basin in other parts of which the deposition of ordinary land débris was going on. The variation of the quantities of quartz, amphibole, and biotite in the alternate beds is easily accounted for in the safe assumption of a variation in the volcanic activity. The alteration and crystallization of the beds are ascribed partly to contact action and partly to mashing. The former was due, no doubt, more to the chemical effects of the solutions passing between lavas, tuffs, and sediments than to heat alone. The mashing resulted in the contortion of all the beds of the formation.

THE HORNBLENDE-SCHISTS.

The processes which changed the mixed sediments and tuffs of the Clarksburg formation must have been very similar to those which produced the green schists of the Mona formation in the Basement Complex. The ultimate products in the two cases are practically identical, except that the Mona schists are, as a rule, more weathered than the Clarksburg rocks. The final, most crystalline phases of the Mona rocks were described by Williams as schistose "diorites." In this volume they are regarded as the most highly metamorphosed phases of tuffs. Rocks analogous to these exist also in the Clarksburg series. They are very lustrous, foliated rocks, resembling in their hand specimens typical hornblende-schists. The only differences noted between these schists and the amphibolic sediments and tuffs described above are in the greater schistosity of the former and in the greater abundance of biotite and amphibole in them.

In the most typical of the hornblende-schists a small quantity of quartz is present, with the rounded outlines of clastic grains. The hornblende is idiomorphic in cross-section, and is often actinolitic in habit. In a few specimens well-defined crystals of actinolite are surrounded by zones of chloritoid, with the deep bluish-green pleochroism of this mineral. In others a light-green amphibole is surrounded by hornblende with the properties of uralite. In the majority of specimens, however, only one amphibole occurs, and this is usually the uralitic variety Moreover, it is often cellular, including many grains of magnetite, and in some cases even grains of sedimentary quartz. In origin this hornblende is evidently secondary, and the schists themselves are consequently secondary rocks. They are interbanded with schistose sediments in which the sedimentary structure can still be made out. This latter fact, together with the microscopic structure of the schists, makes it seem very probable that the amphibole-schists are highly foliated, recrystallized phases of mixed sediments and tuffs in which the tuffaceous material predominates over that of sedimentary origin.

If this view of the origin of the schists is correct, these rocks throw considerable light on the origin of the hornblende-schists of the Mona series, and add considerable weight to the statement made in a former chapter to the effect that these rocks are mashed tuffs.

THE BRECCIAS AND CONGLOMERATES.

In the discussion of the Clarksburg formation the breccias and conglomerates should be distributed between the sediments, gradation varieties, and tuffs just described; but as this is impracticable, they are considered as a division by themselves.

In this discussion but little distinction is made between those rocks with a conglomeratic habit and those that are more properly breccias, since both contain rounded and angular fragments of preexisting rocks. The breccias contain, in addition, angular fragments of the same composition as the matrix inclosing them. In the following pages the two terms are used indiscriminately.

In describing the essential features of the conglomerates it is almost impossible to avoid repetition of facts already stated with respect to the tuffs and sediments of the formation, since the matrices of the conglomerates are frequently identical with the material of these rocks. Sometimes the material is sedimentary in character, sometimes tuffaceous, and sometimes crystalline. The sedimentary and tuffaceous matrices do not differ in any essential features from the sediments and tuffs already described, while the crystalline matrices are often similar to mashed greenstones or amphibole-schists.

The conglomerate-schists, when viewed in the ledge, often present the appearance of a black biotite-schist or hornblende-schist, containing fragments of quartz and feldspar, of granite, of grünerite-schist, and of a light-colored sandy rock, and very large irregular pieces of a lustrous black rock of nearly the same character as the schist itself. On the weathered surface the fragments stand out plainly, but on the fresh fracture only the quartz and the sandy rock become visible, the rock as a whole resembling a well-crystallized "augen-schist."

In other cases the matrix of the conglomerate is a tuff that differs very slightly, if at all, from the tuffs already described. Its fragments are large pieces of biotite-schist, and smaller ones of the sandy rock. These latter in many instances are banded, when they are identified as fragments of the sedimentary beds interstratified with the conglomerates. Grains of quartz are also noticeable scattered among the feldspar fragments and crystals that help to make up the tuffaceous groundmass, and occasionally fairly large pebbles of the same minerals are met with.

A third class of the conglomerates is characterized by the sedimentary nature of its groundmass. These rocks resemble true conglomerates and breccias more closely than do those with the schistose or those with the tuffaceous matrix. Their groundmass is identical in structure and composition with the rocks constituting the sedimentary beds of the formation. In this are embedded tuff fragments, fragments of biotite-schist, occasionally large pieces of an amphibole rock that resembles a slightly foliated greenstone, pebbles of iron ore, and others of a fragmental rock similar to that forming the matrix. Usually the fragments are not so abundant but that the character of the matrix is easily recognized. In a few cases, however, they are present in such large quantities that the existence of any matrix can with difficulty be detected.

The conglomerates of all classes are more or less clearly banded, and all are foliated in some degree at least. The most schistose phases are those whose matrix resembles a biotite-schist, and the least schistose are those with a sedimentary groundmass. Garnets are common in all of these rocks. They are apparently most abundant in those that contain the greatest amounts of basic components. In the conglomerates with the schist matrix they are most common. Here the garnets exist as pink granular lines marking the bedding planes of the original rock.

The microscopical examination of the conglomerates and breccias adds little to the knowledge concerning their nature which is gained from observation of the rocks in the field. The matrices, as has repeatedly been stated, are similar to the materials of the sediments and tuffs that constitute such an important portion of the entire Clarksburg formation, although in no case are they purely sedimentary or tuffaceous, as are some of the nonconglomeratic sediments or tuffs. Usually there is an admixture of sedimentary and volcanic material in the groundmass of these rocks as well as in the pebbles embedded in it.

The schist-conglomerates have a matrix composed of quartz, biotite, hornblende, magnetite, occasionally a little altered plagioclase, and sometimes a few crystals of tourmaline. The quartz and biotite are arranged to form a foliated groundmass, through which the other components are scattered. In this schistose groundmass are also the small fragments of quartz, graywacke, quartzite, iron ore, and greenstone already referred to above. The quartz is often in rounded grains, as though waterworn. The other fragments are also more or less rounded at times, but more frequently they are sharply angular.

The hornblende is of the green variety common to the beds already described. It occurs in the usual large grains, which sometimes are idiomorphic in cross-section, sometimes irregular in shape, and always more or less cellular. The grains occur independently, lying in all azimuths in the schistose matrix, or they are grouped together into little sheaf-like bundles. They are much more abundant in some bands than in others, often occurring so thickly as to exclude from them all biotite. In other bands no amphibole occurs, and in these biotite is abundant. Moreover, in these bands the quartz grains are much more fragmental-looking than those in the hornblendic bands, and besides there exists between them a very fine grained aggregate of quartz and plagioclase, mainly the former.

The fragments in the schist-conglomerates require no special mention. They are pieces of the tuffs and sediments, interstratified with the conglomerates, or of the ores and quartzites of the Marquette series below the Clarksburg formation, or of greenstones that may have been portions of interleaved lava flows, or perhaps portions of dikes occurring in the pre-Clarksburg beds, or, finally, fragments from the Basement Complex. Some of the fragments are waterworn, while others are sharply angular.

The explanation of the schistose conglomerates is that they were originally beds made up of alternating layers of sediments, tuffs, and mixtures of these, in which were embedded bowlders and pebbles of preexisting rocks and irregular fragments ejected from the volcanic vent. Some of these fragments must have been portions of the walls of the orifice through which the eruption took place, for they are certainly pieces of the rocks that constitute the Clarksburg formation. True volcanic bombs have not yet been recognized, though it is possible, and, indeed, probable, that some of the lustrous black fragments embedded in these conglomerates are of this character. These beds were rapidly hardened and afterward made schistose by mashing. Since the biotite flakes wind about the garnets, it is concluded that these minerals formed before or during the mashing. After this, contact action or later metasomatic change resulted in the production of the amphibole. This is shown by the fact that the small crystals lie in all azimuths, their longer axes cutting the plane of schistosity. The contact effects were probably the result not so much of the heat alone to which the beds were subjected as to the hot solutions that passed between the basic tuffaceous beds and the acid sedimentary ones, and between the basic and acid components of the mixed beds.

The conglomerates with a tuffaceous groundmass present in the thin section nearly the same appearance as the hornblendic bands of the sedimentary rocks described in the last few paragraphs. Very rarely is a typical tuffaceous structure observable, although on the sides of the weathered ledges this structure is very plain. Biotite is present in small quantity only, while green hornblende is abundant. In nearly all cases some sedimentary material can be detected as a fine-grained, almost dusty aggregate between the large amphibole grains, but in no case is it in any large quantity. In these conglomerates the most interesting fragments are those that are similar to the sedimentary rocks of the formation. Many of them are large, white, rounded pebbles, which in thin section are found to possess a well-preserved fragmental structure. They consist of quartz and altered feldspar grains, the former predominating, sericite and biotite in very small quantities, and magnetite in dust grains. Scattered here and there through the mass are delicate plumose groups of green hornblende that are evidently much younger than the clastic grains. In cross-section the amphiboles are idiomorphic. In all its essential features the rock of these pebbles is identical with that of the sedimentary beds interstratified with the tuffs, even to the presence in it of the introduced idiomorphic amphiboles. The other fragments occurring in these rocks need no description.

The only other class of conglomerates distinguished is that in which the rocks possess a sedimentary groundmass. This is composed of a fragmental aggregate of quartz and a little feldspar, large quantities of brown biotite, a small quantity of magnetite, and the usual spicules and crystalloids of the green amphibole, occurring sometimes in single grains and sometimes in plumose or sheaf-like bundles.

CONCLUSIONS.

In the petrographical study of the rocks we find abundant confirmation of the accuracy of our conclusions regarding the origin of the Clarksburg formation. This is unquestionably a set of sediments, tuffs, lavas, and volcanic and sedimentary conglomerates that were deposited beneath the surface of some body of water. The volcanic contributions to the series probably exceeded in volume those contributed by aqueous agencies, although these latter were by no means small in amount. Of the volcanic contributions the larger portion was in the form of volcanic cinders, ashes, etc., a much smaller portion being in the form of lavas. This fact would indicate that the eruptions were violent, like the type represented by Vesuvius at present, rather than quiet, like the Hawaiian volcanoes. That they were intermittent is proved by the numerous alternations of tuffs with sedimentary layers. The conglomerates that occur in the formation are simply tuffs or sediments containing large fragments of preexisting rocks, sometimes waterworn and sometimes angular. The former were worn from rocks that were exposed to the action of the waves when the deposits in which they are found were being laid down. The latter were torn from the throat of volcanic vents or were produced by the shattering of rock beds already existing, or perhaps, in the case of some tuff fragments, by the breaking of the rock beds actually in process of formation at the time when the conglomerates containing them were being built up.

All forms of volcanic products are recognized among the beds comprising the series except volcanic bombs and perhaps those peculiar breccias produced by the breaking of a lava's crust and the cementing of the fragments thus formed into a solid rock by the cooling of the liquid mass in which they became embedded. The bombs may possibly be represented by some of the altered greenstone bowlders occasionally met with in the conglomerates, and the lava breccias may be represented by some of the schistose conglomerates in which irregularly shaped schistose fragments are embedded. If so, however, there are no positive proofs of the facts.

INTERESTING LOCALITIES.

Good exposures of the rocks of the Clarksburg series are found along the north and west lines of the NW. $\frac{1}{4}$ sec. 4, T. 47 N., R. 29 W. (Atlas Sheet XIII), near Champion. The hill immediately north of the west quarter post of the section is made up in large part of well-bedded conglomeratic rocks with a green schistose matrix. The beds strike a little north of west and dip uniformly to the north at varying angles. These conglomerates are interbedded with wide or narrow bands of a fine or coarse grained graywacke or quartzitic rock, sometimes the conglomerate and sometimes the sedimentary rock being in excess. The matrix of the conglomerate is often coarsely crystalline, with a very rough, dark-green, weathered surface. The roughness is caused by the projection of numerous hornblende crystals beyond the general surface of weathering. The latter is often dark-gray, like that of the interbedded graywacke. Often bands of the graywacke and bands of the amphibole-bearing rock alternate, forming together the matrix in which the fragments are embedded. At other times the matrix is a brilliantly black hornblende-schist or biotite-schist. The pebbles and bowlders embedded in this matrix are sometimes waterworn, but oftener they are sharply angular. The rounded fragments are principally quartzites and grünerite-schists, and the angular ones are similar in composition to the graywacke interbedded with the greenstone-conglomerates. On the weathered surfaces the contact between the pebbles and the matrix is sharp and clear, but on the fresh fracture the materials of pebble and matrix appear to grade into each other. On the north side of the hill the interbanding of the light-weathering graywacke and a dark-weathering "greenstone" is well shown. The dark rock is composed almost exclusively of hornblende and garnets. In the hand specimens it appears thoroughly crystalline, but in thin section there are seen numerous grains of quartz which appear to be of clastic origin. Both the graywacke and the greenstone become conglomeratic at times, the former containing pebbles and large bowlders of the latter rock, and this in turn containing bowlders of the graywacke. All the beds at this place are much contorted, and often they are crossed by numerous faults with small throws.

On the top and along the south side of the ridge in the northern part of the section the conglomeratic rocks are beautifully exposed. Here great flat surfaces exhibit a strikingly handsome brecciated structure. The interbanding of the graywacke and the dark rock is not so plain here, although fragments showing the interbanded rocks are met with embedded in other rocks. Large irregular fragments of a black schistose rock, like the matrix of the conglomerate near the west quarter post of the section, are found inclosed in a plainly fragmental greenstone resembling a tuff, and, on the other hand, equally as large fragments of tuff are found in the schist.

The impression made on the mind by the confused association of these different rocks is not cleared up until the nature of the rocks is revealed through the microscope. It then seems plain that we have here a series of tuffs, sediments, and lavas. The tuffs contain a great deal of sedimentary material, and the sediments much tuffaceous material. The two are interbedded and grade into each other. The dark lustrous rock is an almost pure tuff in some cases, and in others a lava. A lava flow caught up fragments from the tuffs and sediment. Later this lava contributed fragments to subsequent tuffs and sediments.

The little group of hills east of Champion, in the SE. $\frac{1}{4}$ sec. 32, T. 48 N., R. 29 W. (Atlas Sheet XII), affords other excellent exposures of the conglomerates. Here the black, lustrous, schistose groundmass is usually full of little garnets. Large bowlders and sharp-edged fragments of grünerite-schist, granite, and quartzite are crowded into the schist in great numbers. The conglomerate appears also to be interbedded with narrow seams of a fine-grained quartzite. The rocks are all very much contorted, the bedding planes of the black schist being marked by rows of garnets.

The hills north of the railroad track, in sec. 13, T. 47 N., R. 28 W. (Atlas Sheet XXII), present a somewhat different aspect. They are built up of alternating conglomeratic and nonconglomeratic beds striking about N. 20° W. and dipping 50° NW. The conglomeratic beds are composed principally of tuffaceous material, and the nonconglomeratic ones mainly of sedimentary substance. All the rocks are schistose, with the foliation inclined to the bedding, dipping in the same direction as the latter, but at a smaller angle. At the base of the hill, on the south side, are true slates or fine-grained graywackes interbedded with the tuffs, and a little to the northwest, across a north-south valley, are some small sheets of the tuffs interbedded with massive crystalline greenstones.

In all the instances described the major portion of the volcanic part of the Clarksburg rocks consists of tuffs and lavas, the former predominating. Occasionally dikes and small knobs of massive greenstone are associated with these, but they are rare. In secs. 7, 17, and 18, T. 47 N., R. 28 W.

(Atlas Sheet XIX), southeast of the village of Clarksburg, however, the case is different. Here coarse greenstones, in the form of knobs, are the predominant rocks. These are associated with a few amygdaloids and occasionally with tuffs. Sedimentary beds are present in small quantity in the interior of the area, and when present the sediments are freely intermingled with tuffaceous materials. Toward the northern and southern borders of the belt sediments are more abundant, but the transition from well-marked tuffs into typical sedimentary rocks is more sudden here than elsewhere along the belt.

Because of the great abundance of coarse greenstones at this place, the location of the principal vents for the volcanic portions of the formation are supposed to have been here. The knobs are taken to be volcanic plugs or portions of thick flows that have escaped erosion. The amygdaloids are lava flows. Tuffs may have been present in large quantity in the valleys between the knobs, but if so they have been almost entirely removed by denuding agencies.

SUMMARY.

The Clarksburg formation is a set of interbedded tuffs, lavas, sedimentary and volcanic conglomerates and breccias, and other sediments, cut through and through by dikes and bosses of an altered diabase or basalt that is similar in composition to the older greenstones intrusive in the pre-Clarksburg beds of the Marquette series. The eruptive materials are basic. They are in all probability the surface facies of the greenstones above mentioned as intrusive in the Marquette series.

From its relations to the Goodrich quartzites and the Michigamme slates it is learned that the period of deposition of the volcanic series embraced the closing stages of Ishpeming time and the opening stages of Michigamme time.

All the rocks of the Clarksburg series except the greenstones and the lavas are banded and bedded. Most of them are foliated, and nearly all are more or less completely recrystallized. Although originally approximately horizontal, the beds are now contorted and folded so intricately that no accurate estimate of the thickness of the formation can be made.

The bosses of greenstone mark the sites of the old volcanic vents from which the materials of the tuffs were erupted. The most prominent of these were situated a few miles to the southeast of the village of Clarksburg, though others were opened from time to time to the eastward and the westward of this center.

The ashes and lavas sent from these vents fell into water and were interbedded with sediments. The pyroclastic material became consolidated into tuffs and the sediments modified into slates, schists, and graywackes. The former mark the periods of volcanic activity and the latter mark periods of rest. Mixed tuffs and sediments were formed during the less violent stages of the eruptions. After deposition the beds were hardened by alteration and by the formation of new products resulting from the decomposition of the constituents already existing in the beds, with the addition, perhaps, from extraneous sources, of a little quartz.

The conglomerates and breccias interstratified with the sediments and tuffs are simply these rocks with the addition to them of bowlders and fragments, mainly of preexisting rocks cast out through the volcanic vents or broken from ledges by the action of the waves, but occasionally of portions of lavas and tuffs shattered in the process of solidifying. In the latter case the fragments are very similar to the rock masses in which they are embedded.

The lavas associated with the fragmental rocks are rare. They consist of altered diabasic or basaltic amygdaloids that have lost nearly all of their original structural features.

All the evidence obtained through the microscope confirms the conclusion of the field study, viz: That the Clarksburg series consists of an accumulation of the ordinary deposits of Ishpeming and Michigamme sediments, with interbedded pyroclastic material erupted by a volcano whose principal vents are located by the greenstone knobs in the vicinity of Clarksburg village.

In their present forms the greenstones are altered diabasic porphyrites; the lavas, basalts or diabases; the pure sediments, graywackes or slates; and the tuffs, "Schalsteins," where much weathered, and where but slightly weathered, aggregates of amphibole, biotite, altered plagioclase, magnetite, garnet, and quartz. The garnets and amphibole are unquestionably new products. Both are idiomorphic, and both occur in large crystals. The biotite is a red-brown variety that apparently resulted from the decomposition of portions of the original materials of the rock, especially where these contained some proportion of sedimentary material. Where these new products are present in large quantity the original structure of the tuffs has nearly, if not quite, disappeared. Where they are scarce the rock retains its tuffaceous character. In this latter case fragments of plagioclase and crystals of this mineral are found to be embedded in an aggregate of small fragments of the same substance, flakes of biotite, spicules and plates of chlorite, fibers of green hornblende, grains of magnetite, and an interstitial aggregate of cryptocrystalline quartz. Where the tuffaceous material is mixed with sedimentary substances there are found also, in the aggregate, rounded grains of quartz. In the foliated phases of the tuffs and mixed tuffs and sediments the biotite exists in very large quantity, so large, indeed, that these phases often resemble biotite-schists. In them a few quartz grains are observable, and a fine-grained matrix that appears to have been derived from a fine-grained, clastic, interstitial filling between the larger grains of the original rock.

CHAPTER V.

THE IGNEOUS ROCKS.

By W. S. Bayley.

The igneous rocks associated with the Marquette sediments and ores, while varying in their present character, were originally nearly uniform in their mineralogical composition. Although occurring as bosses, dikes, interleaved sheets, surface flows, and tuffaceous beds, which have suffered a greater or less amount of alteration into products which are now not a little unlike one another, they were all, so far as has been determined, originally basic rocks of the composition of diabases. The variety at present exhibited by them is due almost exclusively to subsequent alterations.

Most of the rocks here considered, including the "diorites," "diorite-schists," "chlorite-schists," "magnesian-schists," "soapstones," and "paint-rocks," have been regarded by some geologists as metamorphosed sedimentary fragmentals. As we shall discover later, there is not a particle of evidence for this assumption. Even the most schistose of these rocks, with the possible exception of some of the "soapstones" and "paint-rocks," are certainly of igneous origin. The pyroclastic beds, so abundantly developed in the western portion of the district, and constituting a large portion of the Clarksburg formation of the Upper Marquette series, are, of course, fragmental, but they are of volcanic and not of sedimentary origin.

For convenience of discussion the igneous rocks are separated into two classes, in the first of which are placed those associated exclusively with the beds below the Clarksburg formation, and in the other those cutting also the beds above this terrane. The latter are evidently younger than the

Clarksburg rocks, while the former are believed to be mainly of Clarksburg age, and to be the lower portions of the rock masses whose surface facies are represented in part by the flows and tuffs that constitute the main mass of the Clarksburg formation. It has been suggested by Lane that the younger intrusives cutting the Michigamme formation may in a similar manner be dikes from the volcanoes that yielded the Keweenawan lavas.

The Clarksburg "greenstones" are discussed in connection with the other rocks of the Clarksburg series.

SECTION I.—THE PRE-CLARKSBURG GREENSTONES.

The igneous rocks associated with the beds older than the Clarksburg formation, and especially those in the iron-bearing formation, have been very thoroughly discussed by the different geologists who have studied the Marquette district, while the dikes of later age have scarcely been mentioned. Practically all the references to "diorites," "greenstones," "dioritic schists," and "chloritic schists" that are met with in the literature of the district apply to the "greenstones" and schists in the iron formation, and these, as has already been seen, were usually regarded as interleaved sheets, or as beds of metamorphosed sediments.

Structurally the pre-Clarksburg eruptives occur principally as dike-like bosses or as dikes, although sheets and tuff beds are also known to exist.

The dike and the boss masses are very much more common than the other structural forms of the greenstones, and are those that have hitherto been studied most carefully. They may be divided into two classes—those occurring as typical dikes, and those forming bosses or boss-like dikes. There are no essential differences between the rocks of the two classes, except that the dike masses have been much more completely altered than the boss masses.

The boss masses form the large knobs of "greenstone" or "diorite" that are so prominent a feature of the topography in the neighborhood of Ishpeming and Negaunee. (Atlas Sheets XXVIII and XXIX.) Some of these knobs may be regarded as parts of very large dikes, as, for instance, the knobs in the northwestern portion of Negaunee, which together form a high ridge some $2\frac{1}{2}$ miles in length and not more than an eighth of a mile in width. Other assemblages of knobs cover irregular but nearly equidimensional areas. There can be detected no striking differentiation of their parts. They are nearly uniform in composition and structure throughout, and hence they have features that ally them with boss masses. In one instance a laccolitic character is plainly discernible in a mass of greenstone that has raised into a dome the grünerite-schists which cover it. The place in question is in sec. 12, T. 47 N., R. 29 W. (Atlas Sheet XVI), where the relations between the greenstone and schists are as indicated in fig. 17, p. 330. (See also Pl. XI.)

Geographically considered, the knobs are not found east of the center of R. 26 W. From this point west to the extreme limit of the mapped area they occur in greater or fewer numbers, being most abundant in the Ishpeming-Negaunee mining area and in that north of Michigamme Lake and along Michigamme River. In this western area they form long, narrow ridges rather than irregularly shaped knobs. Moreover, the rocks in these ridges have a composition different from that of the rocks forming the knobs farther east. They seem to have suffered dynamic metamorphism to a greater degree than the eastern rocks, while the latter have suffered more severely from the effects of weathering. (See also pp. 329–330.)

THE BOSSES.

THE EASTERN KNOBS.

RELATIONS TO MARQUETTE SEDIMENTS.

