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DEPARTMENT OF THE INTERIOR

U. S. GEOGRAPHICAL AND GEOLOGICAL SURVEY OF THE ROCKY MOUNTAIN REGION

J. W. POWELL, IN CHARGE

REPORT

ON THE

GEOLOGY OF THE HIGH PLATEAUS OF UTAH

WITH ATLAS

By C. E. DUTTON
CAPTAIN OF ORDNANCE, U. S. A.

WASHINGTON
GOVERNMENT PRINTING OFFICE
1880

WASHINGTON, D. C., *April* 19, 1880.

SIR: Herewith I have the honor to transmit a report of explorations and studies in Utah Territory prosecuted during the years 1875, 1876, and 1877, in connection with the survey of Maj. J. W. Powell, under the Interior Department. This report is made in conformity with Special Orders of the War Department No. 90, May 13, 1875; No. 134, July 3, 1876; No. 89, April 26, 1877, which require that the report be made to the Secretary of War.

I respectfully request that the report may be forwarded to the honorable the Secretary of the Interior, with a view to its publication in connection with the survey work of Major Powell.

Very respectfully, sir, your obedient servant,

C. E. DUTTON,
Captain of Ordnance.

The Hon. SECRETARY OF WAR,
(Through the Chief of Ordnance, U. S. A.)

[Indorsement.]

ORDNANCE OFFICE, WAR DEPARTMENT,
Washington, April 20, 1880.

Respectfully submitted to the Secretary of War. Approved.

S. V. BENÉT,
Brigadier-General, Chief of Ordnance.

WAR DEPARTMENT,
Washington City, April 22, 1880.

SIR: I have the honor to transmit herewith a report of Capt. C. E. Dutton, of the Ordnance Department, of explorations and studies in Utah, prosecuted during the years 1875, 1876, and 1877, in connection with the survey of J. W. Powell, under the Interior Department.

In accordance with the wishes of Captain Dutton I respectfully request that the report referred to may be published in connection with the survey work of Major Powell.

Very respectfully, your obedient servant,

ALEXANDER RAMSEY,
Secretary of War.

The Hon. SECRETARY OF THE INTERIOR.

[Indorsement.]

DEPARTMENT OF THE INTERIOR,
April 23, 1880.

Respectfully referred to Maj. J. W. Powell.

GEO. M. LOCKWOOD,
Chief Clerk.

PREFATORY NOTE.

BY THE DIRECTOR OF THE SURVEY.

The Colorado Plateaus extend from southern Wyoming through western Colorado and eastern Utah far into New Mexico and Arizona. They are bounded on the north by the Wind River and Sweetwater Mountains, on the east by the Park Mountains, on the south by the Desert Range Region, and on the west by the Basin Range Region.

The Plateaus are chiefly drained by the Colorado River, but a small area on the northwest is drained into Shoshone River, another on the northeast into the Platte River, still another on the southeast into the Rio Grande del Norte, and finally the western margin is drained by the upper portions of the Sevier, Provo, Ogden, Weber, and Bear Rivers. The general elevation is about 7,000 feet above the level of the sea—varying from 5,000 to 12,000 feet. The ascent from the low, desert plains on the south is very abrupt—in many places by a steep and almost impassable escarpment In the Plateau Province an extensive series of sedimentary formations appear, embracing Paleozoic, Mesozoic, and Tertiary strata, but crystalline schists and granites are found in some of the deep cañons.

A marked unconformity exists between the Silurian and Devonian rocks; another between the Devonian and Carboniferous; another, but not so well marked, between the Carboniferous and Mesozoic, and lastly an unconformity between Cretaceous and Tertiary is usually well defined. The Plateaus have been above the sea since the close of the Cretaceous period but during early Tertiary times extensive lakes existed throughout the Province. In Mesozoic and Tertiary times the Basin Province to the west was the principal source of the materials deposited in the Plateau Province. In general, each formation is exceedingly persistent and homogeneous in its characteristics, but in passing from one formation to another in the vertical scale great heterogeneity is observed. To a very large extent the formations still lie in a horizontal or nearly horizontal position. The entire surface is traversed by faults or their homolognes, monoclinal flexures, having in general a north and south direction. Following any given line of displacement frequent transitions from faulting to flexure are observed. The method of transition is variable; sometimes the flexed beds are found to be partially faulted so that the throw is part by faulting and part by flexure; sometimes a great fault divides into two or more minor ones in such a manner that the entire throw is accomplished by a series of steps. Still other importaut phenomena are observed in these faults; to explain them, the terms *throw* and *upheaval* are used as relative to each other. In the cases to be described the upheaved beds have their edges flexed upwards. This is explained in the following manner: First, a displacement occurred by flexure; second, another displacement, reversing the first, occurred by faulting, so that the thrown beds of the first displacement were the upheaved beds of the second. The evidence of this reversed action is sometimes exhibited in beds deposited at a time intervening between the two movements; in this manner the beds last deposited are displaced only by the last movement. This reversal of displacement along the same plain or zone is frequently seen. It is sometimes by faulting and sometimes by flexure, thus giving rise to many complications in the positions of strata. The great displacements began in early Tertiary time, and are probably yet in progress. The evidences of the recency of some of these movements appear in the escarpments frequently seen along the line of faults where Quaternary beds have been broken at a time so recent that the escarpments have not been destroyed by atmospheric agencies, and further evidence is exhibited in the small amount of talus frequently found at the foot of a recently formed fault-scarp. By these displacements the region is divided into blocks with a north and south trend; but this geologic characteristic serves only in part to divide the region into plateaus.

The streams which traverse the region have their sources in the Wind

River Mountains on the north; in the Park Mountains on the east, and a number of tributaries come from the west. In their courses through the plateaus they run in cañons. These cañons are profound gorges corraded by the streams themselves. The "country rock" of the region is composed of sedimentary beds, nearly horizontal, as already stated. The region is also excessively arid, but the mountains that stand on the rim of the basin precipitate a large proportion of moisture, and in this manner streams of comparatively large volume head in the mountains, run through the plateaus and descend rapidly to the level of the sea, while the country through which they pass is very meagerly supplied with moisture. Under these conditions the profound gorges have been cut, as the process of cañon cutting is more rapid than the lateral degradation of the country. In this manner every river runs in a deep gorge, and these cañons further serve to divide the region into plateaus.

The division is completed by lines of cliffs. These cliffs are bold escarpments hundreds and thousands of feet in altitude—grand steps by which the region is terraced. As the rivers corrade their channels more rapidly than general degradation is carried on, the stratigraphic conditions of the horizontal beds play a very important part in the method of degradation. Here degradation by surface erosion is less and degradation by sapping greater, and thus the walls of the cañons retreat slowly in a series of steps by this sapping process. Softer beds easily yield to atmospheric agencies, while harder beds resist and stand in bold escarpments.

Thus by faults and monoclinal flexures, by deep cañons, and by lines of cliffs the surface is cut into a great number of plateaus.

In addition to the Plateaus proper, there are mountains due to upheaval and degradation. The more important of these are the Zuñi Range, to the south, and the Uinta Range, far to the north. The Uinta Range is carved from a broad upheaval having an east and west axis. On either flank of the upheaval there is a line or zone of maximum displacement where the upheaval is by flexure or by faulting. Between these zones there is a gentle flexure either way to the axis. Thus the upheaval is in part by general flexure from the axis as an anticlinal, and in part by faulting and monoclinal flexure, as in the Kaibab structure. Again there are small areas which are zones of diverse displacement: these districts are broken into smaller blocks by faults and flexures, and often the blocks have been excessively tilted and warped in diverse directions. On the flanks of plateaus and mountain systems of the Uinta type where monoclinal flexures occur monoclinal ridges are frequently seen The position of these monoclinal ridges is frequently varied by the occurrence of transverse faults. Where a great Kaibab, Uinta, or anticlinal upheaval is found broken by a transverse fault, that portion of the grand upheaval which has the greater amplitude will have its monoclinal ridges placed more distant from the axis of upheaval and that portion which has the less amplitude will have its monoclinal ridges nearer the axis. In this manner, by vertical movements in transverse faulting, the monoclinal ridges may be placed back and forth from the axis of grand upheaval in such a manner as to give the appearance of lateral faulting, *i. e.*, faulting in a horizontal direction.

On the plateaus stand buttes, lone mountains, and groups of mountains.

The buttes are mountain cameos, composed of horizontal strata with escarped sides—they are mountains of circumdenudation.

The mountains are composed in whole or in part of extravasated matter and may be classed structurally under three types.

I. Those having the HENRY MOUNTAIN STRUCTURE—where the locus of volcanic deposition is below the base level of degradation.

II. Those having the TUSHAR STRUCTURE—where the locus of volcanic deposition is at the base level of degradation.

III. Those having the UINKARET STRUCTURE—where the locus of extravasation is above the base level of degradation.

In the first, the mountains are composed in part of volcanic and in part of sedimentary materials. The volcanic matter exists as laccolites, over which sedimentary strata have extended in great mountain domes, but such strata may have been carried away, more or less, by atmospheric degradation. In this class each mountain is a mass of volcanic material, with sedimentary beds upon its flanks, and often these sedimentary beds extend high up or even quite over the volcanic materials.

In the second, the mountains are composed wholly of volcanic materials erected upon a base of sedimentary strata. The mass is composed of many outflows, which are often separated by unconformities due to intervening atmospheric degradation.

In the third, the mountains are composed in part of sedimentary and in part of extravasated materials. The sedimentary beds constitute the central masses, over which extravasated rocks are spread. The locus of extravasation being above the general base level of degradation, as the adjacent country was carried away by atmospheric agencies the underlying sedimentaries were protected and left as mountain masses. Usually the extravasation has been continued from time to time through a series of vents marked by cinder cones, and in a general way the earlier ones appear nearer the summit of the mountain masses, the later ones nearer the base. In this manner the several sheets are inversely imbricated; that is, the upper edge of the lower sheet is placed on the lower edge of the upper sheet. "Table Mountains," with caps of lava, are the simplest forms of this structure.

There are many varieties of each of these grand classes, and through them the systems of structure coalesce in such a manner that the characteristics of demarkation are not absolute.

The Colorado Plateaus may be divided into a number of groups, based on topographic and geologic characteristics, of which the High Plateaus constitute one of the most important. The great tabular masses are composed of sedimentary formations of early Tertiary and late Cretaceous age, nearly or quite horizontal and usually capped with formations of extravasated matter. These lavas are of exceedingly complex arrangement. The period of volcanic activity was long, and between the outbreaks atmospheric degradation, local transportation, and deposition intervened. To unravel these complexities and discover the line of sequence has been a task of great magnitude. In the earlier explorations of this country under the direction of the writer, the general sequence of sedimentary formations was discovered, as well as the general characteristics of displacement, many of its principal faults had been traced, and the origin of the cliffs and cañons was known. All this was the result of a series of reconnaissance surveys. But the principal work of the geological survey of the region still awaited accomplishment. It was necessary that the sedimentary formations should be studied in detail, that the great structure lines, the faults and flexures, should be carefully traced, and the displacements determined quantitatively; but the most important part of the investigation to be made was presented in the study of the volcanic formations, which are the chief characteristics of the group of High Plateaus. No systematic work had been done in this field. Our knowledge of it was chiefly confined to its geographic extent and to a general belief that an extensive series of volcanic rocks would be found, and that the subject was of great complexity. At this stage Capt. C. E. Dutton, of the Ordnance Corps, was induced to undertake the investigation. Three seasons were devoted by him to field labor, and the intervening months were chiefly given to laboratory study of the materials collected in the field. With great labor and skill the work has been accomplished, and its results are presented in this volume, which will be found to extend our knowledge of the geology of the United States and to be an important contribution to geologic philosophy.

To a large extent the sedimentary region embraced in the survey of which this volume treats is destitute of vegetation and soil and its rocks are so naked that good sections are obtainable on every hand. Again, the region is dissected by deep cañons. From both of these reasons the geology is plainly revealed. Every fault, every flexure, the relations of successive strata, unconformities, and all facts of structure are seen at once. But there are two sonrces of obscnrity. First, some of the highest plateaus are covered with forests and vegetation. Second, the extravasated rocks are aggregated in a much more confused manner than the sedimentary beds, and greater labor and care is reqnired in tracing them, and after the utmost care uncertainties and doubts remain. Thus it is that in describing the structural geology of the region the details of examination do not appear as in reports on regions of country less favorable to geologic examination. To a large extent, also, the details of structure are omitted from the text and appear in the graphic illustrations which accompany the report. It has been the policy of the survey to relieve its reports to the utmost extent of bnrdensome details of verbiage, by presenting them, as far as possible, through graphic methods to the eye.

The early reconnaissance of the country was in part made by Mr.

E. E. Howell, whose elaborate notes were placed in the hands of Captain Dutton, and from time to time he has in his volume given Mr. Howell credit for the material which he has used. It was unfortunate for Mr. Howell that his labor was suspended prematurely, and that he was not able to elaborate a report upon the country studied by him.

The geography of the district, as exhibited in the atlas accompanying this volume, was the study of Prof. A. H. Thompson, who was my assistant in charge of that branch of the work during the earlier years of exploration and survey. Through his skill and industry the geography has been represented with all the accuracy and detail that the adopted scale will permit.

I am especially indebted to Brig. Gen. S. V. Benét, chief of the Ordnance Bureau, for the interest he has taken in the geologic and geographic researches prosecuted by the survey under my direction. Through the wise policy of administration adopted by him, Captain Dutton has been enabled to carry on his labors as a geologist outside of the general operations of the Ordnance Bureau. The contribution to science which he here presents will abundantly justify the course pursued by his distinguished chief.

To the Secretary of War and the General of the Army, the survey is indebted for assistance rendered in various ways—especially in furnishing subsistance to field parties from the commissariat of the Army, but chiefly in the opportunity given Captain Dutton to prosecute his researches.

J. W. POWELL.

APRIL 1880.

PREFACE.

In the year 1874 my kind friend Prof. J. W. Powell proposed to me that I should undertake, under his direction, the study of a large volcanic tract in the Territory of Utah, provided the consent of proper authority could be entertained. Distrusting my own fitness for the work, I felt that it would be better for him if his proposals were thankfully declined. In 1875, however, he renewed the proposition in such a friendly and complimentary manner that a refusal seemed ungracious. He therefore laid the matter before the Secretary of War, the General of the Army, and the Chief of Ordnance, all of whom gave their cordial approbation; and by order of the War Department I was detailed for duty in connection with the survey of the Rocky Mountain Region in charge of Professor Powell. The field which he assigned me to study was the District of the High Plateaus, and the investigations were made during the summers of 1875, 1876, and 1877. The preparation of a report or monograph upon the district has several times been interrupted by the pressure of other official duties to which the writer has been assigned during the last three years.

In submitting this work, the dominant feeling in my own mind is a keen sense of its many imperfections and a consciousness that it falls far short of my hopes and expectations. The defects have arisen in a great measure from want of experience in western geological field work prior to the inception of this undertaking, and especially from want of observation in the class of phenomena of which the work principally treats. Probably, also, the magnitude of the task proposed was too great even for much more experienced observers to accomplish within the time allotted to it. It involved not only a study of the immediate district under discussion, but the investigation of large areas surrounding it to which the district stands in intimate relations. In the brief season during which work in such a region is practicable the investigation must be pushed with the utmost vigor and rapidity, and the greatest portion of the time must be devoted to acquiring a general and connected view of the broader features, while details cannot often receive the attention which their importance really demands. From the nature of the case, therefore, the work must be somewhat superficial in many respects.

In preparing a monograph upon this district, it has been necessary to lay the greatest stress upon a few subjects of inquiry, and these would naturally be those which the facts most fully exemplify. It was important, however, at the beginning to discuss it as a part of a great geological province, in which are found certain categories of facts possessing a peculiar interest, displayed in a remarkable manner, and of the highest importance to physical geology. The "Plateau Country" of the west is, I firmly believe, destined to become one of the most instructive fields of research which geologists in the future will have occasion to investigate. Of its subdivisions the District of the High Plateaus is one of the most important, and the relations of the district to the province were studied with great care. The results of those studies are set forth in general terms in the first two chapters.

In the treatment of geological phenomena occurring within the district the investigation has been devoted chiefly to three lines of inquiry. The first is geological structure—those attitudes of the strata and the topographical forms which have been caused by the vertical movements of the rocks. The displacements which have occurred there are very striking both in respect to their magnitude and to their systematic arrangement. In their forms and modes of occurrence they are also somewhat peculiar, especially when brought into comparison with displacements found in other regions. Ultimately such facts must take their place in that branch of geological philosophy which treats of the evolution of the earth's physical features, the building of mountains, and the elevation of continents and plateaus; but at present the observed facts do not appear to group themselves into the relation of effects to causes. The broader facts relating to structure are discussed in the second chapter.

The second and principal subject of investigation comprises volcanic phenomena. The High Plateaus are in chief part a great volcanic area, in which eruptions have occurred upon a grand scale. The period of activity has been a very long one, its initial epoch having been not far from the Middle Eocene; and the eruptions have occurred with probably long intervals of repose throughout the remainder of Tertiary and Quaternary time, the most recent ones having to all appearances taken place only a few centuries ago. The variety of eruptive products is exceedingly great, all of the commoner kinds from the very acid to the very basic groups being well represented. The preponderating masses are trachytic, but rhyolites, andesites (including propylites), and basalts are found in great abundance. Perhaps the most striking masses were the accumulations of fragmental volcanic products—the beds of conglomerate and tufa, which occur in prodigious volume, especially in the central and southern portions of the district. These proved to be extremely interesting, yielding many themes of inquiry and speculation.

It would have been impossible, under the circumstances, to apply to a region so extensive, so varied, and so ancient, the exhaustive analysis which Scrope has given to the volcanoes of the Auvergne or Geikie to the volcanic rocks of the Basin of the Forth. Of all geological investigations the most difficult are those relating to volcanology. Where the accumulations are of great extent the student for a long time recognizes nothing but confusion, and the difficulty of evoking anything like order and a succession of events is about proportional to the amount of extravasation. And where the atmospheric forces have through long periods been at work destroying the piles which have been built up by eruption, the difficulty is still further augmented. Individual facts, indeed, are numerous and even bewildering by their number and variety. But we want something more than facts; we want their order, their relations, and their meaning; and it is rare to find the facts and relations so displayed that they are readily discerned and comprehended. It seemed best, therefore, to limit the inquiry to a very few questions. The one which was regarded with the most interest had reference to the Order of Succession of Volcanic Eruptions. Since the publication of Richthofen's "Memoir on a Natural System of Volcanic

Rocks," this subject has been of peculiar interest to American students of western geology. The discussion of it as applied to the District of the High Plateaus will be found in the third chapter.

The great conglomerates composed of fragmental volcanic materials also furnished an interesting subject of inquiry. There are many other districts in the West where similar masses are found sometimes in even greater quantity, and their origin and mode of accumulation became an attractive problem. That these formations are accumulations of ejected fragments seemed inadmissible, and the further the investigation proceeded the more untenable did this view appear to be. While great bodies of tufaceous matter are usually found surrounding volcanic orifices, the conglomerates in question do not conform either in the structure of the beds or in the distribution of their masses to those of ordinary tufa cones. At the present time there are now accumulating in the valleys between the great tables extensive alluvial formations, which upon careful examination seem to correspond closely to the older conglomerates now exposed in the palisades of the plateaus, and the conclusion was reached that the ancient conglomerates and modern alluvia were produced by the same process. The discussion of these formations is contained in the tenth chapter, and the conclusions are embodied in the latter part of the third chapter.

Another interesting subject was the metamorphism of clastic beds derived from the detritus of volcanic rocks, and it is treated in the latter part of the eleventh chapter relating to the East Fork Cañon in the Sevier Plateau.

Very naturally one of the most prominent objects of investigation was to find the localities in which were situated the vents or orifices from which the great eruptive masses were outpoured. In the case of the basalts, which are comparatively recent in their dates of eruption, there was in most cases no difficulty. But with the older rocks, the rhyolites, trachytes, and andesites, it is quite different. Some of the rhyolites show very plainly even to the most superficial investigation whence they came. Others do not. So powerfully have the destroying agents wrought upon the old volcanic piles, and so vast is the mass which has been torn down and scattered, that the work of restoration is exceedingly difficult. The task of finding the old centers, however, is by no means impossible. In a considerable number of cases the larger and more important centers are still discernible, though some are doubtful and exceedingly indistinct. The obscurity probably arises in many cases from the fact that while the greater accumulations of lavas outflowed from great central vents or from *loci* within which numerous vents were thickly clustered in close proximity, there were numberless scattered orifices from which a few eruptions or even a single eruption took place. And these dispersed vents were probably scattered about in the intervals between the central localities of eruption. Such craters would in the lapse of ages be wholly obliterated, and their outpoured masses reduced to mere remnants The general effect of secular decay has been to level the volcanic piles and build up the lowlands with the *débris*. On the other hand, the great faults have brought up to daylight masses of bedded lavas which otherwise would have been concealed, and erosion has in many places attacked the faulted edges of the upraised blocks and sawed deep ravines and chasms in which the igneous masses are tolerably well displayed. Thus we are enabled to gain information concerning the location of the centers of eruption which would otherwise have been unattainable. But the knowledge so gained is far less perfect than is desirable.

Although it may seem that an investigation of such importance ought to be easy, it is by no means so. The vastness of the masses displayed at any center of eruption is such that no conception of their totality or of their general arrangement can be gained without a somewhat protracted investigation of a large area. But so rugged and formidable are the physical features that such an investigation is about as difficult an undertaking as ever falls to the lot of a geologist.

The petrographic work has not been embodied in this volume. It has not yet been completed, though considerable progress has been made. Yet if it had been practicable to obtain the means to prosecute this branch of research to the end, and to publish the results in such form and with such illustration as the scientific student of the present day demands, it would have been done. It was originally intended to make a thorough series of chemical analyses of the volcanic rocks of this district. Many hundreds of thin sections for microscopic investigation have long since been made. It was intended, also, to describe these rocks thoroughly and illustrate the microscopic characters with a large collection of colored plates. But the contemplated work was too costly for the very limited appropriation at the disposal of Professor Powell. A considerable number of chemical analyses have been made by myself, but petrographers have very properly adopted the habit of relying upon other parties to furnish their chemical analyses, and I have therefore omitted to publish them. My conviction is that the chemical analysis of volcanic rocks should, whenever practicable, accompany the description of microscopic characters, for it seems to me that the two lines of investigation are mutually dependent. It is hoped that at no distant day the contemplated work may be brought to completion in a supplementary volume, for the want of it is most deeply felt in presenting the present one.

THE ATLAS.

The atlas which accompanies this work has been prepared with great care. The first double sheet represents by contours the topography of the country. The primary triangulation is by Prof A. H. Thompson, and the topographical work by Messrs. J. H. Renshawe and Walter H. Graves, under Professor Thompson's supervision. Having been in immediate contact with these gentlemen during much of the time occupied by their field work, and having familiarized myself with their methods, I can testify to the great care and accuracy with which that work has been performed. The detail work has been done with plane-tables upon sheets on which the primary and secondary triangulations had been accurately plotted. These sheets were carefully filled up with details in the field, and when they were brought back to Washington contained the material which was used in the preparation of the final map. Whatever could be sighted from the stations occupied has been located by triangulation and plane-table sights and not by sketching. Messrs. Renshawe and Graves acquired great skill in the use of the plane-table, and worked with surprising accuracy and rapidity. Each of them covered more than 2,000 square miles in a season.

The geological map has been colored by myself. The northern half of the sheet is for the most part held to be accurate in details. In the

Pávant the Carboniferous is represented as occupying exclusively the western side of the range. It is believed, however, that a few remnants of Triassic beds are to be found in that locality, but I am not able to designate accurately their positions. On the northwestern side of the Tushar also I am informed that there are some Archæan rocks, of which the exact location cannot be specified. A portion of the northwestern flank of the Tushar and the western side of the Pávant I have not visited, and the geological coloring is adopted in those portions as representing merely the dominant rocks. A considerable portion of the country lying south of the Wasatch Plateau is colored from data derived in part from my own observations and in part from those of Mr. Edwin E. Howell. There was some difficulty here in fixing in the field the demarkation between the Tertiary and Cretaceous, since the two series are not always well distinguished either by lithological characters or by fossils. But if the horizon chosen was properly selected the delineation is believed to be accurate. South and southwest of the Markágunt Plateau a similar difficulty occurred in separating the Jura from the Trias, and the uncertainty here is somewhat greater. The boundary between those two formations, as delineated upon the map, may, upon more thorough investigation, receive some notable modifications, though I believe it represents very approximately the truth. In the valley of the Pária some slight modifications also may be necessary in locating with precision the same boundary line; and again upon the southeastern slopes of the Aquarius Plateau, around the net-work of cañons tributary to the Escalante, the Trias and the Jura were utterly inaccessible, and the location of the separating horizon was inferred from the colors of the beds and the arrangement of the rocky ledges viewed from a distance. The colors and sculptural forms are most exceptionally characteristic in these two formations, and in this locality there is no possibility of mistaking them whenever they can be distinctly seen, whether from great or small distances

The large area of the map devoted to the trachytes should be understood as meaning that in that area the trachytes are the dominant rocks. Commingled with them are the principal bodies of conglomerate and very extensive masses of andesite and dolerite. To define these intercalary lavas and the conglomerates would obviously be impossible. With the foregoing exceptions the distribution of the strata is given with great confidence. In the exceptional cases the errors are believed to be so small as not to sensibly impair the accuracy of the map.

The relief map was prepared in the following manner: A plaster cast about five feet square was made, the horizontal and vertical scale being the same. The data for the cast were obtained from the contour map. The cast was then photographed, and a copy of the photograph was drawn upon stone.

The map (Sheet No. 4), showing the arrangement of the faults and flexures, was designed to show at a glance the connection, relations, and in some cases the continuity of the greater structure lines of the High Plateaus with those of the Kaibab district around the Grand Cañon of the Colorado. The Kaibab or Grand Cañon faults have been already worked out in an admirable manner by Powell. The importance of connecting the two districts by these common features is very great, and is not only essential to the present work, but will have, if possible, still greater importance when the geology of the southwestern part of the Plateau Province is discussed. Only the greater displacements are here given. There are very many smaller ones which are not so well known nor so well identified. Those which are given have been traced rigorously mile by mile so far as they are represented, excepting, however, the portions which extend south of the Colorado. The course of these faults south of the Grand Cañon has been given to me by Mr. G. K. Gilbert, who has in part identified their existence in that region, though I presume that he would not wish to be understood as attaching a very high degree of accuracy to his designations, having made merely a preliminary reconnaissance in that region.

The stereogram has been worked out with great care. It is the consolidated expression of a very large number of sections made in the field, together with the results obtained by tracing continuously each fault along its course. This mode of illustrating displacements is by no means all that could be desired and has some serious defects. But it seems to be a great improvement in the means of illustrating structure, since it groups the dominant features together in their proper relations. Probably the greatest value of it is the facility it affords the student of testing the accuracy of his work. He cannot commit a serious error in making his stereogram without knowing it. He cannot proceed far in his work without becoming conscious of the defects and gaps in his knowledge, and, best of all, he obtains an index pointing to the very localities which he must revisit in order to supplement the deficiencies. A stereogram is a laborious work, but it abundantly repays the labor expended upon it. The writer who achieves one will know the structure of the objects he is describing in a way and with a thoroughness he could never hope for from any other means. Unfortunately this method of systematizing observation is of very limited applicability. Much disturbed regions and countries which have preserved very obscurely the records of their displacements are hardly capable of such a discussion. The stereogram cannot take the place of the ordinary geological sections, though it can embody in one illustration some of the most important features of a hundred or more.

It is my pleasant duty to acknowledge the obligations which I owe to Professor Powell for the earnest support he has given me during the work of exploration and while the report has been in process of preparation. Every facility which he could supply has been placed at my disposal, whether in the field or in the office. But the greatest debt which I owe him is for the scientific advice and assistance he has given me. He has been not merely the director and administrator of his survey, but in the most literal sense its chief geologist. During the period of his field work in the Plateau Country (from 1869 to 1874) he had mastered with great rapidity and acumen the broader facts and had co-ordinated them into a system which was novel in many respects and which further research has proved to be perfectly sound. The geological phenomena encountered in that region are indeed governed by the same fundamental laws which prevail elsewhere, but the conditions under which those laws operate are altogether novel and peculiar, and the results which they produce are so singular that they seem at first anomalous and then mysterious. The geologist who is skilled in the conventional methods of investigation, the older applications of principles, and the routine logic which have long been in vogue, might well have been excused if he had found in this strange land little else than paradoxes. But with Powell it was not so. His industry and energy in the collection of facts, his stubborn resolution and dauntless courage in overcoming the physical obstacles which nature has there placed in the way of investigation, would alone have secured his fame; but even these are less admirable than the analytic power with which he traced the facts back to their causes, and the synthetic skill with which he grouped them together. He has made the Plateau Country a most alluring field of geological study, and evolved from it a new range of geological thought and philosophy. The principles and fundamental generalizations with which he wrought are indeed old and long established, but the facts being new and strange, it required in order to comprehend them, a sagacity and penetration analogous to that which is necessary for the citizen of one civilization to understand the ethics of another. Not only has he grasped the details of his subject—the salient features of the geological history, the stratigraphy, the erosion, the displacements, the sculpture, the structure, the drainage, the origin of the cliffs and cañons of the Plateau Country—but he has woven all these details and many others into a compact and consistent whole, in which each part of the scheme gives support and bond to all the others. The pressure of administrative duties and the prosecution of other work which he could not avoid, chiefly ethnographic, have retarded the appearance of the great work he has contemplated upon the Plateau Country; but those whose privilege it has been to continue the study of that region under his direction, to consult with him daily, to benefit by his advice and thorough knowledge of the field are deeply sensible of the fact that their own work has been merely tributary to the broader scheme which originated with him and of which he is unquestionably the founder and master.

I must also acknowledge my indebtedness to Mr. Edwin E. Howell for some very important material which has been embodied in this work. In the year 1873 Mr. Howell was attached to the survey of Lieut. (now Capt.) George M. Wheeler, of the Corps of Engineers, and under the able and energetic direction of that officer he rapidly traversed a large portion of the Plateau Country. His brief but very instructive report is contained in Vol. III, Geology, Surveys West of the One Hundredth Meridian, Lieut. George M. Wheeler in charge. In the year 1874 Mr. Howell joined Professor Powell's survey and rapidly traversed the District of the High Plateaus and portions of the region southwest of that district. During that year he succeeded in fixing the geological horizons of the chief sedimentary beds there occurring, and also began the study of the structural features of the northern part of the district in the Wasatch Plateau and in the Pávant. In the following winter he withdrew from the survey in order to engage in business, and left copious notes of his observations and drawings of geological sections which I have had the privilege of consulting. His drawings of the sections made by him in the northern part of the district are embodied in this volume. He is entitled to high praise for the ability and accuracy of his work, and it is much to be regretted that he was induced to abandon geological fieldwork.

I am also indebted to Mr. G. K. Gilbert for many valuable suggestions. He has traversed this district several times on his way to and from his own field of research and has given me information which has often proved of great utility.

The atlas has been lithographed by Mr. Julius Bien, of New York, and bears abundant evidence of his great skill and intelligence in that kind of work.

C. E. DUTTON,
Captain of Ordnance.

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LIST OF HELIOTYPES.

HELIOTYPE I.—THE GATE OF MONROE.

This picture represents the narrow gorge through which the drainage of the Monroe Amphitheater passes to join the Sevier River. It is situated in the western wall of the Sevier Plateau, near its loftiest part. The gorge is cut in a large mass of hornblendic propylite, and forms a cleft about 20 feet wide and nearly 400 feet deep. In the background is seen one of the large hills within the amphitheater, composed of trachyte and augitic andesite.

HELIOTYPE II.—CONGLOMERATE IN THE TUSHAR.

The cliff here exhibited is upon the eastern flank of the Tushar facing Circle Valley. In the face of the cliff are seen about 1,300 feet of conglomerate surmounted by 400 feet of lava. The bedding here is much less conspicuous than is usually the case in such formations.

HELIOTYPE III.—TUFA.—MARKÁGUNT PLATEAU.

This material has been derived from the complete decay of lavas, and consists of aluminous silicate, accumulated as a deposit in the bed of a small lake, where it was consolidated and subsequently eroded. Such formations are not very uncommon on the Markágunt and elsewhere.

HELIOTYPE IV.—VOLCANIC ALLUVIAL CONGLOMERATE ON TRACHYTE.—PANQUITCH CAÑON.

The beds here exhibited were derived from the break-up of older volcanic masses situated in the vicinity. At a former epoch the river flowed at a level as high as the summit of the cañon wall, and the upper portion of the conglomerate was eroded. An uplifting of the locality subsequently took place, and the river cut its cañon, exposing the structure of the beds. It will be noted that the layers present an arrangement suggestive of false stratification or cross-bedding, since their planes of stratification do not conform to the surface of the trachyte below. This is the normal structure of all alluvial cones.

HELIOTYPE V.—METAMORPHOSED TUFAS.—EAST FORK CAÑON.

The beds here seen are all water-laid and occur within the inner gorge of the cañon. The upper member exhibited is a massive rock, with all the lithologic characters of an intrusive igneous rock. Some of the thin layers below have the same character. (See Chap. XI.)

HELIOTYPE VI.—TUFA AND CONGLOMERATE.—EAST FORK CAÑON.

On the right are seen the continuations of the same beds as in the preceding illustration. The hill in the distance is composed of the same rocks below with coarse volcanic conglomerate above.

HELIOTYPE VII.—PINK CLIFFS.—LOWER EOCENE.—PAUNSÁGUNT PLATEAU.

The picture represents the southern termination of the Paunságunt, and is a good example of the sculpture which is seen in this formation around the rim of the Pària Amphitheater for a distance of 40 miles. The rocks are exquisitely colored.

HELIOTYPE VIII.—CROSS-BEDDED JURASSIC SANDSTONE.

Taken in Johnson's Cañon, on the road from Sevier Valley to Lower Kanab. Much finer instances may be seen in any of the deep cañons cut in this formation.

HELIOTYPE IX.—CROSS-BEDDED JURASSIC SANDSTONE.

The same as the preceding.

HELIOTYPE X.—THE RED GATE.—LOWER TRIAS.—SHINÁRUMP.

Taken at the southeast flank of Thousand Lake Mountain. The beds in the cliff are variegated in color, being banded horizontally, and the colors are very deep and rich. The sculpture is very characteristic of the formation.

HELIOTYPE XI.—PHONOLITE.—EAST FORK CAÑON.

GEOLOGY OF THE HIGH PLATEAUS.

BY CAPT. C. E. DUTTON.

CHAPTER I.

GENERAL CONSIDERATIONS RELATING TO THE TOPOGRAPHY AND GEOLOGICAL HISTORY OF THE HIGH PLATEAUS AND THEIR RELATIONS TO THE PLATEAU PROVINCE OF WHICH THEY FORM A PART.

Situation of the High Plateaus.—The westernmost range comprising the Pávant, Tushar, and Markágunt.—Sevier Valley.—The second or middle range comprising the Sevier and Paunságunt Plateaus.—Grass Valley.—The third range comprising the Wasatch, Fish Lake, Awapa, and Aquarius Plateaus.—Structural features of the Park, Plateau and Basin Provinces.—The High Plateaus form the western district of the Plateau Province.—Relations of the High Plateaus to the Plateau Province at large.—Geological history in outline during Cretaceous time.—Interruption of continuity between the Upper Cretaceous and Tertiary.—Unconformity between Cretaceous and Tertiary.—Early Tertiary history.—The lacustrine condition of the entire Plateau Province during early Eocene time.—Gradual desiccation of this Eocene lake.—Cretaceous-Eocene strata occupying its locus at the close of the Eocene.—Their vast bulk and gradual subsidence *pari passu* with deposition.—The counterpart of this subsidence, viz, the elevation of the surrounding mountain chains.—Post-Eocene history.—Erosion.—Its conspicuous display and the certainty of its evidence.—The drainage system of the Colorado River.—Its origin.—Its stability of location.—Priority of drainage channels to structural features.—Their persistence.—The methods of erosion.—Centers of erosion and the recession of cliffs.—The San Rafael Swell.—Vastness of the results accomplished by erosion.—Effect of the removal of great bodies of strata from large areas.—The erosion chiefly accomplished in the Miocene.—Summary of the relations of the High Plateaus to the Plateau country at large and to the Basin Province adjoining them on the west.

The region to be discussed in this work is centrally situated in the Territory of Utah, occupying a belt of country extending from a point about 15 miles east of Mount Nebo in the Wasatch, south-southwest, a distance of about 175 miles, and having a breadth varying from 25 to 80 miles. The total area of this field of study may approach 9,000 square miles. If we examine the old War Department maps of the western half of the United States and those maps which have been derived from them, we shall find the Wasatch Mountains laid down as extending southward with an increasing westerly trend until the range reaches a point near the southwestern corner of Utah. This delineation conveys to the eye the general truth that along this belt of country there is a lofty and, in a qualified sense, a mountainous barrier separating the drainage system of the Colorado River from that of the Great Basin of the West. It would be impracticable upon a map of small scale to designate clearly the fact that the Wasatch as a distinct mountain range ends at Mount Nebo, 75 miles south of Great Salt Lake, and that it is here overlapped *en échelon* by a chain of plateau uplifts which extend southward, gradually swinging around the southeastern rim of the Great Basin.

These plateaus are not a part, either structurally or topographically, of the Wasatch, but belong to another age, and are totally different in their forms and geological relations. The extension of the name "Wasatch Mountains" south of Nebo is a misnomer. The region south of that mountain has nothing in common with the belt to the north of it, except the mere fact that it carries the boundary line between the two drainage systems; otherwise the two belts constitute one of the most decided of those strong contrasts of topography and geological relations which are sometimes presented in adjacent portions of the Rocky Mountain Region. Those who have studied these plateaus have recognized their distinct character, and it seems necessary to give effect to this recognition to the extent of employing for purposes of geological discussion a distinguishing name. It has seemed to me that for these purposes the belt of country which they occupy would be sufficiently characterized by giving to it the name of the DISTRICT OF THE HIGH PLATEAUS of Utah.

These uplifts have certain analogies to mountain ranges, but in most cases are distinguished by their well-marked tabular character.

COMPONENT MEMBERS OF THE GROUPS OF HIGH PLATEAUS.

There are three ranges of plateaus within the district, and each range can be subdivided into individual tables. The westernmost range is made up of three component masses, or members—the Pávant at the north end, the Tushar in the middle, and the Markágunt at the south. The Pávant is a curious admixture of plateau and sierra, the eastern side being tabular in form and detail, while the western side is a common mountain front, like many others found in the Great Basin. The Tushar is also a composite structure, its northern half being a wild bristling cordillera of grand dimensions and altitudes, crowned with snowy peaks, while the southern half is conspicuously tabular. The Markágunt is a true plateau, of the normal type and of great expanse, and though very lofty (about 11,000 feet), is in utter contrast to a mountain uplift. A narrow, and in some portions profound, valley separates the western from the middle range of plateaus. This is the Sevier Valley, bearing a small river of the same name, which collects the drainage of the greater part of the district and pours it into a wretched salina of the Great Basin, where it is evaporated. But the valley is an important one, because it is one of the principal highways of travel, and, still more, because it has already become the granary of Utah, and promises to increase in importance as an agricultural district.

The second range of plateaus consists of the Sevier Plateau on the north and the Paunságunt Plateau on the south. The Sevier Plateau is 80 miles in length and only 12 to 20 in width. Its great elongation and the bold sculpture of its fronts would assimilate it to a mountain range, and such it seems to be in some portions of its extent as we look up to its grand pediments from the valley below. But its structure and topography are seen to be conspicuously tabular when viewed from lofty standpoints. It is cut in twain near the middle by a tremendous gorge, which carries the East Fork of the Sevier River, which drains the plateaus to the eastward and southward.

The Paunságunt Plateau is a flat-topped mass, projecting southward in the continuation of the long axis of the Sevier Plateau, bounded on three sides by lofty battlements of marvelous sculpture and glowing color. Its terminus looks over line after line of cliffs to the southward and down to the forlorn wastes of that strange desert which constitutes the district of the Kaibabs and the drainage system of the Grand Cañon of the Colorado River.

Between the second and third range of plateaus is a second valley parallel to that of the Sevier. This is called Grass Valley. It is long and rather narrow, walled upon the west by the long barrier of the Sevier Plateau and upon the east by the battlements of the third chain. It is treeless yet not wholly barren, for it is situated at that altitude where the possibility of agriculture is extremely doubtful, and where the grasses are rich enough for profitable pasturage. It carries the drainage of portions of both the second and third chains of plateaus, and the streams uniting from north and south near the southern end of the valley burst through the profound gorge of East Fork Cañon in the Sevier Plateau and join the Sevier River.

The third range of plateaus begins much farther north than the others. The northernmost member of it is the Wasatch Plateau, which overlaps the southern end of the Wasatch Mountain Range *en échelon* to the eastward. It is a noble structure, nearly as lofty as the summits of the Wasatch Mountains, but is a true plateau, or rather the remnant of one left by the erosion of the country to the east of it. It has not been studied as yet with the care and thoroughness it deserves, because it lies too far from the more compact district to the southward; is, in a certain sense, an outlier of the main group. Its southern terminus is walled by great cliffs, which look down upon a broad depression separating it from the next member of the range.

This next member to the south is the Fish Lake Plateau. It is small in area, but one of the loftiest (11,400 feet), and is a true table Its length does not exceed 15 miles, while its breadth is about 4 or 5. Its southeastern escarpment looks down into a profound depression nearly filled by a beautiful lake about 6 miles long and rarely picturesque. This plateau is difficult to separate from the next member, the Awapa. Indeed, it is nearly confluent with it. The Awapa is of less altitude, and this constitutes the principal reason for separating it. This plateau feebly slopes to the eastward, somewhat after the manner of the half of a watch-glass. Its extent is very great, being 30 miles in length and nearly 20 in breadth. It is quite treeless, though it stands at an altitude where timber usually flourishes luxuriantly; and the scarcity of water combines with the monotonous rolling prairie of its broad expanse to make it as cheerless and repulsive a locality as can well be conceived.

But south of the Awapa stands the grandest of all the High Plateaus, the Aquarius. It is about 35 miles in length, with a very variable width. and its altitude is about 11,600 feet. Its broad summit is clad with dense forests of spruces, opening in grassy parks, and sprinkled with scores of lakes filled by the melting snows. On three sides—south, west, and east—it is walled by dark battlements of volcanic rock, and its long slopes beneath descend into the dismal desert in the heart of the "PLATEAU COUNTRY."

THE THREE GEOLOGICAL PROVINCES.

For convenience of geological discussion, Professor Powell has divided that belt of country which lies between Denver City and the Pacific and between the 34th and the 43d parallels into provinces, each of which, so far as known, possesses structural and topographical features which distinguish it from the others.* The easternmost division he has named the Park Province. It is characterized by lofty mountain ranges, consisting of granitoid and metamorphic rocks, pushed upward and protruded through sedimentary strata, the latter being turned upwards upon the flanks of the ranges and their edges truncated by erosion. The general transverse section presented by these ranges, on the assumption that the sedimentaries prior to uplifting extended over their present *loci*,† is that of a broad and extensive anticlinal sometimes profoundly faulted parallel to the trend, the sedimentary strata which may once have existed being removed by erosion. The intervening valleys still retain the sedimentary series, including the Tertiary beds. This form of mountain structure, with its resulting topographical features, gradually passes as we proceed westward into another type, arising from the decreasing frequency of the greater displacements or differential vertical movements of the earth's surface; but such movements as have occurred have been vast in extent and involve greater masses, though the displacements have been fewer in number. Great blocks of country have been lifted with a singular uniformity with comparatively little flexing and with

* Geology of the Uinta Mountains. J. W. Powell.

† This assumption may be regarded as generally true for Palæozoic and Mesozoic beds, but not for Cenozoic.

little disarrangement, except at the fault planes which bound the several blocks. These divisional lines are sometimes sharp, trenchant faults, sometimes that peculiar form of displacement to which Messrs. Powell and Gilbert have given the name of monoclinal flexures,* but most frequently the dislocation is a combined monoclinal flexure and a fault or series of faults with all shades of relative emphasis. If we look solely at the amount of energy displayed in the vertical differential movements, we shall probably reach the conviction that it does not fall much, if any, below that required to build the most imposing mountain ranges; yet within the limits of any one of the great blocks into which this country has been divided the strata have preserved their original attitudes with a singularly small amount of warping, flexing, and comminution. Sometimes the blocks are slightly tilted, causing a slight dip, and in the immediate neighborhood of a great dislocation a single flexure of the beds is usually seen; but, on the whole, the amount of bending and undulation is very small. This small amount of departure from horizontality of the beds as they now lie has played its part in the determination of the topographical features as they appear in the landscape, and justifies the name which has been applied to it with one accord by all observers—THE PLATEAU COUNTRY.

West of this province lies a third one—the Great Basin. Its topography and structure are characterized by jagged ranges of mountains, ordinarily of very moderate length, and separated by wide intervals of barren plains. These ranges are usually monoclinal ridges produced by the uptilting of the strata along one side of a fault. Sometimes the faults are multiple; that is, consist of a series of parallel faults, the intervening blocks being careened in the same manner and direction. This repetitive faulting is of frequent occurrence. Other modifications, and even different types of structure, are presented; but there is throughout the Great Basin a striking predominance of monoclinal ridges, in which one side of a range slopes with the dip of the strata, while the other slopes lie across the upturned edges. The forms impressed upon these masses by erosion are rugged, bristling, and sierra-like, and their peculiarities are aggravated by

* Mr. Jukes describes a great flexure of similar nature in Ireland under the name uniclinal flexure, which name is evidently defective in etymology. The nature of monoclinal flexures is most ably discussed by Professor Powell in Expl. of Colorado River, 1869–1872.

the fact that before these "mountains were brought forth" the platform of the country from which they arose had been plicated, and the plications planed down again by erosion. The Basin area is the oldest of the West,* its final emergence being of older date than the Jurassic, and most probably as ancient as the close of the Carboniferous.

Between the Plateau and Park Provinces there is no definite boundary. Gradually as we proceed westward from the easternmost ranges of the Rocky system the valleys widen out, and the country gradually expands into a medley of terraces bounded by lofty cliffs, which stretch their tortuous courses across the land in every direction, yet not without system.. The boundary separating the Plateau Province from the Basin is, on the contrary, tolerably definite, and in some portions of its extent remarkably so. It lies along the eastern flank of the Wasatch, south of the Uintas, as far as Nebo; thence along the Juab Valley, in the Pávant Range, as far as the Tushar Mountains. Here for a time it is concealed by immense floods of old lavas, and is not seen for a distance of 50 miles. It reappears near the southern end of that range, continuing south-southwest along the western base of the Markágunt Plateau, near a string of Mormon settlements scattered along the route from Beaver to Saint George, and follows the great fault which makes the Hurricane Ledge to the Arizona boundary. Here an offset carries it to the westward to another fault which walls the Grand Wash, and it then extends southward to the mouth of the Grand Cañon of the Colorado and crosses the river. Here is the maximum westing of the Plateau Province. A few miles south of the crossing it swings back to the southeastward, and continues beyond the explorations of this survey. This boundary is frequently very sharp and distinct, and throughout the greater portion of its extent the breadth of the doubtful or transitional zone lies wholly within the limits of a narrow valley or a narrow mountain range. The Pávant is a range of which the eastern side presents conspicuously the features of the Plateau type, while the western side presents those of the Basin type. The Tushar Range shows a distinct plateau form in its southern half, while the northern half is masked by floods of volcanic rock. From Toquerville to Parowan the Markágunt Plateau faces

* I refer only to large areas. There may be, and probably are, small areas of equal or greater antiquity.

the westward, looking across a valley floored with recent alluvium to typical Basin Ranges lying to the westward. The district of the High Plateaus is therefore a portion of the western belt of the Plateau Province, and its western boundary is the trenchant one just described.

THE PLATEAU PROVINCE AT LARGE.

To the eastward of the High Plateaus is spread out a wonderful region. Standing upon the eastern verge of any one of these lofty tables where the altitudes usually exceed 11,000 feet, the eye ranges over a vast expanse of nearly level terraces, bounded by cliffs of strange aspect, which are truly marvelous, whether we consider their magnitude, their seemingly interminable length, their great number, or their singular sculpture. They wind about in all directions, here throwing out a great promontory, there receding in a deep bay, but continuing on and on until they sink below the horizon, or swing behind some loftier mass, or fade out in the distant haze. Each cliff marks the boundary of a geographical terrace sloping gently backward from its crestline to the foot of the next terrace behind it, and each marks a higher and higher horizon in the geological scale as we approach its face. Very wonderful at times is the sculpture of these majestic walls. Panels, pilasters, niches, alcoves, and buttresses, needing not the slightest assistance from the imagination to point the resemblance; grotesque forms, neatly carved out of solid rock, which pique the imagination to find analogies; endless repetitions of meaningless shapes fretting the entablatures are presented to us on every side, and fill us with wonder as we pass. But of all the characters of this unparalleled scenery, that which appeals most strongly to the eye is the color. The gentle tints of an eastern landscape, the rich blue of distant mountains, the green of vernal and summer vegetation, the subdued colors of hillside and meadow, all are wanting here, and in their place we behold belts of fierce staring red, yellow, and toned white, which are intensified rather than alleviated by alternating belts of dark iron gray. The Plateau country is also the land of cañons. Gorges, ravines, cañadas are found in every high country, but cañons belong to the region of the Plateaus. Like every other river, the Colorado has many tributaries, and in former times had many more than now, and every branch and every twig of a stream runs in cañons. The land is thoroughly dissected by them, and in many large tracts so intricate is the labyrinth and so inaccessible are their walls, that to cross such regions except in specified ways is a feat reserved exclusively to creatures endowed with wings. The region at levels below 7,000 feet is a desert. A few miserable streams meander through it in profound abysses. The surface springs will not average one in a thousand square miles, for the cañons in their lowest depths absorb the subterranean water-courses. But in the High Plateaus above we find a moist climate with an exuberant vegetation and many sparkling streams.

RELATIONS OF THE HIGH PLATEAUS TO THE PLATEAU PROVINCE AT LARGE.

It is impossible to gain any adequate conception of the broader and more general features of the High Plateaus apart from their relations to the Plateau Province at large. The geological history of the district is inseparable from that of the province of which it is a part, and that history is full of interest and instruction. Beyond Cretaceous time it is unfortunately vague and uncertain at present; and even during the Cretaceous our knowledge is limited as yet to a few salient facts too conspicuous to be overlooked, but of very great geological importance. We now know that during Cretaceous time the ocean stretched from the Wasatch to Eastern Kansas, Nebraska, and Dakota, and from the Gulf of Mexico far northwards toward the Arctic Circle. The area now occupied by the Great Basin was then a large island, or possibly a portion of some unknown continental mass. East of it probably lay numerous islands. Around the southern border of this area the Cretaceous ocean joined the Pacific, covering the entire extent of the Plateau Province and more to the southwestward. We find throughout the plateaus vast bodies of Cretaceous stata which seem in a general way or collectively to correspond with those which have been studied and described by Meek and Hayden in the Great Plains of Nebraska, Dakota, Montana, Wyoming, and Colorado, and by Newberry in New Mexico and Arizona. Although the subdivisions of the Plateau Province have not been wholly correlated with the marine Cretaceous of the other territories north and east, there can be little doubt that the series as a whole agrees in general. The lower member (Dakota group) can probably be correlated very approximately, although presenting a somewhat different fauna; but the upper members (2, 3, 4, and 5 of Meek and Hayden) cannot be so satisfactorily distinguished nor subdivided in the same way as elsewhere, though it seems probable, in a high degree, that all these members are represented. The lithological characters show the same agreement, though not an observed correspondence of details. In one respect, however, there is a notable distinction. The entire Cretaceous series of the Plateau Province abounds in coal and carbonaceous shales, while in the more eastern exposures coal appears to be confined to the higher members.

CLOSE OF THE CRETACEOUS—UNCONFORMITIES.

The closing period of the Cretaceous marks a change in the physical condition of the region. The ocean gave place to brackish waters. What orographic movements or what uplifts of broad areas may have accomplished this change we do not know in detail, and it is at present impossible to form any very definite idea of the geography of the region during that period. We only know that the uppermost Cretaceous strata have hitherto furnished only brackish-water fossils, and we naturally infer from them that the Cretaceous ocean was subdived into a number of Baltics or Euxines by the rearing of mountain chains and broad land areas around their borders, but leaving narrow straits communicating with the sea. The brackish-water fossils either mean that or they are at present inexplicable. These movements, however, involved no other changes in the physical condition of the country, for the deposit of shaly, marly, and arenaceous strata with seams of lignite went on as before, and continued through a long period until the accumulations reached in many places a thickness of nearly 2,000 feet without any interruption which can be specified. These Upper Cretaceous beds are without much doubt the equivalents of the Judith River beds of Meek and Hayden and the Laramie beds of King.

The continuity of deposition was at last broken. Resting upon these Laramie beds is a series of calcareous shales alternating with sandstones, which, through a thickness of 100 to 250 feet from the base, contain also a brackish-water fauna, but which as we ascend gives places to molluscan fossils of purely fresh-water types The junction of the two series is unconformable, and is often highly so. This unconformity is seen in many localities on both sides of the Uintas, along the eastern slopes of the Wasatch, and becomes even more strongly pronounced to the southwestward. During the course of this work, localities will be mentioned where it is conspicuously displayed, the Upper Cretaceous (Laramie) beds being flexed at a high angle, the flexures planed off by erosion, and the overlying series resting across the beveled edges, or even upon the Jurassic beds below. It was at this unconformity that Professor Powell drew the dividing horizon between the Tertiary and Cretaceous. Quite independently of any physical break, Professor Meek had chosen the division at the same horizon upon the evidence of invertebrate fossils, though that evidence was regarded by him as being too meager and the species too few and indecisive to justify an unqualified opinion.* Professor Marsh also reached a similar conclusion much more decisively from mammalian fossils from beds just above the unconformity which he referred approximately to the horizon of the London clay or the base of the Eocene.† The physical break which separates these divisions of time is of wider distribution and more emphatic than was supposed when first detected, for the Upper Cretaceous (=Laramie) beds are often greatly flexed and eroded beneath the Tertiary, and these occurrences are frequent throughout the province. Very often, and probably in most of the exposures distant from the mountains, the contact is apparently conformable, for the obvious reason that neither series has been sensibly disturbed from original horizontality, or the disturbances have been of late occurrence, involving both series alike. The separation in such cases then becomes a purely lithological one, or sometimes none can be detected. The fossils do not indicate any break, since the base of the Tertiary and the summit of the Cretaceous are lignitic, and furnish only brackish-water mollusca, which are indecisive and have a very great vertical range in nearly all the species.

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* Invertebrate Palæontology (1876), Dr. F. V. Haydey's Survey, pp. xlvii *et seq.*

† Expl. 40th Parallel, C. King, vol. ii, p. 329.

THE EOCENE OR LACUSTRINE AGE.

The early Tertiary history of the Plateau Province is much clearer than its history during prior epochs. The shore of the great Eocene lake which covered its expanse and received its sediments can be defined with tolerable accuracy throughout those portions of it which lay within the area constituting the field of this survey. Its northern and the greater part of its western shore line has been traced from the Uintas to the Colorado, and most of the way coincides with the boundary already described as separating the Plateau Province from the Great Basin. South of the High Plateaus, however, the Eocene lacustrine beds stretch westward beyond this boundary, and are found among the southern Basin Ranges. We know, too, the origin of a large portion of its sediment. Much of it came from the Great Basin, and probably still more from the degradation of the Wasatch, the Uintas, and the mountains of Western Colorado, which girt about its northern half. The southern shore line is not at present known, and there is much uncertainty at present as to the exact course of its southeastern coast. From what is known, however, we may wonder at the vast dimensions of such a lake, which must have had an area more than twice that of Lake Superior, and may even have exceeded that of the five great Canadian lakes combined. Still more astonishing is the vastness of the mass of strata thrown down upon its bottom. Around the flanks of the Uintas and Southern Wasatch the thickness of the Eocene beds exceeds 5,000 feet, though they attenuate as we recede from the mountains, but never fall below 2,000 feet so far as yet observed. And where this minimum is observed there is good evidence that the deposition had terminated long before it ceased elsewhere, and that the series was never completed.

The deposition ended in the southern and southwestern part of the lake area much earlier than in the northern part. Around the southern portions of the High Plateaus no later beds than the Bitter Creek (which constitute the lower one-third of the local Eocene) were deposited so far as known at present. The inference is that about that time the southern and southwestern portions of the lake began to dry up, while to the northward around the Uintas the lacustrine condition persisted for a much longer period. In other words, the lake contracted its area from south to north during at least the latter half of the Eocene, and at the close of that age finally disappeared.

SUBSIDENCE OF CRETACEOUS-EOCENE SEDIMENTS.

A most interesting but perplexing problem is suggested when we consider the enormous bulk of the Cretaceous-Eocene strata of the Plateau Province and the peculiar circumstances under which they were deposited. The whole series abounds in coal and carbonaceous shales, and remains of land plants are abundant, even where carbonaceous matter is absent. If current theories of the formation of coal are not radically wrong, we seem compelled to believe that throughout that vast stretch of time which extended from the base of the Cretaceous to the summit of the Eocene the whole province, with the exception of a few possible but unknown land areas, maintained its level almost even with that of the ocean. The Dakota sandstone could not have been deposited here much if any below that level, nor the Wasatch beds much if any above it. And yet we have the paradox that 6,000 to 15,000 feet of strata were deposited over an area of more than 100,000 square miles with comparatively few unconformities and contemporary disturbances, while the level of the uppermost stratum always remained at sensibly the same geographical horizon!

It is incredible that the Cretaceous ocean at the commencement of that age could have had a depth equal to the thickness of the strata and that the sediments filled it up. The facts are wholly against such a supposition, and point clearly to shallow waters. The only conclusion which appears tenable is that the strata sank as rapidly as they were deposited. The case is analogous to that of the Appalachians during Palæozoic time, and especially during the Carboniferous; and the more we reflect upon the similarity the stronger does it become. It fails, however, when we come to consider the phenomena presented in the two regions in the period subsequent to the deposition; the Appalachian strata were flexed and plicated to an extreme degree, while those of the west are for the most part calm and even. Only in the vicinity of the mountains and shore lines do we find them much disturbed.

But if we are to admit that the strata sank as rapidly as they accumulated we cannot shake off some ulterior questions. By virtue of what condition of the underlying magmas was such a subsidence possible? If they sank, they must have displaced matter beneath them, and what became of the displaced matter? If we look around the borders of the area and partially within it, we shall find a problem of an inverse order. The Uintas, the Wasatch, the Great Basin have suffered an amount of degradation by erosion, which is perhaps one of the most impressive facts which the physical geologist has yet been brought to contemplate. From the Uintas more than 30,000 feet of strata have been removed since their emergence. From the Wasatch the removal has been much more; from the Great Basin the degradation has been many, we know not how many, thousand feet. We are not prepared to believe that the Uintas ever stood 8 miles high, nor the Wasatch 12 miles high, but we know that their altitudes are merely the difference between elevation and erosion. It was from these ranges that the heaviest masses of the Cretaceous-Eocene sediments were derived. As fast as, or even faster than, the mountains were devastated to supply mass for the new strata, they continued to rise. But if they rose, fresh matter must have been thrust under their foundations, replacing the rising strata. Whence came the replacing matter? It may be premature as yet to say that the elevation of the mountains and subsidence of the strata are correlated in the way which these inquiries suggest, but the juxtaposition of the facts must be regarded as significant.

POST-EOCENE HISTORY—EROSION.

With the desiccation of the Eocene lake began a new order of events in the history of the Plateau Country; in truth, its most instructive and impressive chapter. The lessons which may be learned from this region are many, but the grandest lesson which it teaches is EROSION. It is one which is taught, indeed, by every land on earth, but nowhere so clearly as here. If we could but find the evidence, we might be able in other regions to point to erosions of much greater amount. We may suspect that in the Appalachians a denudation has occurred compared with which the denudation of the Plateaus is small; and such an inference has no intrinsic improbability, though the proofs are difficult beyond a certain amount. The great value of the Plateau Country is the certainty and fullness of the evidence. Nature here is more easily read than elsewhere. She seems at times amid those solitudes to have lifted from her countenance the veil of mystery which she habitually wears among the haunts of men. Elsewhere an enormous complexity renders the process difficult to study; here it is analyzed for us. The different factors are presented to us in such a way that we may pick out one in one place, another in another place, and study the effect of a single variable, while the other factors remain constant. The land is stripped of its normal clothing; its cliffs and cañons have dissected it and laid open its tissues and framework, and "he who runs may read" if his eyes have been duly opened. As Dr. Newberry most forcibly remarks: "Though valueless to the agriculturist, dreaded and shunned by the emigrant, the miner, and even the adventurous trapper, the Colorado Plateau is to the geologist a paradise. Nowhere on the earth's surface, so far as we know, are the secrets of its structure so fully revealed as here."

In the new era, beginning with the desiccation of the lake, we have the history of a process which resulted in the destruction and dissipation of those great bodies of sediment which had been gathered and stratified during Mesozoic and Eocene time. Then, too, appears to have begun in earnest the gradual elevation of the entire region which has proceeded from that epoch until the present time, and which even yet may not have culminated. The two processes of uplifting and erosion are here inseparably connected, so much so, that we cannot comprehend the one without keeping constantly in view the other.

From the very inception of the process the drainage system of the Plateau Province has been that plexus of streams which unite in the Colorado River. This is the trough through which the waste of the land has been carried to the Pacific. Its origin goes back to the emergence of the land now drained by it from its lacustrine condition. Even prior to that we may conjecture the existence of a Cretaceous-Eocene strait connecting with the ocean that area which was covered by the Laramie beds and the brackish water deposits at the base of the local Eocene; and many considerations lead to the inference that this Hellespont occupied the same position as the lower course of the Colorado from the mouth of the Virgin to the Pacific. Whether the connection was at first elsewhere and at an early epoch in Tertiary time shifted to this place may be doubtful, but the probabilities at present are that the connection was southwestward along the lower course of the present river. But after the desiccation of the lake began in the latter part of the Eocene, the course of the Colorado was fixed for the remainder of Tertiary time. In order to conceive the growth and evolution of this river, let us endeavor to imagine what might happen if the whole region of the Canadian lakes were to be progressively uplifted several thousand feet. In due time the St. Lawrence would sink its channel by the increasing corrasive power of its waters, and would drain in succession Ontario, Erie, Huron, and Superior, becoming a great river with many branches, while the lakes would be emptied. Such was the early history of the Colorado; first a Hellespont, then a St. Lawrence, then a large river heading in the interior of a continent.