The relations of the eastern greenstones to the rocks with which they are associated prove conclusively that they are intrusive in them, and are neither interleaved flows, as they have so frequently been stated to be, nor areas of the Basement Complex from which the Marquette beds have been eroded, as was supposed by N. H. Winchell. That they are intrusive is shown by the peripheral dikes extending from some of them into the surrounding sedimentaries and by the nature of the disturbances created in the bedding of the intruded rocks near the contacts with the greenstones. At the south of the hard-ore open pit of the Lake Superior mine in Ishpeming (Atlas Sheet XXVIII) a number of small dikes may be seen in the jaspers and ores, sometimes being parallel to the bedding of these rocks and sometimes cutting across it. In the underground working some of these dikes may be traced continuously into the large greenstone bluff south of the mine, and others into that east of the pit. A few of the dikes still preserve their diabasic structure, but most of them have become "chlorite-schists" or "soapstones." In composition they are identical with the peripheral schistose portions of large knobs. The disturbance created in the bedding of the sediments contiguous to many of the boss masses, moreover, is of such a nature that it admits of but one interpretation, viz, that the knob greenstones are irruptive into the Marquette, not as interleaved sheets, but as true bosses, in some places with laccolitic features. In the majority of cases the bedded rocks dip away from the contacts, and at much higher angles near the greenstones than at a distance from them. Besides, wherever small areas of the bedded rocks lie between the arms of an irregularly outlined knob the beds are usually bent into little folds, with axes pitching away from the greenstone. Further, a glance at the detailed maps of the area around Ishpeming and Negaunee (Atlas Sheets XXVIII, XXIX, and XXXI) will show that the exposures of the greenstones, in this area at any rate, are so irregularly distributed throughout the iron-bearing formation as to indicate that the crystalline rocks are bosses and not interleaved sheets. An accurate mapping of the greenstones, wherever undertaken, effectually disposes of this latter idea, even in the absence of the intrusive phenomena described above. It would seem that the intrusive relation of the knob greenstones to the bedded rocks is settled beyond reasonable doubt.

The greenstone knobs are very much more abundant in the iron-bearing formation than in any other, though they are by no means limited to it. They occur in all the formations of the Lower Marquette and in the lower members of the Upper Marquette, but their number in these other formations is inconsiderable and their size small.

PETROGRAPHICAL CHARACTER.

The material of the eastern knobs differs in no essential respects from much of the basic material intrusive in the Basement Complex. All the rocks comprising them are altered diabases, sometimes coarse-grained, sometimes medium-grained, and rarely fine-grained. In many of them the diabasic structure is still very plainly visible, while in others it has been lost through alteration and through mashing. The more massive of the greenstones, more particularly those occurring in the knobs, are the miners' "diorites."

Macroscopically the material of the eastern knobs is a light or dark grayish-green, mediumly coarse grained rock, that is rarely massive. Usually some trace of foliation may be distinguished in the hand specimens. Frequently the schistosity is so slight in amount that it is recognizable only in the ledge. In other cases the rocks are highly schistose, when they merit the name of greenstone-schists. While the schistosity of many of the knobs is more pronounced around their peripheries and along joint planes than elsewhere within their masses, the schistose greenstone may occur anywhere within a greenstone area, even in the midst of great areas of perfectly massive rock. The intimate relations existing between the schistose and massive greenstones indicate conclusively that both are phases of the same rock mass, which yielded here and there to some force, with the result that motion was set up between its parts, which have, as a consequence, become schistose. Along joint planes are often shear zones, and at these places the rocks are as completely schistose as are chlorite-schists.

In nearly all specimens of the eastern knobs, even in some of those that are schistose, the diabasic structure may be detected. When not apparent in the hand specimen, it can nearly always be observed in the thin section, although in most cases all traces of the original components of the rocks have disappeared and their places have been taken by secondary substances. In the freshest of the rocks, which usually come from the centers of the knobs, cores of pale-violet or almost colorless augite, surrounded by rims of green hornblende, altered plagioclase, chlorite, epidote, and often calcite, are arranged in the typical ophitic manner. The plagioclase, by its alteration, has given rise to the chlorite, epidote, and calcite, and often to a sericitic substance, which in some instances appears to be genuine muscovite.

A typical knob, from the petrographical standpoint, and one which exhibits all the varieties met with in the eastern knobs, is that which extends from Gunpowder Lake, at the east quarter post of sec. 11, T. 47 N., R. 27 W.

(Atlas Sheet XXVIII), southeastward to a little beyond the east quarter post of sec. 13 in the same township. Only that portion of the knob that lies in sec. 12 has been sectioned, although the entire knob has been carefully sampled (fig. 27). Of the eleven sections made from this portion of the knob, three contain remnants of augite. The balance of the specimens are amphibole rocks.

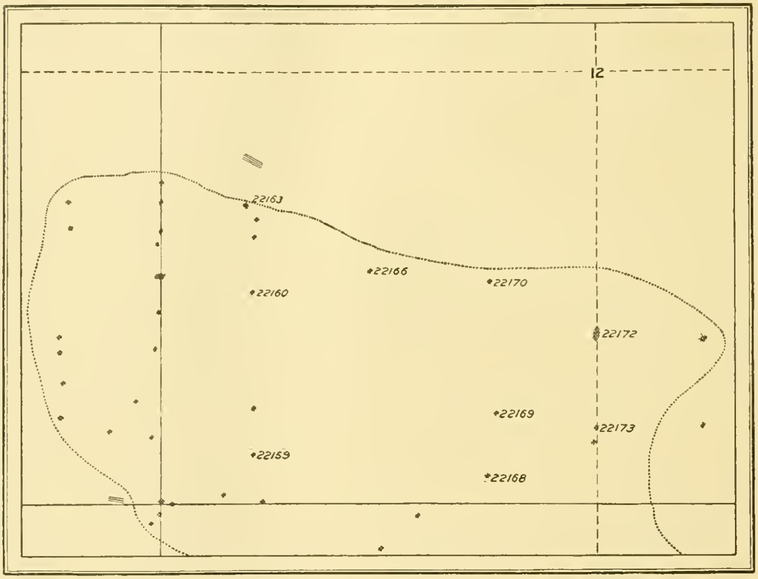


Fig. 27.—Position of specimens of greenstone from south half of sec. 12, T. 47 N., R. 27 W.

The commonest phase of the greenstone is a dense granular rock showing compact hornblende. Under the microscope this latter mineral is typical uralite. It is strongly pleochroic in light yellowish-green and dark bluish-green tints, and is often bordered by dirty-brown biotite. The hornblende is often twinned, and often it possesses idiomorphic outlines. The plagioclase is not very abundant. The crystals are shattered. Fibrous hornblende of the same nature as the larger, more compact grains, together with chlorite, has filled the fissures thus produced. Some biotite occurs in the midst of even the most compact amphibole, and brown ocher colors portions of most of the feldspars. In spite of the fact that this rock has been so changed, its diabasic structure remains, the compact hornblende occupying the place of the original augite, while the altered plagioclase, the fibrous hornblende, and most of the biotite and of the chlorite occupy the place of the original feldspars.

Some of the rocks from the interior of the knob (Specimens 22168 and 22173) are dark-gray, rather dense-looking, and perfectly massive, exhibiting very decided luster-mottling, and showing plainly in the hand specimen the diabasic structure. Under the microscope the augite that remains is found to be limited almost exclusively to the mottled areas, and to be the mineral to whose presence the latter is due. The pyroxene is almost colorless. It occurs as very raggedly irregular cores surrounded by light-green hornblende. It is penetrated by what were originally plagioclase laths but are now largely an aggregate of small saussurite crystals, between which are here and there patches of feldspar. The green hornblende is very slightly pleochroic. It borders the augite mottlings, and elsewhere in the sections it occupies wedge-shaped areas, penetrated, like the augite areas, by laths of plagioclase. Chlorite is also present in small quantities, and it likewise is in ophitic wedges. The plagioclase has nearly all disappeared into its decomposition products. Leucoxene and epidote are the only other important minerals present. The latter is in small yellow grains, often in the midst of chlorite, and the former in fine pseudomorphs after crystals of ilmenite, cores of which occasionally remain in the centers of the leucoxene masses.

Other varieties of the rock (Specimens 22159, 22160, and 22169), from well within the rock mass, resemble very closely the augitic phases described above, except that they appear a little more altered, and their plagioclase is in places reddened. Under the microscope they are aggregates of light-green hornblende and chlorite, often stained with ocher, in a mass of altered plagioclase whose principal decomposition products are epidote, saussurite, and chlorite. The epidote is embedded in chlorite, either as pale-yellow plates or as little grains, often with crystal outlines. Occasionally a large crystal of andesine, or of some plagioclase whose chemical composition is in the neighborhood of this mineral, is embedded in the mass and so gives a porphyritic habit to the sections. Leucoxene is abundant. The original structure of the rock is obscured by the abundant secondary substances occurring in it, but the ophitic texture is clearly apparent. In one phase (Specimen 22169) the amphibole is more fibrous than in the others, but in the center of an amphibole cluster a small core of augite was noticed.

The rocks nearer the periphery of the mass (Specimens 22166, 22170, and 22172) show glistening areas of hornblende and small brilliant laths of plagioclase in a dull-green groundmass. In thin section they are apparently porphyritic, for large crystals of feldspar are embedded among the small laths of this mineral and the amphibole which together make up the larger portion of the rocks. None of these rocks differ essentially from those above mentioned. Chlorite is more abundant in them, but the amphibole is of the same light-green color, and is present in the same ophitic areas. The plagioclase is more altered than in any of the other rocks mentioned, but its original outlines can still be recognized.

At the very edge of the knob is a dark-green schistose phase of the rock. The hand specimen is made up of small, dark, glistening areas resembling those of amphibole. The thin section is a nearly uniform aggregate of tiny chlorite and small brown biotite flakes, grains of magnetite or ilmenite, and very small grains, sometimes laths, of clear plagioclase. This uniformity is broken in places by lenses of altered plagioclase, in which badly defined feldspathic substance is cut by spicules of chlorite.

In the study of these sections from a single rock mass we become acquainted with the different forms which may be assumed by a mediumly coarse grained diabase under the influence of processes that are mainly weathering and metasomatic phenomena but partially phenomena due to dynamic agencies. The original rock was a coarse diabase. This has given rise to epidiorites containing secondary fibrous hornblende, to "diorites" in which the amphibole is a compact and sometimes an idiomorphic variety, and to uralite-diabases. Where mashing has taken place in addition to the weathering, chlorite-schist has been produced.

There is not a particle of evidence in these sections that the schist or any of the forms of the massive greenstone were ever fragmental rocks.

The composition and structure of even the more altered forms are proof that all have originated by ordinary processes from an igneous magma.

In order to determine the chemical differences that exist between the augitic phases of the greenstone and those phases in which all the augite has been changed to amphibole, analyses of two specimens were made by George Steiger in the Survey laboratory. His results are as follows:

Analyses of greenstones.

	I.	II.
SiO_2	48.44	48.85
TiO_2	.71	1.28
Al_2O_3	18.84	15.83
Fe_2O_3	2.21	2.50
FeO	9.56	10.79
MnO	....	.11
CaO	8.89	6.20
BaO	....	.09
MgO	3.79	5.82
K_2O	....	1.31
Na_2O	....	2.79
H_2O at 100°	....	.27
H_2O above 100°	....	3.77
SO_3	....	.06
P_2O_5	....	.22
Total	....	99.89

I.—No. 22168. From SW. ¼ sec. 12, T. 47 N., R. 27 W. Massive greenstone containing pale augite in fairly large quantity.

II.—No. 22159. From a point near No. 22168. Typical nonaugitic greenstone, like the greater portion of the miners' "diorites."

Evidently there is no great difference in the composition of these two rocks. The more altered one contains less alumina and lime than the less altered one, and a little more iron oxide and magnesia; otherwise the two are similar. These analyses afford no evidence confirmatory of the view that in the formation of amphibolites from diabases iron oxides are removed and condensed into ore bodies.[1]

The rocks of the other eastern knobs present few features different from those described above. From six different knobs specimens were collected whose slides show remnants of nearly colorless augite when examined

[1] Report of State Board of Geological Survey for 1891 and 1892, Lansing [Mich.], 1893, p. 180.

under the microscope. In most of the rocks, however, no traces of augite remain. Hornblende or chlorite has taken its place, and the rocks are now either uralitic diabases, in which the hornblende is compact and pseudomorphic after the augite, or epidiorites, in which the amphibole is fibrous, and in which the ophitic structure of the diabase has in some cases entirely disappeared. The rocks of both these varieties are dark-green in color, fibrous in texture, and often schistose in structure.

Under the microscope they are found to be composed most largely of light-green amphibole, remnants of altered plagioclase, large plates of epidote, much chlorite, large masses of very beautiful leucoxene surrounding ilmenite, and nests of calcite. In the freshest of the uralitic diabases the augite has given rise to compact, dark-green uralite, and the plagioclase to epidote and calcite. In the epidiorites the amphibole has become fibrous. Not only are areas formerly occupied by the augite now filled with fibrous amphibole, but long, slender needles of the mineral extend far out into the surrounding rock materials.

The plagioclase in these rocks has suffered extreme alteration. Its twinning bars have nearly disappeared and its material has been changed to kaolin, chlorite, saussurite, epidote, and calcite. Sometimes one and sometimes the other of these substances predominates, and not infrequently there occur scattered through the slides perfect calcite pseudomorphs of lath-shaped crystals of plagioclase that preserve even the twinning of the original feldspar.

The epidote is in the usual green plates. While often an alteration product of the plagioclase, it is sometimes a result of the decomposition of the augite, when it is intermingled more or less freely with chlorite and calcite. The chlorite is in little nests scattered between the other minerals, and in groups of fibers pseudomorphing feldspar. It is an alteration of the amphibole as well as of the plagioclase.

Further alteration of the uralitic diabases and the epidiorites gives rise to chloritic rocks in which chlorite has replaced the hornblende. The chlorite here is in pale-green, very weakly doubly refracting fibers that form pseudomorphs of the amphibole and preserve the ophitic texture of the original rock. Epidote, calcite, and leucoxene are abundant in these rocks, and sometimes there are present small nests of secondary quartz. All plagioclase has entirely disappeared. The forms of its crystals are preserved by calcite and epidote, or perhaps by calcite alone, which pseudomorphs the feldspar.

Where rendered schistose by mashing, as happens on the peripheries of most of the knobs, the alteration of the greenstones is far advanced. Chlorite and calcite, with a little magnetite, quartz, and other minerals in small quantity, sometimes constitute the entire rock, which is then a typical chlorite-schist. In no cases observed are the greenstone-schists enveloping the more massive greenstones of sedimentary origin, as might be inferred to be the case from Wadsworth's[1] earlier statements. In all cases the schistose rocks differ from the more massive ones in being more highly foliated through mashing, which was naturally more easily possible on the peripheries of the rock masses than elsewhere. The schists often exhibit traces of the diabasic structure, even when greatly altered. The degree of alteration to which they have been subjected appears, however, to have increased with the degree of the foliation, so that the most schistose of the peripheral rocks have lost all traces of their origin. It is principally through their gradation into less highly foliated phases that their true nature is made out.

Under the microscope the foliation of the schists is plainly seen to be an effect of motion in a solid rock mass. Broken crystals of plagioclase, crystals faulted along cracks, others crushed into powder on their borders, and others fissured, with their cracks filled with a secondary mosaic like that of the rock's groundmass, all bear strong evidence that the rocks in which these phenomena are found have been at some time subjected to great stresses. The foliation is due to the arrangement of the chlorite and amphibole in parallel fibers, and, since the direction of the parallelism corresponds with that along which the particles of the broken crystals have been moved, it is concluded that the schistosity is also an effect of pressure.

While the rocks described above are the predominant ones in the eastern knobs, there is another type that should be mentioned. A considerable number of the greenstones are dark-green in color and coarse-grained. On a freshly fractured surface brilliant black columnar crystals of

[1] Bull. Mus. Comp. Zool. Harvard Coll., Geol. Series, No. 1, 1880, p. 41.

hornblende are seen lying in a greenish-gray groundmass, and producing in places a well-defined luster-mottling. The hornblende of these rocks is a compact blue-green variety, in long columnar crystals that are idiomorphic in the prismatic zone. Occasionally they are aggregated into areas resembling those of ophitic augite, but usually they appear to be scattered indiscriminately through the rock mass, which consists largely of chlorite, epidote, and the remnants of very much decomposed plagioclase. The amphibole has undoubtedly been formed at the expense of previously existing pyroxene, for the hornblende rocks are in many instances but local phases of well-defined altered diabases. The hornblende has grown until it has extended beyond the areas formerly occupied by augite into the matrix produced by the decomposition of the plagioclase. This hornblende is always compact, and its crystals are often twinned. The rocks containing them are "diorites" in structure as well as in composition, though, of course, they are not diorites which have crystallized directly from a magma.

In another class of the diorites, represented by the knob in the center of sec. 12, T. 47 N., R 27 W. (Atlas Sheet XXVIII), the compact, apparently idiomorphic amphibole is evidently a pseudomorph of augite. Remnants of pink augite may still be detected in the individual hornblendes, and occasionally nearly complete crystals of the minerals may be observed. Rocks of this kind were originally augite-porphyrites.

One other exposure deserves to be mentioned, on account of its peculiar appearance. It is on the north side of the Duluth, South Shore and Atlantic Railway track, in the garden of a house built on a hill about half a mile east of the Ishpeming station. The rock exposed is a coarse-grained, slightly foliated one, with a smooth, glaciated surface, marked by concentric or spiral lines, resembling on a large scale the perlitic cracks in glassy rocks. When broken the fresh fracture of the rock presents no unusual features. The phenomenon noticed on its exposed surface is apparently that of spheroidal weathering, for the partings which produce the lines do not extend any considerable distance below the surface.

Contact phenomena around the eastern greenstones are rarely seen. The only evidence of endomorphous contact action noticed in any of the eastern knobs was observed in that forming the foot-wall of the open pit near the NW. corner of sec. 10, T. 47 N., R. 27 W. (Atlas Sheet XXVIII). In other places some of the greenstones, where not schistose, are slightly finer grained on their borders than in the interiors of the knobs, but in this case the greenstone, near its contact with the rocks of the iron formation, is highly charged with magnetite. Some of the magnetite is certainly titaniferous, like the most of the magnetite of the normal greenstone, but the greater portion of it is nontitaniferous. The rock consists mainly of almost amorphous chlorite. Scattered through this are large plates of a colorless lamellar mineral that appears to be muscovite, and some grains of quartz. A few long, columnar crystals of tourmaline, pleochroic in pink and very dark bluish-green tints, are also scattered here and there among the other components, but its presence is only doubtfully referred to contact action, as tourmaline has been found in small quantities in other greenstones both of the eastern and of the western knobs.

THE WESTERN KNOBS.

RELATIONS TO MARQUETTE SEDIMENTS.

As topographical features, the western knobs differ from the eastern ones in that they are linear and dike-like in shape rather than irregular in outline. The most typical of these knobs are in the area directly north of Lake Michigamme, where they constitute well-defined hills rising boldly as bare knolls above the general level of the surrounding country. Similar greenstones occur also in the Republic trough, being best known at Republic Mountain, where they are associated with the jaspers and schists of the iron-bearing formation. At this place they are not higher than the iron-bearing beds; hence they appear at first sight as interleaved sheets that have been planed down by erosion equally with the iron-formation rocks.

That the linear masses are intrusive rather than effusive is shown by the following facts: The knobs, while arranged in approximately straight lines, are not continuous, but are separated from one another by little valleys of sedimentary rocks; occasionally the individual knobs are not confined to a definite horizon in the Marquette series, but cut across the beds of a formation, or even cross the line between two contiguous formations and traverse parts of each, as is the case with the knob in sec. 21,

T. 48 N., R. 30 W. (Atlas Sheet V); further, numerous inclusions of the grünerite-magnetite-schists are found at one place within the greenstone (Pl. XII).

With respect to the Republic greenstones, Rominger[1] well says:

> The whole slope of the hillside is composed of an endless succession of banded ferrugino-siliceous, actinolite schists, united into bulky, compact masses, which are here and there interrupted by intrusive diorite belts of short, local extension, and not, as represented by Major Brooks, in regular continuous bands encircling the whole side of the mountain.

Although it is clear that all the greenstones of the western knobs and those of Republic Mountain are intrusive, it is not known in all cases whether they possess the features of dikes, sheets, or bosses. In some cases, as at the Spurr mine, the greenstones are apparently interbedded with the sedimentary formations; but even here the supposed beds are of short linear extent, and may be dikes that happen to coincide in direction with the strike of the bedded rocks at the position of the present plane of erosion.

From the general relations of the western greenstones, exclusive of the smaller dikes, it would appear that most of them are boss-like dikes whose courses on the surface are approximately parallel to the strike of the sedimentary beds intruded by them. A few may be in the form of sheets, but if so they are intrusive and not surface sheets, and hence are not available for working out the structure of the Marquette series. They do not constitute well-defined beds at definite horizons in the series, as was supposed by Brooks.

PETROGRAPHICAL CHARACTER.

The rocks of the western knobs differ materially from those of the eastern knobs in their microscopic features, although some of them are very like the latter macroscopically. Originally there was probably no difference between the two types of rock. In the eastern greenstones, however, the alteration was degradational in its nature. The diabases have passed through epidiorites and chlorite-schists into aggregates of calcite, chlorite, epidote, etc., all of which may be regarded as final stages in the weathering of plagioclase and pyroxene. In the western greenstones dynamic processes

[1] Geological Survey of Michigan, Vol. IV, p. 101.

appear to have played the more important rôle. In these rocks the amphibole is dark-green and compact. It is never pale-green and fibrous. Moreover, chlorite is rare, except locally, while fresh brown biotite and grains of quartz are abundant, and in many cases there has been produced a mosaic of the latter mineral and albite, as in the case of the hornblendic schists of the Basement Complex.

These differences between the eastern and the western greenstones may be explained by the differences in form and in the geological conditions under which the rocks are found. The eastern knobs are irregular in shape and are boss-like in their features, while the western knobs are linear in shape and dike-like in their general features. The former were able to withstand stress more successfully than the latter, and so have suffered less dynamic metamorphism than these. Moreover, in the western part of the Marquette district the folding and mashing of the formations were more severe than they were in the Ishpeming-Negaunee area. (See Metamorphism, Chapter VII, pp. 573–575.) Consequently, as a rule, the western greenstones are more schistose than the eastern ones. They are darker in color, fresher in appearance, and more crystalline-looking. Often large, brilliant, dark-green or black amphiboles lie in a dark-green groundmass, through which small, sparkling crystals of the same mineral are thickly strewn, with their longer axes in the planes of schistosity. In their macroscopic features these rocks resemble very closely schistose diorites and camptonites.

Under the microscope all their sections are fresh-looking. The weathering products so noticeable in the eastern greenstones are rarely observed. Biotite is their characteristic component. It occurs as large and small plates of a deep reddish-brown color, like that in the micaceous schists of the Basement Complex. It is derived very largely from the plagioclase. In those specimens in which the plagioclastic nature of the altered feldspar is still clearly apparent, small brown biotite flakes, little spicules of hornblende, and granules of epidote are scattered in large quantities through the feldspathic substance, and here and there quartz also is present. Upon further alteration of the plagioclase the quartz becomes more and more abundant, and sometimes secondary albite is formed. In the final stage of the change all the plagioclase has been replaced by an aggregate of biotite, quartz, some hornblende, and a little epidote, with the addition in many cases of a quartz-albite mosaic between these components.

The hornblende, as already mentioned, is a dark-green, compact variety that is often idiomorphic in cross-section and is often twinned. Its crystals lie in a matrix having the structure and composition of the aggregate described above as the final alteration product of the plagioclase. In some cases the aggregate is rich in biotite, while in other instances biotite is present only in very small quantity, and the aggregate is practically a plagioclase-quartz mosaic.

The larger hornblendes, which appear as phenocrysts in the hand specimen, differ from the smaller columnar crystals mainly in size. Their relations to the aggregate are the same. In both cases the mineral shows its secondary nature by the frayed ends of its crystals, and by the fact that large areas of almost pure hornblende are made up of bundles of small, compact, columnar crystals. Another form of amphibole is frequently encountered. In this many individual crystals are bound together in sheaf-like bundles, with their ends extending far out into the surrounding groundmass. The rocks in which the amphiboles are of this kind resemble very closely the "diorites" and altered tuffs of the Mona formation.[1]

In the thin section the schistosity of these rocks is very striking. All their constituents are arranged with their longer directions approximately parallel, and lenses of mosaic, with their major axes running the same way, wind in and out among the other components. In spite of their great alteration the diabasic structure can still be detected in some of the specimens, especially when their thin sections are viewed against a white background. Under the microscope this structure can rarely be recognized, since the hornblendes in their growth have extended beyond the areas originally occupied by the augite. Sometimes hornblende crystals, biotite, and chlorite fill ophitic spaces between the decomposition products of plagioclase, but these cases are rare.

As the schistosity of the greenstones increase in amount their material appears to become better crystallized, except where the foliated phases are in contact with other rocks, in which case they have suffered not only extreme

[1] Cf. fig. 1, Pl. XVI, Bull. U. S. Geol. Survey No. 62, by G. H. Williams.

mashing but great chemical changes as well, for they are now often pure chlorite-schists, composed of a solid mesh of small chlorite fibers, between which are occasionally small areas of quartz mosaic, tiny grains of magnetite, biotite flakes, and pyrite crystals. In some cases quartz mosaics pseudomorph the original plagioclase grains, and in others large garnets occur scattered indiscriminately through the rocks. These latter are well seen at the Michigamme and Spurr mines and on the borders of some of the boss-like greenstone masses in Humboldt Mountain, where they have been regarded as possibly the result of contact action, since they are often as well developed in the sedimentary beds contiguous to the greenstones as they are in the greenstones themselves The garnets in the greenstones exhibit no anomalies, so far as seen They are almost colorless, isotropic bodies, crossed by irregular cracks and containing as inclusions a great many irregular grains of magnetite and very irregularly outlined colorless masses that under the crossed nicols appear to be quartz and plagioclase. At the Spurr mine many of the garnets are more or less completely changed to chlorite, as described by Pumpelly in 1875.

The very schistose phases of the western greenstones, where they are not on the contact with the sedimentary rocks, are almost typical hornblende-schists. This is especially true of those greenstones in the Republic trough. As we pass southward from the Magnetic mine, in sec. 20, T. 47 N., R. 30 W. (Atlas Sheet VII), it is noticed that the greenstones become more and more schistose and at the same time more crystalline. Their quartzose component increases in quantity until in some of the rocks, especially those in the vicinity of Republic (Atlas Sheet XI), it makes up a large proportion of the rock masses. Many of these rocks are composed of crystals of bright-green amphibole, often with idiomorphic cross-sections, large lenticular grains of quartz and plates of epidote, and, between these, masses of altered plagioclase, consisting largely of kaolin, epidote or saussurite, and biotite. Leucoxene and magnetite also occur in the schists, the former mineral with the habit of sphene and the latter with very irregular outlines. Others of the schists contain large quantities of a bright-green hornblende with extremely ragged contours and groups of this mineral composed of numbers of small grains and spicules of amphibole variously orientated, several together often forming small prismatic crystals idiomorphic in the prismatic zone, and the whole forming a very irregular area. Nearly all of the areas are cellular. Their component parts are filled with inclusions of the quartz, feldspar, epidote, etc., that make up the body of the rock. The hornblende in these instances is certainly secondary, and was probably the last of the principal rock constituents to form. Fig. 4 of Pl. XXXII illustrates the structure of one of the clusters in a greenstone from Republic Mountain.

The other components of these rocks are identical in form and nature with those of the predominant schists.

The greater schistosity of the Republic greenstones, as compared with those near the Michigamme and Spurr mines, and their more crystalline character, are accounted for in the same manner as are the greater schistosity and higher degree of crystallization of the western greenstones in general as compared with the eastern greenstones, viz, by the fact that in the Republic trough the mashing of the igneous rocks, along with the sedimentary beds, was greater than anywhere else in the Marquette district with the exception of the Western trough.

The general features of various rocks of the western greenstone knobs and dike masses have been described. Descriptions of the special features of the different exposures, so varied are they, would consume more space than would be justifiable in a discussion which is not purely petrographical. A brief description of one or two exceptional phases, however, will be made.

Some of the greenstone-schists deserve mention for the beautiful chloritoid found in them. This mineral has all the properties of true chloritoid. It forms large plates that are pleochroic in greenish-blue and greenish-yellow tints, and has an extinction of 1° to 3°, and often more. Lane, Keller, and Hobbs (see Chapter I, pp. 129, 148) have described this chloritoid very fully. But Lane and Keller state that "all the Michigan chloritoids, so far as yet known, occur in altered arkoses or similar rocks." In the present instance, and in some others to be mentioned later, the rocks in which the chloritoid exists are quite certainly mashed eruptives. They consist of brownish-green biotite, large flakes of the chloritoid mentioned, crystals of clear and almost colorless epidote, and small grains of magnetite, forming areas between which are other lighter areas composed of quartz, saussurite, calcite, and large irregular cellular garnets.

A singular set of knobs is north of Lake Corning, in the SW. ¼ sec. 5, T. 47 N., R. 27 W. (Atlas Sheet XXV). The main mass of these knobs is a coarse-grained uralitic diabase resembling a camptonite, with lath-shaped feldspars and hornblende crystals scattered through a fine-grained, grayish-green matrix (Specimen 19547). On the top of the hill the rock is coarser, and its feldspathic constituent is in patches and is of a pinkish tinge (Specimen 19548). The hornblende is in acicular crystals. Farther east the feldspar crystals are larger and redder, while the hornblendes are not acicular (Specimen 19549). Certain patches in the rock were taken for inclusions. They are pink in color and are very much finer in texture than the main mass of the rock, and around their edges they are bordered by bands of green, as though they had been affected by contact action. Other patches are epidotized throughout. In both cases the "inclusions" resemble fine-grained granites that have been altered by the greenstone.

In thin section the main mass of rock is seen to have a coarse diabasic structure. The hornblende is always found in ophitic areas, either alone or with chlorite and epidote. The plagioclase is changed to a mixture of saussurite, calcite, and epidote, which is cut through and through by hornblende spicules. The rock is thus a uralitic diabase, like so many others of the knob greenstones, and not a camptonite, as it appears to be from its macroscopic habit.

The porphyritic phases on the top of the hill (Specimen 19549) are composed of large, partially idiomorphic, altered, and often crushed and reddened plagioclases in a matrix of small laths of the same mineral and small triangular masses of chlorite that have evidently been derived from hornblende. Leucoxene is also present in large quantity. The supposed inclusions are fine-grained diabases. They contain only small quantities of the chloritic interstitial substance, while large quantities of calcite and leucoxene are present in them. The epidotized inclusions are of the same nature, except that they contain an abundance of epidote.

The "inclusions" may be fragments of a preexisting, fine-grained diabase, caught up by the coarse diabase in its upward passage, or they may be but local phases of the latter rock. There is no evidence of contact action in them. The epidotization noticed around their edges is but one exhibition of the general epidotization which much of the mass of the knob has suffered. Nests and veins of epidote are common at the eastern end of the westernmost knob, and, so far as known, they bear no definite relation to the occurrence of the "inclusions."

THE DIKES.

The typical dikes intrusive in the pre-Clarksburg rocks can not be sharply distinguished from the boss-like dikes that have already been described. They vary in width from a few inches to 60 feet, and so are distinguished from the larger masses in size. Moreover, their walls are parallel and their courses usually straight, and these features again distinguish them from the rocks that constitute the knobs. However, the small dikes often are but apophyses of the boss-like dikes, and therefore they are but portions of the latter, from which they do not differ in any essential respects. The rocks that originally composed them were of the same nature as the materials of the larger masses; at present they differ from the latter to a slight degree in consequence of their greater proneness to alteration.

While many of the small dikes are composed of greenstone identical in composition with the materials of the knobs, the majority consist of the highly schistose and much altered rocks which constitute the "diorite-schists," "chlorite-schists," "soapstones," and "paint-rocks" of the miners. The dikes of this kind are sometimes offshoots of the great knobs of greenstone; at other times they appear as isolated bodies, which, however, in all probability are connected underground with the bosses or with their downward extensions.

The dike rocks are in all respects so similar to the boss rocks that no doubt could arise as to their intrusive nature even were their field relations not clearly those of intrusives. Every gradation exists between the most schistose dikes and those which still preserve, faintly it is true, the diabasic structure. These obscure diabases are identical with similar rocks forming the knobs, and the latter may be clearly traced into true diabases, in which augite may still be detected. None of the chlorite-schists and none of the schistose greenstones associated with the iron-bearing rocks, so far as known, are of fragmental origin. All of them are metamorphosed igneous rocks.

In some cases the smaller dikes are fresh, dark olivine-diabase or basalt. These appear to be independent bodies that are younger than the schistose dikes and the bosses, for they traverse the latter as well as the fragmental beds. One of them may be seen on the side of the cliff overlooking the lake shaft of the Cleveland mine. Most of these dikes are the quartz-diabase of Lane, and are identical in nature with the fresh diabases cutting the Archean rocks below the Lower Marquette series, and with those occurring in the upper portion of the Upper Marquette series. They are therefore of post-Clarksburg age, and are discussed with the younger dikes.

The small greenstone dikes, like the boss greenstones, are found to cut all the rocks below the top of the Clarksburg formation, but also, like the boss masses, they are confined principally to the iron-bearing formation. They are very frequently met with in traversing the country underlain by this formation, but are even more numerous than they appear to be. Many of their exposures are small and badly decomposed, so that they often escape notice even where not completely covered by loose material. In the mine workings, however, their lower extensions are brought to light, when their abundance is better appreciated. In Chapter III, Section VI, they are shown to be closely connected with the accumulation of ore bodies. In those areas where the alteration of the dikes and the inclosing schists was not carried so far, as, for instance, at Mount Humboldt (Atlas Sheet XVI), where the iron formation is chiefly represented by grüneritic schists rather than by jaspers, ores, and ferruginous schists, the dikes may easily be recognized on the surface, and their number is fully realized. The sketch map (Pl. XXXIII) of the W. ½ of sec. 12 and the E. ½ of sec. 11, T. 47 N., R. 29 W., shows approximately the number of dikes met with in traversing at intervals of one-eighth mile a square mile of territory.

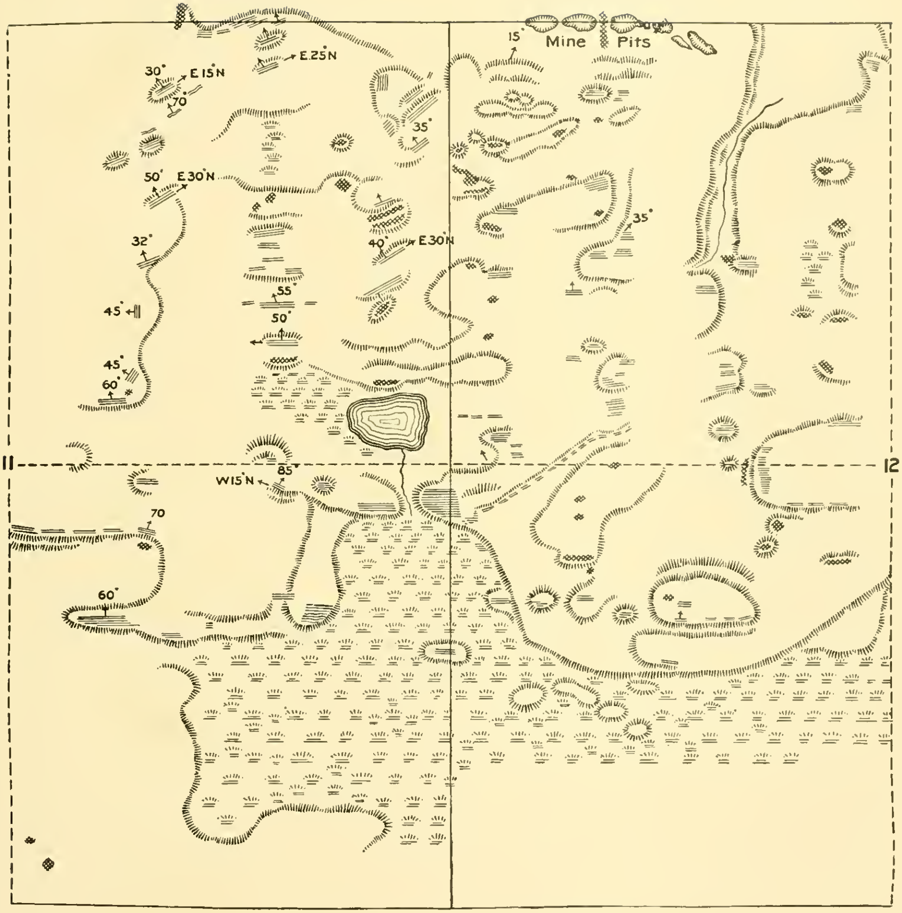
It is possible that some of the greenstones that are considered as dikes may be interleaved sheets, since some of the latter are chlorite-schists that are identical with the chlorite-schists of undoubted dikes. The number of the sheets, however, is probably not great, and it is not important to distinguish between them and the dikes, especially since many of the former are undoubtedly intrusive, just as are the dikes themselves.

PETROGRAPHICAL CHARACTER.

Many of the dike rocks are so similar to the altered forms of diabase characterizing the knobs of the eastern portion of the Marquette district that detailed descriptions of them are unnecessary. The extremely schistose varieties of the greenstones are especially prominent in the smaller dikes, including as they do the chlorite-schists and talc-schists, the "soapstones" and the "paint-rocks" of the miners. The former occur throughout the entire district, but are of course much more common in those areas where there has been a great amount of mashing.

The great majority of the less schistose dikes contain large quantities of fibrous amphibole and the remnants of altered plagioclase Sometimes the feldspar is represented by saussurite, quartz, or by these minerals, calcite, and chlorite; at other times by a sericitic mineral and quartz; and again, very frequently, by a mosaic of quartz and fresh feldspar Biotite is also present in some of the schists, especially those containing large quantities of the quartz-feldspar mosaic. The principal bisilicate constituent is always either amphibole or amphibole and its alteration product, chlorite. Occasionally, even in the schistose rocks, these minerals occur in ophitic areas, but usually the mashing has been so great that the darker-colored components of the dike rocks, as well as the lighter ones, are in narrow lenticular bodies. The cause of the foliation of the dike masses, like that of the boss masses, is clearly seen to be dynamic. Not only are the components nearly always in the lenticular forms referred to, but very frequently the altered plagioclases are crushed and broken and their fragments moved apart in the direction of the foliation. Moreover, on their edges the larger grains are not infrequently granulated.

The petrographical varieties of these dike rocks are very numerous, but their features are in general not different from those of the boss masses. A few varieties, however, should be mentioned as peculiar. In one or two instances (as in Specimen 16180, from a dike 8 feet wide in one of the pits in the NW. ¼ sec. 12, T. 47 N., R. 29 W., and in Specimen 17505, from a large ledge in the NW. ¼ sec. 30, T. 47 N., R. 30 W.) the rocks were originally porphyrites, or, perhaps, basaltic phases of diabase. The first of these rocks now shows plagioclase crystals, that are more or



SKETCH MAP OF THE DIKES OF MOUNT HUMBOLDT.

less chloritized, in an altered groundmass filled with skeleton crystals of magnetite. Apparently this groundmass was originally glassy. It now consists of chlorite and certain indefinite, brownish-green, fibrous substances in a light-colored matrix that polarizes feebly in places, like an altered feldspar, and in other places acts like an isotropic substance. The second rock has been entirely recrystallized. It now consists of large, fresh plagioclases and small areas of quartz mosaic in a groundmass cut through and through by light-green amphibole crystals resembling actinolite. The interstitial substance between these is a mosaic of quartz and plagioclase. There are among the dike rocks a few other porphyrites, but they are coarse-grained, and differ from the nonporphyritic phases merely in that they contain phenocrysts of plagioclase.

The most schistose phases of the dike rocks include the chlorite-schists, the talc-schists, and the kaolin-schists.

In the chlorite-schists chlorite predominates over all other components. The rock of the dike at the old Gilmore mine (Atlas Sheet XXXV), near the north quarter post of sec. 26, T. 47 N., R. 26 W., for instance, is an aggregate of bundles of a fibrous green chlorite, through which are scattered laths of plagioclase. The latter can be seen only in polarized light, since in natural light the green color of the chlorite obscures them. A little limonite stains the chlorite here and there, and a few magnetites are besprinkled through it. Other chloritic schists are very similar to this one, though not many of them are so nearly devoid of components other than chlorite.

In the rock of two dikes, one at Humboldt and the other 835 steps W., 700 steps N., of the SE. corner of sec. 24, T. 48 N., R. 31 W., are great plates of chloritoid of the same character as that in the western knob greenstones described on page 504. In the first dike (Specimen 14777) the chloritoid is in beautiful fresh columnar crystals, having an extinction varying between 0° and 16° and twinned parallel to their longer axes, and in large plates with the cellular structure of secondary minerals, which plates are probably basal sections of the columnar crystals. The chloritoid, with fibrous chlorite, forms a network, in whose meshes are flakes of colorless muscovite, little grains of epidote, and grains of quartz.

Magnetite grains are scattered everywhere throughout the section. The rock of the second dike differs from that of the first one in being coarser-grained. The chloritoid is developed in large plates whose pleochroism is very marked in greenish-blue and yellowish-green tints. Biotite, muscovite, magnetite, and quartz are included in small quantity in most of the plates, though some of them are entirely free from inclusions of all kinds. Between the plates are little nests of calcite and large irregular areas of plagioclase and its alteration products, chlorite, kaolin, quartz, biotite, and needles of amphibole. The biotite is also present in large flakes of the usual color, and the quartz in large, clear grains, the former mineral being usually in the feldspar and at its contact with the chlorite, and the quartz occurring especially between chloritoid plates.

The talcose-schists are rare. They are limited almost exclusively to the ore horizons, where the processes that have resulted in the accumulation of the ores have at the same time leached the iron salts from schistose diabases and made them talcose-schists instead of chlorite-schists. By further leaching magnesium is removed and the schists become kaolin-schists. Some of the iron salts abstracted from the diabases may have aided in the formation of the ore bodies, but they certainly did not contribute the main bulk of the ore deposits.

The talcose-schists, "soapstones," and "paint-rocks" are varieties of the same rock. They are all talcose-schists, which differ from the chlorite-schists in the fact that their magnesian component is talc rather than a chlorite. The "soapstones" are the almost pure, light-colored phases of this rock, while the "paint-rocks" are varieties that have been colored red or brown by the infiltration of red or brown ocher. Many of these rocks are so much decomposed that little remains to tell their history. The "soapstones" are composed largely of quartz, talc, probably a little sericite, and calcite. Chlorite is also present in most specimens. In some it occurs in but small quantity; in others it is more abundant; while in still others it is present in such large quantities that these rocks must be regarded as linking the purer talcose-schists with the typical chlorite-schists. In other words, there is an unbroken gradation between the talcose-schists and the chlorite-schists. Since the latter are altered diabase dikes, the former are probably likewise altered diabases. The alteration in the two cases is somewhat different, since in the talcose-schists all of the original iron, which in the case of the chlorite-schists was largely retained in the chlorite, has been lost. The talcose-schist dikes are confined mainly to the vicinity of the ore deposits in the soft-ore mines, while the chlorite-schists are less common here than they are in the hard-ore mines, although they are practically universal in their distribution. Evidently the talcose-schists may be looked upon as chlorite-schists from which the iron has been leached by the same process that secreted the ore bodies in their neighborhood.

The "paint-rocks" require but little special mention. The ocherous coloring matter coats the talc fibers and the grains of the other components in the schists, into which it has evidently been introduced since the rocks were transformed into schists. In a few of the "paint-rocks" the coloring matter is magnetite or martite rather than ocher or limonite. The oxide in these rocks occurs as little octahedra embedded in the talc and quartz. It was introduced after the schist became foliated, for its grains are scattered through the rock mass without respect to its foliation, and, so far as has been noticed, they have produced no effect upon the disposition of the talc fibers in their vicinity. There is no bending of the fibers around the larger crystals, as would be the case were these present when the rock became foliated, but they are cut off abruptly by the opaque iron oxide, as though they passed directly through its crystals. Although the greater portion of the magnetite and martite crystals are opaque, on their borders they are often changed to hematite, and little plates of this substance also occur as elongated lenses in the body of the rock. These latter plates appear to be altered forms of a preexisting magnetite. They probably represent little grains of this substance that were present in the original diabase.

There are a few other light-colored schistose rocks that are sometimes met with as dikes cutting the iron-bearing formation. They are not usually distinguishable from the talcose-schists in the hand specimen, and so they have generally been confused with the latter rocks, and have been called by the same names as these, viz, soapstones when light-colored, and "paint-rock" when stained. Under the microscope the fibrous component of these schists is discovered to be kaolin instead of talc. Patton[1] has already described one of these dike masses; so we quote his statements concerning it:

The iron ores in the region around Ishpeming are frequently cut by dikes of diabase so thoroughly altered as to be no longer recognizable except by their dike form. * * *

Under the microscope this kaolin-like rock shows very well preserved the diabase structure * * * , but in place of the plagioclase laths and the augite grains there is a white, earthy substance with interspersed colorless quartz grains, as well as black magnetite. The magnetite presents about the same appearance as in the unaltered rock, and is evidently the only ingredient that has not been altered. A chemical analysis of this rock, made by Mr. Fred. F. Sharpless, shows that it is composed of about 79 per cent kaolin and 20 per cent free quartz (magnetite and impurities amounting to 1 per cent). It appears that in the process of alteration Na, Ca, Mg, and Fe, as well as SO_2, have been removed and H_2O has largely increased.

Patton's description of this kaolin rock applies as well to some of our specimens collected in the district. The rocks are evidently in the form of dikes. They represent the extreme phase of alteration to which the diabases in a few instances have been subjected

It should be remarked, before leaving the discussion of the talc-bearing and other light-colored schists, that there are certain other rocks, found associated with the ores in some of the mines, that resemble very closely the schists that are derived from diabases. These rocks are included by the miners with the "soapstones" that occur as dikes. They are white schists, often interbedded with quartzite and sometimes immediately overlying the hard-ore deposit at the base of the Upper Marquette series. In the field these schists may occasionally be traced into well-characterized quartzites. Under the microscope they are found to be fragmental in structure and to consist of altered and mashed feldspathic quartzites, not very different from some of the finer-grained phases of the Palmer gneisses. Many of them contain considerable quantities of sericite, so that in the hand specimen they possess the same soapy feeling that is possessed by the talc-schists. While very similar in appearance to the true soapstones occurring in dikes, these rocks are not soapstones. They are sericite-schists,

[1] Microscopic study of some Michigan rocks, by H. B. Patton: Report of the State Board of Geological Survey for 1891 and 1892, Lansing, 1893, pp. 185-186.

which may often be distinguished from the true soapstones by the coarse grit in their powder, due to the presence of the fragmental quartz grains.

A small number of the dark-colored dike greenstones of the district are abnormal in that they contain no amphibole. Their original nature has not been made out. As at present constituted they are composed of altered feldspar grains in a mosaic matrix of quartz and plagioclase, containing reddish-brown biotite of the usual kind. Calcite, sericite, kaolin, chlorite, and epidote are mingled with the other components in large quantities, so that the rocks as they now exist consist exclusively of secondary products. These rocks remind one strongly of the less highly foliated varieties of the micaceous schists in the Basement Complex.

CONTACT EFFECTS.

In the field work on the dike rocks extensive and careful search was made for contact effects in the intruded rocks, but the only evidences that were thought possibly to indicate contact action were noted on Mount Humboldt, upon Republic Mountain, and near the Magnetic mine. The Mount Humboldt occurrence is the most characteristic. Here we find cutting the grüneritic schists of the northwest portion of the hill a highly schistose, dark-green chlorite-schist, which on its edges is thickly besprinkled with dodecahedral garnet crystals measuring about 2 mm. in diameter. The grünerite-schists on the other side of the contact are likewise crowded with similar crystals. Other crystals of the same kind, however, are often met with in the schists at long distances from visible contacts with dikes, but never so abundantly. Therefore the unusual concentrations of garnets along the dikes are believed to be due to chemical interactions between the two rocks subsequent to the intrusions.

The chlorite-schist in the middle of the dikes is not essentially different from the chlorite-schists already described. Near the contacts some of the schists contain groups of grünerite needles identical with those in the grüneritic schists. Idiomorphic hornblende crystals are also occasionally observed in them, and magnetite is everywhere present. Fibrous green hornblende is a prominent component, and biotite is abundant, intermingled with the amphibole in some specimens and in others accumulated around the garnets. The garnets are identical in nature with the garnets in the garnetiferous knob greenstones. They are perfectly isotropic. In color they are very light pink, almost colorless. Their principal inclusions are magnetite, but they always inclose also small quantities of chlorite, quartz, biotite, altered feldspar, and often crystals of pyrite and needles of actinolite. In all cases the garnets are crossed by great fracture cracks, which are sometimes so coarse that they give the crystals a granular appearance. In these rocks the garnets, although idiomorphic, appear to be the youngest component present, with the exception of the biotite, which surrounds them peripherally, and which must be regarded as constituting a reaction rim.

Other garnetiferous dike greenstones are more like mica-hornblende-schists than like chlorite-schists. They contain large quantities of quartz, and are thus similar to the quartzitic greenstones of the Republic and Magnetic mines, from which they differ mainly in the possession of garnets. In these latter rocks the garnets are often granulated, as though the rock in which they occur had been mashed after their formation.

From the above description it is noticed that the garnetiferous schists differ from the other schistose geeenstones simply in the possession of garnet and in some cases of grünerite, both of which minerals are found as normal constituents in the grüneritic schists through which the greenstones cut. The inference from these facts is that the garnetiferous rocks are not contact rocks in the usual sense, but that their peculiar features are due to reactions between solutions passing between the intruded and intruding rocks and carrying dissolved salts from the one into the other. Mechanical action may also have been instrumental in the formation of the new products in the schists, but it is not believed that the heat of the dikes was at all effective in their production. The phenomena are believed to be those of metasomatism and of dynamic metamorphism rather than of contact action.

THE SHEETS AND TUFFS.

Only a few undoubted sheet eruptives and a small number of areas of volcanic fragmental rocks have been positively identified in the beds older than the Clarksburg formation. In one or two instances the sheet rocks are thought to be surface flows, while of course the tuffs are always surface rocks. In other cases the sheets appear to be intrusive, where they are with difficulty distinguishable from the dikes. Indeed, while it is believed that by far the greater number of the narrow bands of schistose greenstone associated with the pre-Clarksburg sediments are true dikes, it is thought that a large number of them may possibly be sheets. The distinction between the two, however, is not so important as it would be were the sheets effusive ones.