The relations of the Colorado to the strata through which it runs present certain phenomena which, when rightly understood, become a master-key in the solution of a whole category of problems of a most interesting and instructive character. It would be difficult to point out an instance of a river under conditions more favorable to stability in respect to the location of its course than the Colorado and its principal tributaries. Since the epoch when it commenced to flow it has been situated in a rising area. Its springs and rills have been among the mountains, and throughout its history its slope has been increasing. The relations of its tributaries in this respect have been the same, and indeed the river and its tributaries constitute a system and not merely an aggregate, the latter dependent upon and thoroughly responsive to the former. Now, the grand truth which meets us everywhere in the Plateau Country, which stands out conspicuous and self-evident, which is so utterly unmistakable, even by the merest tyro in geology, is this: The river is older than the structural features of the country. Since it began to run, mountains and plateaus have risen across its track and those of its tributaries, and the present summits mark less than half the total uplifts. The streams have cleft them to their foundations. Nothing can be clearer than the fact that the structural deformations (unless older than Tertiary time) never determined the present courses of the drainage. The rivers are where they are in spite of faults, flexures, and swells, in spite of mountains and plateaus. As these irregularities rose up the streams turned neither to the right nor to the left, but cut their way through in the same old places. It is needless to multiply instances. The whole province is a vast category of instances of river channels running where they never could have run if the structural features had in any manner influenced them. What, then, determined the present distribution of the drainage? The answer is that they were determined by the configuration of the old Eocene lake bottom at the time it was drained. Then, surely, the water-courses ran in conformity with the surface of the uppermost Tertiary stratum. Soon afterward that surface began to be deformed by unequal displacement, but the rivers had fastened themselves to their places and refused to be diverted. Many of the smaller streams have dried up and perished through the failure of their springs and the advent of an arid climate. These have left traces here and there in the shape of dry cañons and gulches. Many more are still perishing. But the larger streams heading far up in moist Alpine highlands still meander through the desert, and have never ceased to flow from the beginning.

In order to comprehend the relations of the High Plateaus to the province at large, it is necessary to advert to some of the salient features of the general erosion of the Plateau Country which followed the desiccation of the great lake, and which continued without interruption during Miocene time and down to the present day. Its history during Miocene time must be spoken of only in general terms. In truth, during that great age there is no evidence of the occurrence of any critical event aside from the general processes of uplifting and erosion which affected the province as a whole. What forms and what topography were sculptured we know not. Of its climatal condition we can only suppose that it was similar to that of neighboring regions similarly situated—moist and subtropical. The vast erosion of the region has swept away so much of its mass, that most of the evidence as to details has vanished with its rocks. But the more important features of the work, its general plan in outline, have left well-marked traces, and these can be unraveled. It was a period of slow uplifting, reaching a great amount in the aggregate; and it was also a period of stupendous erosion. The uplifting was, however, unequal. The comparatively even floor of the old lake was deformed by broad gentle swells rising a little higher than the general platform. In consequence of their greater altitudes, these upswellings at once became objects of special attack by the denuding agents, and were wasted more rapidly than the lower regions around them. Here were formed centres, or short axes, from which erosion proceeded radially outward, and the strata rising very gently toward these centres, or axes, from all directions, were bevelled off. As erosion progressed, so also did the local upliftings, thus maintaining the maximum erosion at the same localities.

It is a most significant fact that the brunt of erosion throughout the Plateau Country is directed against the edges of the strata and not against the surfaces. This is directly traceable to the fact that the strata are nearly horizontal, the dips rarely exceeding four or five degrees, and even then only where a great monoclinal flexure occurs. The rains wash and disintegrate most rapidly where the slopes are steepest, and where the strata are flat the steepest slopes are the valley sides and chasm walls. Thus the battering of time is here directed against the scarps and falls but lightly on the *terrepleins*.

Ordinarily, the local uplifts have one diameter longer than the others, and we may call the greatest the major axis. The strata dissolved away in all directions from this axis, and after the lapse of long periods the newest or uppermost stratum encircled the centre of erosion at a great distance from it, the next group below encircled it a little nearer, and so on. This has been the history of each of the subdivisions of the central part of the Plateau Country. Upon the western and northern sides of the Colorado five of these centres are now easily discerned. By far the largest and probably the oldest is around the Grand Cañon; a second lies east of the Kaiparowits Plateau; a third is found about 50 miles south-southwest of the junction of the Grand and Green; the fourth is the Henry Mountains, and the fifth is what is known as the San Rafael Swell, lying between the

Green River and the Wasatch Plateau. All these had their inception in Miocene time except the one around the Grand Cañon, which goes back into the latter part of the Eocene. This gradual dissolution of the strata by the waste of their edges constitutes what Powell has called the *Recession of Cliffs.*

Of these five centres of maximum erosion, the San Rafael Swell is by far the best suited for study, and may be regarded as the type of them all. If we stand upon the eastern verge of the Wasatch Plateau and look eastward, we shall behold one of those strange spectacles which are seen only in the Plateau Province, and which have a peculiar kind of impressiveness, and even of sublimity. From an altitude of more than 11,000 feet the eye can sweep a semicircle with a radius of more than 70 miles. It is not the wonder inspired by great mountains, for only two or three peaks of the Henry Mountains are well in view; and these, with their noble Alpine forms, seem as strangely out of place as Westminster Abbey would be among the ruins of Thebes. Nor is it the broad expanse of cheerful plains stretching their mottled surfaces beyond the visible horizon. It is a picture of desolation and decay; of a land dead and rotten, with dissolution apparent all over its face. It consists of a series of terraces, all inclining upwards to the east, cut by a labyrinth of deep narrow gorges, and sprinkled with numberless buttes of strange form and sculpture. We stand upon the Lower Tertiary, and right beneath our feet is a precipice leaping down across the edges of the level strata upon a terrace 1,200 feet below. The cliff on which we stand stretches far northward into the hazy distance, gradually swinging eastward, and then southward far beyond the reach of vision and below the horizon. It describes, as we well know, a rude semicircle around a centre more than 40 miles to the eastward. At the foot of this cliff is a terrace about 6 miles wide of Upper Cretaceous beds, inclining upwards towards the east very slightly, and at that distance it is cut off by a second cliff, plunging down 1,800 feet upon Middle Cretaceous beds. This second cliff describes a smaller semicircle like the first and concentric with it. From its foot the strata again rise gently towards the east through a distance of 10 miles, and are cut off by a third series of cliffs as before.

There are five of these concentric lines of cliffs. In the centre there is an elliptical area about 40 miles long and 12 to 20 broad, its major axis lying north and south, and as completely girt about by rocky walls as the valley of Rasselas. It has received the name of the San Rafael Swell. Its floor is covered with the lowest Triassic strata, and probably in some portions of it the Carboniferous is laid bare, though it has not yet been seen. But, at all events, we know that the Carboniferous is very thinly covered, even if it be not exposed.

Thus, as we pass from the summit of the Wasatch Plateau to the floor of the Red Amphitheatre, we cross the outcrops of nearly 10,000 feet of strata. The Tertiary is found only at a distance of 40 miles from it. Yet if we look back to Eocene time we shall find that the whole stratigraphic series from the base of the Mesozoic to the summit of the Eocene covered this amphitheatre. One after another, in orderly succession, the vast stratigraphic members have been stripped off, and the edges of the remaining portions are seen in the successive cliffs which bound the encircling terraces.

Still more vast has been the erosion which took place in the vicinity of the Grand Cañon of the Colorado. Here the Carboniferous now forms the floor of the country, though a few patches of Trias still remain in the vicinity of the river. But the main body of Triassic rocks now stands 50 miles north of the river, and beyond them, in a series of terraces, rise the Jura, the Cretaceous, and the Tertiary, the latter usually capped by great masses of volcanic rock.

We may note here another question which presents itself in connection with the differential movements among the various parts of the province. Those areas which have been uplifted most have suffered the greatest amount of denudation. Is it not possible in some cases and under certain restrictions to invert this statement and say that those regions which have been most denuded have been most uplifted, thereby assuming the removal of the strata as a cause and the uplifting as the effect? May not the removal of such a mighty load as 6,000 to 10,000 feet of strata from an area of 10,000 square miles have disturbed the earth's equilibrium of figure, and the earth, behaving as a quasi-plastic body, have reasserted its equilibrium of figure by making good a great part of the loss by drawing upon its whole mass beneath? Few geologists question that great masses of sedimentary deposits displace the earth beneath them and subside. Surely the inverse aspect of the problem is *a priori* equally palpable. That some such process as this has operated in the Plateau Country looks at least plausible, and if there could be found independent reasons for believing in its adequacy the facts certainly bear it out. Yet its application is not without some difficulties, and the explanation is not quite complete. Granting the principle, it will still be difficult to explain how these local uplifts were inaugurated, and we can only refer them to the operations of that mysterious plutonic force which seems to have been always at work, and the operations of which constitute the darkest and most momentous problem of dynamical geology. On the whole, it seems to me that we are almost driven to appeal to this mysterious agency to at least inaugurate and in part to perpetuate the upward movement, but that we must also recognize the co-operation of that tendency which indubitably exists within the earth to maintain the statical equilibrium of its levels The only question is whether that tendency is merely potential or becomes in part kinetic, and this again turns upon the rigidity of the earth. But it is easy to believe that where the masses involved are so vast as those which have been stripped from the Kaibabs and from the San Rafael Swell, the rigidity of the earth may become a vanishing quantity.

The great erosion of the Plateau Province was most probably accomplished mainly in Miocene time, but continued with diminishing rapidity throughout the Pliocene. But it is necessary to say that the terms Miocene and Pliocene have here no definition. They cannot be correlated except in a very general manner with events occurring outside the province. We have only a vast stretch of time, with an initial epoch near the close of the local Eocene. The greater part of the denudation is assigned to the Miocene, because the conditions appear to have been more favorable to a rapid rate of destruction in that age than subsequently. The climate appears to have been humid, while the elevation was at the same time gradually increasing, both conditions being favorable to a rapid disintegration and removal of the rocks. The Pliocene witnessed the gradual development of an arid climate similar to that now prevailing there. To this age belong the cañons and the great cliffs, which could not have been produced in an ordinary or humid climate, nor at low altitudes. That this aridity is by no means a condition of recent establishment is indicated by many evidences. They consist of remnants of a former topography, preserved in a few localities from the general wreck of the land, and which show the same general facies of cliffs and cañons as those of more recent formation. And as the more recent sculpture owes its peculiarities in great part to the aridity, so, we conclude, must these more ancient remnants The Kaiparowits Plateau presents an excellent example. Its surface is in many places rendered utterly impassable by a plexus of sharp narrow cañons, of which the heads have been cut off by the recession of the gigantic cliff which forms the eastern wall of the plateau. They have long been dug, and have remained with but little change for an immense period of time.

And now the relation of the High Plateaus to the Plateau Province at large becomes evident They are the remnants of great masses of Tertiary and Cretaceous strata left by the immense denudation of the Plateau Province to the south and east. From the central part of the province the Tertiary beds have been wholly removed and nearly all of the Upper Cretaceous. A few remnants of the Lower Cretaceous stretch far out into the desert, and one long narrow causeway, the Kaiparowits Plateau, extends from the southeastern angle of the district of the High Plateaus far into the Central Province and almost joins the great Cretaceous mesas of Northeastern Arizona, being severed from them only by the Glen Cañon of the Colorado. The Jurassic has also been enormously eroded. This formation, which is of great importance and bulk in the northern and northwestern portion of the province, and especially around the High Plateaus, appears to have thinned out towards the south and southeast. In large portions of New Mexico it is wholly wanting and was probably never deposited there. In the northwestern portion of that Territory only a few thin beds of that age are found. But in the northern part of the province a conspicuous and wonderful sandstone formation of most persistent character is found, overlaid and underlaid by shales holding a distinctly Jurassic fauna. This formation once extended over the Grand Cañon area probably as far south as the river itself, and possibly farther, but has all been swept away as far north as the southern end of the district of High Plateaus. From the region east of the High Plateaus also very large areas of it have been removed. The Upper Trias has also been greatly denuded, and the Lower Trias nearly as much so. The erosion of the Carboniferous has been small, being confined chiefly to the cutting of cañons—most notably the Grand and Marble Cañons, which are sunk wholly in that series, and in several places have been cut through the entire Palæozoic series system.

The average denudation of the Plateau Province since the closing periods of the local Eocene can be approximately estimated, and cannot fall much below 6,000 feet,* and may, nay, probably does, slightly exceed that amount. Of course this amount varies enormously, being in some localities practically nothing and in others nearly or quite 12,000 feet. It is a minimum in the High Plateaus Within that district the average denudation will fall much below 1,000 feet in the sedimentary beds. The enormous floods of volcanic emanations have protected them, and these have borne the brunt of erosion, and their degradation has given rise to local accumulations of sub-aerial conglomerates in all the valleys and plains surrounding the volcanic areas, thus increasing the protection.

The general cause which has enabled these strata to survive within the limits of the High Plateaus while they have been so terribly wasted elsewhere may be stated briefly. Until near the close of the Pliocene the High Plateaus were not only the theatre of an extended vulcanism, but those portions which never were sheeted over by lavas were low-lying areas, where alluvial strata tended to accumulate. They remained, in fact, base levels of erosion during the greater part of Tertiary time.

Turning now to the Great Basin, which lies even lower than the mean level of the Plateau Country, we find that the pre-eminence of the High Plateaus is due to a totally different cause. Here the difference of altitude is due altogether to differences in the amounts of uplifting. Since the

*My own estimate exceeds by a few hundred feet that of Professor Powell and also that of Mr. Gilbert. The latter places it at about 5,500 feet.

Eocene, the High Plateaus have risen from 10,000 to 12,000 feet, while the adjoining Basin areas have risen from 5,000 to 6,000. As we pass from the Basin eastward and ascend the High Plateaus we mount the long slopes of great monoclinal flexures, or scale the giant cliffs which had their origin in the long major faults which traverse the district from south to north. As we pass westward from the heart of the Plateau Province and ascend the High Plateaus, we ascend cliffs of erosion. The fact that those cliffs which had their origin in displacement, with very rare exceptions, face westward, has attracted much attention and has received various interpretations. It seems to me that the explanation is exceedingly, almost amusingly, simple. The country to the east of them, and also the belt of country which they occupy, has been elevated from 5,000 to 6,500 feet above the country to the west of them. These figures express, of course, relative vertical displacements. The passage from west to east across the belt of country, which may be called the border-land between the two provinces, discloses a succession of faults and monoclinal flexures which are the obvious results of such a displacement.

CHAPTER II.

STRUCTURAL GEOLOGY.

Homology of faults and monoclinal flexures.—Their systematic arrangement.—Those of the High Plateaus belong to the same system as those of the Kaibabs.—The Grand Wash fault.—Hurricane fault.—Tushar fault.—Toroweap fault.—Sevier fault.—Western and Eastern Kaibab faults.—Thousand Lake fault.—Musinia faults.—Age of these displacements.—Their relative recency.—Difficulty of assigning their periods in definite terms.—Argument of recency from amounts of erosion.—Argument from the amounts of accumulation of valley deposits.—Age of the faults with reference to evidences of glaciation.—Importance of knowing the ages of these faults.—Some are more recent than others.—An older system of faults of Cretaceous-Eocene age.—Water-Pocket flexure.—San Rafael flexure.—Parallelism of recent major faults to the old Cretaceous-Eocene shore-line.—Evidences of recent uplifting in the cañons.—Comparison of structural forms in the three provinces, the Basin, the Plateaus, and the Parks.—Types of the Parks.—Effects of erosion upon structure.—Absence of horizontal forces in the elevation of the Plateaus.

The great structural features of the High Plateaus are the faults and monoclinal flexures. Faulting is an almost universal concomitant of great disturbances of the strata and of the uplifting of mountains and plateaus. Of their causes geology has taught us but little beyond the bare fact that they are produced in the great majority of cases by differential uplifting by vertical forces, which is hardly more than an identical proposition. The nature of the forces we know not, and can only speculate vaguely about them. We do not always know even whether a fault is produced by uplifting upon one side of a given vertical plane or by sinkage on the other, and there must always be an implicit reservation when we speak of them as produced by upliting, so that nothing more is meant than that the strata have been sheared vertically, and that one portion is left on a higher plane than the other. Why the vertical forces should undergo an abrupt change or even total extinction in passing from one side of a given line to the other is a mystery which we cannot hope to solve until we know the origin of the force itself. All that is left us at present is to study the faults themselves carefully, ascertaining, as far as practicable, what movements have really taken place, how they are related to each other, what dislocations have been produced by them, and what are the present and what were probably the former attitudes of the disturbed masses; and yet there are very few subjects in the range of geology so difficult to study. It seems as if Nature were ashamed of her scars, and resorted to numberless tricks and devices to hide them from sight; here smoothing over the break and deftly hiding it with a mantle of soil; there confusing the inquisitive student by a multiplicity of perplexing forms, which are sure to worry if not to mislead him; and always shy of the truth. Throughout the greater part of the Plateau Province, Nature is so poorly clad in the raiment of soil and vegetation and the earth is so well dissected by erosion that these features do not easily escape the scrutiny of the determined and experienced investigator. In the High Plateaus, however, the faults are less readily scrutinized than in some other parts of the province, though much more conspicuously displayed than in smoother and moister countries or than in countries of more complicated structure. While I suspect that many minor faults have escaped detection, I am confident that all of the grander ones have been discovered and their principal features and relations unraveled.

All of the greater displacements of the district present certain well-marked habitudes. Most important among them is the strict homology of the faults with monoclinal flexures. In truth, so close is the homology, that we are justified in calling a monoclinal in some of its aspects a modified fault. The only difference for structural purposes is that in the case of a typical fault of the simplest form the shearing is along one plane, while in the monoclinal the shearing lies between two planes. We have also cumulative or repetitive or "step-faults," where the shearing is subdivided among several planes. All have this in common, that the passage from the uplifted to the lowest thrown side is through a very narrow zone, which has its width reduced to zero in the case of the single or simple fault. All of the great lines of displacement assume all of these modifications in different parts of their extent. In one place the fault is simple. A few miles farther along its course it may become subdivided into a series of "step-faults;" still farther on, into a perfect unbroken monoclinal; it may be at another locality a faulted monoclinal—a part of the displacement being through flexing and a part through shearing. In any case the effect is in its broader aspects the same. One side has been uplifted, the other side "thrown."

The true monoclinal in its perfect form is much more common in the sedimentary than in the volcanic beds The latter seem to lack that flexibility or rather adaptability which enables strata to undergo differential distortion without fracture. In the sedimentaries, on the other hand, the monoclinal seems to be the favored form of displacement, though trenchant faults are common enough. In the volcanics there is a tendency to the monoclinal form, but the unyielding nature of the rocks has produced comminuted fracture in places where a monoclinal would doubtless have been produced had the strata been more compliant. Hence the volcanics seldom preserve the unbroken monoclinal, though there is one good example of this preservation. This comminution is a source of perplexity in resolving the displacement into its constituents, and frequently renders it necessary to stay long and scrutinize abundantly before the extent of it and its true method can be properly ascertained.

Another striking characteristic of these displacements is their systematic arrangement. Viewed in one way they approach parallelism, but there is a noticeable convergence of the lines as we trace them from south to north. In disturbed regions the faults and flexures usually tend to parallelism, and while the tendency is as decided here as it is elsewhere, yet the converging tendency is a noticeable characteristic. These great displacements of the High Plateaus are the northward continuations of those which have been described by Powell and Gilbert in the vicinity of, and crossing, the Colrado River at the Grand Cañon. But in the Grand Cañon district (where they gave origin to the Kaibabs) the belt of faulted country is wider and the intervals between the faults and flexures are greater than in the High Plateaus. This width diminishes northward, and several of the grander faults at length become merged into one vast monoclinal flexure, forming the western flank of the Wasatch Plateau. South of the Colorado these faults have not been studied, but the indications now are that they also converge in that direction, giving the greatest expansion to the system just where the Colorado cuts across it. It is impossible to separate the faults of the High Plateaus from their systematic association with those of the Kaibabs, for the two districts have a common history, so far as relates to their more recent structure. The individual faults overlap, and both districts sympathized in the vertical movements. Indeed, the Hurricane and Eastern Kaibab faults form structure lines of the first magnitude in both districts, with no break in the continuity. The indications are unmistakable that the upliftings of the Kaibabs and High Plateaus were sensibly synchronous and formed one movement, and that any attempt to separate them would be to ignore their proper relations.

The westernmost of the series is the *Grand Wash fault.* It crosses the Colorado at the lower end of the Grand Cañon. Southward it curves gradually in its trend, and at the farthest point to which it has been traced its course is to the southeast. Northward from the river the curvature of the trend is still preserved though much less distinct, and its course is nearly due north. It runs out apparently about 35 miles from the river. Its maximum displacement is about 5,500 feet, and the lifted side forms the Sheavwits Plateau.

Next in order comes the *Hurricane fault.* Its southern terminus south of the Colorado is unknown. It crosses the river just west of Mounts Trumbull and Logan, forming the Hurricane Ledge, and its course is nearly north, with a very slight swerving to the eastward. At the Grand Cañon its displacement is about 1,800 feet, and this amount is maintained with little variation for about 40 miles north of the cañon. Here its throw (to the west) rapidly increases. It becomes the western boundary of the great Markágunt uplift—the southwesternmost of the High Plateaus, and is at the same time the boundary which sharply separates the Plateau Province from the Great Basin. Continuing on past the Mormon town, Cedar, and just before reaching Parowan, it suddenly swings eastnortheast, making almost a sharp angle. Thereafter it swings slowly back towards the north until it reaches the western flank of the Tushar, where its throw has much diminished. The precise point where it runs out is not known, since it is covered by basaltic eruptions, but it is not seen beyond the middle of the western flank of the Tushar. Its maximum throw is near Cedar, on the western flank of the Markágunt, where it reaches on an average, along 20 miles of its course, a displacement of about 5,000 feet.

From the Grand Cañon northward for 40 miles it is a nearly simple fault, though in some places it shows comminution of the rocks in the vicinity of the fault plane, and in a few places the beds on the thrown side are turned up. Along the southwestern base of the Markágunt the fracture becomes very complicated. The upper beds have been eroded backward from the fault plane on the lifted side of the fault, and the lower beds on that side have in several places been turned up with a sharp flexure and stand nearly vertical—in one instance have been turned past the vertical. This movement seems to be exceptional, no other instance of the same kind having been seen anywhere. It is difficult to understand by what application of forces such a contortion could have been effected. The Carboniferous has been brought up by it so as to abut against the Tertiary on the thrown side of the fault, and right at the plane of shearing the displacement of the lower beds seems to be about 12,000 or 13,000 feet. But away from the fault plane the beds quickly come back to their normal position, with an uplift of about 4,000 feet. A few miles south of this point another equally abnormal displacement occurs. A small branch of the fault runs into the uplift and a huge block seems to have cracked off and rolled over, the beds opening with a V, and forming a valley of grand dimensions. About six miles north of the great upturn all trace of that peculiar flexure has vanished and the beds are neatly sheared. The Hurricane fault nowhere appears to take on the true monoclinal form. The length of this great displacement is probably more than 200 miles.

The third great fault is that which lies at the eastern base of the *Tushar*. Most of the faults have their throws to the west, but the throw of the Tushar is to the east. It commences with two branches at the southeastern base of the range and the branches converge near the middle of its eastern flank They are obscure and difficult to locate exactly on account of their concealment by the alluvial *débris*, resulting from the waste of the ancient lava beds and the somewhat chaotic nature of the tract through which they run; for this tract is one of the old centers of eruption. But some well preserved beds of conglomerate turned up on the thrown side and matched with beds appearing above at last revealed them, and the discovery of a series of peculiar trachytic beds on both sides of the fault planes confirmed the belief that the faults really existed. In the middle of the range the obscurity is still greater. Volcanic activity, producing great distortion and destruction of the stratification, has made it impossible to unravel the complications of the displacement. I only know that the upper Jurassic beds appear at the base and again high up in the heart of the range and in a very distorted and more or less metamorphic condition at intermediate places. I have cut the knot, and represented the movement in the stereogram as a simple fault. Near the northern end of the Tushar the fault is shown more clearly, and is there relatively simple, though not without some slight complexities arising from undulation of the strata. The same line of displacements extends beyond the Tushar along the eastern flank of the Pávant, which is the northern continuation of that range. Here it is at first a simple fault, but gradually becomes a monoclinal beyond the town of Richfield by the thrown strata flexing gradually upward until they meet the ends of the beds on the lifted side.

Opposite Salina it suddenly changes its trend to the northwest and forms the western wall of Round Valley—a depression cutting through the Pávant obliquely. The length of this displacement is about 80 miles.

The *Toroweap** *fault* cannot be reckoned among the greater faults, though it is so noticeable and conspicuously exhibited that it deserves mention. It crosses the Grand Cañon near Mount Trumbull, about 11 miles east of the Hurricane fault, with a throw to the west of about 700–800 feet, but in the course of about 20 miles to the northward it probably runs out. Very little is known concerning it south of the river. It is a fault of the simplest order.

The fourth great displacement is the *Sevier fault.* It commences about 35 miles north of the Grand Cañon. It makes its first appearance at "Pipe Spring," at the base of the Vermilion Cliffs, and presents a remarkable attitude.† Approaching it from the west, the beds are turned down on the

*The *Toroweap* is a valley opening upon the middle terrace of the Grand Cañon from the north side. It was excavated and its stream dried up before the commencement of the cutting of the inner chasm, and its floor, therefore, remains about on a level with the middle terrace. It is a magnificent avenue of approach to a sublime spectacle of the Grand Cañon, bringing the observer to the brink of the inner abyss, where he may look vertically downwards more than 3,000 feet and with more than 2,000 feet of wall above him. The name Toroweap signifies "a clayey locality."

†There are some indications that it extends a few miles south of Pipe Spring, but it is covered with soil and sand.

thrown side and remain horizontal on the other. The beds, five miles from the fault on the thrown side, come back to horizontality at about the same levels which they occupy on the other side of the fault, Fig. 3. The trend of the fault at first is northeast. Ten miles from Pipe Spring it is a simple fault. Farther on, in Long Valley, it is "stepped" with two branches. Passing on to the base of the Paunságunt at Upper Kanab the beds on the thrown side are flexed upward, while on the lifted side (east) they are horizontal. This form continues northward from Upper Kanab for about 13 miles, when branch faults appear on the thrown side and the fault is stepped and here and there somewhat comminuted, but with one predominant shear, forming the western wall of the Paunságunt Plateau. These modifications disappear about 6 miles farther on, and the fault becomes simple with a diminished throw; the displacement opposite the village of Hillsdale not exceeding 800 feet. Beyond Hillsdale the throw is nearly uniform for about 10 miles and then increases again. The increase is slow but steady for the next 60 miles. Along the east side of Panquitch Valley it is very difficult to study, because it cuts the volcanic rocks, which are much confused, and here is one of the great eruptive centers. It is probably somewhat complicated, though the principal displacement is distinctly revealed in the great plateau wall on the east, and in the great ravines and chasms which cut across it and open into the valley below. Opposite Circle Valley the fault splits off a large piece from the Sevier Plateau by means of a branch which leaves the main displacement and then reunites with it. At East Fork Cañon the thrown beds, consisting of volcanic conglomerate, are turned up monoclinally, but are sundered by the fault at the summit, with a shear of 3,000 feet. A little north of this cañon a branch diverges from the main displacement, running off into the Sevier Valley, where it rapidly dies out. The maximum displacement is apparently attained a few miles south of the Mormon village Monroe, and from that point northward it rather rapidly diminishes. Between Glenwood and Salina the apparent shear has become zero. But the circumstances are remarkable. The fault from Monroe northward is a secondary displacement superposed upon an older one. The zero point of the fault is quickly succeeded in the same line by a resumption of the shear, but in the opposite direction; *i. e.*, the throw north of the zero point is to the east while south of this point it is to the west. The fault with its throw reversed now continues northward, crossing the lower end of San Pete Valley, and becomes the eastern wall of the San Pete Plateau, its shear increasing until it reaches nearly to Mount Nebo. It has not been traced farther, but where it has last been verified it is still in considerable force. The length of this displacement, so far as now known, is nearly 220 miles. It forms the western fronts of the Paunságunt and Sevier Plateaus and the eastern front of the San Pete Plateau.

The *Western Kaibab fault* is the fifth great displacement. It is supposed at its southern extension across the Grand Cañon to unite with the Eastern Kaibab fault, as it is known to do at its northern end at Paria, about 40 miles north of the head of Marble Cañon. Its trend describes a large bow, of which the Eastern Kaibab fault is the chord. Between them the Kaibab Plateau has been uplifted. Through the portions immediately north of the Grand Cañon it is stepped, but the steps unite into a true monoclinal flexure opposite the middle of the Plateau. Towards the north it gradually dies out, and near the junction with the Eastern Kaibab displacement it is but a gentle monoclinal swell and hardly perceptible.

The *Eastern Kaibab fault* is the longest line of displacement of which I have ever heard. It comes up out of unknown regions in Arizona from the vicinity of the San Francisco Mountain, and appears near the mouth of the Little Colorado River as a double displacement, but probably considerably complicated.* The displacement has two parallel branches, which appear to be faults where they cross the Colorado, but about 10 miles northward they gradually pass into two beautiful monoclinal flexures, the strata being unbroken, except by erosion at the surface. At House Rock Valley the two flexures merge into one, which continues northward past Paria, trending first northnortheast, but gradually swinging in a curve around to the northwest, always preserving its true monoclinal form. As it approaches Table Cliff, it dwindles as if about to die out; but opposite the southwest angle

* Professor Powell is probably the only geologist who has seen these faults in this locality. The place is a terrible one to reach unless by boats through the entire length of the Marble Cañon, and even then the approach is formidable. He would be a bold man who should endeavor to reach the locality from above.

of the Aquarius Plateau it is joined by an important fault coming from the southsouthwest. This is the Paunságunt fault, which lies near the eastern base of that plateau. As its throw is in the opposite direction to that of the Kaibab fault, the two are apparently distinct, though they really are branches of one displacement. The displacement now continues north along the western front of the Aquarius Plateau, and presents complication with subordinate faults. Still northward it has the Awapa Plateau for its uplifted and Grass Valley for its thrown side, the minor faults gradually merging with the principal one.

Near the north end of Grass Valley it rapidly passes into a sharply-flexed monoclinal, forming the northwest shoulder of Fish Lake Plateau, and the monoclinal so formed gradually expands into a broader flexure, with an increasing displacement, and becomes the great monoclinal of the Wasatch Plateau, one of the grandest flexures of the Plateau Country. This flexure forms the southeast side of San Pete Valley for about 50 miles. It has not yet been traced beyond the northern end of this valley, but from the topography it is supposed to extend far beyond it, being in full force where it has been last observed. Its total length, reckoning as one displacement the Wasatch, Grass Valley, Table Cliff, and Eastern Kaibab portions, cannot fall much short of 300 miles, and may considerably exceed that after the termini have been discovered. It presents many phases or modifications, but the dominant feature is the monoclinal form. The maximum displacement is at the Wasatch Plateau, and reaches nearly 7,000 feet.

The easternmost fault (*Thousand Lake fault*) of this system begins upon the southern slopes of the Aquarius Plateau, trending due north. It crosses that plateau with a dislocation of 500–600 feet, and splits into two faults, which reunite upon the northern base. Crossing the lower end of Rabbit Valley, it passes along the western base of Thousand Lake Mountain, and then swings to the northeast The throw is to the west, and in passing from the foot of the Aquarius to the base of Thousand Lake Mountain the displacement rapidly increases to about 3,500 feet, and then as rapidly diminishes, again becoming zero about 20 miles northnortheast of the mountain. But it immediately recommences with a throw in the opposite direction (east), repeating the phenomenon presented by the Sevier fault a little south of Salina. Resuming its northerly trend, the fault with a reversed throw passes along the west side of Gunnison Valley with a shear of at least 3,000 feet, and runs obliquely up on the great Wasatch Monoclinal, forming a superimposed displacement, and then cuts obliquely down into San Pete Valley, where it disappears. It may continue farther northward, but it has not been traced in that direction beyond San Pete Valley. Its total observed length is very nearly 100 miles. It is everywhere a true fault, though at several places it is complicated by minor fractures and some flexing of the thrown beds.