THE SHEETS.

The undoubted sheet rocks are exposed in a few places on the surfaces or sides of ledges as a series of bands of a fine, crystalline, green rock, sometimes amygdaloidal on both edges, sometimes on one edge only. These rocks are interbanded with genuine sediments, with which they conform in strike and dip. The best exhibition of the bands, which are believed to represent old volcanic flows, is on the little hillock in the NE. $\frac{1}{4}$ sec. 28, T. 47 N., R. 27 W. (Atlas Sheet XXVI), where three greenstone beds are interstratified with graywacke-like quartzites.

Again, in the cut on the Chicago and Northwestern Railway in the NW. $\frac{1}{4}$ sec. 8, T. 47 N., R. 26 W. (Atlas Sheet XXXI), about $1\frac{1}{2}$ miles southeast of Negaunee station, there is an excellent section exposed through seven bands of chlorite-schists that are interleaved with "flag ores." Rominger gives a sketch of the cut in his report,[1] and describes it as follows:

> The strata in the cut form two successive anticlinal arches, which are in two places transversely intersected by wedge-like masses of chloritic schists intruded from below. The upper portion of the ledges is formed of the banded alternating beds of pale brownish jasper and of siliceous ore seams like the jasper-banded rocks of the McOmber mines. * * *

As shown by fig. 18, p. 332, the present authors observed but a single anticline in the schist bands, and discovered portions of seven sheets of the chlorite-schists instead of the two pictured by Rominger. The intersecting "wedge-like masses of chloritic schists" were not seen. Only two of the sheets show the complete fold, but the others are so regularly disposed about the axis of this fold that there can be little doubt that the bands on

[1] C. Rominger, Geol. Surv. of Michigan, Vol. IV, p. 79.

its two sides were continuous over the apex of the anticline before this was removed by erosion. Whether they were surface flows or intrusive sheets is not known, since the rock composing them is a chlorite-schist which has lost all traces of its original structure. It seems probable that these sheets are intrusive, while the amygdaloidal ones described below are effusive.

The few sheet-rocks discovered, like the dike-rocks of the district, were originally diabases or basalts. They are now composed largely of amphibole, chlorite, and altered plagioclase. They are either massive or schistose in structure, with the massive phases porphyritic in texture. Some of the latter are holocrystalline, while others originally possessed a glassy groundmass.

The rocks of the little hillock already mentioned as existing in the NE. ¼ sec. 28, T. 47 N., R. 27 W., originally included both glassy and crystalline phases. In the former the glass which was formerly present in the groundmass has entirely disappeared. It has undergone change into a pale-green chloritic substance. The resulting rock is a dense, green, schistose one, whose mass is speckled with bright, glistening surfaces of plagioclase. In thin section small plagioclase crystals and groups of crystals, some fresh and others changed to calcite, and small flakes of brown biotite, are seen in a groundmass of smaller plagioclases, biotite wisps, tiny amphibole needles, and granules of leucoxene embedded in a fibrous mass of chlorite that is supposed to represent the original glass.

The other sheet-rocks occurring in the same hillock differ from the one just described mainly in the structure of their groundmasses. All of them, whether amygdaloidal or not, possess an altered diabasic groundmass in no wise differing from the rocks that have been called uralitic diabases and epidiorites. The amygdaloids occurring here are dark-green porphyrites, with phenocrysts of plagioclase and hornblende, and amygdules filled with magnetite and calcite in an altered diabasic groundmass speckled with magnetite. Under the microscope the feldspar phenocrysts are discovered to be changed into calcite, and the green groundmass is found to be composed of small plagioclases, pseudomorphs of calcite after plagioclase, green chlorite, and leucoxene, with here and there some epidote and a few grains of magnetite. The nonamygdaloids are like the amygdaloids except that they lack amygdules.

The only essential difference between these sheet eruptives and those occurring in dikes is in their structure, which in the former rocks is porphyritic and in the latter ophitic.

The chlorite-schists interbedded with the iron-formation rocks at the cut in the Chicago and Northwestern Railway are in all respects like the chlorite-schists that have been described as forming dikes.

THE TUFFS.

The tuff deposits among the pre-Clarksburg rocks are not widely spread. So far as known they occur only at two localities, where they are very closely associated with knobs of greenstone. One of these is the western end of the knob near the east quarter post of sec. 20, T. 47 N., R. 27 W. (Atlas Sheet XXVI), and the other is the western end of the northern of the two hills, near the east quarter post of sec. 4 (Atlas Sheet XXV), in the same township. The relations of the tuffs to the massive rocks are not clear at either of these places. In the first locality, however, the tuffaceous beds are cut by large dikes of greenstone, similar to the rock that forms the main body of the hill. The recognition of these rocks as fragmental eruptives is due to microscopic evidence and to the conglomeratic aspect of their weathered surfaces. Light-gray, pebble-like areas appear in a schistose green matrix containing small fragments of altered feldspar and pieces of green schists.

The tuffs are composed of exactly the same minerals as are found in the schistose dike-rocks and other greenstones, but their structure is obscurely tuffaceous. Under the microscope fragments of plagioclase may be seen distributed thickly among the other rock components, and large, rounded and irregular fragments of a fine-grained diabase may be detected here and there embedded in a schistose, hornblendic, and chloritic groundmass. These tuffs are not unlike those occurring in the Basement Complex. They differ from the Kitchi schists mainly in the manner and degree of their alteration.

SECTION II.—THE POST-CLARKSBURG GREENSTONES.

The freshest of the igneous rocks of the Marquette district are those which constitute the independent dikes that have already been mentioned as being in all probability the youngest dikes in the entire area, because they cut indifferently the larger dikes of altered diabase and all the formations of both the Upper and the Lower Marquette series, and because they are only locally schistose.

Most of these younger rocks exist as well-defined dikes with sharply marked walls, although in several instances they occur also as boss masses. They are found as dikes in the Basement Complex on Light-House Point (Atlas Sheet XXXVIII); in the Lower Marquette series, cutting the quartzites and marbles southwest of Lake Mary, in T. 47 N., R. 25 W. (Atlas Sheet XXXVII); in the iron-bearing formation at many of the mines; and in the Upper Marquette series in the Ishpeming and Michigamme formations, especially in the western portion of the area mapped. They are even more abundant still farther west, in the slates between Michigamme and L'Anse, beyond the limits of the map.

The boss masses of these younger greenstones are rare so far as the area under discussion is concerned. The most typical occurrence is that of the knob in secs. 35 and 36, T. 48 N., R. 30 W. (Atlas Sheet VIII), on the shore of Lake Michigamme.

PETROGRAPHICAL CHARACTER.

Petrographically these greenstones are aphanitic to medium-grained, dark-gray or black basic rocks, in which secondary products may be abundant, but in which the original structures are well preserved. As has already been indicated, these rocks are scarcely ever schistose, in which respect they are sharply contrasted with the greenstones of pre-Clarksburg age. They are massive rocks that resemble strongly some of the dike and sheet rocks of the Keweenawan series on Keweenaw Point, and hence they have been thought by Lane to be the lower portions of the Keweenawan eruptives, in the same way that the pre-Clarksburg intrusives are regarded as the lower portions of the Clarksburg greenstones.

The principal lithological types recognized among the younger greenstones are diabases, porphyrites, and basalts. The diabases are sometimes nonolivinitic, but more frequently they contain olivine in different stages of alteration, and often small quantities of quartz, usually in micropegmatitic intergrowths with feldspar. The porphyrites are mainly diabase-porphyrites in which plagioclase is the principal if not the only phenocryst. The basalts differ from the diabases in the possession of a distinct groundmass.

QUARTZ-DIABASES.

The most characteristic of the younger greenstones are those that have been called quartz-diabases by Lane.[1] They are more frequently found west of the area discussed in this monograph than within it, though an excellent representative of the type is the rock constituting the mass of the knob on the shore of Lake Michigamme. In his descriptions of these rocks Lane states that they—

are always massive, and of a dark, black, or brownish gray color with white specks of glassy, more or less lath-shaped feldspar that shows with a pocket lens twinning lines on the cleavage faces. In the thin section we see that the other components are magnetic iron ore and a brown augite that has more or less of a violet tinge. All these components have at times their own crystalline shape, and the interstices between them I have called acid interstices. They are similar to those described by A. C. Lawson (American Geologist, 1891, Vol. VII, p. 153) from the Rainy Lake region. Where augite comes in contact with these interstices it is coated with a dark-brown hornblende like basaltic hornblende and utterly unlike uralite. When feldspar adjoins them we can tell by its optical properties that from being at the center a lime-soda feldspar, like labradorite, the soda more and more predominates as we go toward the margin, until at the margin we often have growths springing out, to form with the quartz what is known as micropegmatite. These growths sometimes fill the whole remaining space. At other times there is some quartz in compact grains. Another curious feature of these interstices is that they are often crossed in all directions by needles of apatite. * * * Folia of biotite often occur in the interstices near magnetite, sometimes evidently derived from it.

These interstices occur in their most characteristic forms in the freshest rocks, and their structure can not be due to weathering nor to pressure, for it occurs in rocks which show no trace of pressure. It seems * * * that when the rock consolidated there were left interstices filled with hot alkaline water or dissolved water-glass,

[1] Report of the State Board of Geological Survey for the years 1891 and 1892, Lansing, 1893, p. 177.

which was probably the last residue of the lava. * * * Into these interstices the apatite needles grew, and the alkaline solution attacked the augite and magnetite, turning them into brown hornblende and mica. Finally the heated solution cooled, depositing the quartz and feldspar. * * *

* * * Olivine, or its alteration product, serpentine, may often be observed microscopically as an occasional accessory, especially in marginal forms, but is seldom abundant enough really to characterize the rock, and certainly is not characteristic of the group as a whole.

The rock of the knob in secs. 35 and 36, T. 48 N., R. 30 W. (Atlas Sheet VIII), corresponds very closely in the main with Lane's description except that no olivine has been detected in the few slides made from it. The augite, moreover, is more or less altered into green amphibole and chlorite, and the cleavage cracks in the plagioclase are lined with the latter mineral. It is also noticed that large crystals of titaniferous magnetite occur amid the interstitial substances Since this mineral is one of the oldest, if not the oldest, in the rock, its presence among the interstitial substances may indicate that these have not in all cases the origin ascribed to them by Lane.

Another variety of rock from this knob exhibits a different structure from that described. In a few specimens the augite is in idiomorphic grains and the magnetite in large skeleton crystals. In more altered forms quartz is present as large grains occupying the centers of the interstitial spaces, and surrounding them are beautiful feathery growths of granophyric quartz and feldspar. In other cases the granophyre extends from a nucleus of plagioclase, or forms a zone around plagioclase laths, while again its areas possess the outlines of feldspar crystals. If the granophyre represents an acid base, then the interstices in these specimens occupied a greater volume than did the solid portions at the time the micropegmatite began to form. It would seem probable that some of the granophyre at least is secondary.

OLIVINE-DIABASES.

Some of the quartz-diabases, as Lane observes, contain olivine in small quantity. There is another class of dike-rocks, however, in which olivine is an important component. These are fresh, heavy, basaltic-looking rocks, which under the microscope appear as very fresh olivine-diabases.

Occasionally their olivine is changed more or less completely into a green, earthy decomposition product, which extends out from the olivine grains and fills cracks in the neighboring plagioclases, which are usually quite fresh. These rocks present no unusual features. They are typical olivine-diabases. The best example of the type is found on Green Island, in Lake Michigamme, situated in the SE. ¼ sec. 27, T. 48 N., R. 30 W. (Atlas Sheet VIII.)

PORPHYRITES.

The porphyrites differ from the olivinitic diabases and the quartz-diabases in the absence of quartz and olivine and in the presence of porphyritic plagioclases. These rocks resemble the porphyritic phases of the older greenstones, from which, however, they are distinguished by their greater freshness and by the retention of their typical porphyritic structure.

Although all the porphyrites are, on the whole, so very much fresher than the pre-Clarksburg greenstones, they nevertheless show some alteration. Their principal alteration products are those characteristic of weathering processes. Decomposition products resulting from dynamic processes are rare, except along local shear zones within the masses of the dikes and along their borders. When much altered the rocks do not differ greatly from the older greenstones in the eastern knobs, except that their original structure is so much better preserved that it can nearly always be observed in the hand specimen.

A single section made from a specimen collected from a dike cutting the rocks of the iron formation in one of the pits of the Jackson mine, in the SE. ¼ sec. 1, T. 47 N., R. 27 W. (Atlas Sheet XXVIII), is enough different from the types described above to deserve mention. The rock is apparently a porphyritic diabase. In the hand specimen it shows white plagioclase groups in a dark-gray groundmass that is cut by small, almost silky, white fibers. Under the microscope the section shows only fresh plagioclase, magnetite, and olivine. The plagioclase is in the usual lath-like forms, which are very small in some portions of the section, and in others are grouped together into large complex aggregates. These latter constitute the larger white areas seen in the hand specimen, while the small isolated crystals are the tiny fibers. Many of the feldspars are zonal, with cores of altered and reddened plagioclase, surrounded by perfectly fresh material. The magnetite is the most interesting component. It occurs in the ophitic spaces between the plagioclases, and is apparently all, or nearly all, a decomposition product of augite or of olivine, remnants of which have been left in its mass. No traces of the latter mineral have been detected in the section, but from the shapes of some of the magnetite areas it is thought very probable that pyroxene was once present in the rock. The complete substitution of augite and olivine by magnetite is unusual in rocks of this character. The processes to which the substitution is due in the present instance were probably related to the processes that gave rise to the ores.

BASALTS.

The rocks that have been referred to as basalts are rare. They constitute well-defined dikes. In the hand specimen they are dark, dense rocks, occasionally dotted here and there with small white spots consisting of plagioclase. Under the microscope plagioclase laths, magnetite grains, and small spicules of augite are detected in a glassy groundmass, which is often filled with green alteration products, and sometimes almost entirely replaced by these substances.

SUMMARY.

The igneous rocks occurring in the Marquette series are all basic, with the composition of fresh or altered diabases of various kinds. They occur as dikes, bosses, sheets, and tuff beds. An association of sheets and tuff beds is found to constitute a well-defined horizon in the Upper Marquette series. These rocks, called the Clarksburg formation, have consequently been separated in the discussion from the other igneous rocks. The remainder of the igneous rocks, which may be classed together under the convenient and noncommittal name of greenstones, have been further divided into two classes. In one of these are placed all the greenstones associated only with rocks older than the Clarksburg formation, and in the other those associated also with the beds younger than this formation.

Among the pre-Clarksburg greenstones dikes and boss masses are common, while sheets exist to some extent, and tuffs are rare. The dikes and boss masses are very similar in the nature of their material. Both comprise schistose forms of diabase, in which all, or nearly all, of the augite has been changed to green hornblende. Along the peripheries of the boss masses and throughout many of the dikes the rocks are very schistose. They have likewise suffered great changes in composition, and are now often chlorite-schists or talc-schists

In the eastern portion of the area nearly all the boss greenstones have the characteristics just mentioned, but in the western bosses the rocks have suffered a different change. In addition to the green hornblende, there have been formed considerable quantities of quartz and not a little brown biotite. These rocks have also suffered much more dynamic metamorphism than have the eastern ones. They resemble in many respects the micaceous hornblendic schists of the Basement Complex, and thus furnish additional evidence in favor of the view that these rocks are squeezed eruptives.

Of the sheet greenstones, a very few seem to have been surface flows. Others were intrusive sills. Only a few instances are known in which the existence of the latter forms of greenstone may be shown to be probable, although it is believed that many other cases of intrusive sills occur in the Lower Marquette series. They have escaped detection, however, since their material is similar to that of the dikes, and in a district of complicated stratigraphy it is almost impossible to distinguish between dikes trending with the strike of the sedimentary beds and flows interleaved with these beds.

The tuff beds, in the few cases noted, are associated with knobs of nearly massive greenstone.

Since the material of the pre-Clarksburg greenstones is similar to that of the Clarksburg rocks, and since the former do not occur in beds younger than the Clarksburg formation, it is inferred that they are the lower portions of the flows, tuffs, and associated greenstones that constitute the Clarksburg formation.

The post-Clarksburg greenstones comprise only dikes and bosses. The rocks, while more or less altered, are all much fresher than the older greenstones, and all of them have preserved distinct traces of their original structure. These greenstones cut all the rocks of the Basement

Complex and the Marquette series. They are in the main nonfoliated, even where the rocks into which they are intrusive are well-characterized schists. For these reasons they are separated from the older greenstones, and because they are very similar to the basic rocks of the Keweenawan series on Keweenaw Point they are thought to be the equivalents of some of the Keweenawan eruptives.

These greenstones comprise olivine-diabases and quartz-diabases, porphyrites, and basalts. Of these the porphyrites are most like the older greenstones, from which they are distinguished by clear-cut and well-preserved porphyritic structure. The basalts are like modern basalts, except that their groundmass is always much altered. The olivine-diabases are typical rocks of this class. The quartz-diabases are peculiar in that they contain a little olivine and sometimes a large quantity of quartz, which occurs in micropegmatitic intergrowths with plagioclase.

None of the larger masses of the greenstones of the older or the younger kinds are in the form of great interbedded sheets, as has been stated to be the case by the earlier geologists. The sheets that do occur are thin, and, so far as known, they are not continuous for long distances, nor do they appear to occupy any distinct and definite horizons in the bedded series outside of the Clarksburg formation.

CHAPTER VI.

THE REPUBLIC TROUGH.

BY HENRY LLOYD SMYTH.

INTRODUCTION.

The Republic syncline (Atlas Sheets IV, VII, X, and XI) is sharply marked off from the rest of the Marquette district by the simplicity of its structure and by the fact that the folding has taken place about an axis which strikes northwest and southeast, or in a direction considerably inclined to the general course of the great Marquette synclinorium. The Republic syncline is thus transitional to the north-and-south type of structure that prevails beyond it to the west over three townships, and to the south as far as the Felch Mountain trough, in T. 42 N. The Republic area proper begins near the south end of Lake Michigamme and continues southeast to the northwest sections of T. 46 N., R. 29 W. As thus defined, it is a simple syncline in Algonkian rocks, about 7 miles in length, with nearly parallel sides from one-half to 1 mile apart; on both sides and at the southeast end it is inclosed by Archean rocks, while at the northwest end it rather suddenly flares out into the main Marquette synclinorium.

To the northeast it is separated from the southern boundary of the main Marquette trough by an area of Archean granite and gneiss about 6½ miles broad. To the west and southwest about half this distance, over similar Archean rocks, divides it from the next narrow Algonkian syncline. While the general direction of the main Marquette fold is nearly east and west, the fold is constricted on a section through the Champion mine, where it is only 2 miles wide, and its southern boundary has a northwestward trend, to which the Republic fold is very nearly parallel.

The topography is as simple as the structure. The Michigamme River, on entering the syncline about 1 mile south of Lake Michigamme, flows through the trough nearly to its southeastern end, mainly over the upper members of the bedded series. The river valley substantially coincides with the bedded rocks. East and west it is flanked by Archean uplands, consisting of rounded granite knobs of characteristic glacial and disintegration forms, often bare or covered with a thin drift mantle. In the immediate neighborhood of the southeastern termination of the trough the river first swings to the east into the eastern granite wall, and then returns to the southwest, occupying a large part of the interior of the trough in the structurally determined expansion of Smiths Bay, and finally leaving it on the western side, about three-quarters of a mile northwest of its southeastern end. Within the general topographic depression bounded by the Archean areas the bedded rocks and the greenstone intrusives within them occasionally form considerable elevations, none of which, except Republic Mountain itself, reaches the average height of the granite uplands.

The rocks of the Republic area consist of (1) granites, gneisses, and crystalline schists, which form the basement upon which the iron-bearing series were laid down; (2) quartzites, mica-schists, and ferruginous schists, of both Lower and Upper Marquette age; and (3) later igneous intrusives.

SECTION I.—THE ARCHEAN.

The granites, gneisses, and crystalline schists here constitute the unclassified Archean. These rocks have been studied only incidentally near their contacts with the iron-bearing series, and chiefly from the point of view of their structural relations with the latter. It appears that of the three kinds of rocks into which the Archean may be divided the granites are by far the most common. These are usually normal granular rocks, made up of orthoclase and microcline, plagioclase, quartz, light and dark colored mica, and often hornblende, with the usual accessory minerals. Often the orthoclase is present in large porphyritic Carlsbad twins, which sometimes attain a length of 2 inches. This coarse-grained granite is the prevailing type at Republic. It weathers light-gray or white, sometimes with a marked red tinge. The constituent minerals show no parallel arrangement.

Of gneisses, properly so called, none have been found in the Republic area except those that have unmistakably been derived from the normal granite by dynamic metamorphism. These are best seen in the immediate neighborhood of the contacts with the overlying series, and they are so characteristic of these contacts that where gneissic foliation is present the contact may confidently be looked for close at hand. This gneissic structure is largely due to the development of mica, usually muscovite, along surfaces of breaking which, while individually irregular and waving, yet in the aggregate are distinctly parallel in strike and dip to the contact surface and to the bedding planes in the overlying sediments.

The gneissic structure is most strongly developed at the contact. In departing from the contact it diminishes by degrees, and finally, at distances which usually do not exceed 200 feet, it disappears altogether or is found only in narrow, irregular, and discontinuous zones. That this structure is really due to the processes of dynamic metamorphism acting on the normal granite is evident both from observation in the field, where it may be seen in all stages of development, and also in thin sections, where it is clearly proved to result from granulation of the original quartz and feldspar, and the passing over, in some cases partial and in others complete, of the latter into quartz and into the new light-colored micas, which are orientated with the directions of fracture.

In the Archean areas are found certain dark-colored hornblende-schists and amphibolites. These occur usually in narrow bands and are exceedingly variable in the degree of schistosity which they exhibit and in crystalline character. Some, at least, are without question old dikes, originally diabase or diorite, in which a parallel arrangement of new minerals has, with more or less completeness, been effected by dynamic metamorphism. In many cases the progress of these changes may be traced from a massive crystalline interior into nearly perfectly foliated zones at the walls. In other cases the schists are completely crystalline throughout, and these bear no evidence of their igneous character. In age these schists doubtless vary enormously. Some have furnished pebbles to the basal conglomerate of the Lower Marquette series, and these pebbles are as thoroughly crystalline and schistose as any of the schist bands that can now be found in the Archean areas. Others are almost certainly younger than the Upper Marquette sediments, and are genetically connected with the great intrusions of diabases which are found abundantly in this series.

In one locality south of the Magnetic mine a dike of fine-grained red granite was found cutting the ordinary coarse gray granite. No other clear proof of the existence of younger intrusive granites was found in the Republic area proper.

SECTION II.—THE LOWER MARQUETTE SERIES.

The bedded rocks of the Republic area belong to two unconformable series of Algonkian age. The lower of these, to which the name Lower Marquette series has been applied, consists of two distinct members, a lower fragmental member of small thickness, probably not exceeding 100 feet, and an upper iron-bearing member, which in its maximum development, including intrusive greenstones, can not be less than 1,500 feet in thickness. The lower member, from its usual lithological character, is known as the Ajibik quartzite, while the upper member, from its constant ferruginous character, may be distinguished as the iron-bearing member or Negaunee formation.

THE AJIBIK QUARTZITE.

The lower member of the Lower Marquette series in this part of the district is relatively a weak rock, and as its thickness is small it rarely outcrops above the glacial mantle in the Republic area. At the present time but seven or eight localities are known. These are, however, so widely distributed over the area that it is very probable that the lower member is present wherever the Lower Marquette series is represented at all. In these exposures the rock usually appears as a white quartzite, sometimes vitreous, but often of an opaque white color from the large amounts of contained muscovite or sericite. The mica is frequently present in such abundance that the rock becomes properly a mica-schist. In only one known locality, in which it is found to rest in direct contact upon the Archean, does it appear as a coarse conglomerate made up of recognizable fragments derived from the underlying granites and crystalline schists.

In thin sections the various phases of this member are seen to be eminently crystalline. The vitreous varieties consist mainly of interlocking areas of quartz, within and between which are plates of light and dark mica and, less often, of chlorite. Magnetite and garnet are more rarely seen, and nearly complete the list of contained minerals. In the more schistose varieties the mica is more abundant, and occurs in long plates which have a parallel physical orientation. In none of the many slides that have been studied do any feldspar grains appear, nor has a trace been detected of the outlines of original rolled grains. These have been obliterated in the course of the profound changes through which the rock has passed since its deposition, and the feldspar of the original granitic débris is now doubtless represented by the light micas and secondary quartz.

In many cases the larger structures of the original rock have survived. Faint color banding and alternations in texture and composition parallel to the original deposition planes are often seen, and in one locality a beautiful false bedding can be distinctly recognized.

THE NEGAUNEE FORMATION.

The iron-bearing formation is not generally exposed in the Republic area, except at the extreme southeastern end of the syncline, where magnificent outcrops extend from the old Kloman mine in the SW. $\frac{1}{4}$ sec. 6, T. 46 N., R. 29 W., almost entirely around the horseshoe, through a large part of sec. 7 (Atlas Sheet XI). Within this area of nearly a square mile, which comprises Republic Mountain, there are small portions only of the interval between the Ajibik quartzite beneath and the Goodrich quartzite above that are not somewhere represented by outcrops. The rock of the iron formation has many phases, but consists essentially of finely crystalline quartz, a pale-green radiating amphibole which has been determined to be grünerite, and the iron oxides. Within this area the iron-bearing member has been divided by intrusive masses of diorite mainly parallel with the stratification planes, and near the contacts with these it frequently carries large amounts of red garnet. The three chief constituents of this rock are not always present. Two, or even one, may predominate to the partial or nearly entire exclusion of the rest. So the rock is found in certain phases to be made up mainly of quartz and grünerite, or of quartz and iron oxides, or of grünerite and iron oxides. The iron oxides, too, may be either magnetite or hematite. These mineral constituents are arranged in very distinct narrow bands which are parallel to the upper and lower bounding surfaces of the rock. The bands are not wholly regular, nor are they continuous for great distances. They thicken and thin, taper out, and break joint. It is certain that none of the minerals which now make up the rock are original, and that the parallel banded structure signifies that the processes of metamorphism through which it has reached its present constitution were controlled by a primary bedded structure.

The variations in external appearance produced by these considerable variations in composition are great. These variations are not wholly irregular, and it is possible to distinguish in the different phases a definite distribution through the iron-bearing member, which holds good within the limits of the Republic area. The lower portion of the formation is, on the whole, characterized by the presence of grünerite and gray or dark-colored quartz with magnetite, while the higher portion is characterized by the almost complete absence of grünerite and by the presence of specular hematite and red quartz or jasper, which owes its color to the intimate mixture of the little particles of hematite with the quartz. The study of the western portion of the Marquette area alone would probably justify, on the basis of difference in composition and external appearance, a division of the iron-bearing member into two distinct formations, a lower grünerite-magnetite-schist member and an upper specular jasper member.

In the Republic area magnetite also increases in amount in going from lower to higher horizons, while grünerite decreases, so that just beneath the specular jasper the iron-bearing member is mainly made up of bands of exceedingly fine grained magnetite alternating with bands of dark to black quartz, the color of which is due to the presence of a large amount of included magnetite.

Under the microscope the chief interest centers in the question of the nature of the quartz, whether it is partly or wholly of fragmental origin.

In the study of the slides no evidence has yet been found that any of the quartz is fragmental. Here and there traces are seen of an original oölitic structure, such as is so beautifully shown in the more modern and less altered iron formation of the Mesabi range. In the Michigamme jasper of the Menominee district, which is regarded, on stratigraphical grounds, as the equivalent of the Lower Marquette iron formation, an original oölitic and concretionary structure is common.

The question of the nature of the rock from which the iron-bearing member has been derived is fully discussed by Professor Van Hise elsewhere in this memoir. Whether, as seems probable, the various phases which the iron-bearing member now presents have been derived from a single original rock of sensibly uniform character or not, it is very evident that much of the differentiation is of long standing and occurred before the Upper Marquette transgression. That this is so appears from the presence of pebbles from both the magnetite-grünerite-schists and the specular jaspers in the basal conglomerate of the Upper Marquette series. In the Republic and adjacent areas at least, the specular jaspers occur at a definite stratigraphical position in the highest horizon in the Lower Marquette series. They are present only in those places where large thicknesses of the lower series remain, as at Republic Mountain and in the range along the northwest side of Lake Michigamme. Where the lower series has been more deeply eroded before the deposition of the Upper Marquette rocks the specular jaspers are far less continuous and of less common occurrence than the magnetite-grünerite-schist phases of the iron-bearing member. These facts appear to bear strongly against the view that the specular jaspers are due to later metamorphic processes which acted along the contact with the Upper Marquette quartzite after the latest folding, while they are what would be expected if these two chief phases existed in substantially their present condition before the Upper Marquette series was laid down.

Another fact is also significant. It has been said that the grünerite, quartz, and iron oxides of the iron-bearing member have a very distinct banded arrangement and yet are not original minerals, and that this banding is parallel to the upper and lower boundaries of the formation. It is probable that a set of parallel structural planes has controlled the segregation of the present constituent minerals during the changes through which the rock has passed, and that these planes must have been original bedding planes. As the parallel banding is confined to this one direction, it is certain that during its development no other system of parallel planes existed in the rock. The last severe folding, which has determined the larger structural features of the Marquette district, has also affected the rocks in a more intimate way. In certain localities strong minor, even minute, crenulations have been produced, and also parallel cleavage, which sometimes traverses the banding of the rock at right angles. The little folds are often broken and faulted and the siliceous bands reduced to fragments. Along the parallel cleavage planes movement has often taken place, as is shown by the displacement of a particular band on the two sides. Along this secondary cleavage, which dates from the period of general folding after Upper Marquette time, no great development of new minerals, except the iron oxides, has taken place, while the displacement which the minute faulting has caused in the banding conclusively proves that this structure was present before the folding.

From these various lines of evidence, from the apparently definite stratigraphical position of the two main varieties of the iron-bearing member, from the presence in the upper conglomerate of pebbles of all the various kinds of rock which are now found in the iron-bearing member, and from the mechanical effects which the last folding has produced in the banded structure, it seems beyond question that the iron-bearing formation had essentially its present character at the time when the Upper Marquette series was laid down.

CONTACTS BETWEEN THE LOWER MARQUETTE SERIES AND THE ARCHEAN.

It has already been said that the Ajibik quartzite has been foand in only a few places. The contact between this rock and the Archean is almost everywhere drift-covered, and actual juxtaposition has been found in but two localities. The evidence at one of these as to the relations between the two series is very clear and convincing.

In the eastern part of the NW. ¼ of the NE. ¼ sec. 18, T. 46 N., R. 29 W. (Atlas Sheet XI), is a large outcrop of the quartzite, which was discovered by Pumpelly and Credner in 1867. The locality is at the extreme southern end of the Republic syncline. A short distance southwest of the quartzite is a ridge running northeast, made up mainly of granite. Near the southwest end and on the northwest side of this ridge, which has a steep northwest slope, is found, lying upon the granite, a northwesterly dipping fringe of conglomerate which extends some 50 feet along the strike as a continuous rock mass, and occurs besides in occasional disconnected patches farther north on the sloping face of the hill. The granite is of the usual gray variety, and carries large orthoclase crystals up to 2 inches in length.

The conglomerate consists of pebbles of granite, quartz, and black hornblende-schist embedded in a matrix of quartz and mica-schist. The cement is distinctly color-banded, the bands being parallel to the contact surface. They are thrown into small folds about axes which pitch northwesterly in the direction of the dip of the rock. The pitch is closely parallel both with the axis of the main Republic fold and with a pronounced parallel cleavage which affects the overlying grünerite-magnetite-schists, the conglomerate cement, and also the underlying granite for a considerable distance back from the contact. The granite pebbles vary in size from a fraction of an inch up to 5 feet in diameter, and are unmistakably water-rounded. The larger are comparatively thin slabs, lying with their flat sides in the bedding of the matrix which often follows around the inclusions. The granite of the pebbles is lithologically identical with that of the main mass on which the conglomerate rests.

The contact itself is very definite. Between the undoubted conglomerate above and the undoubted granite below is a narrow zone, a few inches wide, of schistose material, which probably represents a shear zone affecting both rocks, due to movement along the contact during the folding. At the north end of the main outcrop a large mass of granite is traversed by thin seams of the conglomerate, one of which tapers to a point at one end and connects with the main body of conglomerate at the other. It is impossible to avoid the conclusion that this represents an original crack in the somewhat irregular surface upon which the conglomerate was laid down, into which the finer sand and pebbles were washed.

The facts at this contact can only be interpreted as signifying that the gray granite upon which the conglomerate now rests existed in its present condition at the time that the conglomerate was laid down, that it supplied a large part of the materials out of which the conglomerate was built, and furnished the basement upon which it was deposited. In short, the contact is one of erosion, the conglomerate is a basal conglomerate, and the facts indicate an important time-break at its base.

At the other locality, in sec. 7, T. 47 N., R. 30 W. (Atlas Sheet VII), a short distance south of the Magnetic mine, the evidence is not so clear. Between the undoubted granite and the iron-bearing member is a considerable interval occupied by banded gneisses and mica-schists, which certainly include part of the horizon of the lower quartzite, but how much it is impossible to determine. Some of the gneisses and schists have evidently been derived in place from the granite, through shearing parallel to the contact; others seem clearly to be metamorphosed sediments in which it is possible to detect here and there traces of the larger quartz pebbles. But between them there is a considerable interval of somewhat similar gneisses and schists the origin of which is wholly indeterminate. The facts here are quite in harmony with the view that the contact is an erosion contact, although they do not give it direct support.

The two contacts, therefore, at which direct juxtaposition is found justify the conclusion that the relations between the Lower Marquette series and the Archean are those of an erosion unconformity, that the Archean in its present form is the older, and that a considerable interval of time elapsed between the formation of the Archean rocks and the deposition of the Ajibik quartzite.

The lithological character of the Ajibik quartzite, wherever it is found, must be taken as corroborating this conclusion. It will be remembered that this rock is composed of quartz with variable proportions of light-colored mica, muscovite, or sericite as essential constituents. These micas have probably been derived from the alteration of original orthoclase or microcline, feldspars characteristic of the Archean granites, of which the quartzite otherwise shows now no traces. The quartzite was then probably a feldspathic sandstone, composed of granitic débris such as the breaking down of the adjacent underlying granite would unquestionably furnish. The persistence of its lithological character and the fact that it is always found in close proximity to granite, the disintegration of which would have supplied all of its essential constituent minerals, certainly raise a strong presumption that such actually has been its origin.

SECTION III.—THE UPPER MARQUETTE SERIES.

In the Republic area proper only the lower member of the Upper Marquette series, the Goodrich quartzite, is well exposed. This is, in the main, a white quartzite, usually massive and heavily bedded near the base and passing upward into the mica-schist of the Michigamme formation. At the base, conglomerate layers occur, in the pebbles of which all the underlying rocks are abundantly found. The conglomerates, while usually unimportant, are represented in great volume at the south end of the trough, where they are beautifully exposed by the extensive mining operations about Republic Mountain. In these conglomerates the great majority of the pebbles have a local origin, being derived from the rocks upon which the conglomerates directly rest.

Under the microscope the Goodrich quartzites and quartz-schists show a decidedly less degree of metamorphism than do the Ajibik quartzites. Roundish grains of feldspar, usually microcline, derived from the underlying granites, are plentiful, and the quartz areas often exhibit distinct indications of original rolled nuclei. In the quartz-schist and mica-schist, into which the more massive quartzite usually passes upward, certain definite layers of a darker color are often distinguishable, in which iron oxides, usually magnetite, abundantly occur. In these layers false bedding is often strongly brought out, and it is believed that the iron oxides are in large part original sediments.

The Goodrich quartzite is, on the whole, the thickest rock in the Republic area, and, by reason of its volume and character, that which most frequently outcrops.

The Michigamme schist occupies the center of the tongue, and, because less resistant than the inferior formations, the Michigamme River does not wander far from its borders. In most respects this schist is similar to the remainder of the formation elsewhere, and therefore will not be further considered here.

CONTACTS OF THE GOODRICH QUARTZITE WITH THE LOWER MARQUETTE SERIES AND WITH THE ARCHEAN.

Direct contacts of the quartzite which forms the base of the Upper Marquette series with the underlying rocks are very numerous, and the evidence in detail, as well as the more general facts, leaves no room for doubt that this quartzite was laid down on a deeply eroded surface and that the relations are those denoting a most profound time-break.

The detailed facts, which may be observed on the exceptionally fine exposures about Republic Mountain, are these: (1) There is a slight but very persistent discordance in stratification—more evident at any single locality in dip than in strike—between the Goodrich quartzite and the underlying formation of the lower series. This difference in dip is on the average not far from 15°. (2) The basal conglomerate of the upper series is crowded with fragments of the iron-bearing member upon which it lies. These fragments are often of large size and imperfectly rounded, and evidently have not moved far. The included fragments at the immediate contact are almost wholly from the subjacent formation, and from their often irregular shapes and great preponderance might frequently be mistaken for the products of brecciation, if it were not for the sparse presence in the conglomerate cement of quartz and feldspar derived from the more distant granites. (3) The structural details of the contacts prove unconformity. The layers of the underlying iron formation are often for short distances traversed at large angles by the contact surface. Extending back into the mass of the iron formation cracks are occasionally found into which the fine material of the conglomerate cement has sifted. Finally, in the conglomerates in the lower member of the upper series pebbles of all the underlying rocks are seen, from the Archean to the top of the Lower Marquette series.

The more general facts of the relation of the Upper Marquette series to the underlying rocks may be summed up in the statement that within the narrow limits of the Republic area the upper series rest, in one locality or another, on each of the older formations (Atlas Sheets IV, VII, X, and XI). The maximum thickness of the Lower Marquette series is found at

Republic Mountain. In going north from Republic Mountain on the east side of the fold the lower series is progressively and rather slowly cut out, so that at the old Chippewa exploration, in sec. 22, T. 47 N., R. 30 W., the Goodrich quartzite rests directly upon the Archean. Thence northward, and eastward almost to the Champion mine, the lower series probably does not again emerge.

On the west side of the fold the lower series is entirely gone on the west side of the river, opposite the Republic mine, and the Goodrich quartzite rests directly on the granite. It reappears to the north only in patches, once at the Standard location, possibly again at the Metropolitan, and again at the Erie. Beyond the Erie it appears again and continues beyond the Magnetic mine and the limits of the area now described.

The evidence, which it is not thought necessary to present here in greater detail, is thus conclusive, and settles beyond the possibility of question that between the deposition of the Lower Marquette series and that of the Upper Marquette series an interval of time elapsed during which the lower series was elevated, folded, probably metamorphosed, and deeply denuded. This break in continuity of deposition between the two series lasted sufficiently long to permit the removal in many places of the entire Lower Marquette series and a deep gnawing into the Archean. The present uneroded thickness of the Lower Marquette series on Republic Mountain is at least 1,500 feet. How much in all was removed by erosion before Upper Marquette time there is no means of knowing. Fifteen hundred feet of Lower Marquette strata, with an unknown thickness of Archean, is the minimum amount taken away in the Republic area. The time-break in the Marquette district is far less impressive than that below the upper series on the north shore of Lake Superior (with which, indeed, we do not know that it was conterminous), because the earlier folding on the south shore was less severe, while the later folding, which followed Upper Marquette time, was far more severe than on the north shore; and hence the structural discordances and the differences in degree of metamorphism between the two series are less pronounced. But the conviction remains that this is one of the great breaks in the geological record.

SECTION IV.—LATER IGNEOUS INTRUSIVES.

These are the diorites of Brooks, and they occur in great abundance in both the upper and lower series. They are dark-green to black, often coarsely crystalline rocks, composed essentially of green hornblende, biotite, and plagioclase, and doubtless were originally diabases. They occur in sheets intruded parallel to the stratification of the bedded rocks, in dikes, and in irregular bosses. The great regularity of some of the intruded sheets, such as those on Republic Mountain, is remarkable, and led Brooks to regard them as regularly interbedded and continuous members of the stratified series. Close examination, however, shows that even here they often really traverse the banding of the iron-bearing member at small angles or in steps. In one case a dike several feet wide was found to leave the main sheet and to cut the structural planes of the inclosing jasper at an angle of 45°. In the immediate neighborhood of the ore deposits bodies of so-called soaprock are found, which have in many cases intrusive relations to the iron-bearing member. At Republic it was not possible to follow these soaprock bodies in any instance into a rock which retains traces of an original crystalline structure, but at the Champion mine exactly similar soaprock, occurring in similar relations to the ore, in several instances was found to run into typical diorite.

In age, many, probably most, of these rocks are younger than the Upper Marquette sediments. Some, however, penetrated the Lower Marquette series before Upper Marquette time. In sec. 23, T. 47 N., R. 31 W., the basal conglomerate of the Upper Marquette series is seen to rest upon and to hold numerous fragments of an old diorite. Within the Republic area no surface eruptives have been seen in either the upper or the lower series.

SECTION V.—GENERAL GEOLOGY.

All the rocks of the Upper Marquette and Lower Marquette series have been closely folded in the Republic area into a syncline the axis of which runs about northwest and southeast. The present fold for most of its length is sunk deeply into the Archean, and the axis is practically horizontal. Southeast of Smiths Bay, however, the axis rises with a pitch of nearly 45°, the several formations swing around successively in horseshoe form through an angle of 180° from the northeastern to the southwestern side, and the fold, so far as it affects the Algonkian rocks, abruptly terminates. Through the greater part of the length of the trough the rocks on the two sides of the axial plane have been squeezed nearly into parallelism. None of the many surface observations show in the Ishpeming quartzite a dip less than 80°. The formations in the underlying Lower Marquette series dip at a uniformly higher angle on the eastern side, being either vertical or slightly overturned toward the west, while on the western side, owing to the absence of the lower series for much of the way, observations are rare, but a similar divergence in dip is found in two or three places.

If the base of the Goodrich quartzite be developed into a horizontal straight line along any cross-section (thus approximately restoring the conditions to what they were before the last folding), it will be seen that the rocks of the underlying lower series on the two sides of the trough dip toward each other (Atlas Sheet XI, secs. A′A′ and B′B′). This convergence in dip along a developed section points clearly to the existence of a gentle syncline in the Lower Marquette series before Upper Marquette time, within the limits of the rocks included in the present fold. The very slight discordance between the strikes of the members of the two series, which, broadly regarded, is measurable in feet per mile rather than in degrees, would indicate that the axis of the later fold is sensibly parallel to that of the older, while the greater thickness of the lower series remaining on the east side of the present trough, as compared with that remaining on the west, gives good ground for the inference that the axis of the old syncline lay somewhat east of the present axis. This previously existing synclinal axis doubtless determined in the later folding the position of the present trough.

It has been said that the trough as a whole pitches, at its southeast end, toward the northwest at an angle of about 45°. This is not far from the average pitch at the surface. With depth this angle slowly diminishes, and at about 900 feet below the surface it is less than 40°. The distance in which the turn is made at the southeast end of the trough is relatively very short. The average radius of the generalized curve into which the base of the Goodrich quartzite has been thrown can be very little greater than the thickness of that formation (Atlas Sheet XI, secs. AA and BB). Field study shows clearly that the neutral surface[1] of the column of folded material lay below the base of the Goodrich quartzite, and included a considerable portion of the Negaunee formation. This is proved by the severely plicated condition of the thin-bedded jaspers, and by the same structure on a larger scale in the more heavily bedded quartzite. The crowding of the rocks above the neutral surface into a very constricted space has resulted in the formation of three synclines of the second order separated by two anticlines, all subordinate to the main fold. The most eastern of the synclines occurs at the great open pit of the Republic mine; the middle, in the ground opened by the Morgan, Pascoe, and Ely shafts, and the westernmost at the Swamp shaft. Upon these folds of the second order are superimposed a multitude of smaller anticlines and synclines of various dimensions. They are more numerous and more closely compressed in the iron-bearing member than in the Goodrich quartzite.

In the iron-bearing member, which is a thinly bedded rock, these little folds are especially numerous in the Morgan-Pascoe-Ely syncline and in the anticline immediately west of it. The effect of this prevalent crinkling and close compression is to give a general northwesterly direction to the individual bands, which in the narrow spaces open to observation underground, or in small outcrops on the surface, may lead to erroneous conclusions as to the real direction of the strike and dip of the rocks. This northwesterly structure is really at right angles to the direction of continuity of the rock. The true strike is determined by the plane tangent to the little folds, and the true dip by the angle of pitch of their axes. Even on the surface in the larger outcrops the observer may sometimes be misled. The larger subordinate anticline between the Swamp shaft and the Morgan is topographically indicated by a high spur, on which the specular jasper outcrops. The jasper is thrown into innumerable little folds, the axes of which pitch to the northwest at an angle of less than 45°. The northern slope of the spur is nearly as steep as the angle of pitch, and so the surface cuts the

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 596–598.

little folds nearly parallel to their axes. In effect, therefore, the jasper outcrops on this northern slope show a parallel banding striking northwest. On the top of the hill, however, the true strike is clearly brought out on the vertical cross joints.

The Goodrich quartzite, which is much more massive and heavily bedded than the Negaunee formation, yielded to the intense compression by differential movements of one bed on another, and doubtless also by thickening. The effects of the movement of bed on bed are clearly and strikingly shown at numerous points in the horseshoe, perhaps particularly well in the small open pit east of the Ely shaft. Here the individual quartzite beds, from 1 foot upward in thickness, are separated by parallel selvages of ground-up quartzitic material, varying in thickness usually from 2 to 4 inches. In the case of one the measured thickness was 11 inches. These selvages, known locally as a variety of "soaprock," show frequently a vertical pressure cleavage.

FAULTS

Maj. T. B. Brooks shows, on his large-scale map of Republic Mountain[1] and vicinity, the course of a probable fault cutting diagonally across the syncline in a northeasterly direction along the river in sec. 7, north of the horseshoe. Brooks was led to infer the existence of this fault from the fact that he regarded the diorites as regularly interbedded and continuous members of the stratified series, and from his failure to recognize the unconformity at the base of the Goodrich quartzite.

On the northeast side of the syncline diorite outcrops a short distance north of the Milwaukee and Northern Railroad water tank, on the east side of the river, and lies directly in the line of strike of jaspers that are well exposed a few hundred feet away on the west bank.

On the southwest side of the syncline, north of the horseshoe, the Lower Marquette rocks which lie below the Goodrich quartzite on the east side of the river would, if prolonged along the strike, be carried directly against granites which occupy the west bank, west of the West Republic

[1] Geol. Surv. of Michigan, Atlas accompanying reports on Upper Peninsula, Pl. VI, by T. B. Brooks, 1869-1873.

mine. Hence, on Brooks's assumptions, there is displacement on both sides of the trough at the line of the river, and a fault is clearly indicated.

It is susceptible of demonstration, however, that no fault exists involving the Goodrich quartzite. On the northeast side of the fold the contact of the upper quartzite on the lower series, which is a surface of economic interest, has, since the time of Brooks's studies, been definitely fixed at numerous points on both sides of the river where it is not naturally exposed by diamond-drill borings. These points, when accurately platted, fall on a line which shows no displacement at the river.

At the southwest side of the fold the upper quartzite is abundantly exposed on both sides of the river, and its base has been located at many points in the West Republic mine, under the river, and in several test pits and drill holes on the western side. The platting of these data shows conclusively that no displacement can exist which has heaved the upper quartzite to the extent of 100 feet.

The disappearance of the lower series on the west side of the river, on the southwestern side of the fold, presents, however, a real difficulty. That its absence is due to a sudden bending of the strike toward the northeast is very improbable, because in the few outcrops of the iron-bearing member nearest the river there is almost perfect conformity in strike with the upper quartzite. Also, underground in the West Republic mine, the jasper was followed nearly to the west bank of the river. It seems necessary to believe, therefore, that the formations of the lower series continue without sensible change in strike as far as the river, and there terminate squarely against the granite. Such relations can be best explained by supposing that the granite on the west bank either had intruded the lower series or had been brought to the level of the old surface by a fault before Upper Marquette time. Between these two explanations there is no present means of choosing.

On Brooks's map, already referred to, a tongue of the upper quartzite is represented as forking from the main mass of the same rock and running northwest along the top of the Republic bluff, a thin wedge of the underlying specular jasper being interposed between them. No explanation of this singular fact was given by Brooks in the text of the Michigan report. Wadsworth[1] has lately endeavored to explain these relations by the assumption that the wedge of the specular jasper included between the two quartzites does not belong to the lower series, but to the upper, and was deposited later than the quartzite tongue. It is believed, however, that the phenomena are really due to faulting. (Pl. XXXIV, fig. 2.)

The best exposures of the two quartzites, the included jasper, and the underlying iron formation of the lower series, with all the contacts, may be seen on the natural cross-section afforded by the breaking down of Republic Mountain north of the Thompson pit. The conglomerate at the base of the main mass of the quarztite is exposed on the steep western face of the bluff. It holds pebbles of red jasper, of jasper banded with ore, of ore, and of quartz, which last, with ferruginous matter, forms the cement. The jasper inclusions are large, many of them are angular, and near the contact small quartz grains fill irregular cracks in the underlying jasper tongue. The conglomerate is distinctly basal, and unquestionably was laid down on an eroded surface. From this contact, for about 16 feet to the east, the jasper tongue comes in. This rock is greatly brecciated, but it contains no mixture of foreign fragmental material. To the eye and under the microscope it is not to be distinguished from the ordinary specular jasper of the underlying iron formation. For the next 5 feet occurs a mixture of large angular pieces of jasper (one measured 3 feet by 1 foot), of quartz, and probably quartzite, many somewhat rounded pebble-like forms of all these, and much siliceous cement. About 6 feet of westerly dipping quartzite, constituting the quartzite tongue, follow, and then come 3 to 4 feet of conglomerate, entirely similar to the first conglomerate and having similar relations to the specular jasper, which continues in an unbroken body to the east.