I have not included the *East Musinia fault* among the greater displacements, though it has considerable length—perhaps 45 miles—and at one place in Gunnison Valley the shear reaches more than 2,000 feet, and possibly near to 3,000 feet. It is, however, an important feature, and almost entitled to rank with the greater faults of the system. It is parallel to the northern portion of the Thousand Lake fault last described, and might be called a mate to it, since the two hold between them the sunken block of Gunnison Valley and the continuation of that block obliquely across the great Wasatch Monoclinal.

This sunken block is an interesting occurrence, and belongs to that kind of complicated fracture which Powell has named "*Zone of Diverse Displacement.*" The part of it which lies in the lowest portion of Gunnison Valley has been analyzed and described by Mr. Gilbert. It extends both north and south from this locality, and in the former direction continues to display the same comminuted fracture in great variety for a distance of more than 20 miles, while the width of the zone does not exceed 3 miles. It appears to be a very clear case of a block dropping through the drawing apart of the strata and sinking to fill the gap thus produced. Another instance occurs along the western base of the Aquarius Plateau in the southernmost portion of Grass Valley. Here the block between the faults, instead of shearing sharply on both sides, has partly careened and settled down synclinally.

These displacements do not belong wholly to any one period. There is evidence that different faults belong to different ages—not widely separated probably, but recognizably distinct. There is evidence that different portions of some of the faults did not occur simultaneously, or, perhaps more properly, at the same rate of progress. There is evidence that some portions of a fault progressed through intervals of alternate repose and activity. But while the entire Tertiary history of this district, or at least that portion of its history since the Eocene, was marked by the recurrence of disturbing forces here and there, there is one period which appears to have been pre-eminently a period of faulting and uplifting, standing out conspicuously as a culminating period in the movements. It was this period which more than any other gave, not indeed birth, but certainly the maximum growth and expansion to the structural features of the district. This period was a comparatively recent one. To name it in terms of the ordinary geological calendar would probably convey the impression that the means of determining and correlating the ages of events occurring within the district with reference to those occurring outside of it are greater than they really are. Since the middle Eocene all direct connection of the Tertiary history of the Plateau Province with external regions ceases. Since then everything is relative. The order of sequence is plain, but so far as time is concerned we are out of sight of stars and landmarks, and run through the succeeding periods only by dead reckoning. The next age which we can fix after the Eocene is the Glacial period. We recognize high up in the plateaus and mountains the traces of local glacial action, and it has the same general traces of geological recency and historic or prehistoric antiquity as elsewhere. But between these two ages we are conscious only of a vast stretch of time, in which great results were accomplished in a certain definite order. Each individual feature in that progressive evolution was one which by its very nature required long periods to accomplish, and the last of them all was the great uplifting and fracturing of the rocks which had previously accumulated,

I place the age of the principal displacement in a period which had its commencement in the latter part of Pliocene time, and extended down to an epoch which, even in a historical sense, may not be extremely ancient, and which certainly falls on this side of the Glacial period. Perhaps it is still in progress. Perhaps the plateaus are to-day growing higher and the faults increasing their shear. But the beginning of this last period of faulting, whether the period is closed or not, goes, I believe, only back into the late Pliocene. These faults are so important not only to the history of the High Plateaus, but also to the general history of the Plateau Province at large, that it seems proper to enter at some length upon the considerations which have led to this opinion concerning their age.

Recognizing the great magnitude of the results accomplished in this region by erosion since the Eocene, we are naturally led to inquire whether we may not here and there gain some conception of the relative ages of certain events by ascertaining the amount of erosion which has been effected since their occurrence. The laws of erosion, both generally and in their somewhat abnormal application to this strange region, are sufficiently understood to enable us to decide where erosion ought to be most rapid and where most sluggish. Of all portions of the Plateau Province the best watered is the District of the High Plateaus. It is also the loftiest, and gives, therefore, to its water-courses the swiftest descents and the greatest transporting power. On the other hand, its rocks are the hardest and most durable. Thus the altitude and copious rainfall favor a rapid rate of erosion, while the greater durability of the rocks retards it. Not all of the rocks, however, are of this adamantine character. Indeed, some of the most voluminous formations are conglomerates, some well consolidated, but most of them only moderately so. Around the borders of the district are the sedimentaries, differing lithologically in no material respect from those of the province at large. By comparing the effects of erosion in rocks of different classes similarly situated we find great irregularities, but so far as can be seen these irregularities are due chiefly to the relative durability of the rocks. The sedimentaries are most powerfully eroded, and clearly disintegrate far more rapidly than the volcanics, and considerably more so than the conglomerates. There is seldom difficulty in distinguishing the erosion which has occurred during or since the faulting from that which may have occurred before it; and when we first separate this erosion from the earlier we find that in the sedimentaries it is very considerable. Vast ravines havo been scored and deep cañons cut into the risen blocks. The fronts have been battered and scoured by the storms of unknown millenniums and pared off until they stand back of the fault-planes which mark the rifts where they were severed from the platforms below. Realizing how slowly to human senses these processes operate, the thought of the long ages through which they have been at work at first oppresses us, and we are conscious only of a duration which we can no more comprehend than we can comprehend eternity. Yet, when we come to compare the work which has been done upon the flanks of the plateaus with what we are sure has been done upon the regions they overlook, the former sinks into insignificance.

Since the commencement of the faulting ravines have been excavated 2,000 or 3,000 feet in depth; some of the living streams have sunk their cañons from a few hundred to a thousand feet; here and there a patch of exposed country has lost some hundreds of feet of strata; old volcanic vents on which possibly stood cones have moldered away and left barely a heap of unintelligible ruins. More than this: we know that since the same epoch the inner gorge of the Grand Cañon has sunk under the incessant grinding of its turbid waters 3,000 feet into the earth, and its side gorges near the river have deepened an equal amount. Doubtless many other changes have occurred, the precise nature and extent of which we can only conjecture. Such as we recognize seem stupendous to us and even stagger us when we look at the instrumentality to which we must attribute them. But these are only the last touches of the work which has denuded an empire, sweeping from its surface 6,000 feet of strata.

When we study more closely the later erosion, we find that by far the greater part of its results are of that class which is effected with the greatest ease and rapidity. Slow as the process seems to our senses which has cut gorges and cañons, it is swift and trenchant when compared with the moldering of cliffs and the decay of buttes and mesas; and this slow decay is far less slow than the decay of platforms and terrace summits. It is in ravines and cañons that the denuding forces work to the utmost advantage. Let a plateau or mountain range arise, and the streams will dissect it to its core before it will have materially suffered otherwise. Such uplifts as we find in the Plateau Province have given to the streams which flow from them the most favorable opportunity to corrade, and they have cut profound gorges; but the amount of waste upon the summits and even upon the great palisades which bound them has been insufficient to sensibly modify their general outlines or even their larger details along the structure lines The same is true of the heart of the province. The evidence is clear and irrefragable that at a comparatively recent epoch there has been a widespread uplifting coming upon the country suddenly as it were after an immense period of repose. Before its advent the streams had long remained at the limiting levels where they could sink no more, and the slower processes of decay, the recession of cliffs, the widening of valleys, the shrinkage of mesas, the lateral expansion of cañons, had been in progress long enough to have produced very extensive results. As this uplifting came upon the land the rivers were at once disturbed and resumed their occupation of deepening their channels, and sank them almost as fast as the country rose. But they remain to-day with walls but little affected by lateral waste. Every indication points to the conclusion that they are freshly cut and are still cutting.

Thus the study of the effect of erosion upon the uplifted sides of the great displacements of the High Plateaus everywhere indicates relative recency. The time during which these displaced edges have been subject to the action of the elements is trifling when compared with the interval which separates us from the Eocene. It is represented only by a work which is relatively small and easy of accomplishment and performed under circumstances most favorable to rapidity and efficiency. But the general denudation which dates back to the Eocene is incomparably greater in amount, considering only equal areas; and represents in chief part the kind of degradation which is relatively slow, performed under circumstances not always favorable to rapidity.

There is another point of view from which we arrive at the same conclusion, that the great displacements are very young. The volcanism of the country has a history which we are able to unravel as to its broader features. It began after the disappearance of the Eocene lake which covered the Plateau Province. How long after the desiccation we cannot say even relatively. The lake had withdrawn apparently from the High Plateau District soon after the close of the Upper Green River epoch, which represents a period in the latter part (but before the close) of the local Eocene Resting unconformably upon the Upper Green River beds is a series of beds, displayed in all parts of the district, composed of the waste of volcanic rocks. The rocks which furnished these sands and marls are nowhere discernible. Either they have been buried beneath the later lava-floods or have been wholly removed by erosion. Deep in the recesses of some of the plateaus, at a very few places where the grander gorges have eaten their way into them, the oldest observed Tertiary eruptives, the propylites, are revealed. Of these earliest propylitic eruptions we know exceedingly little historically. They are covered with great floods of andesite and trachyte. There is evidence that these eruptions had their periods of activity alternating with long periods of repose. These periods represent an immense amount of devastation wrought upon the older volcanic mountains by the elements, for their *débris* is found in the form of huge beds of conglomerate stratified in a manner which leaves no doubt in my mind that the process of accumulation was the exact counterpart of that which is now building similar beds in the valleys—a purely alluvial process. The earlier andesitic mountains were almost utterly destroyed by this process. Then came another period of activity, followed by another period of denudation. We have older and younger conglomerates. The older contain the andesitic and some trachytic fragments; the younger contain trachytic, doleritic, and even basaltic fragments. But both conglomerates represent an enormous period of denudation, for the aggregate thickness of the beds will frequently exceed 2,000 feet, covering very large areas. At length a period of faulting set in. These conglomerate beds were sheared or flexed, and now form the walls and summits of the great plateaus for many scores of miles in alternation with the remnants of the old volcanic sheets. Again the process of degradation set to work tearing down these tables, the streams rolling the fragments down into the valleys and building up along the foot of each wall a row of very low alluvial slopes, often beautifully stratified, and the exact counterparts of the conglomeritic strata which are now seen edgewise in the plateau-walls. Since the uplifting began the amount of accumulation in this way will probably reach three or four hundred feet in some places, though it is not probable that the average will exceed 200 feet. But this modern accumulation has been made under peculiarly advantageous circumstances. The process will become slower and more difficult as the streams sink their channels and every additional yard of deposit will be accumulated at a slower rate.

It was the uplifting along great lines of dislocation which set this cone-building process going. The abrupt descents gave the creeks and brooks their power to transport this coarse *débris*, and those slopes are now long and steep. But as the work proceeds the mountains and tables are gradually rounded and smoothed down and the valley plains built up. As yet comparatively little has been accomplished in this direction, but the work is under full headway. In comparing what has been effected since the beginning of the displacements with work of the same character which has been accomplished in ages prior to the displacements, we shall be most forcibly impressed with the littleness of the one and the greatness of the other. It is a comparison of hundreds with thousands. More than that: the hundreds of feet of modern valley cones represent the utmost activity of a process which has worked without interruption and under conditions the most favorable, while the thousands of feet of ancient accumulations represent the same process in all degrees of activity, now intense, now fading and dying out, and then probably long intervals of cessation.

Thus, whether we view the denudation of the High Plateaus or the accumulations in the valleys at their bases, we reach the same conclusions. The faults are very late occurrences in the history of the district. But when we come to ask what is the age, in terms of the geological chronology, to which they must be referred, we can give no further answer than this: they belong to a very late one. There is no record of Miocene or Pliocene in this disturbed region, and we have nothing to mark the lapse of time, except relatively, since the close of the Eocene. But in other parts of the world, where we have some knowledge of the strata, we infer that the Miocene was a longer age than the Pliocene and the Pliocene longer than the Quaternary, though these are impressions rather than conclusions, and to be held lightly. Judging, however, by the magnitude of results accomplished by erosion in the High Plateaus since the faults were started, and comparing these results with similar work accomplished in other localities, and taking into the account the conditions under which they were accomplished, it seems perfectly safe to say that if we carry back the faulting to the middle of the Pliocene we shall have dealt generously with any one who may be disposed to push them back to the remotest possible epoch.

But it may be asked if erosion may not after all have proceeded slowly in this region on account of the arid climate, and whether there may not have been long intervals when its rate was insignificant. I think the answer must be decidedly in the negative so far as the time is concerned which lies on this side of the epoch of displacement. The High Plateaus are not arid, but are watered copiously—less, indeed, than the regions east of the Mississippi, but far more abundantly than the deserts which lie to the east and to the west of them. It must be remembered that their altitude is great, and that their length and breadth is far greater than most of the Rocky Ranges. They are the most prominent topographical barrier which the westerly winds strike after leaving the Sierra Nevada, and though the plains and even the ragged ridges of the Great Basin are parched and dry, yet the High Plateaus wring from the air notable quantities of moisture. The rainfall is not known, but 30 inches per annum is a small estimate of the probable precipitation on the Plateau summits. In the valley plains of the Great Basin the rainfall seldom exceeds 8 inches, and in the painted desert to the east of the High Plateaus it could not reasonably be expected to amount to so much as 4 inches. But there is evidence that in the past—in Glacial and Post-glacial time—the rainfall was far more abundant than now. The drainage of three-fourths of the district was gathered in those periods into the grand expanse of Lake Bonneville, of which Great Salt Lake and Sevier Lake are the remnants. At present this drainage is absorbed and finally evaporated in Sevier Lake alone. Very abundant must have been the rainfall and moist the atmosphere which, with such a relatively moderate water-shed, could have kept such a lake as Bonneville brimming.

Nor is there at present any evidence that the erosion was materially affected either in degree or kind by the presence of ice during the Glacial epoch. On the contrary, the evidence is strongly in favor of the conclusion that in that period the climate was not glacial in this district. The ravines and valleys are conspicuously water-carved and conspicuously *not* ice-carved. As if to furnish proof that the absence of all indications of ice action in the valleys and plateau flanks should be construed as meaning that none existed, we do find at the very summits unmistakable indications of the action of local and very small glaciers, with beautifully preserved *terminal* morains. But I have never seen a morain in the High Plateaus at a lower level than 8,500 feet, and 9,000 feet may be considered as the mean level at which they are first encountered. We find even these only on portions of flanks which bound the loftiest parts of the tabular summits, showing that the loftiest parts alone accumulated ice and generated small glaciers. This will not seem surprising even to those who hold strongly pronounced views on the subject of the Glacial period if we assume that during that period the plateaus stood considerably lower than at present. That they did stand lower then is not improbable. We cannot look to the Glacial period, therefore, for the discovery of any cause which would retard the process of erosion; but, on the contrary, we find in its moister climate reasons for thinking that it may have been notably more rapid than now.*

I have discussed this subject at some length, because the age of these faults is very important in the geology of the region, and is even more important to the southern and southwestern portions of the Plateau Province, if possible, than to the High Plateaus. They are associated with the later history of the cañons and cliffs and with the climatal changes of the province in the most intimate manner. The evolution of that region has long since shown a tendency to cluster; it has even taken form; around certain marked events of which one of the most prominent was the faulting, and the consequences of these faults reach out in a manner which cannot be appreciated until the whole region is described and the history of its constituent parts delineated; a work which I trust will be accomplished in the near future. They everywhere betray in numberless ways their recency, and I have presented only that evidence which strikes the eye at once where we first encounter them.

But while they are all comparatively recent some are older than others. The two Kaibab faults in particular are apparently older than the rest, at least in part Those greater faults which cut through the heart of the

* Whether erosion would proceed faster under the action of ice than of running water is a question which I do not raise. It has no present bearing.

eruptive district seem to have had portions of their shearing before the beginning of the principal epoch of displacement. But these earlier symptoms are usually like old wounds which had once healed and afterwards broke out again with increased disorder. The Sevier fault, in particular, shows signs of two epochs of activity in some portions of its extent. Between Monroe and Gunnison it appears as a fault cutting along the axis of a small but sharp monoclinal flexure. The flexure is clearly older than the fault. The Musinia faults cut obliquely across the great monoclinal of the Wasatch Plateau, and show little sympathy with it. The Paunságunt fault, uniting with the northern extension of the East Kaibab flexure, is plainly independent of it, and is decidedly younger. It is a most curious circumstance that where we find this two-period displacement the motion of the fault is often reversed—the lift of the first period is the throw of the second. It is not always so, but I believe it to be true in a majority of cases where the double movement has been detected. On the other hand, where the shearing of both periods has been in the same direction, the movements would be much more difficult to separate, and many such double movements doubtless have escaped observation.

All of the displacements thus far discussed belong to the same system. Whether older or younger, they lie along the same lines and very seldom show any interferences. None of them will go back of the Pliocene in age, and I think it probable that none of them will go behind the middle Pliocene. Older displacements along these lines, if they exist, are wholly covered up and obliterated, and cannot be separated at present from the later ones of this system.

There is, however, a totally distinct system of displacements, belonging to a much earlier age, which the grander and more general erosion of the country has brought to light, but which can never be confounded with the Pliocene-Quaternary system. They make a wide angle with the latter series and have a history wholly independent of them. They are only occasionally revealed in a fragmentary manner in places where deep gorges have cut through thousands of feet of Tertiary formations and volcanic emanations, or where erosion has swept off corresponding amounts of strata from broad districts. Only in two or three places in the heart of the High

Plateaus are they brought to light; but around the southeastern borders of the district they are displayed conspicuously. The age of these flexures is apparently Post-Cretaceous and Pre-Tertiary; that is, they occupy, in respect to time, an interval which separates the Mesozoic from the Tertiary.* They consist of a series of monoclinal flexures, quite perfect in form, which trend from northwest to north-northwest. They involve the Mesozoic beds, but not the Tertiary. They come up from the southeast, and disappear under the Aquarius Plateau, and on the southern and southeastern flanks are laid bare by a vast erosion. Just before they reach this plateau they are seen to be eroded, and near the summit the Eocene beds are seen to lie unconformably across the beveled edges, and still farther on near the lava cap they rest upon the Jurassic. All around the southern and eastern flanks of the Aquarius and along a part of the northern flank, also entirely around the circumference of Thousand Lake Mountain (with the possible exception of its northern end), the contact of the Tertiary with the Jurassic is obvious.

Farther eastward in the heart of the Plateau Province, outside of the district of the High Plateaus, are three more displacements of grand proportions, of which I can make but a passing mention. The southernmost is the Echo Cliff flexure, a great monoclinal seen south of the Colorado near the Moquis towns. Trending a little west of north, it crosses the river at the head of Marble Cañon, and continuing along the Paria River dies out near Paria settlement at the base of the Vermilion Cliffs. Farther east is the Water-Pocket flexure, one of the grandest monoclinals of the West. It crosses the Colorado in the heart of Glen Cañon, and running north-northwest between the Henry Mountains and Aquarius for nearly 60 miles, swings around to the west in a great curve and disappears under Thousand Lake Mountain. The third is the San Rafael flexure, beginning as a branch of the Water-Pocket flexure, where the latter changes its trend, and running north-northeast along the eastern side of the San Rafael swell, passes off into the northeast and dies out again. These are all monoclinal flexures of imposing dimensions and of perfect form. Their age I cannot speak of at present in any detail, though it is hardly doubtful that they go far back in Tertiary

* Here, as elsewhere in this work, the Laramie beds are reckoned with the Cretaceous, of which they form the upper group of beds.

time and possibly are Pre-Tertiary. Mr. Gilbert has studied the Water-Pocket flexure, and believes that its epoch belongs to the interval which separates Tertiary from Cretaceous time. The Echo Cliff flexure is probably much younger. The San Rafael flexure remains to be studied. None of them appear as yet to have any sympathy with the Pliocene-Quaternary faults of the High Plateaus.

It yet remains to speak of another interesting relation of the later system of faults. They have throughout preserved a remarkable and persistent parallelism to the old shore line of the Eocene lake, following the broader features of its trend in a striking manner. The cause of this relation is to me quite inexplicable, so much so, that I am utterly at a loss to think of any subsidiary facts which may be mentioned in connection with it and which can throw light upon it. It seems best, therefore, to allow the main fact to stand by itself, and not to confuse it with any others with which it has no certain relation.

The faulting and flexing has been associated with a general increase in the altitude not only of the district of the High Plateaus, but of the country south and east of them. The uplifting has by no means been confined to the few tabular masses. Wherever we look in the western part of the Plateau Province the signs of this elevation are unmistakable. In some localities it was much greater than in others, but the signs of it are common to all. It is betrayed in the drainage channels. At a comparatively recent epoch there has been a sudden renewal of activity on the part of the streams, by which they have taken to cañon-cutting with renewed energy as if their slopes had been increased, and this is especially observable in the Colorado itself, where the effect has been a maximum. The tributaries have responded and have acted in like manner. Just prior to the advent of this regional uplifting, the aspect of the region appears to have been that which would naturally have resulted from a long period of stability at the same altitude. The cañons and intervales were wide, and long stretches of the rivers were at or near their base-levels, having eroded as deeply as possible, then slowly widened their valleys and made flood-plains. All at once a new era of cañon-cutting set in, and profound narrow chasms were sawed in the strata and are to-day sinking deeper.

These traces are less conspicuous on the eastern terraces than upon the southern, but are seldom absent. In the Great Basin west of the plateaus there is no evidence of any such general uplifting in the later periods, at least within many leagues of the High Plateaus, although local disturbances of no small magnitude have occurred, and doubtless the southwestern ranges have gained notably in altitude.

It is interesting to compare the structural forms produced by the displacements of the High Plateaus and Kaibabs with those observed in other countries and in other parts of the Rocky Mountain Region. The earliest ideas acquired by geologists concerning mountain structure were derived from the study of the Alps and Jura The conspicuous fact there presented is *plication*—waves of strata like the billows of the ocean rolling into shallow waters, and often a more extreme flexing until the folds become closely appressed. With the extension of observation among the other mountain belts of Europe, and wherever the traces of great disturbance among the strata were found, the same phenomenon of repetitive flexing was discerned, seldom amounting to "close plication," but undulating in greater or less degree. At a later period, when geology was colonized in America, its systematic researches were first prosecuted in the Apalachians, where the same order of facts was presented in a degree of perfection and upon a scale of magnitude far surpassing the original types of Switzerland. At a still later period the geologists who inaugurated in the Sierra Nevada and Coast Ranges the study of the Rocky system disclosed another grand example of the same relations. Thus the increase of observation has been for many years strengthening the original induction that plication and mountain-building are correlative terms.

But the rapid and energetic surveys of the remaining portions of the Rocky Mountain Region have within a few years brought to light facts of a different order. From the eastern base of the Sierra Nevada to the Great Plains are very many mountain ranges, a large proportion of which have come under the scrutiny of geologists; and of those which have been hitherto studied sufficiently to justify any conclusions concerning their structure not one has been found to be plicated. Not one of them presents any recognizable analogy to the structure which is so remarkably typified in the Apalachians. It is certainly true that the study of these mountains has not been so minutely detailed nor so long continued as that of mountains situated in populous countries; that a considerable portion of them have not been examined geologically at all. But, on the one hand, the number of which we already possess a preliminary knowledge is considerable, and on the other hand the remarkable distinctness with which structural facts are there displayed, and the comparative ease with which they may be read, justify more confidence in our conclusions than might otherwise have been admissible. No one familiar with the progress of knowledge in this special direction can fail to recognize the conspicuous absence of plication in the mountain structures which are found east of the Sierra Nevada.

Yet in some portions of this great expanse of territory there are important flexings and warpings of the strata. This is particularly true of the Basin Ranges. But a very significant distinction is necessary here. These flexures are not, so far as can be discerned, associated with the building of the existing mountains in such a manner as to justify the inference that the flexing and the rearing of the ranges are correlatively associated. On the contrary, the flexures are in the main older than the mountains, and the mountains were blocked out by faults from a platform which had been plicated long before, and after the inequalities due to such pre-existing flexures had been nearly obliterated by erosion. It may well be that this anterior curvation of the strata has been augmented and complicated by the later orographic movements. But it is not impossible to disentangle the distortions which ante-date the uplifting from the bending and warping of the strata which accompanied it, and it is only the latter that we can properly associate and correlate with the structures of the present ranges. These present no analogy to what is usually understood by plication. The amount of bending caused by the uplifting of the ranges is just enough to give the range its general profile, and seldom anything more. The same fact is presented in the noble ranges of Colorado. Along their flanks the sedimentary strata roll up usually with a single sweep, and high on the slopes are cut off by erosion. The typical anticlinal axis is not a characteristic feature of the Rocky Mountain system

The type-section of the Park Mountains of Colorado, as given by the late A. R. Marvine, shows a series of broad platforms, uplifted with a single monoclinal flexure or a fault on either side. The width of these platforms varies from 20 to 45 miles, and from these masses the individual mountain-piles have been carved by erosion. The restored profiles obtained by replacing the material removed by erosion are not indeed horizontal nor straight lines, but ordinarily convex upwards, with slight curvature, becoming abrupt or even passing into a great fault at the margin of the uplift. Inasmuch as almost any configuration of the strata which is convex upwards, be it never so little, is called an anticlinal, these platforms would probably be so characterized by most geologists. But what a contrast to the short, sharp waves of the Apalachians! If we analyze the form carefully, it will become apparent that we have to do with a structure which has nothing in common with a true anticlinal except this slight convexity, and which possesses characters which the true anticlinal does not.

It has already been indicated that faults and monoclinal flexures are homologous terms. They represent varying degrees of abruptness in the passage from the thrown to the lifted side of a displacement. In the case of the fault the shearing is confined to a single plane; in the case of a monoclinal flexure the shearing is distributed through a narrow zone between two planes. Both mean essentially the same thing. In the Park Mountains we have uplifts with a fault or equivalent monoclinal on one side or on both. Most frequently it is on both sides, but the shearing is almost invariably more strongly emphasized on one side than on the other. It rarely happens that the fault is clean and trenchant, but is accompanied with much fracturing and shattering of the thrown edges of the strata, and there are cases when the dragging of the fault has been accompanied by the overturning of a great slice of strata torn from the thrown edges. Instances are abundant where the rocks in the flanks of these ranges in the vicinity of the faults have been subjected to the most "heroic" treatment; but at short distances from the faults in both directions the disorganization quickly diminishes. Upon the summits of the platforms the traces of violence and distortion attending the upward movement are much less. Where erosion has laid bare the most ancient rocks they are ordinarily found to be more or less flexed, but the flexing, according to Mr. Marvine, is chiefly of very ancient date—certainly Pre-Tertiary.

Thus the lifting of these platforms has no significance corresponding to an anticlinal fold. It is expressed by the conception of a block of strata having a fault or equivalent monoclinal flexure upon both sides. But while these characteristics predominate strongly throughout the more easterly ranges of the Rocky system numberless changes are rung upon them. One dislocation is usually greater than the other. One fades out to a mere inclined plane, while the other becomes a gigantic fault; all shades of difference are found from the evanishment of one to the sensible equality of both The relative courses of the two displacements constantly vary; here parallel, there converging, and again diverging. But throughout this diversity the dominant type-form is still persistent. These broad platforms have upon their surfaces in most cases a certain amount of minor flexing and undulation. Occasionally a sharp turn of the strata upwards or downwards produces a minor or superimposed wave with a well marked anticlinal and synclinal profile. Minor faults and local shattering are also seen here and there. But those systematic repetitive parallel waves of strata which are conveyed to the mind when we speak of plication are not found in any known region east of the Sierra Nevada and west of the Apalachians.

In the Uintas we find a repetition of the Park Mountain type upon a grand scale. This has been illustrated admirably by Professor Powell in his work on the geology of the Uinta Mountains. It consists of a block somewhat broader than those of Colorado, but otherwise the type presents no essential modification. It has a great monoclinal upon the southern flank and a colossal fault upon the northern. Between the dislocations there is a notable amount of superimposed undulation and subordinate fracturing and flexing; but the greater part of it antedates the Tertiary history of the range, and very much of it is at least as old as the Carboniferous.

In the Plateau Province there are very few mountains, and such as occur are of volcanic origin. Some of them are constructed in a most singular manner, presenting in their genesis and structure an utter contrast to the Alpine and most of the Colorado forms. Lenticular masses of igneous rock have been intruded between the Carboniferous and Mesozoic strata, hoisting the upper beds into great domes. Mr. G. K. Gilbert has studied in great detail the Henry Mountains of southeastern Utah, which present this singular phenomenon in perfection. This group of mountains consists of five individual masses, two of which are of great magnitude, and all of them have been domed up by lava rising from the depths and accumulating in reservoirs several thousand feet below the surface. Each of the mountains has a considerable number of these reservoirs and the two larger masses have many of them. The lava intruded itself at various horizons and congealed, leaving lenticular masses, which are now laid bare and admirably dissected by erosion. There are no indications that any notable quantity of the lava ever outflowed. To these intrusive masses Mr. Gilbert has given the name of "laccolites." These are by no means isolated instances of this extraordinary origin of mountains. The Sierra Abajo on the east wall of the Colorado and a small neighboring range called El Late present the same phenomenon. The Navajo Mountain at the mouth of the San Juan River is similarly constructed.* Several of the Colorado ranges, according to Dr. Peale, owe their structure in part to "laccolitic" intrusion. But mountains on the whole are rare occurrences in the Plateau Province. The uplifts there are almost wholly of the tabular form. Yet, when we come to examine their structure, we find that those plateaus which are due to displacement have a construction strikingly similar to the broad platform-ranges of Colorado and to the Uintas. They are found along the western belt of the Plateau Province in the Kaibabs and in still more perfect development in the High Plateaus. Here the uplifts have been blocked out by the usual faults and monoclinal flexures. Most of them have a single fault upon the western side, inclining at a very small angle towards the east. The western limit is the lifted side of the fault; the eastern limit is the thrown side of the next fault. All traces of the anticlinal have vanished and the structure is of the simplest possible order. In a few of these uplifts we have a block between two faults or monoclinals of opposite throws. Such is the Kaibab Plateau itself. But the great predominance of the faults which face the west

*The Navajo Mountain is a solitary dome-like mass of grand dimensions upon the very brink of the Glen Cañon. The cañon slices off a segment of its base, and the spectacle of rock-work, looking at it from the end of the Kaiparowits Plateau across the gulf, is overpoweringly grand.

is very striking. If we compare these uplifts with the Park Ranges and with the Uintas, the similarity of the structural profiles is very conspicuous. But in the plateaus there is greater simplicity, less subordinate flexing (indeed almost none at all), and an absence of convexity in the section lines.

Crossing the abrupt boundary which separates the plateaus from the Great Basin, we are at once among mountains of a very different order. The Basin Ranges are many in number and inferior in magnitude to those of Colorado, though of no mean dimensions. They are strongly individualized, each being separated from its neighbors by broad expanses of plains as lifeless and expressionless as Sahara. It is as difficult to find a type-form representing the construction of these ranges as for those of Colorado. Yet there are common features of almost universal prevalence among them and at the same time thoroughly distinctive of the group. There is on one side of the range, sometimes a single great fault, or more frequently a repetition of faults throwing in the same direction, while upon the other side the strata slope down to the neighboring plains and there smooth out again. There is much variety in the details of the dislocations, and so complicated do they become in certain localities, that they sometimes mask the general plan until we carefully unravel it. The strata also are almost invariably tilted to high degrees of inclination, thus contrasting strongly with the low and almost insensible slopes of the plateaus. Hence on one side of the range the slope of the profile is along the dip of the strata, on the other side it is across their upturned edges.