The significant facts at this contact, which seem clearly fatal to the idea that the jasper is an interbedded member of the upper series, are these: The conglomerate at the base of the main quartzite is as clearly separated from the jasper wedge by an erosion interval as the conglomerate below the quartzite tongue is from the main mass of specular jasper. The jasper

[1] Report of the State Board of Geological Survey, Lansing, 1893, pp. 129-130.

wedge can not belong to the upper series unless there are two upper series. The jasper of the wedge, also, is not a fragmental rock, and in it no contemporaneous fragmental material has been recognized except near the lower and upper contacts. The jasper disappears a short distance south of this section, the two quartzites coming together. If this is a member of the upper series, it must have been laid down at the same time that a rather coarse fragmental rock was being deposited a few hundred yards away. It is hardly conceivable that under these circumstances clastic material should not have been mingled with it.

While the relations of the quartzite tongue are correctly represented on Brooks's map, the vastly better surface exposures of the present day and the large amount of exploration done by the Republic Company enable its position now to be fixed with much greater precision.

Several diamond-drill holes north of the Thompson pit have shown that the quartzite tongue extends 500 to 600 feet north of the point where it terminates on Brooks's map, and becomes steadily narrower. As it does not appear at the Kingston and Kloman exposures, on the west side of the river, there is little doubt that it gradually dies out, and that the jasper wedge finally merges into the main body of specular jasper.

Therefore the facts to be explained appear to be these (Pl. XXXIV, fig. 2): A quartzite tongue branches in the south from a large mass of similar quartzite, and after continuing parallel to it for a long distance finally tapers to a point in the north in a mass of specular jasper. The quartzite tongue includes between itself and the main quartzite mass an exactly similar jasper tongue, which starts in the north from a mass of specular jasper and tapers to a point in the south in quartzite, the two tongues interlocking. The quartzite in each case, in the tongue and in the main mass, has similar and unusual relations (those marking a time-break) with the jasper of the tongue and of the main mass. The identity of the two jaspers and of the two quartzites must be taken as established, and the explanation of the facts must be sought in faulting.

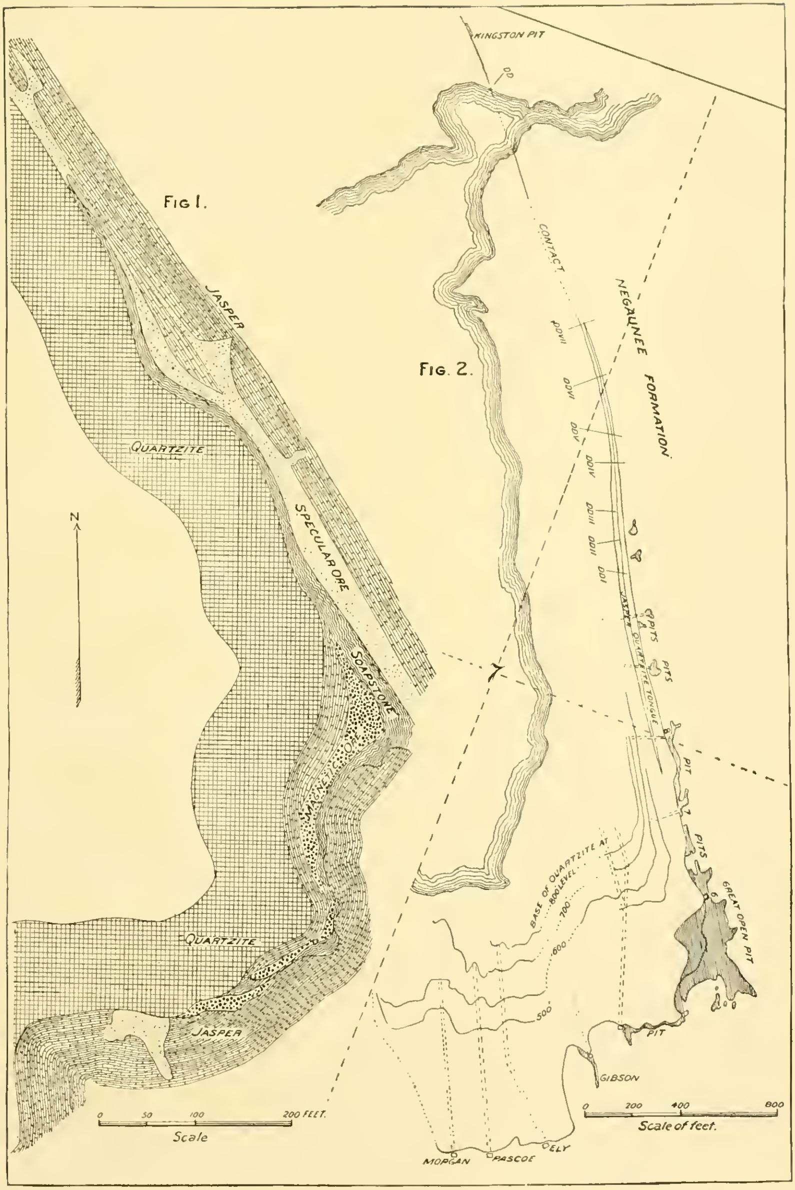
In the horseshoe turn the material above the neutral surface yielded to the compression in part by slipping along bedding planes. If for any

PLATE XXXIV.

PLATE XXXIV.—GEOLOGICAL MAP OF SOUTHEAST END OF REPUBLIC HORSESHOE.

FIG. 1. Southeast corner of the horseshoe, showing the surface relations of the magnetite and hematite to the jasper, quartzite, and soaprock. The larger ore deposits of magnetite are bottomed by soaprock, making steeply pitching troughs. The specular ore is for the greater part of the distance separated by a belt of soaprock from the magnetite ore and quartzite.

FIG. 2. Map of the vicinity of Republic mine, showing the contact between the Lower Marquette and Upper Marquette series and the quartzite tongue. It will be seen that the great ore deposits occur in the two plunging synclines at the southeastern bend of the trough.



GEOLOGICAL MAP OF THE SOUTHEAST END OF THE REPUBLIC HORSESHOE.

reason such movement could take place more readily along any one surface, the neighboring surfaces would be relieved and one of maximum movement would result. It is conceivable that in the same way one local maximum might relieve several neighboring maxima, and so a large amount of movement might be accumulated along a single surface. A maximum movement starting in the specular jasper would, on account of the slight upward convergence of dip, necessarily tend to cut across the quartzite at the contact. The quartzite might be traversed until a surface of maximum movement in it was reached, which would then be followed and a fault would result, which in the direction of the strike might easily pass from one rock to the other more than once. It is evident that a break formed under such conditions, accompanied by considerable displacement, would result in the surface relations that may now be observed on Republic Mountain.

THE ORE DEPOSITS.

POSITION OF ORE DEPOSITS.

The iron ores of the Republic area all belong to the hard-ore class, and are both magnetite and specular hematite, the specular slate ores being the more abundant. They occur in bodies of very irregular shape and sometimes of great size. The rule that has generally guided exploration in the Marquette district, that the hard-ore bodies occur immediately at or not far beneath the base of the upper quartzite, holds good in the Republic area. It is a significant fact that while this rule of occurrence beneath the upper quartzite has few or no exceptions, the position of the ore bodies with reference to the base of the lower series is exceedingly variable. At Republic Mountain and at the Michigamme mine the ore bodies lie at least 1,500 feet above the granites. At Champion and at the Riverside mine the distance is not more than 400 feet. The hard-ore bodies are therefore not confined to any one horizon in the iron-bearing member, but occur at the particular horizon to which it happened to be eroded at the time the upper quartzite was deposited. The contact deposits of the Republic area have relationships with both the lower and upper series. Some are apparently entirely within the upper series; others are certainly entirely within the lower series; others again are partly in both. In form the bodies are exceedingly irregular, but they may be described in general terms as pod-like in shape, the two horizontal dimensions being usually very much smaller than the third, which follows down roughly parallel to the dip plane of the quartzite, often pitching to one side of the vertical plane normal to the dip plane. Of the two horizontal dimensions, the longer is usually parallel with the stratification, and the shorter normal to it.

Where the ore deposits are wholly contained within the lower series, the contacts between them and the rock of the inclosing iron formation are usually as follows: The siliceous bands in the ferruginous rock become separated into lenses by the encroachment of the adjoining iron bands at frequent intervals along their length, and grow narrower. The siliceous material of which they are composed becomes mixed with a larger proportion of the iron oxides, and as the boundaries of the rich ore are approached the bands separate into oval-shaped units. These finally disappear partly or entirely, and the adjacent iron oxides fill the whole volume of the banded rock. Such passages from the banded rock of the iron formation to rich ore take place both along and across the strike. Sometimes the passage is very gradual, leaving a large zone of more or less lean ore between the rich ore and the rock; but often it is very sudden, and the line of demarcation is sharp. Such sudden passages have been observed at the line of cross joints, along which minute faultings have taken place. It is unusual to find any ore deposit, however, that is directly surrounded by the iron-formation rock on all sides. Generally on either the hanging or foot wall soaprock intervenes between, somewhere along the surface of contact; and in these cases the iron formation is usually present on one side, while the rich ore comes up to the soaprock on the other. These bodies of soaprock have already been referred to as old dikes and intrusive sheets of igneous material.

Of the deposits entirely within the upper series two classes may be distinguished. The first are those deposits which lie at the base of the upper series, and really represent an enriched, very ferruginous phase of the basal conglomerate. At many localities the Upper Marquette conglomerate is made up of siliceous pebbles embedded in a cement of iron ore, part of which is in many cases unquestionably detrital. Where the quartzose pebbles, from the conditions of sedimentation, happen to be few and small, or where they have been removed by subsequent changes, the conglomerate may contain enough iron to constitute a valuable ore. No large deposits of this character have been demonstrated to exist in the Republic area, but some good examples on a small scale may be seen about Republic Mountain. Such ores are usually magnetic. It is believed that a considerable part of the magnetite deposits of the Champion mine belong to this class. In the Republic area, around the borders of the magnetite deposits, where they become too lean to mine, occur certain peculiar rocks, mixtures of clear quartz and magnetite, which are usually known as "black-ore jasper." Higher in the lower quartzite, thin, regularly bedded bands of magnetite and quartz occur, which occasionally rise high enough in iron to become ores. They are found usually a short distance above the transgression plane, and are separated from it by a small thickness of quartzite.

In certain cases the line of contact between the upper and lower series may be traced directly through an ore body, which thus belongs partly in one series and partly in the other. Excellent examples may be seen at the Kloman open pits, north of Republic Mountain.

RELATIONS OF THE ORE DEPOSITS TO THE GEOLOGICAL STRUCTURE.

In the Republic area the only deposits that have had a commercial value have been found in the immediate vicinity of the southeast end of the fold. The largest single body occurs at the southeast point of the horseshoe, in the easternmost of the three main subordinate synclines already mentioned. The middle, or Morgan-Pascoe-Ely syncline, is the locus of a great number of smaller deposits. Several deposits occur also on the straight northeastern side of the trough, within three-quarters of a mile from the horseshoe; but in going north along this stretch the bodies become smaller and farther apart, and north of the Kloman practically disappear. A very close relation is thus indicated between the occurrence of the iron ore in large deposits and the main structural features of the trough.

These larger bodies are both magnetite and specular hematite or slate ore. (Pl. XXXIV, fig. 1.) The magnetite bodies always occur immediately below the upper quartzite, with which they are frequently directly in contact. More commonly, however, the rich ore is separated from the quartzite by a small thickness of black-ore jasper or mixed magnetite and quartz, usually banded, or sometimes by soaprock, while immediately beneath and continuous with the rich magnetic ore specular ore is sometimes found. Soaprock usually, and in the case of all the larger bodies invariably, forms the foot wall. The magnetite deposits are mostly confined to the eastern and middle subordinate synclines, but are also found of small thickness in depth along the straight eastern limb of the main fold

The specular hematite or slate-ore bodies occur both in the contact zone and below it, entirely within the specular jasper. (Pl. XXXIV, fig. 1.) As a rule the deposits of the contact zone contain the richest ore, which is characterized by the large size of the individual crystalline plates. As a deposit is followed back from the contact zone into the jasper, these plates become progressively smaller, and at the same time the ore grows more siliceous. The larger deposits of specular ore are associated with soaprock, which may bound a deposit either on the foot or the hanging wall side.

The deposits of specular ore that occur along the straight eastern limb of the fold all show a well-marked pitch toward the north, in the general direction of pitch of the main fold, but at a very much higher angle. These bodies all lie in the contact zone at the surface, having the upper quartzite on the hanging wall. As they are followed in depth they are found to recede from the quartzite, and to follow the banding of the underlying jaspers, which dip at a higher angle than the quartzite. They terminate in depth entirely within the specular jasper. As one body departs from the quartzite and becomes entirely inclosed by the jasper another frequently comes in above it in the contact zone.

The deposits in the subordinate synclines in the horseshoe turn have not shared the intense crumpling to which the specular jaspers have been subjected. They occur in thin, unwarped sheets, which start with one edge in the contact zone, having the upper quartzite on the hanging wall and set back from it parallel with the local strike of the closely folded jaspers. The longest dimension thus follows down the contact, pitching with the dip of the quartzite, while the longer of the two horizontal dimensions is usually normal to the strike of the quartzite. These deposits occur in the arches or on the limbs of the minor contortions, and never, so far as observed, occupy the troughs. Their attitude with reference to the general strike of the quartzite, and the fact that they do not show the contortions of the inclosing specular jasper, prove that they have come into existence since the folding.

ORIGIN OF THE ORE DEPOSITS.

From the form and general relations of the rich ore deposits it is evident that they were not laid down as bodies of rich ore contemporaneously with the inclosing rocks. It is not conceivable that nearly pure silica and nearly pure iron oxides could be deposited under water at the same time on opposite sides of an imaginary vertical plane. Nor is it any more probable that they have come up from below as igneous dikes which have intruded the sediments of the iron formation. The physical objections alone to this view are such as entirely to exclude it from serious consideration. On the other hand, the phenomena of their relations to the inclosing rocks, which have been described, all lead to the conclusion that they are later concentrations and indicate the main lines along which the concentration was brought about.

In general, this process of concentration has been a removal by circulating waters, in favorable places, of the silica of the old rock, and its contemporaneous replacement by iron oxides. This process has gone on in the contact zone, in the detrital conglomerates, and in the underlying jaspers. The evidence in both cases is abundant and clear. In the case of the iron formation of the lower series the siliceous bands may be traced along the strike in all stages of replacement, until finally they are wholly represented by new iron oxides. In some cases the new iron ore is of coarser texture than the old, and so the original banded structure may still be traceable into a body of nearly pure ore. In the case of the conglomerates, we see in thin sections original rolled quartz pebbles, which are sometimes surrounded by new growths of quartz, studded with iron oxides about the periphery. This process, too, may be traced through all stages, from cases in which the attack on the old pebble had just begun to those in which the quartz of the original grains is almost entirely gone. It is an interesting inquiry, upon which, however, little direct evidence can be brought to bear, as to how far the concentration in the conglomerates has depended upon the new growth of iron ore about rolled nuclei of iron sand. Bearing possibly upon the question is the fact that the crystalline plates of specular hematite are frequently and perhaps always coarser in the slate ores that occur in the contact zone than in those belonging lower down within the iron-bearing member.

The process of concentration in the Republic area has not proceeded indiscriminately throughout the iron-bearing member. The distribution of the important ore deposits shows that it has been localized in accordance with certain physical conditions. The main facts of distribution are (1) that the ore bodies occur within or not far below the contact between the upper quartzite and the iron-bearing member; (2) that they occur in pitching synclines in the vicinity of the greater orogenic disturbances; (3) the larger bodies usually have a basement of soaprock. These relations of distribution are so constant that they must be regarded as necessary conditions. It is evident that the first two conditions were such as to promote comparatively free circulation. In the contact zone the loose texture of the conglomerates afforded connecting open spaces through which waters could readily pass. It is equally evident that the general breaking up attending sharp folding in the underlying iron formation would not only open channels for percolating waters but would also reduce the siliceous bands to a condition in which they could be readily attacked. The third condition was favorable to the concentration of the iron-bearing percolating waters.

From the relations which the ore deposits bear to the structure produced at the time of the later folding, it clearly appears that much of the concentration has been effected since Upper Marquette time; but it does not follow that some of the iron oxide of the deposits was not already in existence at the time of the Upper Marquette transgression. If, as there is strong reason for believing, the specular character of the hematite of the jaspers and of the rich ore deposits of the Republic area is connected with differential movements of bed on bed, produced at the time of the latest folding, it is necessary to believe that concentration either has preceded the folding or went on contemporaneously with it. In the case also of those deposits which are traversed by the plane of division between the upper and lower series, and so lie partly in both, the part of the deposit in the lower series may have been partly concentrated at the time of the Upper Marquette transgression, while that in the upper series may be partly fine débris derived from the underlying body. In all the deposits the processes of enrichment have doubtless proceeded continuously through all subsequent time.

CHAPTER VII.

GENERAL GEOLOGY.

By C. R. Van Hise.

In considering the general geology of the Marquette district we have to deal with three series: The Basement Complex, the Lower Marquette, and the Upper Marquette. These three series are separated by unconformities. The Basement Complex includes granites, syenites, gneisses, many finely crystalline schists, surface volcanics, and various subsequent intrusives. The complex south of the Marquette series is spoken of as the Southern Complex; that to the north as the Northern Complex. The Lower Marquette series, from the base upward, comprises the Mesnard quartzite, 110 to 670 feet thick; the Kona dolomite, 425 to 1,375 feet thick; the Wewe slate, 550 to 1,050 feet thick; the Ajibik quartzite, 700 to 900 feet thick; the Siamo slate, 200 to 625 feet thick; and the Negaunee iron formation, 1,000 to 1,500 feet thick. We thus have a minimum thickness for the series of 2,975 feet, and a possible maximum of 6,120 feet. It is not probable that any single section will give so great a thickness as 5,000 feet. The Upper Marquette series comprises the Ishpeming formation, which includes the Goodrich quartzite and the Bijiki schist, the Michigamme formation, and the Clarksburg formation. It is impossible to give even an approximate estimate of the thickness of the Upper Marquette series, but in the district considered, excluding the volcanics, it is probably less than 5,000 feet. Including the volcanic Clarksburg formation the series is probably over 5,000 feet thick.

Basic igneous rocks intrude in an intricate manner both the Upper Marquette and the Lower Marquette series.

The aim of the following paragraphs is to briefly sketch the history of the district.

THE BASEMENT COMPLEX.

The oldest rocks of the Basement Complex are thoroughly crystalline, foliated schists and gneisses. A close field and laboratory study has failed to detect in them any evidence of sedimentary origin. If any detrital rocks are included in the Basement Complex, they have been so profoundly metamorphosed as to have lost all evidence of their origin. These gneisses and schists have been cut by various igneous rocks at different epochs. The latter occur both in the form of great bosses and in dikes, sometimes cutting, sometimes parallel to, the foliation of the rocks. In some cases the number of intrusive belts of granite parallel to the schistosity is so large and they are so narrow as to give very numerous interlaminations of schist and granite within a short distance.

In the area of the Northern Complex there were volcanic outbursts, and a vast series of lavas, agglomerates, greenstone-conglomerates, and tuffs were piled up. By far the greater part of the volcanic material is of an intermediate or basic character. While the material is undoubtedly a surface deposit, a search year after year in the field has failed to reveal any decisive evidence of arrangement by water. The deposits are strictly volcanic. After the great lava beds and the vast masses of tuffs were piled up there were granitic, syenitic, and diabasic intrusions, for bosses of these rocks and dikes from them cut through the volcanics.

After, and also perhaps during, the building up of the volcanic series the Marquette district was deeply truncated, as a consequence of which many of the different varieties of rocks composing the Basement Complex appeared at the surface. The coarse granites must have formed as deep-seated rocks, and the foliation of the schists must have formed far below the surface; such rocks could have reached the surface only by long-continued denudation, which removed mountain masses of materials. The process continued until the Basement Complex had no great altitude, for before a great thickness of the Lower Marquette series was deposited the sea had entirely overridden the Marquette district.

THE LOWER MARQUETTE SERIES.

THE TRANSGRESSION HORIZON.

Toward the close of the pre-Marquette denudation the sea reached the northeast border of the Marquette district. Advancing upon it, perhaps in part as the result of depression, but largely as a consequence of subaerial and marine erosion, the fragmental sediments of the Mesnard formation were laid down. This advance steadily continued from the northeast toward the southwest and west, the first deposits being everywhere fragmental sediments, at the base usually a coarse conglomerate, and higher up a sandstone which subsequently was changed to the Mesnard quartzite. Long before the seashore reached the western end of the district other formations were deposited in the eastern half of the area, so that we have some measure of the time required for the transgression. The formations thus deposited above the Mesnard quartzite before the sea advanced to Michigamme Lake were the Kona dolomite and the Wewe slate. It follows, then, that in passing from the east to the west end of the district there are in the Lower Marquette series fewer and fewer formations. At the east end is the full succession; at the extreme western are only the two upper members. Lithologically the whole transgression horizon is one formation, marking as it does a continuous belt of conglomerate and metamorphosed sandstone immediately above the Basement Complex. Chronologically, however, different parts of it are to be equated with several formations, that part of it only being called the Mesnard quartzite which was deposited before the beginning of the deposition of the next higher member, the Kona dolomite, and hence it is necessary in the chronological scale to subdivide this lower conglomerate and quartzite between the various formations from the Mesnard quartzite to the Ajibik quartzite. It is not possible to do this accurately in the mapping in all places, and the manner in which on the maps one formation feathers out against the shore-line, to be succeeded by the next one, is more or less arbitrary, although it so happens that there is no considerable difficulty in this particular for most of the district. This arbitrary subdivision is most conspicuous in the quartzite which occurs east of Teal Lake. (Atlas Sheet XXX.)

UNCONFORMITY AT THE BASE OF THE LOWER MARQUETTE SERIES.

As evidence of the unconformity between the Lower Marquette series and the Basement Complex is found all along the lower part of the transgression quartzite, the phenomena showing unconformity are mentioned here rather than in connection with the separate formations among which this belt is divided. However, for the exact locations and detailed descriptions of particular contacts it will be necessary to refer to the descriptions of the individual formations.

At the east end of the south side of the Marquette district there are numerous localities from Lake Superior to west of Lake Mary where a granite-conglomerate is found bearing numerous bowlders of granite, gneiss, and schist, identical with the rocks constituting the Basement Complex immediately adjacent. At several of these localities the actual contact between the Mesnard quartzite and the Basement Complex is seen. Some distance farther to the west the Marquette formations reach the Pleistocene sand plain, the Basement Complex not being exposed. Passing this area, we next find in the Marquette series two islands of the Basement Complex in secs. 22 and 23, T. 47 N., R. 26 W. (Atlas Sheet XXXV). Here are found most magnificent exposures of great bowlder-conglomerate and recomposed granite, resting with visible contact upon the Basement Complex and composed of material mainly derived from it (fig. 11). In sec. 23 the predominant rock of the Basement Complex is a peculiar white schistose granite, and the predominant bowlders of the conglomerate are of the same character. South of the Cascade range, there are again a number of localities from secs. 34 to 32, T. 47 N., R. 26 W. (Atlas Sheets XXXII and XXXV), where are basal conglomerates, the great bowlders again being mainly identical with the adjacent granites, gneisses, and schists of the Basement Complex. In this area in the Basement Complex are some peculiar basic eruptives, and these rocks are found in the form of well-rounded waterworn bowlders in the conglomerate. Toward the west, the next exposure of basal conglomerate is south of Summit Mountain, in the west half of sec. 25, T. 47 N., R. 27 W. (Atlas Sheet XXIX). The conglomerate at this place grades downward into a schist which is scarcely distinguishable from the Palmer gneiss, with which it is in contact. The next contact to the west is in sec. 28, T. 47 N., R. 27 W. (Atlas Sheet XXV). Here the phenomena are similar to those south of Summit Mountain. West of this place no actual contacts between the quartzite and the Basement Complex are found until the end of the Republic trough is reached (Atlas Sheet XI), where again a conglomerate hangs with visible contact upon the flank of the granite, bearing well-rounded waterworn bowlders from it.

At the north side of the Lower Marquette series, and near the east end of the district, there is exposed a magnificent basal conglomerate about 3 miles west of Marquette, north of Mud Lake (Atlas Sheet XXXVI). Here the rocks adjacent to the Mesnard quartzite are the Mona schists, and these peculiar rocks are largely found as detritus in the basal conglomerate. Here also are found granite bowlders similar to the granite masses which a short distance to the north intrude the volcanics of the Northern Complex. The next known contacts to the west are at the base of the quartzite east and west of Teal Lake (Atlas Sheets XXVII and XXX). Here, at a half dozen places, contacts are found, each of the conglomerates having, as usual, as their abundant detritus, the immediately subjacent material at the particular locality. At one place the relations are such that the layers of the conglomerate cut across the foliation of the subjacent schist at an acute angle (fig. 14). Still farther west, in sec. 30, T. 48 N., R. 28 W., the quartzite is found in visible contact with the granite at a number of places (Atlas Sheet XVIII), and again its most abundant material is exactly like the subjacent granite. In some of the places the basal rock is a conglomerate, in others a "recomposed" granite—i. e., it is composed of the separate minerals of the underlying granite. West of this point the only actual contact known is north of the Michigamme mine, although at a number of places strongly feldspathic quartzites occur near the granite.

We thus have more than a score of localities, scattered about the entire area covered by the Lower Marquette rocks, where occur great basal conglomerates, a number of which rest with visible contact upon the rocks of the Basement Complex. In all of the cases the detritus is most distinctly waterworn, and while the major portion of the material in each case must have been derived from the immediately subjacent part of the Basement Complex, other material not occurring in the immediate neighborhood is found, thus showing conclusively that these rocks are not reibungs or fault breccias. The evidence is therefore demonstrative that the Lower Marquette series was deposited unconformably upon the Basement Complex.

As explained later, it will be seen that locally, as a result of the powerful dynamic action to which the rocks have been subjected, the foliation of the Basement Complex and that of the basal quartzite are in the same direction, and that at certain localities the basal conglomerate and quartzite have been so mashed as to pass into completely crystalline schists, which appear to grade down into the foliated schist or gneiss of the Basement Complex. As a consequence, the granites of the Basement Complex have been described by certain geologists as intrusive within the Lower Marquette series. Others have said that it is a case of downward-progressing metamorphism. Taking into account the above facts as to the contacts and conglomerates, there is no escape from the conclusion that this apparent conformity and gradation are illusory, being produced by the metamorphosing processes of profound dynamic action and metasomatic changes.

DEPOSITION OF THE LOWER MARQUETTE SERIES.

In the earlier part of Lower Marquette time, the sea steadily transgressed southwestward from the northeast, depositing a basal conglomerate as it advanced. As soon as the sea had progressed a little beyond a given place, the deposition of sandstones there replaced that of the conglomerates. (See Atlas Sheet IV.) By the time the sea had transgressed as far as Teal Lake on the north and Goose Lake on the south, argillaceous and siliceous limestones began to be deposited in the east end of the district, and hence the western limit of the Mesnard quartzite is placed at these localities. The Kona dolomite probably marks deeper and quieter waters, and therefore indicates that depression had been continuing. A thin layer of slate marks intermediate conditions between those favorable to the deposition of sandstone and those in which the limestone was deposited. However, the area of limestone-building was too near shore and the water too shallow for a purenon fragmental formation to be built up, especially as vigorous erosion still continued on the adjacent land, and hence it is that even the purest dolomite beds bear a greater or less quantity of fragmental material, while they are frequently interstratified with shale, graywacke, and quartzite. Because the sea had not yet overridden the lands of the central part of the district, the Kona dolomite is limited to its eastern part. On the south side of the district the westernmost exposures occur at Goose Lake, and on the north side the most westerly exposures which clearly belong to this formation are those at Morgan Furnace, although a belt of slates very similar to those associated with the Kona dolomite occurs interstratified with the quartzites east of Teal Lake. This belt feathers out about 1 mile east of Teal Lake, and this suggests that here was the western limit of the shore-line at the end of Kona time.

As a consequence of the upbuilding of the Kona formation, combined, perhaps, with a cessation of subsidence, the waters again became shallow, and there followed above the Kona dolomite the Wewe slate. The intermediate conditions favorable for mud deposits continued for some time. On the south side of the district the western limit of the shore-line at this time was in the eastern half of sec. 21, T. 47 N., R. 26 W., and on the north side probably at or near Teal Lake. By the upbuilding of the beds the waters became shallower and shallower until the waves of the sea were able to transport sand throughout the area submerged. There is evidence that in some localities the compacted mud arose near to or above the surface of the water, so as to be cut by the waves and yield fragments to the succeeding sandstone. The sandstone has been subsequently indurated to a quartzite, and hence there follows above the Wewe slate the Ajibik quartzite.

During the time of the deposition of the Kona dolomite and Wewe slate the sea did not advance very rapidly, but erosion had been steadily wearing down the highlands, and during the deposition of the sandstone following these formations there was a rapid advance of the sea toward the west. On the north the sea of Ajibik time pushed west to Michigamme, and on the south as far west at least as the Goodrich mine. The sea therefore gained farther at the north than at the south, the shore-line apparently being diagonal, running in a northwest-southeast direction, still further suggesting what was said at first, that the advance of the sea was from the northeast. The subsidence continued faster than the upbuilding of the sands, so that there followed above them mud deposits, which have been compacted into the Siamo slate. During the time of mud deposits the shore-line continued to advance, and before this formation was completed the sea had entirely overriden the Marquette district, with the possible exception of the southwestern part. Following naturally from the conditions of deposition, the Siamo slate has a greater thickness in the eastern than in the western part of the district, and it does not appear in the southwestern part. Perhaps equivalent to some part of the Siamo slate in age is the basal quartzite from Humboldt to Republic, but as it is impossible to say what part of the quartzite belongs with the Siamo slate and what part with the Ajibik quartzite, it is all mapped as the latter formation because of its lithological likeness to it.

The steady subsidence during the deposition of the Siamo slate so increased the depth of water that a nonfragmental formation began to be deposited. This was the siderite slate, which has been largely transformed into the varieties of rocks of the iron-bearing formation. The conditions which led to the deposition of the iron carbonate are not certainly known. At that time the Marquette transgression had entirely overridden the land of the district, but it is not probable that all adjacent land areas had disappeared, or even that the green schists of the Northern Complex were entirely covered by the sea, although it is possible, or even probable, that the long-continued erosion had reduced the land areas nearly to base-level, and consequently that chemical solution, rather than mechanical wear, was the more important agent of erosion. Thus might be explained the large amount of iron salts which appeared. Doubtless the supply of ferruginous material was in the form of iron carbonate, taken into solution by direct atmospheric agencies, perhaps with the assistance of organic acids. The basic eruptives of the Basement Complex, and especially the surface volcanics on the northern border of the district, are very rich in iron. These latter, being tuffs and lavas, were porous, and perhaps from them came the greater proportion of iron. In the water, also, there was doubtless life. As the iron carbonate came down into the open water it was peroxidized and the iron precipitated as hydrated oxide. When this was buried with organic matter the decomposition of the latter produced carbon dioxide, and the iron was reduced to the protoxide by the organic matter. The two combined and reproduced iron carbonate. Whether the area of deposition of iron carbonate was an arm of a large sea or an almost inclosed lagoon, there are no means of ascertaining, but the widespread distribution of this inferior iron-bearing formation in the Lake Superior region suggests that the areas of deposition of such material were very large.

ERUPTIVES OF LOWER MARQUETTE TIME.

At one locality amygdaloids are interstratfied with the Siamo slates. In others, closely associated with the Negaunee iron formation are volcanic tuffs. It thus appears that in later Lower Marquette time there was volcanic action. Just how extensive the volcanoes were has not yet been determined, as these rocks have not in all cases been discriminated from the later igneous rocks.

UNCONFORMITY AT THE TOP OF THE LOWER MARQUETTE SERIES.

Whether any later formations followed conformably upon the Negaunee iron-bearing formation it is impossible to say, but if so they were subsequently removed by erosion. Following the deposition of the Negaunee formation and all possible later conformable formations, the land was raised above the sea, gently folded, and eroded. In general the discordance between the Lower Marquette series and the succeeding series is not great, being measured frequently by 5° to 10°, at other times by 10° to 15°, and it is only rarely that the plications of the lower series are such as to make the beds abut perpendicularly against those of the overlying series. In these cases the truncated layers are those of the minor plications rather than the major folds (figs. 20 and 21). Erosion cut deeper in the Lower Marquette series in some places than in others. At the east end of the area it left a very considerable thickness of the iron-bearing formation, but in places to the west this formation is quite cut out. Indeed, in places erosion cut through the Siamo slate and the Ajibik quartzite, and in some places even into the

Basement Complex. This particularly occurs in the west and southwest parts of the district, west of Champion and along the Republic tongue, where but few members of the Lower Marquette series were deposited. Even within a short distance the differential erosion was considerable. For instance, at the south end of the Republic tongue the variation was more than 1,500 feet.

To just what extent the Lower Marquette series was altered during this period of folding and erosion it is impossible to say. It is probable that the upper formation, consisting of the readily altered iron carbonate, suffered the most, and there are indications that ferruginous chert and jasper were formed in the upper part of the formation. At least fragments of such materials are found in the succeeding formation, and either these rocks were produced from the iron carbonate during this folding and erosion or else the iron-carbonate bowlders and fragments, in common with portions of the Negaunee formation, were at a later time altered in a like manner, so as to produce the same mineral combinations in the fragments and in the Negaunee formation itself. It is probable that such subsequent modification has occurred to some degree, but many would doubt whether it were possible for such exactly similar changes to have occurred as to make the bowlders and fragments of cherty siderite and the siderite of the underlying Negaunee formation into precisely similar chert and jasper.

THE UPPER MARQUETTE SERIES.

DEPOSITION OF THE UPPER MARQUETTE SERIES.

The Upper Marquette history begins with the second transgression of the sea, as a result of which the Ishpeming formation was deposited. If we may judge by the greater thickness of the Goodrich quartzite of this formation at the eastern part of the district, and the greater erosion of the Negaunee formation at the western part, an anticline had formed to the west, and the transgression of the sea was again from the east or northeast. Thus, the Negaunee formation in the eastern part of the area was more quickly buried. In other words, the western part of the formation was higher and was subjected to longer erosion. Therefore, in the eastern part of the district the sediments of the Goodrich quartzite first began to form. The western part of the district remained for a time above the sea, and therefore at first received no deposits. We thus partly explain the very considerable thickness of the quartzite in the Ishpeming and Negaunee areas, its dying down to an exceedingly narrow stratum in the western end of the district, the considerable thickness of the Negaunee formation about Ishpeming and Negaunee, and its thinning or disappearance at the west end of the district.

The first deposit of the advancing sea was a conglomerate, the detritus of which was derived mainly from the immediately subjacent Negaunee formation. Hence it is that the basal formation is so frequently jasper-conglomerate, chert-conglomerate, and, where the detritus is finer, recomposed chert and jasper, ferruginous slate, etc. However, the detritus was derived not wholly from the Negaunee formation, but in part from the various lower formations. This shows that either within the district under discussion or adjacent to this district erosion had cut into the inferior formations, and even down into the Basement Complex. This is well illustrated by the Palmer belt of the Goodrich quartzite, where the conglomerate contains not only fragments of the Negaunee formation but of the Ajibik quartzite and of the Basement Complex.

Following the basal conglomerate, which is from a few feet to several hundred feet thick, came a sand deposit. This sand was largely composed of simple, pure grains of quartz, which could not have been derived from the iron-bearing formation, but must have come from lower formations outside of the district discussed. This probably implies that adjacent to the district erosion by this time had removed large areas of the Negaunee formation. Mingled with the coarse simple grains of quartz are also fine complex fragments of chert and jasper, which shows that in places the Negaunee iron formation was still being cut. This sandstone has been subsequently changed to a quartzite.

Early in the time of sand deposits along the southern part of the district, an east-west fissure was formed near Clarksburg, and a major and probably at least two minor volcanoes were developed. As a consequence there was piled up the Clarksburg formation, a mountainous mass of material, consisting of lavas and tuffs, some of which were rearranged by water, and of volcanic materials interstratified with ordinary sedimentary rocks.

The area over which the volcanic material was deposited gradually grew, reaching east as far as Stoneville and west as far as Champion. These more remote deposits are comparatively thin, and show evidence of water arrangement. As the lavas and tuffs were piled up, subsidence, possibly due to the burdening of the crust, went on, so that there resulted a great bend of the adjacent formations to the southward. How far to the south and to the north these volcanoes were felt we do not know, but the slates to the north indicate that their ashes reached to the extreme northern part of the district. This volcanic activity lasted for some time; for, beginning in the time of the Goodrich quartzite, it did not cease until a considerable thickness of the Michigamme slate had been deposited. Contemporaneously with the extrusives, it is probable that intrusives penetrated the Basement Complex and the Lower Marquette series.

In the western part of the district the Goodrich quartzite grades upward into a grünerite-magnetite-schist (the Bijiki schist), and this into a ferriferous slate, often sideritic. In the eastern part of the district the Bijiki schist may exist, but exposures have not been found. As the schist is regarded as developing from a sideritic slate, it appears that following the deposition of the sandstone there were waters favorable to the deposition of a non-fragmental sideritic formation—that is, the conditions for the production of the Negaunee formation of the Lower Marquette were repeated, but not with perfection, for the ferruginous slates in much of the district were mingled with greater or less quantities of mechanical sediments. These are more abundant in the eastern end of the area than in the western, where a considerable belt of grünerite-magnetite-schist is comparatively free from mechanical sediments and might be mapped as a narrow separate formation.

The zone of ferruginous shales was apparently of variable thickness. It was followed above by ordinary shales, which, however, are locally ferruginous. Also with the shales was deposited much organic matter, as is shown by the fact that the resultant slates and schists are anthracitic or graphitic. These carbonaceous rocks are particularly abundant at the horizons which are heavily ferruginous, and thus confirm the suggestion made in considering the Negaunee formation, that organic matter was instrumental in reproducing iron carbonate from the precipitated iron oxide. This ferruginous and carbonaceous shale was very similar to some of the Paleozoic shales of the Appalachians, and argues similar conditions of deposition. Subsidence must have steadily continued during the deposition of the shale, for it is of considerable thickness. The sediments varied in coarseness, as shown by the fact that the rocks now found include fine-grained slates, graywackes, and even rocks which approach a quartzite. These rocks indicate waves and currents of varying strength or water of varying depth, or both. The shale and graywacke have been modified over extensive areas into mica-slates, mica-schists, or mica-gneisses.

FOLDING OF THE BASEMENT COMPLEX, LOWER MARQUETTE SERIES, AND UPPER MARQUETTE SERIES.

The Marquette district had been an area of deposition since the beginning of Upper Marquette time, and sediments of great thickness had accumulated. A physical revolution next occurred, as a consequence of which this district was raised above the sea and was folded in a complicated manner. (See Atlas Sheet IV.) Whether there was an epeirogenic movement which raised the plateau above the sea before the orogenic movements, and whether the main folds now found were formed simultaneously or successively, have not as yet been determined. In general, the directions of folding are approximately east-west and north-south. The only important exception to this is in the southwest part of the district, where the Republic arm swings away from the main area of Algonkian in a southeast direction.

The largest but least conspicuous fold of the district is an anticline having a north-south axis, running through Marquette. This fold has a gentle dip, but a breadth of many miles gives it a great amplitude. Its effect upon the minor but more conspicuous east-west folds is to give them a westward pitch. It follows that in going west from Lake Superior the area of the Marquette rocks becomes broader and broader, and higher and higher members appear in successive eastward-pointing U's, the ends being, however, often crenulated, due to the folds of the second and third orders. This great fold is by no means simple in its character, but has, especially near its crown—that is, for the eastern 6 or 8 miles of the district—superimposed upon it folds of the second order, making this part of the fold an anticlinorium. These secondary folds have lengths varying from 1 to several miles, and therefore a given formation may be repeated in an east-west direction along the present plain of denudation. The other major anticline belonging to this system of folds is one running north and south through the east end of Michigamme Lake. From this line the Algonkian belt broadens to the east and to the west. It then follows that all of the district between the center of range 25 west and the east end of Lake Michigamme may be regarded as a great north-south syncline.

The major part of the district has been affected, however, by much more powerful pressure in a north-south direction, so that the folds in an east-west direction are much more conspicuous than the north-south folds of greater wave length and greater amplitude. The conspicuous character of these folds has, in fact, led to neglecting the effect of the folding in the other direction, and thus one of the most important clews to the distribution of the formations was unnoticed. As a result of the north-south pressure, the Upper and Lower Marquette series together have been bent into a great synclinorium. At the east end of the district the Mesnard quartzite is overturned at one place and dips under the Southern Complex at an angle of 80°. The strikes of most exposures are mainly controlled by the east-west folding, but at the east and west ends of the areas of the formations the larger north-south folds already described control the strike. In passing to the west from Lake Superior, on the south side of the district, from Lake Mary to Goose Lake and somewhat beyond, the secondary north-south folds and the primary east-west folds are of about equal amplitude, although the east-west folds are closer and give higher dips. As a consequence of these two sets of folds some belts strike north and south, some east and west, and some in intermediate directions, thus giving, at first sight, an apparently lawless distribution of the formations; but when the character of the folding is understood the distribution is perfectly explained. From the north-south line running through Goose Lake to the west line of range 28 west is the area in which the Marquette series have the greatest width. For this part of the district it appears that the less rigid rocks of the Marquette series have, as it were, been pushed over the rocks of the Basement Complex on the north and south sides of the area. The outer Algonkian formations are closely plicated into a series of overturned and in some places isoclinal folds, the dips on both the north and south sides being toward the center of the trough and away from the Basement Complex (fig. 1). These secondary east-west folds are usually only discovered by tracing the contact between two formations. In passing, on the plain of denudation, toward the center of the trough, one first passes from a lower formation to a higher formation; then apparently above this he may again find the lower formation; and this infolding in extreme cases is repeated several times (Atlas Sheet XVIII). However, on the whole, the great syncline controls, so that finally the inferior formation is not again found. In passing inward toward the center of the Marquette area the minor folds become more open in their character, and in the center have a symmetrical shape (fig. 1). We then have a structure in this district in some respects like the fan-shaped folds of the Alps, with, however, the great difference that the area as a whole is a synclinorium instead of an anticlinorium; that is, the oldest rocks are found on the outside of the fan-shaped areas and the youngest rocks in the center of the area. The significance of this type of fold, which I have named an abnormal synclinorium, is fully discussed by me in another place.[1]

The overfolds on the outer borders of the Marquette belt are best discovered in places where, as a consequence of the pitch given by north-south folds, an east or west termination of the formation appears. A few of the best illustrative areas may perhaps be mentioned. West of Goose Lake, in secs. 22 and 23, by reference to the maps (Atlas Sheets IV and XXXV), it will be seen that there are four Archean areas, separated by Algonkian rocks both in an east-west and north-south direction. Their separation in an east-west direction is due to the secondary north-south folding, and their separation in a north-south direction is due to the isoclinal northwest-southeast overfolds. The latter folds are the closer; consequently the majority of the strikes are northwest and southeast, and the dips are mostly

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 612, 615–621.

to the northeast. The fragmental formations thus appear to plunge under the Archean islands on the south sides of the areas and to lie above them on the north sides. The infolded character of the Upper Marquette and Lower Marquette series is illustrated by the isoclinal overfolds along the north half of the north-south quarter line of sec. 21, T. 47 N., R. 27 W. (Atlas Sheet XXVI). Here a north-south section at one place shows the Negaunee formation; above this, in its proper position, is the Goodrich quartzite; and then there appears above this again the Negaunee formation. At the west end of the Jackson mine also the isoclinal overfolds of the Goodrich quartzite and the Negaunee iron formation are beautifully shown (Atlas Sheet XXVIII). However, the best locality of all to illustrate the isoclinal overfolds is in sec. 30, T. 48 N., R. 28 W. (Atlas Sheet XVIII). Here the infolding is between the granite of the Northern Complex and the Lower Marquette Ajibik quartzite and Siamo slate. A section at the most favorable place passes from the Siamo slate to the Archean granite, then again to the Siamo slate, from this to the Ajibik quartzite, into the Archean granite, in turn into the Ajibik quartzite, granite, Ajibik quartzite, granite, Ajibik quartzite, and probably following this, although topography rather than exposures indicates it, come again the Siamo slate, the Ajibik quartzite, and the Archean. For the whole of this distance the dips are to the south. Two islands of Archean are cut off from the main area. The quartzites and slates occupy the valleys, while the granite is more resistant and occupies the higher land. Controlled by the western pitch, the tongues of quartzite which project into the Archean die out to the east, and open out to the west. We have here, then, the conjoint effect of the close isoclinal overfolding due to the north-south pressure and the great north-south folding caused by east-west pressure which gives all of the formations a westerly pitch. As for the major part of the district the north-south folds are more open and the east-west folds more conspicuous, the latter may be designated the major folding, and the former folds may be considered as cross folds which give the east-west folds a pitch.

The western major north-south anticline at the east end of Michigamme Lake causes the Marquette rocks to here contract; but to the west, in passing toward the next syncline, these Algonkian rocks open out into a broad area which extends beyond the district. It is rather probable that the eastward-projecting land between the west and southwest arms of Lake Michigamme marks an intermediate anticline, which, however, does not rise high enough to bring to the surface any rocks higher than the Michigamme schist. The Republic tongue and the Western tongue are closely compressed synclines which branch off from this main area in southeast and south directions.

It has been seen that the main east-west syncline has superimposed upon it secondary folds; upon these again are those of the third order, and upon these those of a fourth order, and so on, until the plications in many places are microscopic. Pumpelly's principle, that these minor folds are often of the same character and usually have the same pitch as the folds of the next order of which they are a part, has been of great assistance in working out the stratigraphy of the district (Pl. XXXV).

From the foregoing description it is clear that the Marquette district is one of complex folding. In fact, no better example is known to me of this class of deformation.[1]

Where the formations are brittle the close plications have resulted in their being fractured through and through, and in many places they pass into reibungsbreccias (Pls. VII, VIII, IX, and XXVI, fig. 2). These phenomena are particularly prevalent in the Negaunee iron formation and in the quartzites. The more plastic formations have yielded without major fracturing, but in a minor way they show everywhere the effects of deformation. A microscopical study shows that not a cubic inch of material has escaped dynamic action. Almost every original grain of fair size gives evidence of interior movement. The rocks have been kneaded throughout. While, as a further consequence of dynamic action, there has been local faulting at various places, with two or three exceptions no important faults have been observed in the district.

The only fault in the district, besides that in the Republic tongue (described on pp. 541–547), large enough to materially displace the formations, is in sec. 6, T. 47 N., R. 25 W. (Atlas Sheet XXXVII). Here, in the

[1] Principles of pre-Cambrian North American geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 626–631.

FIG 1

FIG 2

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FIG 1 A PITCHING FOLD IN SIAMO SLATE
FIG. 2 FAN FOLD IN FERRUGINOUS SCHIST

southeast quarter of the section, the Carp River flows along the line of a fault, the quartzite formation being displaced laterally some hundreds of feet. The horizontal throw is here perhaps more than 500 feet, but probably less than 1,000 feet. How far this fault extends to the northwest and southeast the outcrops are insufficient to determine.

It is inferred from the phenomena of deformation that, when folded, the rocks which are now at the surface were buried under a thickness of several thousand feet of sediments, not impossibly as much as 10,000 feet. While the Upper Marquette slate has at the present time in this district no such thickness as this, in the Penokee district 10,000 feet is exceeded, and it is probable that this great slate formation once extended with nearly or quite its full thickness over the Marquette district. On the other hand, it appears that the formations were not so deeply buried as to be beyond the sustaining strength of strong rocks like quartzites, or else the layers of these rocks would have been folded upon themselves without the production of reibungsbreccias, as in the case of the Doe River quartzite in Tennessee. Had the rocks which are now exposed not been deeply covered it is hardly possible that the complicated folding above described could have occurred without complicated faulting.

As shown by the above facts, the Marquette district furnishes a beautiful instance of deformation in the lower part of the zone of combined fracture and flowage.[1]

INTRUSIVES.

Abundant altered diabase and other rocks were intruded in both the Lower Marquette and Upper Marquette series. This is shown by bosses cutting across the bedding of the layers or bending them (Pl. XI), by dikes branching off from the bosses and cutting the formations of both the Marquette series (Pl. XXX), and by large and small inclusions of grünerite-magnetite-schist in the greenstone at the Lowthian and Spurr mines (Pl. XII). The most of the intrusive greenstones are of Clarksburg or pre-Clarksburg age. They particularly affect the iron-bearing formation of the Lower

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part 1, 1896, pp. 601–603.

Marquette series, but occur within all the formations of the district. A few dikes are later than any of the Marquette sedimentary rocks. The fact that the intrusives are of far greater abundance in the broken and fractured Negaunee formation than in the other formations suggests that the cracks and crevices here produced by the folding gave avenues of access which were taken advantage of by the igneous rocks to wedge themselves in between the rocks of the iron-bearing members, to force them aside, and thus to form great dikes and bosses of igneous material. Oftentimes they break directly across the bedding (fig. 25); sometimes they produce a subordinate folding (fig. 18); but even in this latter case the material usually breaks across the bedding to a greater or less degree. In many instances there is a quaquaversal arrangement of the formations about the intrusive igneous masses, which suggests that the igneous material has been intruded along the bedding of the formation, thus forming essentially laccolites or batholites. At Michigamme and Humboldt the Siamo slate and the grünerite-magnetite-schist may be seen doming some of the smaller of the laccolites. (Pl. XI, and figs. 24 and 25.) Subsequent erosion has removed the capping iron formation from many of these larger domes and left the greenstone masses in the forms of bosses, the iron formation dipping away from them upon all sides, just as do the sedimentary formations from the Henry Mountain laccolites. The major portions of the greenstones were once diabases, but are now epidiabases. The rather fresh diabase dikes in the district may be contemporaneous with the igneous rocks of the Keweenawan period.