We may now compare the orographic forms prevailing in the three great provinces—the Park system, the Plateau system, and the Basin system. The uplits of the plateaus approach in the forms of their displacements more nearly to those of the Park Ranges than to those of the Basin, but are much simpler, much less complicated by subordinate fracture and flexing, and have undergone a much smaller amount of vertical movement. There is, however, one very striking contrast between the Plateaus and the Park Ranges. In the latter, erosion has played a most important part in their history and development. The mountain platforms have undergone an amount of degradation which never fails to revive astonishment whenever the mind recurs to it. Many thousands—nay, even tens of thousands—of feet of strata have been stripped off from their summits and scattered far and wide. As fast as they were denuded they arose, maintaining, and probably even increasing, their altitudes in spite of the waste. Much of the denuded material has been redistributed in strata around their flanks upon the old lake-bottoms of Tertiary time, where there has been, relatively at least, a gradual subsidence as sedimentation progressed. The great faults and monoclinal flexures where the strata are now hog-backed against the flanks of the ranges are the apparent results of the shearing motion set up by the rise of the mountain platforms on one side and the sinking of the newer deposits on the other. In the plateaus the action of erosion has been strikingly different. The tables have been affected only in comparatively slight degree more than the adjoining lowlands. Indeed, erosion has wrought almost equally upon high and upon low levels. In some portions the denudation has been stupendous, but the denuded material has not been carried down and redistributed in the plains below, but has found its way into the deep cañons which cut below its lowest platforms and has been swept through the Colorado to the ocean. Now, it is unquestionably a true law of nature that the denuding agencies operate more vigorously against highlands than against lowlands, and it is quite as true in the Plateau Country as elsewhere. But the recency of the differential elevations of the Plateau Province has not permitted any very great difference to show itself as yet, though it is easy to see that a difference really exists, and is even conspicuous. Furthermore, the peculiar fact that the deeply sunken drainage channels of the province do not allow of great accumulation and restratification at the bases of the loftier masses is a sufficient reason why lower levels should be eroded as well as higher ones, though to a less extent.

We cannot, therefore, attribute the faulting and monoclinal flexing of the plateaus to erosion of the uplifts and the deposition of the *débris* at their flanks, for no such (relatively greater) amount of erosion is found upon the uplifts, and no such depositions take place upon their flanks. The Kaibabs have been enormously denuded, but not much more upon the highest than upon the lowest portions. The High Plateaus have, compared with the

Kaibabs, suffered but little from erosion. In neither district can we look for the same causation of faults and flextures as we might at first feel inclined to employ to explain those of Colorado and the Uintas. In the first chapter I have alluded to the possible effects attending the removal of great loads of strata from one locality of considerable area and the deposition of the same materials in adjoining areas; and while we may rationally suppose this transfer of loads to have important consequences in respect to vertical movements, we seem compelled to postulate additional forces, which for want of any definite conception as to their real nature we call Plutonic forces. The necessity for such a postulate seems perfectly obvious in the plateaus, and a little consideration will, I think, make its necessity apparent in the mountains of Colorado and the Uintas. It is not impossible that the differences existing between the structural profiles of the Plateaus on the one hand and those of the Parks and Basin Ranges on the other may be largely, or even wholly, due to the fact that in the latter regions the *débris* has been deposited at the bases of the mountains, while in the Plateau country it is carried away through the cañons to another part of the world. Hence in the Plateaus we have the result of the uplifting forces, almost pure and simple, while elsewhere it is complicated, and generally reinforced, by the effects of the transfer of great loads from the mountain platforms to the plains and valleys around their bases, followed by a readjustment of the plastic earth to a statical equilibrium of its profiles.

In comparing the plateaus with the Basin Ranges we have to deal with the fact that the displacements of the latter are in the main older than those of the former, though younger than those of the Eastern Rocky Ranges. Erosion has operated powerfully upon all of the Basin Ranges, and the aggregate displacements are greater than in the plateaus. The strata ordinarily incline at larger angles and exhibit a greater amount of subordinate fracturing and dislocation. There is, however, some similarity between the plateau and basin uplifts. Both present a succession of inclined platforms, sloping in the same direction, with greater dislocations upon the uplifted sides. In the Basin Ranges, the uplifting being greater, the inclination is correspondingly greater, so much so, that we pass from the notion of a plateau or platform to that of a mountain slope. The inclination of the plateau summits is rarely so great as 3°; the inclination of the structure-slopes of the Basin Ranges is rarely so little as 8° or 10°.

As bearing upon the general hypothesis that the great structural features are produced by the action of tangential forces generated by the secular contraction of the earth's interior, it may be remarked that the displacements of the Plateau Province do not furnish any evidence of the operation of such forces. A careful study of the system of the Kaibabs and High Plateaus has established the conviction that in those districts no such force has operated. Evidence, however, is often discerned that the strata, while undergoing displacement, have been subject to tension arising from the increased length of profile caused by the undulations so produced. This lengthening of profiles in the vicinity of the monoclinals is indicated by the repetitive faults with an oblique *hade* or *underlie;* and sometimes also by the dropping of a long wedge of strata between two faults with converging hades. Complications of this character often appear as superimposed features upon the great monoclinal flexures.

CHAPTER III.

VOLCANIC GEOLOGY.

A region of extinct volcanism.—Initial epochs.—Tufas.—The most ancient eruptive rocks.—Propylites.—Hornblendic andesites.—Trachytes.—Rhyolites.—Basalts.—The order of succession of the eruptions.—Richthofen's generalization sustained by the succession presented by the High Plateaus.—Certain modifications of the order given by Richthofen.—Resolution of the order into two semi-series.—Fragmental volcanic rocks.—Their great extent and mass.—Two classes of fragmental deposits.—Tufas.—Considerations as to their origin and mode of accumulation.—They are the detritus of more ancient lavas.—Their age.—Volcanic conglomerates.—Their texture and petrographic characters.—Modes of stratification.—They originate from the break up of massive lavas, and are chiefly alluvial accumulations.—Metamorphism of the clastic volcanic strata.

The District of the High Plateaus is a region of extinct volcanism. The magnitude of the eruptions which have taken place there is small compared with what we know of some other regions, but it is great when compared with what we may see in most of the volcanic districts of Europe. It is smaller, I presume, than that of Iceland, but greater than that of Ætna or Central France. It is not the magnitude, however, which is so very striking or suggestive, but the variety of the phenomena and the great stretch of geological time through which their history ranges. The oldest eruptions go back to the middle Eocene; the latest cannot be as old as the Christian era. It is hard to believe that they are as old as the conquest of Mexico by Cortez. Between the opening and cessation of that activity (if, indeed, it has even yet ceased forever) the eruptions have been intermittent. There have been long periods of repose, but during the pauses the subterranean forces were only gathering strength and material for fresh outbreaks.

The highest interest in the region lies in the remarkable variety of the phenomena presented. It lacks but little of being a complete category of volcanology, and what it lacks it compensates by presenting something new. Nearly every form of eruption is exhibited. Every great group of volcanic rocks, and at least three-fourths of all the important sub-groups have here their representatives. The clastic derivatives are displayed in variety and volume truly extraordinary, commanding as much attention as the massive rocks and presenting some highly interesting problems. It would be impossible, within the limits of a single chapter, to present a good synopsis of these facts with a discussion sufficiently extended (and at the same time precise) to make them intelligible. Since the greater part of the individual phenomena described in this work consists of those which belong to the volcanic category, and since no symmetrical grouping of their entire array has suggested itself to my mind, it will be practicable to set forth here only those few facts of a high degree of generality which appear to be applicable to the entire district. In those chapters of this book which are devoted to the description in detail of the component members of the High Plateaus, such facts as seem to be instructive will be adverted to, together with such of their relations as have been satisfactorily ascertained.

The initial epochs and conditions of the eruptive activity of the High Plateaus are obscure. The oldest observed rocks having an eruptive origin are tufas. It is presumable, however, that tufas, especially such as are here found, are never erupted alone, nor wholly in the fragmentary or pulverulent form, but are in part the concomitants of lava floods, and in far greater part the results of the degradation of volcanic rocks. The tufas of this district are stratified water-laid rocks of arenaceous texture, sometimes marly or even shaly; their materials being derived almost entirely from the decay of lavas. Some of these tufaceous beds are metamorphosed, and the highly suggestive and interesting fact is there presented that the product of this metamorphism is a rock having the essential lithologic characters of a lava.* The rocks from which these ancient tufas were derived are not known. An abundance of old lavas lie in their vicinity, but always on top of them. There is, however, one instance in the great gorge near Monroe where a propylitic mass appears to pass under some of these tufas, but owing to the complications of faulting there may be a mistake about it. Whether the lava sheets which yielded by their decay the clastic materials of these

*See Chapter XI, where this remarkable phenomenon is described and discussed.

deposits still remain buried beneath the immense outpourings of middle and later epochs, or whether they have been wholly dissipated, it is impossible to affirm. The period during which these tufas were stratified must be referred to the latter part of the Eocene. They rest everywhere upon beds, which are either of Bitter Creek or Green River age—are, in fact, the latest stratified masses of the region. On the other hand, they must have been deposited before the final desiccation of the great Eocene lake, which appears to have taken place throughout that part of its expanse now covered by the High Plateaus after the middle and before the close of the local Eocene. They are widely distributed, and could not very probably be supposed to have accumulated in local temporary lakelets. Thus, then, the opening of the eruptive activity goes back into Eocene time.

The oldest massive rocks of volcanic origin are found in but few places. The tabular masses which now front the long valleys with escarpments several thousands of feet in height have been scored by ravines, which cut into their innermost recesses. Here, with thousands of feet of more recent lavas and conglomerates above them, are found large bodies of propylite and hornblendic andesite, the former clearly the more ancient of the two. The propylitic masses appear to have been much degraded by erosion before the eruption of the andesites, for patches of conglomerate with water-worn propylitic fragments are overlaid by masses of andesite, and the contact of the two is often of such a nature that there can be no doubt that the massive propylites were water-carved before the andesites were erupted. It is impossible to say anything concerning the extent of these most ancient emanations, for the later rocks have completely buried them, and all that can be seen are the few exposures laid bare by recent faults and excavations. Two centers from which these rocks came have been determined, and they are also found in two other localities, but under circumstances which render it quite possible, and perhaps probable, that the two latter are connected with the two former, the continuity being lost beneath later accumulations. The two eruptive centers are located, respectively, in the northern and southern portions of the Sevier Plateau. The two exposures exhibiting propylitic rocks, which may have been derived from these eruptive centers are situated in the grand gorge of the Fish Lake Plateau, and in the deepest ravines of the Awapa, near the Aquarius, where profound excavations, near the great faults, have disclosed them beneath nearly 3,000 feet of trachytes.

A question has been carefully considered, without reaching a positive conclusion, whether the tufaceous beds already spoken of may not have been derived from the waste of these propylites. The tufas are wholly water-laid beds. Their ordinary aspect is well represented in Heliotypes V and VI. The stratification has all of the mechanical characters of ordinary arenaceous beds. In numerous places the tufas are seen to pass horizontally by gradual transition into ordinary arenaceous shales, made up wholly of materials derived from the decay of non-eruptive rocks. The propylites alone of all the massive rocks seem to have sufficient antiquity to have supplied the material for these deposits, and the only question seems to be whether these came from the visible propylites or some unknown volcanics of still greater age. The tufas have been carefully studied with the microscope in the hope of settling the question, but no solution has been reached. They contain large quantities of quartz and feldspar, which are often epigenetic, and the remaining contents are so much decayed that their original characters are obliterated. But although the antecedence of the propylites to the tufas cannot be proven, it may at least be said that there is no fact now known which forbids such a conclusion. More than that, the inference has some slight preponderance of probability in its favor.

The hornblendic andesites succeeded the propylites with apparently a long interval between them. They were erupted from the same localities or from vents in the immediate vicinity. The mass of these rocks now exposed is greater than that of the propylites, and the lavas are considerably more varied in texture and appearance. Their principal locus seems to have been in the southern part of the Sevier Plateau, though the masses revealed in the northern part of the same uplift are but little inferior. The outbreaks were in massive sheets, which stretched far to the eastward and southeastward, spreading out over large areas and piling up mountainous masses. It is not, however, the quantity now exposed which gives us the real clue to the magnitude of the andesitic extravasations, but rather the great bulk of the conglomerates derived from their ruins. The andesites, considerable as they were, have been chiefly buried by trachytes, but the conglomerates derived from them are still conspicuously displayed. These fragmental masses lie around the eruptive centers in beds often more than a thousand feet thick, and cover areas of which the aggregate extent must considerably exceed 500 square miles.

The third epoch of activity was by far the grandest of all. It was marked by the extravasation of trachytic masses, alternating with augitic andesites and dolerites. A long interval of time separated these eruptions from the andesitic outbreaks just described, for the andesitic rocks were extensively degraded by erosion and their fragments gathered into conglomeritic masses before the earliest outpours of true trachyte. The area of activity was greatly extended in the trachytic age, new places opened and poured forth immense floods, which at length became so vast that they overwhelmed and buried the greater part of the district, generating a new topography. The northern part of the Sevier Plateau, which had given vent to the propylites and andesites, became a focus of still more extensive trachytic eruptions. From this center they spread in all directions. Those which rolled eastward are most conspicuously displayed, and the first impression is that the larger portion of the trachytes flowed in that direction. Some of the grander sheets extended more than 20 miles to the southeast of their origin, and die out near the base of Thousand Lake Mountain. To the southward they make up the greater part of the bulk of the Sevier Plateau, reaching nearly 25 miles from the vents, and commingling with floods poured from median vents in the plateau. To the northward they stretched beyond the locus of Salina Cañon, where they have been much wasted by erosion, but heavy masses are still left to indicate their former magnitude. To the westward the sheets are abruptly cut off in the face of the escarpment of the west front of the Sevier Plateau, which reveals more than 3,000 feet of their mass resting upon the andesites and propylites. Beyond this a great fault throws down Sevier Valley, in which they are seen in a few places beneath later rhyolites.

It is by no means certain that all the *foci* of eruption have been ascertained. So great have been the changes produced by erosion, that the superficial features have been thoroughly remodeled by it. No lofty, Ætna-like summits or craters are visible, and it is doubtful whether the method of eruption was generally such as would generate mountains of that character; for the larger deluges appear to have emanated from fissures located within restricted areas. Yet apparently some piles of important magnitude were reared by the successive superposition of *coulées* around a central vent or pipe, and still bear evidences of their origin, though they have been reduced to mere remnants by the wear of ages.

In the southern part of the district several *foci* of eruption are discernible. The most important was just east of the old andesitic center. From this one emanated the dark trachytic masses which have built up a great portion of the Aquarius. Another was situated at the southern base of the Tushar, and disgorged the masses which built the southern portion of that range. A line of vents stretched southwest from the Tushar along the western crest of the Markágunt, and sheeted over the greater part of that plateau. Still another occupied the position of Mount Hilgard, at the extreme eastern boundary of the High Plateaus, and a chain of vents stretched southward from it to Thousand Lake Mountain. Around the outskirts of the more compact inner district many minor eruptions occurred, overflowing numerous outlying patches.

The rhyolitic eruptions occur chiefly in the Tushar, the Pavant, and Markágunt—in a word, belong to the western margin of the district. Their grandest masses are displayed in the northern portion of the Tushar. They form the summits of this range, standing in high peaks, which are the loftiest in Utah, excepting two or three in the Uintas. Here no other eruptive rocks are associated with them, except a few small outbreaks of basalt which overlie them. The platform upon which they lie consists of metamorphic Jurassic sandstone, upon the eroded surface of which they were outpoured. We find here evidence that the eruptions did not occur in rapid succession, but were separated by intervals of time sufficient to accomplish much erosion. Old valleys scored in the older lavas were filled up by later floods, which were, in turn, chasmed with ravines, revealing the contacts, and this process was repeated again and again.

Two groups of rhyolitic rocks may be discerned in this locality, each presenting great variety in the texture, as is always the case with rhyolites, but each preserving certain dominant features. The older of the two has the character of liparite—a porphyritic texture with conspicuous crystals of feldspar and quartz, and having a superficial resemblance to some common trachytes, but more glassy or hyaline. They are usually very dark colored. The later varieties are nearly white or cream colored—sometimes ashy-gray, without any apparent crystals even under the microscope, but showing a reticulated or globulitic ground-mass of great beauty and interest. The rhyolites of the Markágunt have a superficial resemblance to trachyte, being dark gray and porphyritic, with a texture which is decidedly trachytic, but the abundance of free quartz and the fluidal aspect of the ground-mass under the microscope reveal its true affinities unmistakably. Upon the western verge of this plateau they have piled up some lofty masses with broad tabular summits. They are seen in many places to rest upon older trachytes and in others are overlaid by basalt.

The basaltic eruptions were very numerous throughout the district, but never attained the magnitudes seen in the other groups. Most of the individual *coulées* are relatively small. The largest masses are seen on the southwestern flank of the Tushar. Here numerous eruptions from the same vents have piled up nearly a thousand feet of basalt and spread the lava confusedly over a considerable area. A large field, with many cones still standing in a dilapidated condition, is found at the extreme southern portion of the Markágunt, and a somewhat smaller basaltic area is found in the middle of that plateau.

In every case true basalt is here the youngest of the eruptive rocks, but much of it still shows considerable antiquity. In the Tushar the larger vents have been so far obliterated that the cones have vanished and left the determination of the sources of the lavas to other characters. In the central part of the Markágunt the cones have nearly faded away, but are still recognizable. On the other hand, some of the basalts are strikingly recent, and a few so fresh that no appreciable change has taken place since their orifices became silent. Just south of Panquitch Lake, in the Markágunt, are a number of streams, which, so far as appearance is concerned, might have been erupted less than a century ago. Half a dozen other streams, in various localities, might be named of which the antiquity can hardly exceed a very few centuries. The cones are perfect, the lava is not faded by time, and even the spongy, inflated scum of the surface is still black as coal or faintly tinged by atmospheric reagents. That the basaltic period was a long one is further manifest by the fact that on the southwestern flank of the Tushar is a conglomerate composed wholly, or nearly so, of basaltic materials. These were derived from the degradation of the massive basalts, which have overflowed that part of the range, and they are well stratified after the peculiar manner of sub-aërial conglomerates.

The basalts, in choosing localities for eruption, show here a tendency to abandon those parts of the district which had been the seats of the grander outbreaks of earlier periods and to find new and independent localities for their extravasation. It is not always so, however, for the greatest basaltic floods outpoured hard by one of the most important centers of trachytic eruption. But, on the whole, their situation relative to the older masses is peripheral. In the Markágunt the greater part of the basalts lie upon the sedimentary beds. In addition to this, we find many lone vents, or a small cluster of them, standing far away from the central fields of more ancient lavas. A large number of basaltic streams have emanated from the very walls themselves. In truth, no one can fail to be struck with a peculiar habit which they manifest of seeking strange places from which to break out. Very many cones are perched upon the brinks of the terraced cliffs or cañon walls. In the western wall of the Paunságunt the lava has broken out from the very face of the wall itself. The least common place for a basaltic crater is at the base of a cliff. In a great majority of cases the vents stand near the faults, but the curious part of it is that they break forth almost always upon the lifted and very rarely upon the thrown side of the fault.

All of the basalts are of the feldspathic varieties, none of the nephelin and leucite bearing varieties having been met with.

THE ORDER OF SUCCESSION IN THE ERUPTIVE ROCKS.

The views of F. Baron Richthofen on the succession of eruptions* have received from American geologists profound attention. Probably no

*A Natural System of Volcanic Rocks. Memoir presented to the California Academy of Sciences by F. Baron Richthofen, May 6, 1867.

living observer has studied this problem more carefully nor included in his observations and generalizations a wider field. His extensive knowledge, his great acumen, and his ability to generalize brilliantly, though cautiously, entitle his conclusions to the most earnest consideration. As the result of his study of volcanic phenomena in many portions of the world, he believes that the various kinds of eruptive rocks reveal a certain order of succession in their relative ages of eruption throughout Tertiary time. Arranging these rocks according to their physical properties and intimate constitution into five groups, or orders, he finds that they have been erupted in the following sequence:

1. Propylite.
2. Andesite.
3. Trachyte.
4. Rhyolite.
5. Basalt.

It will seldom happen that more than two or three of these kinds of rock will be found in direct superposition, the series in any given locality being always incomplete, and in very many cases a single kind will alone be found. But wherever two or more are found superposed, the one having the prior enumeration in the foregoing list will be the older. The only exceptions would be where each order of rocks is represented by numerous individual outbreaks, when the later extravasations of the older order may occasionally be seen to intercalate with the older extravasations of the later order. These considerations apply to what are termed "massive eruptions," where deluges of lava have broken forth from fissures and overwhelmed the adjoining regions with *coulées* far exceeding the ordinary emanations of common volcanoes. They also apply to the history of those grander vents which have maintained an activity lasting through a considerable proportion of Tertiary time. But the smaller vents as a rule are of very brief geological duration, and seldom disgorge more than one kind of lava. In support of his generalizations he adduces his own extended observations in Hungary, Germany, and the Sierra Nevada, and those of many colaborers in Armenia, Mexico, Central and South America.

Those geologists who have made a special study of the volcanic rocks of the Rocky Mountain Region from the Great Plains to the Pacific (each within the limits of his own special field), are almost wholly in accord in the belief that Richthofen's law of succession is there sustained. This great field is indeed not yet fully explored, but a very considerable portion of it has been examined. The display of the phenomena of extinct volcanism is, when taken collectively, probably the most extensive and varied in the world. The magnitude and abundance of the eruptions increase as we proceed westward. In the Basin Ranges hardly one fails to show important masses of eruptive rocks, and in many of them such rocks constitute the greater portion of the visible bulk of the ranges. This is especially true of the southern Basin Ranges south of the thirty-eighth parallel, and still more emphatically true of Oregon, Northern California, and the Territories of Washington and Idaho.

Of these individualized areas the District of the High Plateaus is a conspicuous member, though probably far below some of them in magnitude. But among those which have hitherto been brought to notice, none, I believe, present so full and so approximately complete a lithological series. Here then, if anywhere, we ought to find the means of putting Richthofen's law to the test. This was felt after the first season's work had revealed the amplitude and variety of the materials, and throughout the subsequent study of the district was never lost sight of.* As a result of the study, I am satisfied that Richthofen's law is on the whole sustained. Yet there are certain qualifications which are required in order to express the exact nature of the sequence. These do not essentially affect the validity of the law as a whole, but rather are supplementary to it

There can be no question that the oldest erupted masses now visible there are propylites. Next in age follow the hornblendic andesites. The third series of eruptions, which were by far the most extensive, included trachytic rocks, but not trachytes alone. Their associates will be spoken of

* It may not be amiss to state here that at the commencement of the study I had no prepossession in favor of Richthofen's views—possibly the contrary. I felt rather an intense curiosity. After a year's examination I was inclined to the belief that his generalization was not applicable to this district, or was at most very imperfectly so. It was apparent, however, that there was much complexity, and I determined to examine the best exposures thoroughly and endeavor to unravel this complexity, if possible, in order to ascertain whether any real order of succession existed, or whether the sequences were only accidental or capricious. The result will be seen in the text.

presently. The rhyolites as a group are decidedly younger than the trachytes. Wherever the two are found in contact the priority of the trachytes is, so far as observed, without an exception. Still, there is little question in my own mind that some of the more ancient rhyolites of the Tushar are older than many outbreaks of trachyte in other localities. Finally, the basalts are clearly the youngest of all eruptions

If this stated the whole case, we should have the essence of Richthofen's succession almost perfect. The qualification becomes manifest when we come to the study of the trachytic series. Blended with the heavy masses of trachyte, we find in all of the greater exposures rocks of a totally different character. These intercalary sheets belong to the sub-basic or nearly basic groups, and may be designated, according to their constitution [augitic trachyte], augitic andesite, or even dolerite. It will be seen at once that we have here a group of rocks united by certain common characteristics: First, the possession of notable quantities of augite, sufficient, in fact, to render that mineral a distinguishing compound; second, a similarity of habit and facies, which, though distinctly varied, yet vary within quite moderate limits. The habit and facies are markedly basaltic, being greater or less degrees of that characterization which is superlative in true basalt. The older varieties of these intercalary rocks sometimes carry a predominating amount of orthoclase, which marks them as augitic trachyte; sometimes predominant plagioclase, which relegates them to the augitic andesites. The later varieties exhibit those peculiar labradoritic feldspars in conspicuous, often "glassy," crystals, polarizing in gorgeous bands, with rare sanidin and copious augite included in a glass-bearing base. They are usually coarsely crystalline, and have the rough fracture of some typical trachytes, from which, however, they are separated both chemically and mineralogically.* Such rocks would be designated by Zirkel augitic andesites, I presume, but it seems best (with the greatest deference to such an eminent author) to call them dolerites, and to restrict the designation augitic andesites to less basic varieties.

We have, then, in the age of trachytic eruptions, *two* series of lavas

*No doubt it was such rocks to which Abich gave the name "trachydolerite." Deiters recognized in the Siebengebirge a regular transition from trachyte to dolerite. Zeitschr. d. d. Geol. Ges. 1861.

intercalating with each other and presenting certain antitheses We have as the dominant group the true trachytes—rocks having the characteristics of the sub-acid class, and augitic rocks with the characteristics of the sub-basic class.* And it is interesting to compare this association with Scrope's observations in the Auvergne. It has already been remarked that the volcanic phenomena of the High Plateaus reveal a striking similarity to those of Central France, though upon a much grander scale. Scrope frequently alludes to the general impression prevalent long before he made his investigations in that region, and held by many at that time, that the basalts were younger than trachytes, and he frequently contests the correctness of that opinion. Time and again he cites instances where he finds basalts lying beneath trachytes as proof that the rule is by no means invariable. It would be most interesting to know whether he has not included among his "basalts," as scores of other most careful observers have done, those identical rocks which have here been described as augitic trachytes, andesites, and dolerites, and which a more rigorous classification would separate from the basalts.

Leaving here these groups to return to them presently, we may advert for a moment to the relative age of the rhyolites. Instances occur where it is probable that some of the oldest liparitic outpours are considerably more ancient than some of the youngest trachytes. No infraposition of rhyolite to trachyte has been observed *in situ*, but indirect reasoning leads to the conclusion that the central rhyolitic masses of the Tushar were erupted long before the effusion of some of the trachytes of the Sevier Valley. There are many instances in the Markágunt of rhyolite overlying trachyte, and the more recent age of the former as a group is perfectly apparent and incontestible. Lastly, the true basalts everywhere reveal their greater recency than all other rocks.

It now becomes of interest to inquire whether this sequence is correlated in any regular and progressive manner with the physical properties or constitution of the rocks themselves; whether there is with the progress of the volcanic cycle any regular or systematic method of variation in the chemical constitution, mineral constituents, specific gravity, texture, or other

* The classification here adopted is fully set forth in the next chapter.

properties of the rocks. This inquiry immediately presents itself the instant we settle upon the conviction that eruptions have an assignable order of occurrence, and the mind at once springs to the conclusion that there ought to be such an association. If there be an order of eruption, there must be a cause for it, and for that cause we look to the properties of the rocks themselves. But at first glance no such correlation appears. If we arrange them in a series expressing the great groups in the order of their chemical constitution, and place in juxtaposition an arrangement according to the order of eruption, we fail to find at first a clear correlation. Taking Richthofen's five orders, we have the following comparison:

Arrangement by chemical constitution.	Arrangement by order of eruption.
1. Rhyolite.	1. Propylite.
2. Trachyte.	2. Andesite.
3. Propylite.	3. Trachyte.
4. Andesite.	4. Rhyolite.
5. Basalt.	5. Basalt.

With chemical constitution go the other properties, mineral constituents and specific gravity. No relation here presents itself to the order of eruption. Yet I think that upon closer inspection a systematic correlation may be made to appear by an examination of the sub-groups instead of the great groups, and the correlation of the sub-groups will reflect itself in the great groups. Taking the more important sub-groups, those which are most persistent in their characters, of most frequent occurrence, and of the largest volume, the following succession of eruptions presents itself in the High Plateaus:*

1. Hornblendic propylite.
2. Hornblendic andesite.
3. Hornblendic and augitic trachytes (less acid trachytes).
4. Augitic andesite (Richthofen).
5. Sanidin trachyte (more acid trachytes).
6. Liparite.
7. Dolerite.
8. Rhyolite (proper).
9. Basalt (proper).

* For classification and exact meaning of terms here employed see next chapter.

Now, let us make the following arrangement. Place at the head of the series hornblendic propylite. Select from the list in the order given those rocks which are more acid than propylite. Take next those which are more basic than propylite, and write them also in the order in which they occur. We shall then obtain the following grouping:

1. Hornblendic propylite.	
3. Hornblendic trachyte.	2. Hornblendic andesite.
5. Sanidin trachyte.	4. Augitic andesite.
6. Liparite.	7. Dolerite.
8. Rhyolite.	9. Basalt.

This resolves the lithologic series into two semi-series, each of which displays a distinct and unmistakable progression of chemical and physical properties. The first includes the acid and sub-acid groups, which increase in acidity with the process of the volcanic cycle. The second includes the basic and sub-basic groups, which correlatively decrease in acidity. The law may be thus expressed in terms of chemical properties to which the physical properties stand in a relation of dependence: At the commencement of the volcanic cycle the rocks first erupted are those which belong to the middle of the lithological scale. As the cycle advances, the rocks resolve themselves into two semi-series, growing more and more divergent in character, and when the end of the cycle is neared they become extreme in their contrast.

Taking Richthofen's five orders (major groups) and arranging them on the same plan, we may express the same correlation as follows:

1. Propylite.	
3. Trachyte.	2. Andesite.
4. Rhyolite.	5. Basalt.

Possibly it might be thought that this mode of finding a sequence and a correlation bears a resemblance to some problems in the properties of numbers, in which, any fortuitous collection of numbers being taken and treated to certain manipulations, a law of arrangement appears; the real explanation being a latent *petitio principii.* But this is not so. Even if we took Richthofen's five orders only, the probabilities against a merely fortuitous coincidence of orders of eruption with the above double sequence of physical properties would be as 3 to 1. But if we apply the same treatment to nine sub-groups and find the law still holding good, the probabilities against a fortuitous coincidence becomes thousands to one; in other words, a practical certainty. It only remains to discuss the subject as a question of facts and not of inferences. Do the eruptions follow this law?

There are certain sub-groups which have not been named in the foregoing arrangement, such as quartz-propylite, dacite, phonolites, &c. As regards the quartz-propylites, there appears to be a slight departure from the tenor of the law. Its place is among the earliest effusions, whereas in chemical constitution it lies not far from the middle of the trachytic series. But the disagreement is small. Dacite does not occur in the High Plateaus, and I know too little of its relations to other rocks elsewhere to offer any discussion.* But all the other sub-groups, so far as observed, harmonize admirably with the deduced relation, and in truth I can only express surprise at finding not one instance of real anomaly between rocks which occur in superposition, although such instances have been carefully sought for during two prolonged and active seasons' work and were anticipated.

FRAGMENTAL VOLCANIC ROCKS.