DENUDATION.

From the foregoing paragraphs it is evident that the rocks of the Marquette district were folded into mountain masses. The highest parts of the mountains were probably near the great north-south anticline through Marquette, and the mass next in importance was probably at the western anticline at Lake Michigamme. These major heights must have been connected by numerous cross ridges, corresponding to the close east-west folds. During and subsequent to the folding these mountains were cut down to an approximate plain, so that the district is at the present time merely bluffy. The highest point in the district, the so-called Summit Mountain, is 1,800 feet above the sea. The level of Lake Superior is 600 feet; so that the maximum relief of the district is about 1,200 feet. Beginning at the lake, there is a rapid rise to Negaunee, perhaps 10 miles, the average level there being about 1,400 feet. This eastern slope is a part of the great Lake Superior basin. From Negaunee to the west end of the district, that is, for much the larger part of the area, the variations in elevations are scarcely more than 400 feet. The present differences of elevation, with the exception of the eastward slope to Lake Superior, are mainly due to differential erosion. The hard rocks, whether jaspilites, grünerite-magnetite-schists, quartzites, conglomerates, or greenstones, occupy the higher elevations, and the soft rocks, the slates, shales, and most of the iron-formation rocks, occupy the valleys and swamps. Since the formations south of Marquette were raised high by the eastern anticline, and the whole district has been truncated to an approximate plain, it follows that in the eastern end of the district all but the lowest formations have been removed. Thus south of Marquette we find only the two lowest formations of the Marquette series. In the great syncline between the Marquette anticline and the Michigamme anticline newer and newer formations come in, until the highest member of the Upper Marquette series appears. The Michigamme anticline apparently was not so high as the Marquette anticline, and therefore the higher members of the series are exposed. However, we can not be sure that several of the remaining Marquette formations would not have been removed were the plain of denudation 600 feet lower—that is, at the elevation of Marquette.

METAMORPHISM.

The various formations of the Marquette series differ from one another in hardness and coarseness of grain. It is probable that metasomatic and cementing processes had taken place to some extent before the folding subsequent to Upper Marquette time, and thus they probably differed in strength. When this period of folding occurred the varying texture and strength were important factors in the resultant deformations, so that the readjustments necessary in the folding took place in large measure between the different formations and between dissimilar beds of each formation. As these layers were rubbed over one another schistosity was developed parallel to the bedding in many places. The unconformable contact between the Upper Marquette and Lower Marquette series was one of the greatest planes of movement, and adjacent to it the rocks of both were rendered schistose. The contact between the Archean and the Lower Marquette series was another such plane of movement, and at many places a considerable zone at the base of the Lower Marquette series was transformed into a schist, as was also a zone of the rocks of the Archean immediately below. Where the lower quartzite was thin, as in the Republic tongue, this change affected the entire basal formation. In other places, where the folding was less severe, the rocks still plainly show clastic characters.

These statements as to the adjustment between the layers and the development of schistosity parallel to the bedding do not fully apply to the nearly homogeneous Michigamme and other slates. There apparently occurred in these formations an actual flowage, the whole acting in a way as plastic material; consequently there is frequently a discrepancy between the cleavage or schistosity and the bedding. Oftentimes it happens that the schistosity nearly corresponds with the bedding on one side of a fold and cuts across it upon the other (fig. 16). In this case the complicated character of the folding and the reduplications of the beds are particularly likely to be overlooked. In the crystalline rocks constituting the Basement Complex the north-south pressure was the predominating force, and a nearly vertical schistosity has been extensively developed with an approximately east-west strike. This is particularly conspicuous in the case of the volcanic rocks which, like the Michigamme slate, were approximately homogeneous. The whole mass was mashed together, and flowage resulted in well-developed schistosity.

During the time in which the dynamic forces were at work—that is, while the folds, fractures, cleavage, and schistosity were being formed—chemical and molecular forces were active, and from the old minerals new minerals were developing. Also other mineral material was being deposited in the interstices. Thus we have quartzites or quartz-schists in place of the sandstones; slates, graywackes, mica-slates, mica-schists, or mica-gneisses in place of the shales and arkoses; and the peculiar phases of rocks of the iron-bearing formation in place of the sideritic slates.

In so far as the rocks have a slaty or schistose structure it is believed that the metamorphism was contemporaneous with the folding, but during the long period of quiescence which has subsequently occurred further extensive metasomatic and weathering changes have taken place. These appear to have been particularly potent in the iron-bearing formation, but they have also doubtless produced important changes in other rocks. In this time of quiescence must have occurred the final enrichment of the ore bodies and the extensive impregnation of the various rocks with the granular hematite and magnetite. Finally, during this period of quiescence it is believed that there developed many of the crystals of hornblende, garnet, staurolite, chloritoid, and andalusite, and much of the secondary feldspar of the mica-schists and mica-gneisses.

The metamorphism is more nearly complete in the western part of the district than in the central and eastern parts. In the western part crystalline schists are the rule for all the formations, while in the central and eastern parts of the district, excluding localities of exceptional readjustments, the rocks are semicrystalline. The varying metamorphism corresponds with the closeness of folding. In the western part of the district the folds are closer upon the average than farther to the east.

CORRELATION.

Reasons have been given in previous publications for regarding the Upper Marquette and Lower Marquette series together as the equivalent of the Huronian of the north shore of Lake Huron. These will not here be repeated. Nor will the argument be repeated for placing the Upper Marquette and Lower Marquette as the equivalent of the Upper Huronian and Lower Huronian of the other parts of the Lake Superior region.[1] Accepting these conclusions, this implies that the Lower Marquette series is to be equated with the Lower Felch Mountain and Lower Menominee series.

[1] Correlation papers, Archean and Algonkian, by C. R. Van Hise: Bull. U. S. Geol. Survey No. 86, 1892, pp. 156–199. Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Part 1, 1896, pp. 780–807.

Smyth has recently mapped in detail an area between and nearly connecting the Marquette and Menominee districts. He has made also a general study of the latter district. As the results of his studies, he summarizes the Lower Menominee succession as follows:[1]

Avoiding minute subdivisions, the Lower Menominee consists of—

(1) A basal quartzite, rarely conglomeratic. The thickness may reach a maximum of about 1,000 feet, and over large areas is at least 700 feet.

(2) A crystalline limestone which averages about 700 to 1,000 feet in thickness. On the Fence River, in Ts. 44 and 45 N., R. 31 W., where it largely if not entirely replaces the lower quartzite, the thickness attained, if there are no subordinate folds, is from 1,500 to 2,000 feet.

(3) Red, black, and green slates that are not known to exceed 200 to 300 feet in thickness. The slates here and there contain the iron formation that affords the rich ores of Iron Mountain and Norway. In the southern part of T. 44 N., R. 31 W., the horizon of the slates is in part occupied by altered eruptives that rapidly increase in thickness towards the north, the whole attaining a maximum of nearly 2,000 feet on the Fence River, in T. 45 N., R. 31 W.

(4) The highest member, except volcanics, yet recognized in the Felch Mountain and Fence River divisions of the Lower Menominee is typically developed at Michigamme Mountain, sec. 4, T. 43 N., R. 31 W., and sec. 33, T. 44 N., R. 31 W., and has been called the Michigamme jasper. This is a greatly altered ferruginous rock usually carrying apparently fragmental quartz grains. Various stages in the alteration permit two or three types to be recognized. The least modified seems to indicate that the rock was originally, in part at least, a clastic sediment. The alteration appears to have been effected by the infiltration of iron salts, the formation of cherty silica, and the replacement of the original constituents to varying degrees. The most highly altered type bears the closest possible resemblance in the hand specimen to the banded specular jasper seen on the Republic bluff.

Smyth then makes the following statement as to the Marquette district:

The Lower Marquette series, in the western part of the Marquette area, where it most nearly approaches the Menominee region, consists, when exposed, of—

(1) A basal conglomerate—quartzite—quartz-schist, probably less than 100 feet thick. North of the Michigamme mine the quartzite passes upward into a slate.

(2) An iron-bearing formation which may be divided further into a lower member, composed of actinolite (or grünerite), magnetite, and silica, one or two of which may locally predominate over the rest, and an upper member usually, but not invariably,

[1] The Lower Menominee and Lower Marquette series in Michigan, by H. L. Smyth: Am. Jour. Sci., 3rd series, Vol. XLVII, 1894, pp. 216–223.

characterized by bands of red jasper and specular hematite. The iron-bearing member has a maximum thickness of more than 1,000 feet, but usually it has been cut down greatly, or with the lower quartzite entirely, by the Animikie transgression.

The Marquette iron ores, except those on the Upper Marquette series, occur, as Van Hise has shown, either (*a*) at the contact of the lower iron-bearing member with the upper quartzite, when the ore may be either a concentration in the lower iron-bearing member or a detrital member of the upper series, or, (*b*) more rarely, entirely within the iron-bearing member of the lower series.

These descriptions are expressed briefly in the following table, in which the members of the two series are shown in parallel columns for lithological comparison:

Menominee.	*Marquette.*	
Michigamme jasper	Jasper banded with ore.	Iron formation.
Slates (principal iron formation)	Magnetite-actinolite schist.	
Limestone	Quartzite.	
Quartzite		
Archean	Archean.	

Smyth traces the magnetic Michigamme jasper to within 1½ or 2 miles of the iron-bearing formation of the Marquette series, and he regards the two as equivalent. Toward the north the Michigamme jasper is found to have a lower quartzitic portion, which he places as equivalent to the lower quartzite of the Marquette district.

The whole of the Lower Marquette series would thus be represented by the highest member of the Lower Menominee. What, then, becomes in the Marquette district of the great thickness of limestone, quartzite, and eruptives which lie below the Michigamme jasper in the Menominee, and how is its absence to be accounted for?

The most probable explanation is that the pre-Algonkian basement sank continuously in both districts, but that the Marquette was initially the more elevated, and as a whole was dry land, while the lower quartzite, limestone, and slates were going down in the Menominee. The transgressive movement from the south reached it when the lower portion of the Michigamme jasper was being deposited.

In this discussion Smyth includes under the name Menominee the area which has heretofore been called the Menominee district, and the large connecting area to the north, which is as yet largely undeveloped, and which will later be described in a monograph entitled The Crystal Falls and Metropolitan Iron-Bearing Districts of Michigan. For convenience in discussion the term Menominee will here be used in the sense given it by Smyth.

The chief point upon which more evidence is necessary is the relation of the slates bearing the rich iron ores in the Menominee district proper to the slates associated with the volcanics farther north in the connecting district. If the Menominee slates are different from those to the north and belong above them, the succession in the two districts would be very closely analogous. Using the succession for the entire Marquette district which we have made out, and comparing it with Smyth's succession in his Menominee district, we have the following parallel descending succession:

Upper Marquette.	*Upper Menominee.*
UNCONFORMITY.	
Lower Marquette.	*Lower Menominee.*
Negaunee iron formation, 1,000 to 1,500 feet	Michigamme jasper. Slates bearing rich ores.
Siamo slate, in places including interstratified amygdaloids, 200 to 625 feet thick	Slates and altered volcanics, maximum thickness, 2,000 feet.
Ajibik quartzite, 700 to 900 feet	
Wewe slate, 550 to 1,050 feet	
Kona dolomite, 550 to 1,375 feet	Crystalline dolomite, 700 to 1,000 feet.
Mesnard quartzite, 100 to 670 feet	Basal quartzite, 700 to 1,000 feet.

The succession for the lower series would thus be very closely parallel in the two districts, with the following exceptions:

(1) The Wewe slate, the Ajibik quartzite, and the Siamo slate are placed opposite one member of the Menominee series. These three formations are, however, all fragmental and are equated with a fragmental formation. Together they mark a time of mechanical deposition in each district between the nonfragmental limestone and the nonfragmental iron formation, and thus include the physical change involved in passing from a nonfragmental to a fragmental and then again to a nonfragmental formation. The chief difference is that in the Marquette district two layers of mud were separated by a layer of sand. Another difference is that in the Menominee district volcanics are much more important, and this may account for the absence of conditions favorable to sand deposits. However, it is interesting to note that amygdaloids are found in the Lower Marquette

series, in the Siamo slate—that is, toward the higher part of this great fragmental formation. The Fence River volcanics, in the Menominee district, occupy a similar horizon.

(2) The pure, nonfragmental iron formation of the Marquette district is equated with slates, cherts, jaspers, and the rich ores of the Menominee district. The only substantial difference, however, is that in the Menominee district the rocks bear, with the nonfragmental, a considerable amount of fragmental material. In other words, the conditions in that district were not favorable to pure nonclastic sediments, as they were in the Marquette district.

As there thus seem to be closely parallel successions in the two districts in early Marquette time, it seems highly probable that the western part of the Marquette district, where the lower members of the series do not appear, must have been a high area largely or completely surrounded by water, since the lower members of the series were deposited to the southeast and northeast. This elevated tract included the area west of Ishpeming and Negaunee to Lake Michigamme and thence south to Republic. How much farther it extended to the west, and whether it was an island or a peninsula, it is yet too early to venture an opinion.

Until more detailed studies are made of the Upper Huronian rocks in the Menominee district it is unsafe to attempt a detailed correlation of the formations of the Upper Marquette series with the formations there found. In both districts there are certain general likenesses. The basal formation in each district is frequently an ore and jasper conglomerate, which passes up into a quartzite. In both the Marquette and Menominee districts, not far above this quartzite, near to or associated with the slates, is an iron-bearing formation. The upper predominant formation was a shale, which has been metamorphosed to a mica-slate or mica-schist.

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[Monograph XXVIII.]

The statute approved March 3, 1879, establishing the United States Geological Survey, contains the following provisions:

"The publications of the Geological Survey shall consist of the annual report of operations, geological and economic maps illustrating the resources and classification of the lands, and reports upon general and economic geology and paleontology. The annual report of operations of the Geological Survey shall accompany the annual report of the Secretary of the Interior. All special memoirs and reports of said Survey shall be issued in uniform quarto series if deemed necessary by the Director, but otherwise in ordinary octavos. Three thousand copies of each shall be published for scientific exchanges and for sale at the price of publication; and all literary and cartographic materials received in exchange shall be the property of the United States and form a part of the library of the organization: And the money resulting from the sale of such publications shall be covered into the Treasury of the United States."

Except in those cases in which an extra number of any special memoir or report has been supplied to the Survey by special resolution of Congress or has been ordered by the Secretary of the Interior, this office has no copies for gratuitous distribution.

ANNUAL REPORTS.

I. First Annual Report of the United States Geological Survey, by Clarence King. 1880. 8°. 79 pp. 1 map.—A preliminary report describing plan of organization and publications.

II. Second Annual Report of the United States Geological Survey, 1880–'81, by J. W. Powell. 1882. 8°. lv, 588 pp. 62 pl. 1 map.

III. Third Annual Report of the United States Geological Survey, 1881–'82, by J. W. Powell. 1883. 8°. xviii, 564 pp. 67 pl. and maps.

IV. Fourth Annual Report of the United States Geological Survey, 1882–'83, by J. W. Powell. 1884. 8°. xxxii, 473 pp. 85 pl. and maps.

V. Fifth Annual Report of the United States Geological Survey, 1883–'84, by J. W. Powell. 1885. 8°. xxxvi, 469 pp. 58 pl. and maps.

VI. Sixth Annual Report of the United States Geological Survey, 1884–'85, by J. W. Powell. 1885. 8°. xxix, 570 pp. 65 pl. and maps.

VII. Seventh Annual Report of the United States Geological Survey, 1885–'86, by J. W. Powell. 1888. 8°. xx, 656 pp. 71 pl. and maps.

VIII. Eighth Annual Report of the United States Geological Survey, 1886–'87, by J. W. Powell. 1889. 8°. 2 pt. xix, 474, xii pp. 53 pl. and maps; 1 p. l. 475–1063 pp. 54–76 pl. and maps.

IX. Ninth Annual Report of the United States Geological Survey, 1887–'88, by J. W. Powell. 1889. 8°. xiii, 717 pp. 88 pl. and maps.

X. Tenth Annual Report of the United States Geological Survey, 1888–'89, by J. W. Powell. 1890. 8°. 2 pt. xv, 774 pp. 98 pl. and maps; viii, 123 pp.

XI. Eleventh Annual Report of the United States Geological Survey, 1889–'90, by J. W. Powell. 1891. 8°. 2 pt. xv, 757 pp. 66 pl. and maps; ix, 351 pp. 30 pl. and maps.

XII. Twelfth Annual Report of the United States Geological Survey, 1890–'91, by J. W. Powell. 1891. 8°. 2 pt. xiii, 675 pp. 53 pl. and maps; xviii, 576 pp. 146 pl. and maps.

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"*Provided*, That hereafter the reports of the Geological Survey in relation to the gauging of streams and to the methods of utilizing the water resources may be printed in octavo form, not to exceed one hundred pages in length and five thousand copies in number; one thousand copies of which shall be for the official use of the Geological Survey, one thousand five hundred copies shall be delivered to the Senate, and two thousand five hundred copies shall be delivered to the House of Representatives, for distribution."

Under this law the following paper has been issued:

1. Pumping Water for Irrigation, by Herbert M. Wilson.

GEOLOGIC ATLAS OF THE UNITED STATES.

The Geologic Atlas of the United States is the final form of publication of the topographic and geologic maps. The atlas is issued in parts, progressively as the surveys are extended, and is designed ultimately to cover the entire country.

Under the plan adopted the entire area of the country is divided into small rectangular districts, bounded by certain meridians and parallels. The unit of survey is also the unit of publication, and the maps and descriptions of each rectangular district are issued as a folio of the Geologic Atlas.

Each folio contains topographic, geologic, economic, and structural maps, together with textual descriptions and explanations, and is designated by the name of a principal town or of a prominent natural feature within the district.

Two forms of issue have been adopted: A *library* edition, bound between heavy paper covers and stitched; and a *field* edition, similarly bound, but unstitched.

Under the law a copy of each folio is sent to certain public libraries and educational institutions. A limited number of copies are reserved for distribution to persons specially interested in the region represented. This distribution is at first gratuitous, but when the remaining number of copies of any folio reaches a certain minimum a charge equivalent to cost of publication will be made. In such cases prepayment is obligatory. The folios ready for distribution are listed below.

No.	Name of sheet.	State.	Limiting meridians.	Limiting parallels.	Area, in square miles.	Price, in cents.
1	Livingston*	Montana	110°-111°	45°-46°	3,354	25
2	Ringgold*	Georgia Tennessee	85°-85° 30′	34° 30′-35°	980	25
3	Placerville*	California	120° 30′-121°	38° 30′-39°	932	25
4	Kingston*	Tennessee	84° 30′-85°	35° 30′-36°	969	25
5	Sacramento*	California	121°-121° 30′	38° 30′-39°	932	25
6	Chattanooga*	Tennessee	85°-85° 30′	35°-35° 30′	975	25
7	Pikes Peak*	Colorado	105°-105° 30′	38° 30′-39°	932	25
8	Sewanee*	Tennessee	85° 30′-86°	35°-35° 30′	975	25
9	Anthracite-Crested Butte*	Colorado	106° 45′-107° 15′	38° 45′-39°	465	50
10	Harpers Ferry*	Virginia West Virginia Maryland	77° 30′-78°	39°-39° 30′	925	25
11	Jackson*	California	120° 30′-121°	38°-38° 30′	938	25
12	Estillville*	Virginia Kentucky Tennessee	82° 30′-83°	36° 30′-37°	957	25
13	Fredericksburg*	Maryland Virginia	77°-77° 30′	38°-38° 30′	938	25
14	Staunton*	Virginia West Virginia	79°-79° 30′	38°-38° 30′	938	25
15	Lassen Peak*	California	121°-122°	40°-41°	3,634	25
16	Knoxville*	Tennessee North Carolina	83° 30′-84°	35° 30′-36°	925	25
17	Marysville*	California	121° 30′-122°	39°-39° 30′	925	25
18	Smartsville*	California	121°-121° 30′	39°-39° 30′	925	25
19	Stevenson*	Alabama Georgia Tennessee	85° 30′-86°	34° 30′-35°	980	25
20	Cleveland*	Tennessee	84° 30′-85°	35°-35° 30′	975	25
21	Pikeville*	Tennessee	85°-85° 30′	35° 30′-36°	969	25
22	McMinnville*	Tennessee	85° 30′-86°	35° 30′-36°	969	25
23	Nomini*	Maryland Virginia	76° 30′-77°	38°-38° 30′	938	25
24	Three Forks	Montana	111°-112°	45°-46°	3,354	50
25	Loudon	Tennessee	84°-84° 30′	35° 30′-36°	969	25
26	Pocahontas	Virginia West Virginia	81°-81° 30′	37°-37° 30′	951	25
27	Morristown	Tennessee	83°-83° 30′	36°-36° 30′	963	25
28	Piedmont	Virginia Maryland West Virginia	79°-79° 30′	39°-39° 30′	925	25
29	Nevada City: Nevada City Grass Valley Banner Hill	California	121° 00′ 25″-121° 03′ 45″ 121° 01′ 35″-121° 05′ 04″ 120° 57′ 05″-121° 00′ 25″	39° 13′ 50″-39° 17′ 16″ 39° 10′ 22″-39° 13′ 50″ 39° 13′ 50″-39° 17′ 16″	11.65 12.09 11.65	50
30	Yellowstone National Park: Gallatin Canyon Shoshone Lake	Wyoming	110°-111°	44°-45°	3,412	75

* These folios can now be sent only on prepayment of price stated in the last column.

STATISTICAL PAPERS.

Mineral Resources of the United States [1882], by Albert Williams, jr. 1883. 8°. xvii, 813 pp. Price 50 cents.

Mineral Resources of the United States, 1883 and 1884, by Albert Williams, jr. 1885. 8°. xiv, 1016 pp. Price 60 cents.

Mineral Resources of the United States, 1885. Division of Mining Statistics and Technology. 1886. 8°. vii, 576 pp. Price 40 cents.

Mineral Resources of the United States. 1886, by David T. Day. 1887. 8°. viii, 813 pp. Price 50 cents.

Mineral Resources of the United States, 1887, by David T. Day. 1888. 8°. vii, 832 pp. Price 50 cents.

Mineral Resources of the United States, 1888, by David T. Day. 1890. 8°. vii, 652 pp. Price 50 cents.

Mineral Resources of the United States, 1889 and 1890, by David T. Day. 1892. 8°. viii, 671 pp. Price 50 cents.

Mineral Resources of the United States, 1891, by David T. Day. 1893. 8°. vii, 630 pp. Price 50 cents.

Mineral Resources of the United States, 1892, by David T. Day. 1893. 8°. vii, 850 pp. Price 50 cents.

Mineral Resources of the United States, 1893, by David T. Day. 1894. 8°. viii, 810 pp. Price 50 cents.

On March 2, 1895, the following provision was included in an act of Congress:

"*Provided*, That hereafter the report of the mineral resources of the United States shall be issued as a part of the report of the Director of the Geological Survey."

In compliance with this legislation, the report Mineral Resources of the United States for the Calendar Year 1894 forms Parts III and IV of the Sixteenth Annual Report of the Survey, and Mineral Resources of the United States for the Calendar Year 1895 forms Part III of the Seventeenth Annual Report of the Survey.

The money received from the sale of these publications is deposited in the Treasury, and the Secretary of that Department declines to receive bank checks, drafts, or postage stamps; all remittances, therefore, must be by MONEY ORDER, made payable to the Director of the United States Geological Survey, or in CURRENCY for the exact amount. Correspondence relating to the publications of the Survey should be addressed

To the Director of the
United States Geological Survey,
Washington, D. C.

Washington, D. C., *February, 1897.*

LIBRARY CATALOGUE SLIPS.

Series.

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Department of the interior | — | Monographs | of the | United States geological survey | Volume XXVIII | [Seal of the department] | Washington | government printing office | 1897

Second title: United States geological survey | Charles D. Walcott, director | — | The | Marquette iron-bearing district of Michigan | with | atlas | by | Charles Richard Van Hise and William Shirley Bayley | including | a chapter on the Republic trough | by | Henry Lloyd Smyth | [Vignette] |

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Author.

Van Hise (Charles Richard), **Bayley** (William Shirley), and **Smyth** (Henry Lloyd).

United States geological survey | Charles D. Walcott, director | — | The | Marquette iron-bearing district of Michigan | with | atlas | by | Charles Richard Van Hise and William Shirley Bayley | including | a chapter on the Republic trough | by | Henry Lloyd Smyth | [Vignette] |

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[UNITED STATES. *Department of the interior.* (*U. S. geological survey.*) Monograph XXVIII.]

Subject.

United States geological survey | Charles D. Walcott, director | — | The | Marquette iron-bearing district of Michigan | with | atlas | by | Charles Richard Van Hise and William Shirley Bayley | including | a chapter on the Republic trough | by | Henry Lloyd Smyth | [Vignette] |

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