Some of the most interesting lithological problems presented by the volcanic products of the High Plateaus are those relating to the origin and development of what may be termed the clastic igneous rocks, or rocks apparently composed of fragmental materials of igneous or volcanic origin, but now stratified either as so-called tufaceous deposits or as conglomerates. These are exceedingly abundant in all of the great volcanic districts of the world, and often enormously voluminous. How those of the High Plateaus would compare, in respect to magnitude, with those of other regions, I do not accurately know, but absolutely their bulk is a source of utter astonishment. They cover nearly 2,000 square miles of area, and their thickness ranges from a few hundred feet to nearly 2,500 feet, the average being probably more than 1,200 feet. Lavas are frequently intercalated, but much more frequently no intercalary lavas are seen, and in general they seldom form any large proportion of the entire bulk when they occur in conjunction with the clastic masses. The grander displays of these fragmental accumulations are seen in the central and southern portions of the

* From present knowledge I am inclined to infer that dacite is about as anomalous as quartz-propylite.

district, though a few important ones are found in the northern part of the field. The great western wall of the Awapa, the central and southern mass of the Sevier Plateau, the southern Tushar and northern Markágunt, are composed chiefly of such formations. The grand escarpments which wall the imposing fronts of these plateaus are conglomerates, sometimes capped with lava, sometimes intercalated, and more frequently without them. Near the center of Grass Valley we have, on the east, bounding the western verge of the Awapa, a wall of conglomerate which is more than 2,500 feet thick; and directly opposite, to the west, forming the eastern front of the Sevier Plateau, is an exposure of very nearly equal magnitude, both stretching southward for 25 miles without interruption, save where erosion has opened great gorges and ravines, though diminishing in thickness. From a point a few miles southeast of Marysvale the western front of the Sevier Plateau exhibits a wall of similar nature, extending south a distance of more than 40 miles to the terminus of the plateau, with only two brief interruptions. The southward expansion of the Sevier Plateau is made up chiefly of such masses, and they reappear in the western flank of the Aquarius beneath its monstrous lava cap. Their thickness will average here much more than a thousand feet. In the northern part of the Markágunt they appear to constitute the principal bulk of the area, though no deep exposures are found and their thickness cannot even be conjectured. The southern part of the Tushar rears a wall of similar nature, revealing nearly or quite 2,000 feet of conglomerate, covering an area of at least 150 square miles, and probably very much more. The East Fork Cañon is cut transversely through the narrowest part of the Sevier Plateau, and exhibits on either side a series of terraces rising 3,500 to 4,000 feet above the bed of the stream. The lower 600 to 800 feet consist of "tufaceous" sandstones, and above them are more than 2,500 feet of coarse conglomerate, with a few massive sheets of intercalary lava. These clastic beds are everywhere seen throughout the central and southern portions of the district and are built upon a giant scale.

Equally striking is the remarkable variety presented in their mechanical texture and structure, whether we consider it in the hand specimen or in the palisade and cañon wall. We may consider them under two classes, which are, ordinarily, fairly distinguished from each other, though sometimes we find transition varieties connecting them. The first are the finer clastic beds, which are usually termed tufas or tuffs; the second are the coarser beds, generally termed volcanic conglomerates.

I. TUFACEOUS DEPOSITS.—It has been noted of most of the volcanic regions of the world, where the period of activity reaches backward well into Tertiary time, that the earliest material erupted is seen in the present form of arenaceous or fragmental deposits. The finer or tufaceous beds have by many geologists been regarded as consisting of material blown out in a pulverulent form, and which, gathering into the drainage channels, was swept into neighboring bodies of water or descended there directly, and was stratified after the manner of sand or silt. Thus they infer that the volcanic activity in such regions was opened by the discharge of fragmental materials or "volcanic ashes," which, projected upwards, were wafted by the winds and precipitated over the adjoining country or waters. This view will be discussed further on.

There can be no question that the most ancient volcanic materials hitherto distinguished in the District of the High Plateaus, and of which the relative age can be assigned, are certain sandstones or beds composed of exceedingly fine particles of shattered or rounded quartz crystals, feldspar, hornblende, and mica commingled in a base of amorphous matter, which is chiefly argillaceous or kaolinic and charged with oxides of iron. Wherever the grains are large enough to show their characters or have a gravelly consistency, they exhibit very clearly minute fragments of volcanic rock in a decayed or carious condition, resulting from the prolonged action of water and the atmosphere, and also show extreme mechanical attrition. This serves to distinguish them from ordinary sandstones, which are usually composed of rounded quartz-grains. In the tufas quartz-grains occur in insignificant proportions, and in their place we find granules of the complex but very massive and obdurate volcanic rocks. Fragments of hornblende and mica also occur, sometimes in great abundance. The condition of the ferruginous matter in the tufas is also very different in most cases from its condition in ordinary sedimentary beds. In the latter rocks it is usually present as a peroxide, sometimes hydrated, sometimes not. In the tufas it usually occurs either as the magnetic oxide or protoxide. In the protoxide forms it is always in combination in some of the minerals—the undecomposed hornblendes and micas or such alteration products as epidote or viridite. These alteration compounds, particularly, are more or less thoroughly diffused throughout the mass of the rock, impregnating it with a greenish color, while the unchanged mica, hornblende, and magnetites, disseminated as black particles, give the rocks a gray color of varying shades from very dark to very light. Whenever these beds have been subject to metamorphic action, as has often happened, the proto-compounds of iron are often converted into sesquioxide, producing a pinkish color similar to that of "Scotch granite." Thus the colors of the tufaceous beds would enable us to single them out as presumably composed of materials very different from those constituting ordinary sandstones.

All of these finer beds are stratified after the manner of ordinary aqueous deposits. That they were water-laid is unquestionable. No rocks have been observed which could possibly have been accumulated by the precipitation of volcanic ashes upon the land. The agency of water in arranging them in their present form is altogether too conspicuous to admit of any doubt. The origin of these clastic materials, proximately considered, is in the break up and destruction of older massive volcanic rocks by the ordinary processes of denudation. It is, indeed, possible that some small proportion of their ingredients may have been pulverulent material blown from volcanic orifices and washed into the basins where the strata accumulated, but it seems quite certain that the great bulk of the tufas did not so reach their present positions. They differ in no other material respect from the common lacustrine beds than in the sole fact that they are the *débris* of volcanic rocks instead of sandstones and gneisses. In a number of instances they are seen to pass, along horizontal exposures, by a gradual transition, into common lacustrine deposits, the quantity of material derived from the break up of vocanic rocks becoming gradually less and less, while that derived from the disintegration of foliated rocks becomes greater and greater. Instances of this transition are seen in various parts of the Sevier Plateau and in the beds beneath the lava-cap of the Markágunt. Indeed, I doubt not that those beds, which are apparently most typically "tufaceous,"

HELIOTYPE VI.

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TUFA AND CONGLOMERATE. EAST FORK CANON.

in reality hold among their ingredients a notable percentage of intermingled grains and silt derived from the denudation of sandstones or other quartziferous rocks. Thus, these tufas would seem to be nothing more than sandstones and shales of the ordinary kind, so far as their mechanical characters are concerned, and having the same genesis as any clastic strata, but the materials of which they are composed being derived from volcanic instead of from foliated common rocks.

On this view of the case there is no apparent reason why they should be sharply distinguished from other strata. It would, indeed, be unjustifiable to proceed to the conclusion that in other parts of the world the so-called tufas have all had a similar origin, for there is abundant reason for the belief that considerable deposits of real "volcanic ashes" exist elsewhere But if the tufas of the High Plateaus are similar to those which in other regions are supposed to be accumulations of ashes, there is reason for believing that the bulk of strata presumed to consist of materials erupted in a pulverulent form has been greatly overestimated, and that such strata, instead of being common, are on the whole rare and of insignificant magnitude. Especially I am confident that these beds do not lead at all to the conclusion that the volcanic activity of the High Plateaus was inaugurated by the ejection of vast bodies of ashes. They seem to point much more logically to the conclusion that eruptions of lavas not now discernible or identifiable took place before they were laid down, and were broken up and wholly or partially dissipated to furnish their materials.

These finer deposits rest upon the Eocene beds, which in the southern part of the district I have inferred to be of the age of the Bitter Creek beds of Powell. Whether they are conformable or not is a question I cannot answer. No unconformity has been discovered, both series being very nearly horizontal wherever they are seen in contact It is not certain that the tufas are immediately consecutive in age to the Bitter Creek beds, but at all events I incline to the opinion that no great interval of time separates them. It is an interesting point whether these tufas were deposited before the final recession northward of the great Eocene lake, thus representing the last strata deposited upon this part of its ancient basin, or were accumulated in local lakelets which may have lingered for a period after the great lake had receded. Either view is for the present tenable. The small extent of the individual beds might argue for local lakelets. There is no persistent formation subsequent to the Bitter Creek spreading over the entire area of the district, but merely considerable patches of tufaceous beds from 100 to 250 feet thick, having no discovered connection with each other, but occurring in many localities. We find reason for presuming some to be much more recent than others, for they rest upon volcanic sheets or conglomerates which can scarcely be so ancient as the middle Miocene. Those, however, which rest upon sedimentary beds are probably of middle Eocene age, or thereabout, in the southern part of the district, and a little more recent in the northern part of it. No distinguishable fossils have yet been discovered in any of them. On the view that these beds are the waste of older eruptive rocks, the opening of the volcanic activity of the district is thus carried back into the middle or early Eocene.

II. Conglomerates.—The coarser clastic formations greatly surpass the tufaceous beds in bulk. They are also much more variable in their modes of stratification and mechanical texture and present problems of great interest.

1st *Texture.*—Like all conglomerates, they consist of rocky fragments inclosed in a matrix of finer stuff, and both fragments and matrix are volcanic material, without any admixture of *débris* from ordinary sedimentary and metamorphic rocks. The included fragments range in size from mere grains to blocks weighing several tons. They are of the same petrographic characters as the massive rocks of the neighborhood, and side by side lie pieces derived from widely distinct kinds of lava:—many varieties of rock may be gathered from a few cubic yards of the same conglomeritic mass. Cases occur, however, where for considerable distances along a given stratum the fragments are all of the same variety; in some the varieties are many; in others they are few. There is no constancy of ratio between the quantity of rocky fragments and the sandy or impalpable matrix. In some beds the stony fragments form but a very small proportion of the bulk; in others, the reverse is true; and there is every possible intermediate proportion. The individual beds are usually very heavy and thick, the partings being rare. In many cases the dimensions of the stones are limited in weight to a few ounces and show a sorting or selection of sizes. But in most cases the sizes have a much wider range.

Geologists have been in the habit of distinguishing two classes of the coarser fragmental beds. First, volcanic conglomerates; second, volcanic agglomerates or *breccias*. The conglomerates contain fragments more or less rounded by attrition, which is held to be an indication that they have been gathered together and arranged by the action of the water. The *breccias* contain fragments which are angular and are presumed to have been showered down around the vents from which they are supposed to have been projected. Beds corresponding to both classes are abundant in the High Plateaus and of very great thickness and area. But I am disposed to accept the conclusion that they have all had a similar origin, and that the projection of fragments from active vents and their descent in a *mitraille* has had very little to do with their accumulation. As a rule, nearly all of the fragments show comparatively little abrasion. Some, indeed, are considerably worn; most of them are very little rounded at the angles of fracture, and a great proportion are in a condition in which it is difficult to say whether they have been abraded slightly or not at all; for when detached from the matrix the surfaces are corroded by some action which may have been weathering prior to their final burial or the solvent action of percolating water after their burial and prior to the consolidation of the stratum. None of the fragments exhibit the sharp edges formed by fresh surfaces of fracture. Thus, while well rounded fragments (like those of glacial drift or stream gravel) are uncommon, it is not certain that any notable proportion have been absolutely free from attrition. The average amount of attrition is generally small—far less than in conglomerates usually occurring in a regular system of fossiliferous or stratified rocks. No sharp distinction can be drawn between those beds of which the included fragments exhibit a considerable amount of abrasion and those in which no abrasion can be clearly proven. There is every degree of this action and every shade of transition Thus it becomes impracticable to draw any line here between conglomerates and breccias.

It has seemed to me that the small amount of abrasion in the conglomerate fragments is susceptible of a partial explanation. The well-rounded fragments of ordinary conglomerates have been ground and worn away by the action of sand and grit carried in suspension by the water. Now the ordinary arenaceous particles are quartz granules, which are exceedingly hard and much more efficient in effecting abrasion than granules of softer material would be. But in a volcanic district, where the only rocks yielding fine detritus are volcanic rocks, quartz sand is a scarce article. The mud and fine stuff carried by the streams consist of fragments of the rocks themselves, particles of feldspar, mica, hornblende, and still more largely clay stained with iron oxide None of these materials possess the hardness of quartz and their abrading power is consequently much less.

The great magnitude of these formations is by itself a source of great perplexity when we inquire as to their origin. Looking up from the valleys below to the vast palisades which stretch away into the distance, and seeing that they are chiefly composed of this fragmental matter, we seem to be face to face with an insoluble problem. How did all this material get to its present position and whence came it? That it was blown into the air in a fragmentary condition and showered down into strata is an explanation which becomes more and more untenable as our studies progress, and at length comes to look quite absurd. These conglomerates are often seen with a thickness of nearly 1,000 feet at distances ranging from 6 to 12 miles from the nearest eruptive focus, and filling all the intermediate space between their outer boundary and the central eruptive mass to which we look to find their origin. Prodigious as the projectile force of volcanoes is known to be, there are no recorded observations which warrant the belief that this force ever becomes so transcendent as would be necessary to hurl such enormous quantities of fragments to such distances. The highest velocity imparted to cannon-shot (over 2,000 feet per second) would be trifling in comparison, and they would have to rise several times higher into the atmosphere than the horizontal distances to which they would be thrown.

But supposing them to be showered down, let us try to imagine them restored to the places from which the outrushing vapors or gases tore them. What enormous vacuities we should be required to fill in order to replace them all! This consideration by itself seems to me sufficient to refute completely the notion that these fragments have been hurled into their present positions by the explosive energy at the vents.

Scoriaceous or slaggy fragments, "volcanic bombs," and the many forms which lava takes when the blast from the crater carries up portions of the liquid and scatters them round the surrounding cone, are not found in the conglomerates—at least I have never observed them. I will except from this statement, however, one locality in the southern part of the Sevier Plateau, where a profound gorge (named Sanford Cañon) gives a brief exposure of what seems to have been an ancient trachytic vent subsequently buried by massive outflows, and which is composed chiefly of cinders. This can hardly be called a conglomerate, however. The fragments of the true conglomerates are apparently pieces of massive lava, just such as are riven by the frost and other agencies of secular decay from cold rocks *in situ*. Very many of them show more or less weathering or corrosion of their surfaces, and very many do not indicate a trace of such action beyond a slight discoloration. That these fragments have been broken from massive rocks is too patent to admit of question.

The only explanation of the origin of the conglomerates which does not involve us in absurdity is that they are derived from the waste of massive volcanic rocks under the normal processes of degradation manifested in all mountainous regions. While active vents usually throw out fragmental matter in great quantities, and while some of the fragments may have been thus derived, yet I conceive that this process has contributed but an insignificant portion of the entirety of the conglomerates. In the chapter on the Sevier Valley and its alluvial conglomerates, I shall describe the process, now in visible operation, by which beds of a similar nature are accumulating at the present day upon a scale of magnitude not inferior to that which produced the colossal formations now seen in the palisades of the plateaus. Throughout the valleys which intervene between the ranges of plateaus fragmental beds are accumulating in vast masses High up in the tabular ranges the frosts, rains, and torrents are gradually breaking up, not only the anciently-outpoured masses of lava, but also the older conglomerates, and are bearing down through the great ravines and gorges the *débris* torn from the rocks, and are scattering them over the valley plains in the form of very depressed alluvial cones, so flat or gently sloped that the conical form is not at first recognized by the eye. Each cone has its apex at the gateway of some mountain gorge, while its base is several miles out in the middle of the valley. These cones are so broad and numerous, that they are confluent at their bases and give the general impression of a very gently undulated surface of alluvium covering the entire expanse of the valley. Could we see them in vertical cross-section, we should find them to possess a well-marked stratification agreeing with the stratification of the older conglomerates. A few fortunate exposures have here and there revealed their internal structure, and a careful comparison leaves little doubt that the valley alluvium and the ancient conglomerates were formed in substantially the same manner and by the same process.

If it be true that these conglomerates have been derived from the secular decay of massive eruptive rocks, of which the *débris* have been carried down the old mountain slopes by running water and stratified in great beds of alluvia, then we may expect to find certain correlated facts, of which the following are examples: (1.) We should expect to find these conglomerates grouped around ancient eruptive centers still preserving remnants of the massive rocks which are presumed to have furnished the material of the conglomerates. (2.) We should also expect to find that these remnants consist of rocks of exactly the same varieties as we find in the fragments of the conglomerates; provided, however, that eruptions from these centers subsequent to the formation of the conglomerates have not completely overflowed and hidden the older outbreaks. (3.) We should expect to find the loftiest portions or crowning summits of the plateaus to consist not of conglomerates, but of massive rocks; unless, indeed, the relative altitudes of the two classes of rocks has been reversed or modified by subsequent upheavals or sinkages.

The general idea here conveyed is that the process which formed the conglomerates consisted in the transportation of fragmental matter from high-standing ancient volcanic piles to low-lying plains and valleys around their bases or along their flanks. These relations, I think, are very satisfactorily shown after a careful analysis of the facts. We may still discern the more important ancient eruptive centers with the conglomerates grouped around them and the fragments contained in the latter agree with the rocks remaining in the former. But there is much complication and obscurity in many instances arising from the fact that these eruptive centers have again and again been active, the work of one epoch being overflowed and partially masked by the extravasation and still later devastation of subsequent epochs. Moreover, the loftiest points are composed of massive rocks, and the positions of the conglomerates are invariably below those of the centers from which they are presumed to have emanated, except in those cases where the relative altitudes have been changed by relatively recent displacement. The general problem would have been full of anomalies, however, were we not in a position to unravel both the complications arising from vertical movements and those from the recurrence of the volcanic activity. But being able to restore in imagination the displaced blocks of country, and in a considerable measure to separate into periods the course of volcanic activity, we find by so doing that the difficulties vanish and the facts group themselves into normal relations.

A very striking characteristic of these clastic volcanic rocks, both the tufas and the conglomerates, is their great susceptibility to metamorphism. Not only have the beds in many localities been thoroughly consolidated, but they have undergone crystallization. Those tufas and conglomerates which are of older date, and which have been buried beneath more recent accumulations to considerable depths, rarely fail to show conspicuous traces of alteration, and in many cases have been so profoundly modified, that for a considerable time there was doubt as to their true character. The general tendency of this process is to convert the fragmental strata into rocks having a petrographic facies and texture very closely resembling certain groups of igneous rocks. When we examine the beds *in situ* no doubt can exist for a moment that they are waterlaid strata. (See heliotypes V and VI.) The hand specimens taken from beds which are extremely metamorphosed might readily pass, even upon close inspection, for pieces of massive eruptive rocks, were it not that the original fragments are still distinguishable, partly by slight differences of color, partly by slight differences in the degree of coarseness of texture. But the matrix has become very similar to the included fragments, holding the same kinds of crystals, and under the microscope it shows a groundmass of the same texture and composition. Crystals are frequently seen lying partly in the original pebble, partly in the original matrix, and the surfaces of fracture betray no inequality of hardness or cleavage, but cut through the pebbles and matrix indifferently. Microscopic examination discloses a groundmass, differing in no very important respect from such as are displayed by many eruptive rocks. The base, however, has, in all the instances which I have examined, that felsitic aspect which is characteristic of porphyritic rocks, neither glassy nor strictly microcrystalline, but exhibiting that aggregate polarization which is not yet satisfactorily explained. There is an entire absence of glass or fusion products in the groundmass. Free quartz is often found even in those varieties which consist largely of plagioclase and hornblende or augite. The fragmental character of the matrix has disappeared; not a trace of the original clastic condition can be detected, unless it is to be found in some of the quartzes and feldspars.

I see nothing at all incredible in the idea of metamorphism producing rocks so closely resembling some eruptive rocks that they cannot be petrographically distinguished from them. It seems rather that we ought to anticipate just such a result from the alteration and consolidation of pyroclastic strata. The materials which compose them consisted originally of disintegrated feldspar, pyroxene, and the matter which constitutes the amorphous base of all eruptive rocks. In general they are silicates of alumina, alkali, lime, magnesia, and iron, from which, no doubt, portions of the soda, lime, and silica, and to a less extent the iron, potash, and magnesia, originally forming the massive rocks from which they came, have been abstracted by atmospheric decomposition. They still retain portions of all these constituents, and only require the presence of conditions favorable to reaction in order to generate feldspar, mica, hornblende, and, perhaps, fresh quartz. Ordinarily we should anticipate that only small quantities of soda and lime would be present, and inasmuch as these bases are necessary to the formation of feldspar (plagioclase), only a partial crystallization would result. There would be left a considerable quantity of aluminous silicate, with some magnesia, which might form mica or aluminous hornblende, though the greater portion of it would ordinarily remain as an amorphous felsite or impure argillite. The obliteration of all traces of granulation in this residual felsitic base is no more remarkable than it would be in an argillaceous rock. So long as a thorough crystallization of the entire mass remains impracticable for want of the requisite quantity of alkaline and earthy bases, much of the groundmass must necessarily remain amorphous; and there is no difficulty in believing that this amorphous base may take those forms and aspects (both microscopic and macroscopic) which are seen in many forms of porphyroid eruptive rocks.

These rocks, however, never reveal any traces of that igneous fusion which is displayed by the basalts and augitic andesites on the one hand, and by the true rhyolites on the other. Glass inclusions, fluidal textures, fibrolites, or a spherulitic base are never found among them. This absence of all evidence of igneous action at high temperature is a significant characteristic. Hence the similarity of these metamorphic rocks does not extend to all igneous or eruptive rocks, but only to limited groups of them, such as porphyritic trachyte and several other trachytic varieties, to the propylites, and to some varieties of hornblendic andesite.

A detailed description and study of the metamorphic tufas will be found in the portion of the chapter on the Sevier Plateau, in which the rocks of the East Fork Cañon are described.

CHAPTER IV.

THE CLASSIFICATION OF VOLCANIC ROCKS.

Objects to be gained by a system of classification.—Artificial and natural systems.—The best system represents with accuracy the existing knowledge.—Progress is from the artificial to the natural classifications.—All are evanescent and temporary.—Classification of volcanic rocks chiefly with reference to physical properties.—Transitions to porphyritic rocks.—Correlations between physical properties.—Chemical composition.—Mineral ingredients.—Texture.—Density.—Fusibility.—Wholly crystalline and partly crystalline textures.—Texture as correlated to geological age of eruptions.—Not universally a true correlation.—Pre-Tertiary lavas common.—Von Cotta's view adopted.—View tested by comparison with facts.—Magmas of all ages the same.—Texture due to conditions of solidification.—Porphyritic texture.—Difficulty of definition.—No strict demarkation between porphyries and lavas.—Crystalline rocks.—Significance of the wholly crystalline texture.—The two original groups.—Acid and basic rocks.—Subdivision of each.—Andesite.—Rhyolite.—The four major groups.—Conspectus of minerals characterizing the primary divisions.—Rhyolites.—Trachytes.—Andesites.—Basalts.—General system.

The objects to be gained by a good system of classification I hold to be mainly two: first, accuracy of designation; and, second, convenience of treatment. In speaking of any natural object, it is desirable to indicate by a single word as much as possible concerning the attributes and relations of that object, and to avoid as far as possible all confusion with the attributes and relations of other objects. In order to secure this accuracy and convenience it is necessary that a classification should be so constructed as to express both the differences and community of attributes and relations. Where the differences of attributes between two or more objects are small and the community of relations is nearly complete, these objects are grouped together as to most of their features, and separated only by small distinctions, as varieties or species. Where these differences are very great, and the community very highly generalized, they are separated by much broader divisions, as in orders or classes. When a category of objects is once classified and familiarized to the mind, the mention of any one of them will convey not only an idea of the concrete object itself as an individual, but also an idea of its differences and community with other objects of the same category, so far as those differences and community are understood.

The differences and affinities (that is to say, community of attributes and relations) between the members of a category are ordinarily not few, much less single, but numerous and complex; and the value and utility of a system of classification is about proportional to the number of differences and affinities which it truthfully expresses. Systems of classification are spoken of as "artificial" and "natural." My understanding is that an artificial system is one which takes account of the agreements and disagreements of the classified objects with respect to only *one* characteristic or one very limited set of characteristics. The meaning of the expression "natural system of classification" is much more difficult to assign. Most probably different authors would entertain widely differing conceptions as to its meaning, none of which would be very definite or precise. They might, however, agree that a natural system as contradistinguished from an artificial one takes cognizance of all the characteristics and relations of the members to each other; the difference and affinity in any case being rated and valued, therefore, in accordance with the totality of characters and not dependent upon merely one of them. But it is far easier to say this much about a system of classification than it is to comprehend it! The truth is, that a natural system in any such length and breadth is impossible for any category, unless we know all the members of it and the totality of their relations; and there is no reason to believe that human knowledge has ever reached to that perfection. But as knowledge is ever increasing, we may at least hope for the time when it shall be sufficient to enable us to find and designate the greater and more important relations with absolute verity; and if the *systema naturæ* is fitted and keyed together in order and harmony, as we are fain to believe, the outstanding facts will fall readily into their places; just as the final parts of a puzzle are quickly placed when the true arrangement of the other parts is discovered. A purely artificial system marks the initial stage of generalization of knowledge; a perfect natural system is for the time being unattainable. The growth of knowledge and philosophy, however, is marked by a transition, long, laborious and very gradual, from one to the other; a transition, which is marked by an indefinite number of tentative classifications, having less and less of the artificial character, and approaching nearer and nearer to the natural. Each classification represents its author's coördinated knowledge of the category of which he treats, and the classifications which are generally accepted at any time represent the stage of knowledge and induction then prevailing. No system is permanent and none ought to be permanent, but they ought rather to change progressively as knowledge and induction progress. Least of all ought any system to attempt to represent anything more than we actually know. The best system at any time is that which represents most accurately the state of knowledge and rational induction at that time.

The progress of classification, then, is from the simple or artificial systems which take account of one set or scale of characters and relations, to the natural systems which take into account the totality of characters and relations. Hence the classification is gradually growing more and more complex and difficult. The present conditions of most systems of classifications, viewed with reference to their respective stages of progress, seem to be much nearer the artificial than to the natural. Even in those categories of natural objects which sometimes are claimed to be classified according to natural systems, the progress from the purely artificial has often been small and the approach to the natural very distant. Though recognizing that a natural classification must embrace the totality of characters, naturalists still employ and are compelled to employ in many cases only a single set of characters for the grouping of a given category. On the other hand, we are often able to recognize correlations between the various properties or characters of a group of natural objects, such that, when we arrange them according to one set of characters, we find that we have also arranged them (in consequence of those correlations) in logical harmony with the others. But this rarely happens except in very small groups with a narrow range of variation; our knowledge is rarely equal to a full and sufficient recognition of such correlations in large groups. Most of the later classifications, however, assume the existence of such correlations while using a single character as a criterion. Although this course is far from being wholly satisfactory, it appears to be the only practicable one. Sometimes this assumption holds true to a remarkable extent; much more frequently the assumed correlations are, so far as we can discern them, seen to be only very partial and imperfect. Still we may hold that, for the time being, the best classification is the one which expresses the largest number of facts and relations hitherto ascertained, and we may advantageously adopt such a classification in preference to any other, though conscious that it fails to bring into recognizable order some outstanding facts and relations which we are compelled for the present to look upon as anomalies.

In proposing a system of classification of volcanic rocks, I shall endeavor to conform to the foregoing conceptions as to the purposes and scope of any or all classifications. Strictly speaking, I can pretend to nothing more than the most convenient and accurate expression which the nature of the case may admit, of the state of my own knowledge and convictions concerning the properties and relations of volcanic rocks. Holding that all classifications are ephemeral, merely indicating the instantaneous phases of advancing knowledge, it is fully admitted to be an artificial one for the most part, and is natural only so far as nature has been truly discerned and expressed. The object in presenting a new classification instead of selecting and adopting an old one is to give precision to the terms employed, and to lay down from the beginning a systematic statement of the views entertained regarding the affinities of the various kinds of eruptive rocks so far as known and understood by the individual writer. Not only does there seem to be no impropriety in any or every writer expressing as accurately and systematically as possible his own views of such relations and affinities, but it is rather incumbent on him to do so, and in no way can this be accomplished so compendiously as by a scheme of classification.*

In a classification of volcanic rocks, the facts which it is desirable to formulate and arrange are, first, those having reference to the physical con-

*I may advert here to a malpractice of some writers, who take advantage of slight pretexts to coin new names for slightly-altered divisions of old groups. A new name is always an inconvenience, even though it may be necessary; unless, indeed, it be a purely descriptive one, conveying at once its significance or giving some conception of its meaning to one who hears it for the first time. Thus, the introduction of such names as protogene, elvanite, nevadite, miascite, &c., entails the necessity of much labor and effort to fix in the memory their meaning, all of which might have been avoided and every useful purpose subserved by using the terms hornblendic granite, quartz porphyry, granitoid rhyolite, nephelin syenite, &c. Irrelevant terms like the first may be very convenient to the writer or speaker, but they are very inconvenient to the reader or hearer. Inasmuch as all classifications are evanescent and constantly shifting, it is manifestly desirable to make them as easily intelligible as possible.

stitution of the numerous kinds and to their degrees of affinity; second, those having reference to their genesis. In other words, we desire a formula which shall express what the rocks are and the causes which made them what they are. It may be said at once that we have no knowledge of the genesis of volcanic rocks sufficient to make a coherent formula, or out of which we can construct a system of causation, however crude. We know that they came up out of the earth in a molten condition, and that is all we can confidently say of their origin. Our classification, therefore, must, from the necessities of the case, be confined to an expression of what we know concerning their physical constitution. In this direction our knowledge is sufficient to justify an attempt to formulate it.

Let us look first at those physical properties which are common to all volcanic rocks, and which, therefore, serve to distinguish them as a category from all other categories; if, indeed, such a distinction really exists.

1. All volcanic rocks have been in a state of fusion at a high temperature.

2. All volcanic rocks have been displaced from unknown depths in the earth, and have risen in a fiery, liquid condition, either to the surface, where they have outflowed as lavas, or have intruded themselves, part-way up, among colder overlying rocks, where they have quietly solidified.

3. They consist of aluminous silicate, combined with lime, magnesia, soda, and potash; iron is very rarely absent—perhaps never wholly wanting. Moreover, the quantities of these several oxides, though varying, have tolerably narrow ranges of variation. Thus the silica never materially exceeds 80 per cent. nor falls sensibly below 45 per cent.; the alumina ranges from 10 to 20 per cent., the lime from 1 to 10 per cent., &c.

4. All volcanic rocks consist of an amorphous base, holding crystals, except, however, some intrusive rocks, which appear to be wholly crystalline. In some obsidians, on the other hand, crystals are exceeding rare, though probably no great mass of obsidian is wholly without them.

Although it seems as if there ought never to be any difficulty in distinguishing a volcanic rock from any belonging to other categories, yet this difficulty sometimes arises. A rock may have been fused and displaced from its seat; it may have the chemical constitution and "half-crystalline" texture of ordinary lavas, and yet it may not have been erupted or subjected to that mechanical action which is the most conspicuous feature of volcanism. It may have been intruded into a dike, or between strata, and only brought to daylight after the lapse of many geological periods by the agency of denudation. Many of the quartz porphyries and the intrusive or "laccolitic" trachytes of the West, and many basalts or dolerites, are of this character. Are these truly volcanic rocks? Before attempting to answer this inquiry let us advert to the wholly crystalline rocks, such as granite, syenite, diorite, diabase, &c. These are not usually accounted to be volcanic rocks; yet they have been heated and rendered plastic, and they have been intruded into narrow dikes and veins and between strata, though they have never been erupted, so far as we know. Between the intrusive rocks of a wholly crystalline texture and the intrusive rocks of a half-crystalline texture there may be found a true transition of varieties, and a hard and fast line cannot be drawn between them. Chemically, the two classes are sensibly exact counterparts of each other, and are very nearly so in respect to their constituent minerals. But the failure to find a boundary is no bar to classification, which takes account not only of differences but also of affinities; and hence, while speaking of volcanic and granitoid rocks as distinct classes, we must still keep in mind the reservation that there is a border country between them.

Having indicated the characters which belong to all volcanic rocks as a class, and which at the same time serve to distinguish them from other classes, we may next proceed to consider how they differ among themselves, and what affinities exist between the different groups. It may be repeated here that considerations relating to the genesis of rocks—the causes and processes which have made them what they are—should not be directly or primarily taken into the account. We know too little about their genesis, and any attempt to include such considerations would merely lead us to embody what we conjecture rather than what we know, and would almost certainly mislead us. We can take account only of well-known facts, and these are to be found chiefly in those chemical and physical characters which have been extensively studied and compared. These are chiefly as follows: 1. Chemical composition. 2. Mineral ingredients. 3. Texture. 4. Density. 5. Fusibility.

Of these characters the most important surely is the chemical composition. In truth, differences of chemical constitution apparently lie at the foundation of most of the other varying characters. It is the primary determinant of the minerals which are formed in the lavas and certainly also of the specific gravity and fusibility. The texture, also, is to a considerable extent dependent upon it, though in this respect the rock is influenced more by other conditions. But on the whole there is a well-marked correlation among the physical properties of volcanic rocks, and we may easily recognize the important fact that variations in the chemical composition carry with them tolerably definite and dependent variations in the other physical properties.

Correlation between chemical composition and mineral ingredients.—The minerals which are formed in volcanic rocks are to a very important extent determined by the chemical composition of the magma. The most abundant constituent of volcanic rocks is silica; its quantity ranging from 45 to 80 per cent. Those rocks which possess the higher percentages of silica have on the whole more acid minerals than those which possess lower percentages of silica. The minerals of the more acid rocks are quartz and potash-soda feldspars, while those of the more basic rocks are lime-soda feldspars, augite, and olivin. Rocks of intermediate constitution contain both kinds or intermediate kinds of feldspar, with abundant hornblende or equivalent augite. We may discern the principle of selection, which determines the minerals by studying each chemical constituent in detail. It might be readily anticipated that free quartz would be segregated and crystallized in a rock containing a very large percentage of silica. Indeed, the law of definite proportions regulating the combinations of all substances requires us to believe that in all ordinary volcanic rocks holding more than 65 to 68 per cent. of silica this excess of silica must be present uncombined, whether as free quartz conspicuous to the eye or as an intimate mixture of the groundmass. There is no fixed percentage at which silica becomes excessive, since that will depend largely upon the atomic weights and affinities of the other substances present. But, in a general way, those rocks which contain large quantities of alkali (soda and potash) may have a larger percentage of silica without excess, than rocks containing more of lime, magnesia, and iron and less of alkali. Thus trachytes, which have a comparatively large proportion of soda and potash, and very little lime and iron, seldom show any evidence of excess of silica unless the percentage exceeds 68 per cent., and then, as the silica increases, they graduate into rhyolites. On the other hand, such rocks as propylite and andesite, which contain an abundance of lime and iron, begin to show evidence of an excess of silica when the percentage of it exceeds 62 per cent. or sometimes even 60 per cent. The reason for this is not far to seek. The alkalies are capable of forming definite combinations with a much higher percentage of silica than are lime, magnesia, and iron. The alkalies give rise to the acid feldspars, albite, and orthoclase, while the lime gives rise to the basic feldspar, anorthite, and iron and magnesia to the equally basic minerals of the pyroxenic, hornblendic, and olivin groups.

On the other hand, the alkalies sometimes form basic minerals, such as leucite and nephelin. This happens whenever these bases are present in quantities in excess of those required to form feldspar, or, what amounts to the same thing, when the ratio of silicate of alumina to soda or potash is less than that required to form albite or orthoclase. Hence, in basic rocks rich in potash, we find leucite, and when they are rich in soda, nephelin, either or both replacing feldspar.

Turning now to the magnesian minerals, the same kind of correlation is seen. Where the quantity of magnesia relatively to the silica is very great olivin is formed abundantly. This is the most basic mineral occurring in eruptive rocks, and is found only in rocks which are least siliceous. Where the quantity of magnesia is less, augite and hornblende are formed. In the two latter minerals it appears that lime, magnesia, and iron protoxide largely replace each other, lime predominating in augite, and magnesia in hornblende. They are moderately basic, but less so than olivin. In the more acid rocks magnesia takes frequently the form of mica (biotite), in which the quantity of protoxide base is still less than in hornblende.

With regard to alumina, it is somewhat remarkable that although the quantity of this constituent is second only to that of silica, it varies less than any other. It rarely falls below 14 per cent. and rarely exceeds 19 per cent. of the entire rock. There is a tendency to a slight excess of alumina above the quantity required to form feldspar in the acid rocks and a tendency to a slight deficiency for the formation of feldspar in the basic rocks.* Hence the slight excess of alumina of the acid rocks may readily be taken up by the aluminous micas and aluminous hornblende; and in the basic rocks, on account of the deficiency of alumina, the lime cannot all take the form of feldspar, and a considerable portion of it appears in the very abundant augite.

Thus we find that basic rocks have basic minerals and acid rocks have acid minerals, and that the mineral ingredients stand in correlation to the chemical composition of the magma, and that the nature of the latter is a determinant of the former. Perhaps the most striking example is to be found in the varying conditions which determine the formation of augite and hornblende. These two minerals differ but little in chemical constitution, and yet their slight differences are distinctly correlated to differences in the composition of the magmas from which they crystallize. In augite, lime and iron are found in greater quantity and alumina in less quantity than in hornblende. Although the differences in these respects are rather small, they appear to be strictly proportional to correlative differences in the general groundmass in which they respectively occur.

Correlation between chemical composition and specific gravity.—The existence of such a correlation is perhaps too well known and too obvious to require any discussion. In general the density holds an inverse ratio to the acidity.

Correlation between the chemical composition and fusibility.—The fusibility of volcanic rocks has not been investigated so fully as other properties, and neither lithologists nor geologists appear to have attached any very great

*The percentage of alumina, however, is less in the acid than in the basic rocks, and yet the excess above the quantity required to form soda and potash feldspars is usually greater in the former rocks than in the latter, on account of the great acidity of the alkali feldspars; indeed, there is rarely any notable excess of alumina in the basic rocks above what is required for the basic lime-feldspar. Thus the rocks which have the smaller percentage of alumina curiously enough have an excess above the requirements of feldspar, and it appears in the accessory minerals, while the rocks which have the higher percentage are rather deficient in it.

importance to the differences in this respect which may exist between the various groups. Still, we have the investigations of Daubeny, Deville, and Mallet, which are so far concordant that they indicate decisively the existence of a true relation. The acid rocks have decidedly higher melting temperatures than the basic rocks. Many blast-furnace slags approach the volcanic rocks in constitution, and the great amount of experience gathered in iron-smelting amply confirms the same relation so far as the cases are fairly comparable. We may, with considerable confidence, state as an approximate truth that the melting temperatures of volcanic rocks have a direct ratio to their acidity.

The textures of volcanic rocks are no doubt due in part to peculiarities of chemical constitution. The vitreous character of the rhyolites, the coarse, harsh texture of the trachytes, the compact, fine-grained texture and peculiar fracture of the andesites and basalts are surely in due a great measure to their constitution, but how or why we do not know. There is, however, another sense in which texture is ordinarily spoken of, and to which high importance is attached, and this sense takes account of the degree or extent to which the groundmass of a rock is crystallized. By far the most important difference between a volcanic and a non-eruptive plutonic rock, so far as pure petrographic considerations are concerned, consists in the fact that the plutonic non-eruptive rock is wholly crystalline, while the volcanic rock is only partially so. Otherwise the two kinds might be quite indistinguishable—might consist of the same constituents. This distinction, depending upon the extent of crystallization, however, is of great importance, since it arises in all probability from causes associated with the genesis and geological evolution of the rocks themselves. The nature and properties of the silicates are such, that under the conditions ordinarily existing their crystallization is attended with difficulty and proceeds very slowly. An indispensable requisite for crystallization is mobility of molecules *inter se*, and for this mobility a liquid condition of the magma is essential. But the silicates possess the following peculiarity: at a temperature sufficiently high to render them very liquid crystallization is impossible; at a temperature just low enough for crystallization, they are exceedingly viscous and the mobility very much impeded. The crystals, therefore, form very slowly, and time becomes an important element in determining the whole amount of crystallization. It is easy to see that an eruptive lava, rapidly cooling under the sky, may remain but a short time at the temperatures at which crystals can form. On the other hand, an injected or plutonic mass may long retain its high temperature. In the former case the rock finally becomes half-crystalline, in the latter case wholly crystalline. That this is the explanation of the textural differentiation of the plutonic and erupted rocks seems very probable, and thus texture becomes associated with the genesis of the rock and the causes which have made it what it is.

There is a very respectable school of German lithologists who make the geological age of igneous rocks a primary criterion of classification. They place all igneous rocks, whose intrusion or eruption occurred prior to Tertiary time, among the granitoid or porphyroid classes, and all Tertiary or Quaternary eruptives among the true volcanics. For example, all augitic plagioclase rocks of Pre-Tertiary origin are regarded as diabases, melaphyres, or augitic porphyries, &c., while all of Post-Cretaceous origin are regarded as basalts, "trachydolerites," &c. Such a classification most assuredly could be defended only upon the assumption or ascertained fact that certain characters are found in the more ancient eruptives which are wanting in the more recent ones and *vice versa*. Is this assumption universally true? I hold that it is not. That in a great majority of cases the Pre-Tertiary igneous, as we now see them, are granitoid or porphyroid, while those of later epochs are volcanic, thus presenting textural differences, is undeniable. But exceptions exist, and they are highly important ones. It is possible, not to say probable, that many more exceptions might be looked for than can at present be specifically named if there were not a certain looseness in the use of names, by which rocks of the volcanic texture are classified with the granitic groups. This is especially observable in the augitic divisions. The augitic rocks of the Palæozoic system, notably those of Carboniferous age, are frequently classed as diabase, when more properly they might be in many instances placed among the dolerites or basalts. Indeed, some intelligent observers, who are not committed in any way to the foregoing generalization, do not scruple to call the intruded and contemporaneous rocks of the Carboniferous in England and Scotland basalt, while others who desire to be non-committal call them traps, which may mean either diabase, basalt, or dolerite, or even augite-andesite. Professor Geike* specially mentions basalt and dolerite as among the interbedded and contemporaneous Carboniferous traps of Great Britain, and so eminent a geologist is certainly not liable to confuse his technical terms. Mr. Jukes also mentions the basalts of the South Staffordshire coal-fields (Rowley Rag) as being of Carboniferous age. Still more ancient are certain basalts of the northern peninsula of Michigan, of which the fragments are found abundantly in the drifts of Wisconsin and Illinois. These were all erupted prior to the Potsdam period; and though they are usually called greenstones, many of them are certainly basalt. Sir W. Logan and T. Sterry Hunt mention dolerites† of Archæan age in Canada (Grenville), much of it very fine-grained and sometimes amygdaloidal, and Sir William pronounced it to have been erupted prior to the Silurian, which is seen to overlap the denuded dikes in which it occurs. Prof. J. W. Dawson speaks of basalts‡ of Triassic age extensively developed along the eastern shore of the Bay of Fundy, especially in the vicinity of Cape Blomidon. The oldest volcanic rocks from the Rocky Mountain Region of which I have any knowledge, are found in rounded pebbles of the Shinarump conglomerate, which lies at the top of the series to which Professor Powell has given that name, and which is supposed to be of Triassic or Permian age. These are fragments of a very fine-grained basalt, quite indistinguishable from the water-worn pebbles of the latest Tertiary basalts. Numerous cases might be cited of the occurreuce of augitic rocks with a volcanic texture erupted prior to Tertiary time, and far back, indeed, into the Archæan, though unquestionably the augitic rocks of earlier epochs possess in the great majority of cases the granitic texture—in short, may very properly be called diabase. It is difficult to resist the conclusion resulting from the various accounts of these rocks that their textures depend chiefly upon the conditions of cooling. Where this has been rapid, as, for instance, in cases of contact with dike-walls, the magmas have been

* Address British Association, Dundee meeting, 1867.

‡ Geology of Canada, 1863, pp. 36, 653.

† Acadian Geology, pp. 94, 98.

even vitrified (tachylite), and where it has been protracted, the resulting rock has taken the granitoid texture—become, in short, diabase.

Furthermore, instances of Palæozoic trachyte are not wanting. In the Laurentian rocks of Canada they are, according to Dr. T. Sterry Hunt,* very abundant and extensively displayed. At Brome and Shefford they occupy two areas of twenty, and nine, square miles, respectively, and their period of eruption must have been soon after the Quebec epochs At Yamaska a micaceous trachyte occurs differing from the foregoing, and at Chambly and Regaud, a porphyritic trachyte. The island of Montreal offers a great variety of trachytic rocks, some of which, according to Dr. Hunt, cannot readily be distinguished from the trachyte of Puys de Dome. At Lachine a phonolite is also mentioned as associated with trachytic dikes.

Thus we do find among Pre-Tertiary eruptives rocks which possess all the essential characters of true lavas. The occurrence of Tertiary granitoid rocks is probably less common. Still they do sometimes occur. True porphyries of Tertiary age are much more frequent. Those intrusive masses, to which Mr. G. K. Gilbert has given the name of laccolites, are in every sense porphyries. Most of them, however, belong to the non-quartziferous division of felsitic porphyry, and are distinct from the common elvanite or quartz-porphyry. But in the Elk Mountains of Colorado we find laccolitic masses of quartz-porphyry graduating into granite porphyry and porphyritic granite. The age of these intrusions is not accurately known, though it is certain that they are Post-Cretaceous. Laccolitic rocks of trachytic and rhyolitic constitution seem to be tolerably abundant throughout the mountain regions of the West.

Nevertheless, the fact remains that the Pre-Tertiary eruptives are on the whole preëminently granitoid or porphyroid in texture, while the Tertiaries are as decidedly volcanic. It seems, therefore, at first as if a correlation existed between age and texture. Forthwith arises the inquiry, what is the significance of that relation? To this question it seems to me that Von Cotta has given a very satisfactory answer, which may be summarized as follows. The eruptive magmas of Tertiary time did not differ at the time of eruption in any material respect from those of older epochs, any more than

* Geology of Canada, 1863, p. 656.

two eruptions of the same epoch may differ from each other without calling for a distinction in their classification; but the textural differences which we now observe are due to the different conditions under which similar or sensibly identical magmas have solidified. The granites have solidified probably at great depths in the earth and under enormous statical pressure, while volcanic rocks have solidified at the surface. Porphyries, which usually occur in dikes or in intrusive masses, have solidified at intermediate horizons, though under conditions probably more nearly approaching those of volcanic than of granitoid rocks. The Palæozoic and Archæan ages may have had their volcanic rocks, differing in no assignable respect from those of recent date, and upon a scale as grand and equally varied, but denudation has dissipated them. The granitoid rocks now exposed to our view have been brought to the light of day only by an enormous erosion, which has removed the thousands of feet of strata beneath which they received their present texture.

This explanation is fortunately capable of a test by comparison with the facts presented by the rocks themselves, and though all the facts have not been collected and studied in this light, yet our knowledge of their general scope and bearing is considerable, and my belief is that they fairly sustain the theory. The granites and syenites are almost invariably found in localities where denudation has proceeded through a long series of epochs and has been vast in amount.* They are usually associated with metamorphic rocks which have been laid bare by the removal of great masses of superincumbent strata. They are not often found as interjected beds in unaltered or little altered Palæozoic or Mesozoic strata; much less as contemporaneous flows. The eruptive syenites and granites, therefore, harmonize with the theory.

The diorites and diabases have a different mode of occurrence. The diorites, so far as known, are believed to be almost invariably intrusive,† either in the form of dikes or intercalary between sedimentary beds. The same also appears to be true of those diabases which possess an unquestionable granitoid texture. There are, indeed, many rocks to which the name

*It would be impracticable here to enter into a full discussion of particular cases without protracting the discussion indefinitely. The statement will, I think, be generally admitted.

†Jukes and Geike, Manual of Geology.

of diabase is given by some lithologists, but which are really dolerites and basalts, bearing indications of a volcanic origin, and these are found as contemporary or interbedded *coulées*. They differ notably, however, from the intrusive diabases, though they are sometimes confounded with them. In short, the ancient eruptives which remain as *coulées* have the volcanic textures, and those which remain as intrusives have the granitic or sometimes the porphyritic texture, and the diorites and diabases equally with the syenites and granites present no obstacle to Von Cotta's hypothesis, but are to all appearances in full accord with it.

It is as certain as anything in geological science can well be that the texture of the granitoid eruptive rocks could not have been derived (at least directly) from any special conditions existing prior to their eruption. Every theory must presuppose that during their eruption or intrusion they were plastic, and that a portion of their groundmass, if not the whole of it, was amorphous and in a condition of igneous or aqueo-igneous fusion, and in such a condition it is little less than absurd to suppose that any texture at all resembling granite could have prevailed. The closely interlocked crystals of such a groundmass are as antithetical to the very idea of plasticity as it is possible to conceive. The crystalline texture must surely have been a development altogether subsequent to plastic movement.* There is, therefore, a lurking fallacy in the statement that granitoid rocks had their periods of eruption in the earlier ages, while the volcanics had theirs in Tertiary time. The true and rational mode of stating the case may be this: that through all the ages igneous magmas have been erupted, which have, according to their final resting-places and the conditions there existing, consolidated either into granitoid or half-crystalline rocks. The magmas themselves have been the same in all ages, each to each within its own group, and so too have the resulting rocks each to each under equivalent conditions of consolidation. We find in the Tertiaries only volcanic rocks, because the corresponding granitoids are far beneath them and not yet laid bare by secular erosion. We find among Pre-Tertiary eruptions chiefly granitoids, because the corresponding volcanics have been swept away.

* It is of course intelligible that some crystals may have existed in an amorphous fluent paste during the eruption.

Texture, then, if the foregoing views be true, is associated with the genesis of rocks and is determined by the conditions under which the rocks have solidified. Although it may seem to be a trivial character, in reality it is a very important one, since it is an index of conditions and occurrences of vital importance to the genesis of the rocks and their geological relations. For it is of the highest geological importance to know whether certain rocks have been erupted or have been formed *in situ;* whether they are indigenous or exotic. The indications given by texture may be uncertain at times, and occasionally even misleading; but on the whole, so far as they are now understood, they may be relied upon. The differences of texture have heretofore been employed chiefly to distinguish the eruptive from the non-eruptive igneous rocks. The wholly crystalline are non-eruptive; the partially crystalline are eruptive. But, although the wholly crystalline rocks are not commonly found in the form of lava sheets or *coulées,* they are occasionally found in the form of intrusions, and so, also, are the partially crystalline rocks. The intrusive condition is, therefore, a kind of intermediate stage between the eruptive and non-eruptive condition, representing an abortive attempt at eruption, sometimes resulting in a slight displacement of the magma, sometimes almost accomplishing an outpour. In very many cases—probably in many more than we are now justified in affirming—this qualified eruption is associated with a texture which seems to be characteristic of it, the *porphyritic* texture.

A satisfactory definition of "porphyry" is almost impossible to find. The most general conception is that it applies to a rock consisting of crystals, usually feldspar and quartz, imbedded in an "unindividualized" paste or base; but forty-nine-fiftieths of all intrusive and eruptive rocks come fully within such a definition. Except an insignificant quantity of obsidians and aphanitic rocks, all volcanics are decidedly porphyritic. And yet lithologists employ the term to designate a group of rocks different from volcanics, not only in their geological relations, but in their appearance as dependent upon texture. There are certainly some rocks which we do not hesitate to call porphyry, and regard them as being quite distinct from the common lavas; the distinction, moreover, being a textural and not a chemical one. As nearly as we can reach a description of the specialized porphyritic texture, it apparently amounts to this: The groundmass consists not only of crystals embodied in a base of matter which is not visibly crystalline, but both crystals and base have certain distinctive features; the crystals of quartz are more perfectly defined in their outlines and possess more distinctly the perfect forms, edges, and angles of their species, the predominant occurrences being the double hexagonal pyramids. The feldspar crystals are also usually distinguished by their perfect forms, especially at the terminations of the prisms, by their large size and by their many and rare angles. In the volcanics the quartzes are not only fragmental, poorly developed, and of uncertain boundaries, but are often rounded and imperfect at the positions of the edges and angles, while the feldspars are exceedingly irregular and indefinite in shape, not often presenting the well-defined edges and angles distinctive of their species. The base of porphyry is, to a great extent, mysterious and inexplicable. Usually it is (macroscopically) exceedingly fine-grained, homogeneous, and compact, with no visible trace of crystallization. Under the microscope it presents certain appearances which have puzzled for many years all investigators. With polarized light it exhibits a behavior which is characteristic of crystallization, and yet no individual crystals can be detected. It is homogeneous in one sense, and yet seems to be minutely granular, as if with greater magnifying power and better definition it would resolve into minute crystalline points; but the latter expectation generally proves a delusion. Not always, however, for sometimes a moderate power resolves the base into a mosaic of crystals, like the groundmass of granite, reproduced upon a microscopic scale. The base of volcanic rocks is usually more or less glassy or fluidal in texture, full of microlites, and even when granular is not nearly so much affected by polarized light.

Many minute characters might be pointed out, but it is needless here. There is no hard and fast line between the porphyritic and volcanic texture, for the latter often simulates the former to a greater or less extent, and even the differences already indicated sometimes vanish or become so poorly pronounced that we fail to apprehend them with confidence. Still, in the long run and in the great mass of cases, we are able to make a distinction, and we find the differences associated with modes of occurrence of the rock masses. The true porphyries are eminently intrusive rocks.

Into the detailed classification of the granitoid or wholly crystalline rocks it is not intended to enter. It will suffice to say that they have been regarded by almost all geologists and petrographers as separated from the volcanics by wide barriers, resting upon wide differences in their geological relations, in their modes of occurrence, their genesis, and geological history. I have endeavored to show that the distinction is well founded. It seems right that they should be placed in different classes, not because the mere lithological fact that they differ in respect to their degrees of crystallization is such a great thing in itself, but rather because it implies a totally distinct category of relations. Whether a third class should be admitted, viz, the porphyritic rocks, is not so clear. For my own part, I incline to the admission of only two classes of igneous rocks, the volcanic and plutonic—the former eruptive, the latter non-eruptive. I recognize, however, that those who are disposed to regard the porphyries as coördinate in value with the granitoids or eruptives, may have much to say in support of their tenets.

Passing now to the consideration of the volcanic rocks as a class, the principles upon which it is believed they ought to be subdivided have, in general terms, already been indicated. We ought not to endeavor to take account of anything more than their chemical and physical properties, since we should otherwise run the risk of serious error. And it has been pointed out that a decided correlation exists among these properties; so that if we take a rational system, based upon one set of properties, we shall at the same time express the other properties. The broader basis I believe to be the chemical one, and I regard it also as the most convenient.

It has long been recognized that lavas are easily distinguished into two principal groups, contrasting with each other not only in the superficial aspects and in the minerals they contain, but also in their composition. One of these groups was ordinarily a coarse-grained, light-colored rock, of rather low specific gravity. It contained crystals of monoclinic feldspar, sometimes abundant free quartz, and also hornblende and mica. The other group was usually fine-grained, compact, very dark colored, and very heavy, holding triclinic feldspar, augite, and magnetite. Upon analysis, the two groups were found to differ greatly in chemical composition; the lighter orthoclase rocks were found to be much richer in silica and much poorer in iron, lime, and magnesia, than the others. This led to the division into the two well-known groups of acidic and basic rocks. To the former the name of trachytes was usually applied, while the latter were termed basalts. As knowledge of volcanic rocks increased and became more detailed, it was at length recognized (by Beudant) that the basic rocks were susceptible of further division. The study of the South American volcanoes convinced him that two types of basic rocks could be distinguished—one the typical basalts, characterized by an abundance of augite, magnetite, and usually olivin commingled with lime-feldspar; the other apparently a less basic rock, containing hornblende rather than augite, very little magnetite, and never olivin. The two types differed in appearance, the more basic being nearly black, the less basic being usually greenish, and certain tolerably constant differences of texture being easily recognized, though hard to describe; the name basalt being preserved for the more basic variety. Beudant called the other type *Andesite.*

The name trachyte for a long time was used very vaguely, and it is now somewhat surprising to find what a vast range of variety it was made to cover. It was applied not only to the light-colored orthose and quartzose rocks, but was extended over varieties belonging well within the basic division, including Beudant's andesites, and hardly stopped short of anything except the extremely basic olivinitic basalts. The general sense of the more acute lithologists, however, was against such a sweeping use of the name, and in favor of confining it to the orthoclase-bearing varieties. Although in this restricted use of the name trachyte a considerable number of varieties had been noted by various writers, Richthofen appears to have been the first to have clearly discerned that the trachytic group resolved itself into two members. Of these the most acidic division was characterized by the presence of free quartz and a general poverty in all minerals except quartz and orthoclase (sanidin); also by peculiarities of texture. The less acidic division rarely contained free quartz, and never in notable quantity; was richer in sanidin as well as in the accessory or subordinate minerals, hornblende, mica, magnetite, &c. It also possessed in nearly all varieties that coarse, rough texture from which the term trachyte originated. The validity of this distinction has been well established by later investigators, and in Germany and America it is universally accepted. To the more acidic division Richthofen gave the name *Rhyolite*, and preserved the name trachyte for the remainder of the older acidic semi-class.

Thus far we are able to subdivide the volcanic rocks into four parts or groups instead of two, as was usually done in the time of Durocher. The older acidic semi-class may be resolved into two groups, the *Rhyolites* and *Trachytes*, while the basic semi-class may be resolved into two, the *Andesites* and *Basalts*. Now, these four groups represent in a very decided manner a progression in the chemical constitution, and also correlative progressions in mineral constitution, in specific gravity, &c. The rhyolites are at the acidic end of the scale of progression and the basalts at the basic end. The trachytes may be called sub-acid rocks and the andesites sub-basic rocks, thus:

Acid rocks—RHYOLITES.
Sub-acid rocks—TRACHYTES.
Sub-basic rocks—ANDESITES.
Basic rocks—BASALTS.

We shall find further on that this progression is not perfectly rigorous and exact, but presents certain apparent anomalies; that some rocks, for instance, which ought to be and are rationally called andesite are more acid than some rocks which are with equal reason called trachytes. Yet, on the whole, the progression is strongly pronounced and unmistakable, and the seeming anomalies do not invalidate the general law.

If we considered chemical constitution alone, however, we should be unable to determine the relative position of any rock in the lithological scale without a chemical analysis. The patent evidence of its position and character is found in the minerals it contains. These, it has already been asserted, are determined by the chemical constitution, and in return indicate that constitution. Each group of rocks has its characteristic group of minerals, of which some may be regarded as essential to the diagnosis of the rock, while others are merely "accessory," being generally present, but sometimes wanting. The accessory minerals are, with rare exceptions, far inferior to the essential ones in respect to quantity. The following conspectus exhibits these minerals:

CONSPECTUS OF MINERALS CHARACTERISTIC OF THE PRIMARY DIVISIONS OF VOLCANIC ROCKS.

Groups.	Essential minerals.	Accessory minerals.
Group I. Acid rocks—Rhyolites	Orthoclase (usually as sanidin) and freo quartz.	Hornblende, biotite, plagioclase.
Group II. Sub-acid rocks—Trachytes	Orthoclase (usually as sanidin).	Hornblende, biotite, augite, plagioclase (the latter seldom wanting), nephelin (in phonolito), magnetite.
Group III. Sub-acid rocks—Andesites (including propylite).	Plagioclase	Hornblende, augite, biotite orthoclase (in subordinate quantity and seldom wholly absent), magnetito.
Group IV. Basic rocks—Basalts	Plagioclase (in some cases replaced by leucito or nephelin), augite.	Olivin, magnetite.

In addition to the minerals presented in the foregoing scheme, there remain several others of considerable importance. These are chiefly leucite and nephelin. Leucite is found in some basalts replacing the feldspar, and is treated in the classification precisely as if it were plagioclase. Though widely distinct from that group of minerals in its crystallographic forms, it closely approaches them in chemical constitution, differing in this respect mainly in containing a little higher percentage of potash than normal orthoclase. Nephelin holds exactly the same relations and presents the samo distinctions, but holds a high percentage of soda instead of potash. It is found not only in the basalts, but also in phonolite, and is generally held to be the most characteristic mineral of the latter rock. If now we treat these two minerals as just so much triclinic feldspar, we shall find no difficulty in assigning them to their places in accordance with all their natural affinities. Leucite rocks will fall readily among the basalts. Nephelin, when associated with other minerals common to the basic rocks, may be considered as replacing labradorite, and the rock containing it may be assigned to the basaltic group. When associated with orthoclase, as in phonolite, the rock will fall among those trachytes which contain notable percentages of plagioclase.

It yet remains to speak of those lavas which contain no distinct minerals, but which are wholly glassy or amorphous, like obsidian, pumice, &c. Here chemical constitution becomes the sole criterion, and although the external or macroscopic facies may often indicate to the trained eye the approximate constitution, the only safe guide to determination is a chemical analysis.

I. RHYOLITES. The rhyolites are distinguished by their high percentage of silica and by the presence of orthoclase and free quartz. The number of varieties of texture found in this group is immense. We find some which have an outward semblance to granite; others containing large, beautiful, and perfect crystals of glassy feldspar an inch or more in length, and large grains of quartz imbedded in a compact matrix; others having the coarse, irregularly granular aspect of trachyte; very many with a groundmass full of elongated vesicles like drawn-out glass and holding small crystals; very many which are so vitreous or slag-like that the crystals are discernible only with the microscope, and many which exhibit no determinable crystals. So protean are the forms, that the lithologist may well feel discouraged in attempting to resolve the group into intelligible or rational subdivisions. Richthofen has attempted it, however, but it seems to me with very partial success. While he has no doubt divided the more prominent sub-groups, cases are often encountered which neither of them appear to satisfy, and microscopic research indicates that many of the characters he has seized upon are less distinctive than the external appearances might at first suggest, and brings to light many others which are of high importance, and which the external appearance does not suggest at all. Considering external characters alone, however, his subdivisions may represent a convenient temporary grouping of the greater part of the rhyolites.

It will be noted that while chemical constitution and mineralogical components are the basis of the larger and broader divisions, the texture may here be employed to distinguish the secondary characters.

GROUP I.—RHYOLITES.

Sub-groups.	Characteristics.
Sub-group 1. NEVADITE or granitoid rhyolite.	Having a superficial resemblance to granite; highly crystalline, with conspicuous quartz and feldspar; the crystals rounded, cracked, and irregular in contour. Base resembling some of the coarser varieties of trachyte.
Sub-group 2. LIPARITE or porphyritic rhyolite.	Having a decided porphyritic texture; compact base; crystals perfect or nearly so, often of large size; not conspicuously vitreous.
Sub-group 3. RHYOLITE proper or hyaline rhyolite.	Having a fluent groundmass, sometimes wholly without crystals, but more frequently with them, but crystals less perfectly developed; vesicular, with vesicles much elongated and drawn out; or not vesicular, but with lines of flow suggesting a vitreous or candy-like mass. Foliated or structureless. Generally fibrolitic or spherolitic.

The microscopic characters of the hyaline rhyolites and some of the liparites have been studied and analyzed in a most admirable manner by Professor Zirkel, and described by him in the volume on Microscopic Petrography in the series of Reports of the Survey of the Fortieth Parallel, to which volume the reader is referred.

II. TRACHYTES. The trachytic group is characterized chemically by a high degree of acidity, but inferior in that respect to the rhyolites. Its dominant minerals are orthoclase, with a subordinate amount of plagioclase. It is distinguished mineralogically from rhyolite by the absence of free quartz, by the greater abundance of plagioclase, and of the subordinate minerals hornblende, magnetite, augite, and biotite. In its texture and physical characters it is also well separated in most cases, showing a tendency to develop the coarsely granular and porphyritic habitudes rather than the hyaline and vitreous, though the latter are not wanting, nor even extremely uncommon. This group is nearly as varied in character as the

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Phonolite. East Fork Canon.

rhyolites, and the same difficulty is experienced in finding a suitable system of subdivision. In attempting to divide them, Richthofen has given two subdivisions, *sanidin-trachyte* and *oligoclase-trachyte.* The admission of an oligoclase-trachyte involves a dilemma. If (as appears from his language) he contemplates a rock in which oligoclase is the dominant feldspar, it cannot, according to ordinary conceptions and definitions, be a trachyte at all, but rather an andesite. If it means that it is abundant, though subordinate to orthoclase, then the same is true of by far the greater portion of the whole trachytic group. Again, sanidin-trachyte also seems objectionable as a characteristic name of a subdivision of the trachytes, since sanidin is the predominant mineral of the entire trachytic group.

And yet my own limited studies have led me to the conviction that Richthofen, with his rare insight into the real nature of the subjects he has investigated, has hit upon a valid distinction, which we may safely follow. Among the older trachytic eruptions we find rocks into which plagioclase largely enters; indeed, to such an extent that we are often doubtful whether it may not preponderate over the sanidin, or at least be very nearly equal to it. In these same rocks we also find an abundance of hornblende and magnetite, giving them the dark iron-gray aspect which is presented by many andesites. These hornblendic trachytes, however, are usually coarser and rougher in fracture than the andesites, and the hornblende crystals are rarely found in such perfection and full development as in the andesites, and macroscopic inspection will generally enable us to form a very good opinion as to which of the two we are dealing with, though sometimes we are deceived. It is evident that such trachytes are not far removed from the andesites, both in chemical and mineral constitution, and they sometimes blend with them.

On the other hand, we encounter among the later trachytes a different series of macroscopic characters. They are very deficient in hornblende, and more often contain mica (biotite). They are usually light-colored, pale-gray, or red, or light brown, and almost never dark gray. In texture they vary widely, but in no case do they ever suggest any affinity to andesite, but rather to rhyolite. Some of the varieties, indeed, approach rhyolite so closely that we often have still greater difficulty in separating them from it than we encounter in separating extremely hornblendic trachytes from andesites. In these trachytes sanidin is the only important mineral, and though plagioclase and hornblende are not uncommon, they are never conspicuous, and never seem to exert any notable effect upon the character or aspect of the rock.

In seeking for purely descriptive names, it seems to me that the older trachytes will be sufficiently discriminated if we call them simply *hornblendic trachytes.* It occasionally happens that the other group requires to be spoken of collectively, and I shall in such cases employ the term *sanidin trachytes*, rather than coin a new name. But for precision it may be necessary to subdivide them rather more minutely, since these so-called sanidin-trachytes embrace very wide variations of lithological aspect. The time has not yet come to divide the immense trachytic group according to definite and final principles. To accomplish that will require the careful study of an enormous range of materials. Although my own observation is far too limited to encourage the hope of finding a complete and satisfactory arrangement, I am tempted to give provisionally and tentatively a subdivision embodying such a grouping as will embrace the facts within my knowledge.

GROUP II.—TRACHYTES OR SUB-ACID ROCKS.

SUB-GROUP A.—SANIDIN TRACHYTES.

	Characteristics.
1. GRANITOID TRACHYTES.....	Trachytes having a superficial resemblance to granitic rocks; holding much orthoclase and less plagioclase, with few other minerals; a very little biotite and hornblende; crystals conspicuous; a somewhat porous base, containing little ferritic matter. Usually very light-colored rocks; seldom dark gray.
2. PORPHYRITIC TRACHYTE....	A base resembling that of porphyrite, with very conspicuous and perfect crystals of orthoclase (usually the turbid or milky variety), often large. The base very fine, compact, and non-vesicular; more or less ferritic, sometimes showing a feeble aggregate polarization. The groundmass shows none of that coarse, rough texture so common in other trachytes.

GROUP II.—TRACHYTES OR SUB-ACID ROCKS—Continued.

	Characteristics.
3. ARGILLOID TRACHYTE	A rock of very clayey or earthy aspect, suggestive of thick slate; very highly charged with ferritic matter, rendering it opaque in the thinnest sections; holding crystals of feldspar (orthoclase) and grains of magnetite, and seldom any other macroscopic mineral. The fracture is highly characteristic, there being no cleavage; but the rock crumbles rather than splits. It is impossible to strike off thin flakes. The fracture is very angular and irregular, though the ordinary coarseness of trachytes is not exhibited. It is a very voluminous rock in the plateaus and well distinguished.
4. HYALINE TRACHYTE........	Trachytes having a fluidal texture, indicative of flowing in a viscous state, with very small, and sometimes few, and always poorly-developed crystals of feldspar. Mostly reddish or purplish; often with a brick-like texture; sometimes foliated and resonant (clink-stone); moderately vesicular. Often slightly quartziferous and approaching the rhyolites.
	SUB-GROUP B.—HORNBLENDIC TRACHYTES.
5. HORNBLENDIC TRACHYTE...	This comprises most of those dark-colored varieties of coarse, harsh texture, exceedingly rough, though many are less so. Hornblende and magnetite are abundant, the former in well-developed prisms. The feldspars are less conspicuous than in the preceding varieties, but are really present in greater quantity, as shown by the microscope. Plagioclase very abundant. Iron gray is the usual color.
6. AUGITIC TRACHYTE.........	It seems doubtful whether this rock should be considered as anything more than a variety of the hornblendic sub-group. It is characterized by the presence of augite in place of hornblende. The varieties are usually finer grained than the hornblendic, and resemble more the augitic andesites, to which, indeed, they are so closely related that it is sometimes difficult to distinguish them. Magnetite abundant and some biotite.
7. PHONOLITE	A rock in which nephelin takes the place of triclinic feldspar. Usually contains also orthoclase and some hornblende; resonant, foliated, and in the rockmass is generally laminated in a very peculiar and striking manner.
8. TRACHYTIC OBSIDIAN	A wholly glassy or vitreous rock, having the normal constitution of trachyte.

III. PROPYLITE AND ANDESITE. Richthofen has made two distinct orders of these rocks, each of equal taxonomic value with the other great groups, *e. g.*, trachyte and basalt. There is no question that a tolerably sharp definition can be drawn between them, and that they are as readily distinguished in most cases by the unaided eye as by the microscope. The microscopic characters have been analyzed and described most thoroughly by Zirkel. But though the distinctions are well-drawn, and once mastered can seldom be confounded, the question arises, are they of sufficiently radical importance to warrant their separation into groups of such high rank as the trachytes and basalts? It seems to me that we cannot do so without a violation of those fundamental principles which have gradually become almost universal in fixing primary characters. On purely chemical grounds so wide a distinction seems untenable, because the chemical difference is very small, and often so indefinite that it cannot be formulated. On mineralogical grounds the distinction is essentially no greater. Both of them are characterized by the predominance of plagioclase, with accessory hornblende or augite and sometimes free quartz. The real difference is found in the respective textures, and in slight though constant differences in the modes of occurrence of the accessory minerals, and in some of the minor characteristics of the feldspars. But these distinguishing characters are precisely the same in their general nature and equivalent in degree to distinctions which are used in the trachytes, rhyolites, and basalts for separating the sub-groups, and which in other rocks have never risen to higher taxonomic values. If we follow the same methods and valuations in these rocks which we adopt in the other groups, it seems to me that we can only assign them to the rank of subdivisions of one principal group.

With regard to the augitic andesites, Richthofen has placed them in the same major group as the hornblendic andesites. Zirkel, on the other hand, has placed them among the basalts. In deciding which of these two authorities it is best to adopt, the following considerations may be presented. It is not obvious that they use the term in precisely the same scope, nor embrace within their respective meanings quite the same rocks. We have certain rocks containing plagioclase, with abundant though subordinate orthoclase, and with proportions of augite and magnetite very much smaller than is usual in the basaltic group. We have also varieties in which the orthoclase is much less though still notable, and the augite and magnetite, accompanied with glassy or slaggy material included in the groundmass, are very copious; and there are many intermediate varieties. It seems probable that Richthofen may have contemplated only the former in his expression of the characters of augitic andesite, while Zirkel, taking the entire range of variety as one sub-group, with the more augitic and vitreous ones as the type, did not find reasons for separating them, and, therefore, placed them together among the basalts, to which his types certainly most nearly approach. It must be admitted that a hard and fast line cannot be drawn within this range, nor can it be satisfactorily drawn between the more acid augitic andesites and the augitic trachytes. Nevertheless, it seems advisable to draw one arbitrarily, and place the more acid varieties among the andesites and the more basic among the basalts (dolerite), thus following Richthofen rather than Zirkel.

GROUP III.—SUB-BASIC ROCKS—PROPYLITE AND ANDESITE.

Sub-groups.	Characteristics.
1. HORNBLENDIC PROPYLITE ..	Consisting of predominant plagioclase and subordinate orthoclase, the former especially, in large, well-formed crystals, abundantly disseminated throughout a compact, homogeneous base. The fracture is superficially like diorite or other medium-grained granitoid rocks. The varieties usually are olive or tawny green color, sometimes reddish, or the green and red are banded, the former greatly predominating. Hornblende is rarely conspicuous to the eye, but in the microscope is seen in abundance in small fragments, disseminated dust-like, or in spangles. It is pale green and with sharply-defined edges. Biotite and brown hornblende sparingly occur. The facies of the rock suggests that it has been more or less altered and the microscope and chemical analysis confirm it.
2. AUGITIC PROPYLITE (?).....	This rock is mentioned by Richthofen, but has not been recognized in the High Plateaus.
3. QUARTZ PROPYLITE	A rock having the essential characters of hornblendic propylite, but with the addition of a notable amount of free quartz. It is generally a more siliceous rock than the latter and in most occurrences is fresher in appearance.

GROUP III.—SUB-BASIC ROCKS—PROPYLITE AND ANDESITE—Continued.

Sub-groups.	Characteristics.
4. HORNBLENDIC ANDESITE ...	Consists of plagioclase, either wholly or with subordinate orthoclase and with hornblende; the latter usually conspicuous; the crystals imbedded in a base which is usually moderately fine, sometimes a little coarse. The color is almost always green, from light to very dark. The fracture is peculiar, splintery or conchoidal, radiating from the point of impact. The hornblendes are mostly of the dark-brown variety; in the thin section with a black, shaded border. The base shows fluidal structure, but not always.
5. AUGITIC ANDESITE	Usually a more basic rock than the foregoing; feldspar almost wholly plagioclase; augite taking the place of hornblende; either gray or nearly black in color, never with greenish cast unless much altered; the more basic varieties merge into the dolerites and the less basic into the augitic trachytes by transition. Resemblances to dolerite most frequent.
6. DACITE OR QUARTZ ANDESITE.	Containing predominant plagioclase feldspar, with free quartz and almost always abundant hornblende. It has a somewhat rhyolitic texture and habit. Sometimes biotite replaces the hornblende.

IV. BASALTS. The classification and subdivision of the basalts present some difficulty. In the basic lavas we have occurrences in which the minerals leucite and nephelin replace wholly or in part the feldspars, and a question arises as to the importance which is to be attached to this substitution. In the other great groups the subdivisions have rested upon texture and general habitus of the sub-groups as well as upon the occurrence of accessory and subordinate minerals in conspicuous quantity. In the acid and sub-acid rocks accessory minerals are relatively in small proportions and variations of texture and habit very strongly pronounced. In the basic rocks the reverse is true—the accessory minerals are more numerous, almost rivaling the primary ones, while the texture, though considerably varied, is far less so than in the acid rocks. These considerations would lead us to rest the subdivisions rather upon a mineralogical basis than upon a textural one. Some authors separate *dolerite* from the so-called "true basalts" on textural grounds, the former being macroscopically crystalline while the basalts proper exhibit distinct crystals only under the microscope. Even an intermediate variety of texture (*anamesite*) has been named in which the crystallization is recognizable but not conspicuous. I fail to discover sufficient reasons for a subdivision on textural characters alone, but differences of habitude which are tolerably constant may, I think, be founded upon the mineralogical constitution. The basalts almost invariably contain olivin in abundance, while in the dolerites it is far less common though sometimes found. The dolerites are as a group more siliceous, though the true basalts sometimes have more than the normal percentage of that constituent. In the true basalts such minerals as augite, magnetite, olivin, leucite, and nephelin reach the extremes of their proportions; in the dolerites the same minerals are on the whole less abundant, and the predominance of the feldspathic ingredient is more emphatic. It has seemed to me, therefore, that the name dolerite should be fully recognized as applicable to a subgroup of the basalts, including those coarser-grained varieties in which the proportion of silica is notably higher than in the typical basalts, and also including the more basic of those rocks which Zirkel has called augitic andesites.

GROUP IV.—BASIC ROCKS—BASALTS.

Sub-groups.	Characteristics.
1. DOLERITE	Distinctly crystalline; plagioclase feldspar with (usually) subordinate orthoclase; augite always conspicuous and in large amount; much magnetite; a glassy base with pronounced fluidal texture; formless clots of black ferruginous material usually considered as amorphous augite. Color, dark gray to nearly black.
2. NEPHELIN-DOLERITE	Similar to the above but with nephelin replacing a part of the plagioclase.
3. BASALT	Fine-grained; feldspar crystals distinguishable only by the microscope. Abundant augite and a glassy base; olivin usually present. Very dark colored, nearly black.
4. LEUCITE-BASALT	With leucite replacing a part of the feldspar and sometimes the whole of it.
5. NEPHELIN-BASALT	With nephelin replacing feldspar.
6. TACHYLITE	A vitreous obsidian-like lava, having the basaltic constitution.

The foregoing scheme of classification is in the following conspectus given as a whole. Of the various sub-groups the following have not yet been detected among the eruptives of the High Plateaus: nevadite, porphyritic trachyte, augitic propylite, dacite, nephelin-dolerite, leucite-basalt, nephelin-basalt. All of the others are well represented. The trachytic group, however, very far overshadows all the others in volume and variety.

GROUP I.—ACID ROCKS. RHYOLITES.

Sub-groups.

1. Nevadite.
2. Liparite.
3. Rhyolite (proper).

GROUP II.—SUB-ACID ROCKS. TRACHYTES.

Sub-group A.—Sanidin trachytes.

1. Granitoid trachyte.
2. Porphyritic trachyte.
3. Argilloid trachyte.
4. Hyaline trachyte.

Sub-group B.—Hornblendic trachytes.

5. Hornblendic trachyte.
6. Augitic trachyte.
7. Phonolite.
8. Trachytic obsidian.

GROUP III.—SUB-BASIC ROCKS. ANDESITES.

Sub-groups.

1. Hornblendic propylite.
2. Augitic propylite (?).
3. Quartz propylite.
4. Hornblendic andesite.
5. Augitic andesite.
6. Dacite.

GROUP IV.—BASIC ROCKS. BASALTS.

Sub-groups.

1. Dolerite.
2. Nephelin dolerite.
3. Basalt (proper).
4. Leucite basalt.
5. Nephelin basalt.
6. Tachylite.

CHAPTER V.

SPECULATIONS CONCERNING THE CAUSES OF VOLCANIC ACTION.

The cause of the succession of rocks apparently a single phase of the more general cause of volcanism.—The probable subterranean *locus* of volcanic activity.—Notion of an all-liquid interior.—Not associated with volcanicity, and gives no explanation.—Large vesicles not tenable.—Localization of volcanic phenomena.—Independence of vents.—Growth and decay of action.—Lavas not primordial liquids.—Comparison of lavas with metamorphic rocks: First, with reference to chemical constitution; second, mineral components; third, texture.—Possibility that lavas are remelted metamorphic rocks.—All lavas cannot so originate.—Average composition of eruptive and sedimentary rocks compared.—Agreement in composition between basalts and sedimentary rocks.—Mr. King's hypothesis of segregation of crystals.—Primitive magma.—Conjectured source of lavas.—Dynamical cause of eruptions.—Cyclical character of volcanism.—Elastic energy of eruptions.—Real nature of the dynamical problem.—The origin of the energy.—Increase of local subterranean temperatures—Relief of pressure.—Access of water.—Linear arrangement.—Mechanics of eruptions.—Penetrating power of lavas.—Expelling power.—Not effervescence, but pressure of denser rocks overlying their reservoirs.—A simple application of hydrostatic laws.—Explanation of the sequence of eruptions.—A compound function of density and fusibilty.—Graphical representation.—Discussion of the hypothesis and objections to it.—Exceptions and anomalies.

I have doubted the propriety of embodying in a work devoted to a statement of observed facts any views of a speculative nature. But the representations of my director and associates have encouraged me to do so, inasmuch as the subject is quite germane to the observations, and the observations are such as have stimulated great curiosity as to their causes. I shall, therefore, present a trial hypothesis, which seems to me to explain the sequence in the eruptive rocks now testified to prevail generally throughout the Rocky Mountain Region.

It seems as if the explanation of such an order of facts could only be a phase of the more general cause of volcanism itself. But the origin of volcanic energy is one of the blankest mysteries of science, and it is strange indeed, that a class of phenomena so long familiar to the human race and so zealously studied through all the ages should be so utterly without explanation. Nothing could be further from my intention than propounding a general theory of volcanism, for neither the facts nor the antecedent generalizations are ready for it. Such a theory must be the work of several generations to come, and must gradually grow into form and coherence as all great theories have done heretofore. Yet there are a few conceptions of a high degree of generality which, perhaps, contain the germs of a theory, though in their present condition they are vague and formless. They may be said to resemble stones in the quarry, rough and unhewn, but which may some time become corner-stones, columns, and entablatures in the future edifice. I shall propose some of these considerations, not in the form of a connected theory of volcanism, but as partial constituents of a theory in a highly generalized form, taking care to proceed no further than existing knowledge may afford at least some justification in proceeding.

I. The first consideration has reference to the probable subterranean locus of volcanic activity. In the present stage of our knowledge it seems little credible that the sources of eruptive materials can be located at very great depths. It is almost impossible that they could have emanated from a general liquid interior. Taking the common notion that the earth has formed, by cooling, an external rocky shell, enveloping a nucleus which was once an intensely heated liquid, and which may still be so, either partially or wholly, the ordinary principles of hydrostatics lead us to conclude that all the primordial volcanic energy ought to have been exhausted even before a stable crust could have been first formed. We are in the habit of regarding the earth as hot within, but gradually dissipating its heat by conduction through the crust and by radiation into space, and if this conception have any truth, or even verisimilitude, then the eruption of portions of its primordial liquid masses ought to become more and more difficult with the process of ages—nay, ought to have ceased at a period long anterior to the most ancient of any of which systematic geology can take direct cognizance; for secular cooling can only strengthen the rigid envelope and continually abstract from the heated magmas below the heat which renders them liquid and eruptible. We cannot in this connection ignore the plainest consequences of hydrostatic laws. A solid crust covering a fluid nucleus, or a portion of that crust covering a large liquid vesicle, could not remain stable for an hour unless the liquid were denser than the crust. If the liquid were lighter an eruption would be inevitable, and once started would continue until the lighter liquid had all found its way to the surface. If the liquid were heavier, it could no more be erupted than a frozen lake could erupt its waters and pour them over its icy covering.

Lest these considerations should seem too purely speculative to authorize us to conclude that lavas cannot be emanations from a general liquid interior or from vesicles holding primordial liquid magma, we may turn to other considerations more concrete and bearing more directly upon the point. Volcanic eruptions are very local phenomena. At any given epoch they are confined to a few localities of very small relative extent. They have no general distribution in the sense of a widely-extended and connected system. Each volcano is an independent machine—nay, each vent and monticule is for the time being engaged in its own peculiar business, cooking as it were its special dish, which in due time is to be separately served We have instances of vents within hailing distance of each other pouring out totally different kinds of lava, neither sympathizing with the other in any discernible manner nor influencing the other in any appreciable degree. Again, we find vents at high levels and at low levels in close proximity with each other, and both delivering the same kind of lava. The great craters of the Sandwich Islands are remarkable instances of this kind, and indicate that each crater derives its lavas from a distinct reservoir. It is inconceivable that a liquid from a common reservoir could rise and outflow from the loftier vent while the lower vent remained open. The same phenomenon is exhibited at Ætna and in Iceland and other active volcanoes. Then, too, we have the outpouring of widely distinct kinds of lava from the same orifice at successive epochs, and as a general rule the grander volcanoes present a succession of eruptions marked by different kinds of lava; and it should be noted that these varieties of ejecta are not intermixed nor formed by the commingling of two or more magmas, nor do they present intermediate and transition types, but each *coulée* has a well-defined character, which serves to distinguish it and assign it to its proper place in the classification. All these subordinate phenomena, and many others which it is needless to mention here, are apparently inconsistent with the assumption that lavas are portions of a primordial, uncongealed earth-liquid, forming either a general fluid nucleus or extensive isolated vesicles. They point rather to many small reservoirs, situated at no very great depths, each of which contains, not a primordial liquid, but a liquid secreted, so to speak, from surrounding rocks, or generated by a secondary and progressive fusion of solidified matter occurring in *maculæ* within the layers of the rocky envelope of the earth. The whole tenor of volcanic phenomena bespeaks a process which is extremely local—a process which has an inception, a growth, a culmination, a decadence, and a final cessation, all within a limited and rather small area and determined by some local cause.

But we find the strongest evidence against the hypothesis that lavas are primordial liquids when we come to the study of their physical, chemical, and mineralogical characters. We do not, indeed, have any very decisive grounds for asserting what the primordial liquids might consist of or what would be their petrographic characters if any of them were erupted to the surface, and so far we might not be justified in saying that the lavas from volcanoes are distinct from them. But there are some eruptive masses which are very plainly not primordial. For instance, a decidedly conspicuous mass of these products are not fused rocks, but hot mud holding large quantities of rocky fragments, which have unmistakably formed the clastic components of strata. The volcanoes of Central America and the Andes and of the Batavian Islands have within the last century disgorged astounding masses of hot mud—material which has not been fused at all, but rendered plastic and capable of flow by the combined action of heat and watery solution. It cannot be admitted that such erupta can have come from primordial materials. And the indications are no less distinct that the greater part of the true lavas have originated from other sources.

The careful and systematic study of the petrographic characters of all rocks, whether sedimentary, metamorphic, or eruptive, has enabled us to compare them intelligently, and to form some conclusions as to the homologies on the one hand and the distinctions on the other which exist between them. The great generalization that the foliated crystalline rocks are altered sediments has long since passed into geological science as a fully accepted theory. But the relations between the metamorphic and eruptive rocks constitute a pending question.

It will be unnecessary here to enter very minutely into a discussion of these relations, and, indeed, a full discussion would require a very long and copious review of the existing state of lithological science. It will be sufficient to state in a summary manner those points of comparison which immediately concern the subject in hand. The conclusion to which this comparison tends is that a large proportion of the igneous rocks have the petrographic characters which we ought to expect would result from the fusion of certain groups of metamorphic stratified rocks. There are three points of view from which the comparison may be made; these are with reference, first, to chemical constitution; second, to mineral components; third, to mechanical texture.

1st. *Metamorphic and igneous rocks compared with respect to chemical constitution.*—The eruptive rocks are highly complex compounds, and always contain certain constituents which may be called essential constituents. These are silica, alumina, lime, soda, potash, and magnesia—six in number. Iron in the form of some oxide is almost always present, but since it is occasionally absent, or found in exceedingly small quantity, it cannot be regarded as a universal and essential constituent. Silica is always the dominant ingredient, and though the quantity of it varies greatly, yet the variation is within tolerably definite limits, almost never exceeding 80 per cent., and almost never falling below 45 per cent. The remaining five constituents likewise vary, but always within tolerably narrow limits. Thus alumina rarely falls below 13 per cent. and rarely exceeds 26 per cent. Lime rarely exceeds 14 per cent. magnesia 10 per cent., soda 9 per cent., and potash 8 per cent. The variations in the relative proportions of these constituents is sufficiently wide to give well-marked specific or even generic differences in the kinds of volcanic products; but the variations are so limited and the relative proportions subject to such moderate departures from normal ratios, that the whole category of eruptive rocks possess at least ordinal if not family likenesses. Turning now to the metamorphics we find a far wider range of chemical constitution. Thus we have quartzites which are almost pure silica; we have crystalline limestones and dolomites which are nearly pure calcic and magnesian carbonates; we have clay-slates, serpentines, chloritic, and mica schists, which have a composition not at all similar to that of eruptive rocks. But while a large proportion of the metamorphic rocks have no chemical correspondence to the eruptive rocks, there is another large proportion of them in which the constituents correspond almost exactly to those of the eruptives. These are the gneisses, the hornblendic and the augitic schists. The greater part of the true gneissic rocks yield by analysis practically the same results as granite, syenite, rhyolite, and acid trachyte. The hornblendic schists have about the same constituents as the diorites, propylites, and hornblendic trachytes, while the more basic hornblendic (sometimes augitic) schists hold the same relation to diabase, dolerite, and augitic andesite Thus, then, we find that the eruptive masses have their representatives (chemically considered) among certain groups of metamorphic rocks.

2d. *Metamorphic and igneous rocks compared with respect to mineral components.*—Chemical identity or similarity implies no necessary and exact correspondence in mineral constituents, for the minerals which may be formed in a rockmass under varying conditions of temperature and environment cannot be determined solely by the chemical composition of the magma. The crystals of the metamorphic rocks are formed according to the commonly accepted theory of metamorphism, at rather low or very moderate temperatures, while the crystals of igneous rocks are in part at least, and perhaps wholly, generated at high temperatures. Hence it is not surprising that metamorphic rocks should contain some crystalline forms which are seldom or never found in the igneous except as alteration products, or should contain some forms in abundance which the latter contain very sparingly. There are, however, some minerals which may be formed indifferently at high or low temperatures, and the most important of these are undoubtedly feldspar and hornblende. Those which form with great facility at low temperatures are certain forms of mica, quartz, chlorite, and the zeolites, and those which seem to be associated with higher temperatures are leucite, nephelin, olivin, and less decidedly augite. By a comparison of the two classes of rocks, therefore, we find an agreement in respect to those minerals which are indifferent to variations of conditions;

and disagreement only in those minerals which are decidedly dependent upon variations of condition. The metamorphics abound in low temperature minerals, the eruptives in high temperature minerals. Both classes contain abundant feldspar, mica, and hornblende, which seem to be but little affected by temperature, so far as concerns the facility with which they are formed.

3d. *Metamorphic and igneous rocks compared with respect to mechanical texture.*—In the modes of aggregation of the rock-forming materials, the two classes of rocks differ radically. Nor could we anticipate any agreement here. The metamorphics have not been melted down, but retain with greater or less distinctness their original foliation. The changes have been purely molecular. Where the metamorphism is complete the rock is ordinarily made up of purely crystalline matter, each crystal being a definite mineral species, with definite optical and crystallographic properties peculiar to its kind, the whole interlocked into a mosaic of great beauty, which is revealed to the eye by a polished surface, or still more clearly by a thin section under the microscope. But the volcanic rocks have a totally different texture, of which the distinguishing characteristic is the presence of a non-crystalline or amorphous base in which crystals are disseminated. Sometimes the crystals are wholly absent, and the amorphous base constitutes the entire rock, as in pitchstone and obsidian. The distinction, then, between the texture of a thoroughly metamorphic rock and an extravasated mass is that the former is wholly crystalline, while the latter is either partially or wholly amorphous. And yet we have rocks which present every shade of transition between the two textures. The gneisses, for instance, lose their foliation and become indistinguishable from granites. The granites present varieties which have larger and more perfect crystals imbedded in a maze of smaller ones. We may select a series in which the mosaic of surrounding crystals becomes finer and finer and the inclosed crystals more perfect and contrasted, and such a group is called porphyritic granite or granite porphyry. Following this chain of varieties, the crystalline base gradually passes into one in which the utmost power of the microscope fails to detect any individualized crystals, but merely indicates by indirection that the base has been in some way influenced by the crystallogenic force, for it continues to polarize light. This is the case with typical porphyries and with many trachytes and rhyolites. In the extreme varieties all traces of crystalline arrangement in the base have disappeared, and the inclosing matter is very similar to common glass, while the inclosed crystals are sharply defined within it.

But while there is a sufficiently close agreement between the eruptive rocks on the one hand and some of the metamorphics on the other, there are many metamorphics which have very little in common with the eruptives. Such rocks as quartzite, limestone, dolomite, and argillite are never found in the eruptive condition. Here it is necessary to anticipate, in part, the course of the argument. The hypothesis to be invoked will consist in the assumption that the proximate cause of eruptions is a local increment of subterranean temperature, whereby segregated masses of rocks, formerly solid, are liquefied. Since a state of fusion is necessary to an eruption, we may throw out of consideration all those materials which are so refractory that they cannot be liquefied by temperatures within the highest range of volcanic heat. But the most refractory metamorphic or sedimentary strata are the very ones which have no correlatives among the eruptives; and, conversely, those strata which are most fusible have rocks of correlative constitution among the eruptives. Hence we may in part clear the way for the proposition that quartzites, limestones, &c., are never erupted, because they are infusible at the highest volcanic temperature. We have not, indeed, the means of directly measuring volcanic heat, but we may infer that it is never in excess of that required to melt the most refractory rhyolites, since these lavas bear no evidence of being heated beyond a temperature just sufficient to liquefy them. Rhyolites and trachytes bear strong internal and external evidence that at the time of eruption they were just fused and no more, while basalts often betray evidence of superfusion. Thus, in the comparison of the two classes of rocks, we may discard from consideration those of simpler constitution, like quartzites, dolomites, argillites, limestones, &c., and confine our discussion to those more complex, stratified masses which alone are fusible and, therefore, alone eruptible.

Our comparison of the metamorphic and igneous rocks, therefore, indicates in many ways and argues strongly for a common parentage. The approximate identity of chemical constitution is what we should anticipate on that assumption. We should expect to find some minerals common to both classes of rocks, while other minerals are found in one class alone. We should look for nothing but contrast in the respective mechanical textures; and we find the anticipated agreements and contrasts.

But there is an important consideration which will not permit us to conclude that all eruptive rocks are derived from the fusion of metamorphics; for whence came the materials of the metamorphic rocks themselves? Accepted theories declare that their ultimate origin was in the primordial materials of the earth-mass, which were broken up, decomposed, and the several components sorted out and arranged in the form of sediments; and these sedimentary formations gradually accumulated until they completely buried the primordial mass, so that no portion of it is anywhere exposed, so far as has yet been discovered. But when the primitive mass was finally buried, from what sources could the materials have been derived which could add fresh layers to the covering? To this there is but one possible answer. After the greater portion of the original surface had been covered, additional sediments must have been derived from the extravasation of primordial matter. This conclusion seems to be logically perfect. In the past epochs these primitive materials must have been continually extravasated, though, as the body of sedimentary formations increased, it is possible that they too began to be erupted by secondary fusion, and with the lapse of time formed an increasing proportion of the total extravasation, while the proportion of primitive matter as gradually diminished. Now, have we any reason for supposing that the evolution of the earth has so far advanced that primitive matter has ceased to erupt, and that modern outbreaks consist wholly of materials which had once before in the world's history been poured out, broken up, decomposed, stratified, metamorphosed, and again erupted? If so, then the body of stratified rocks is no longer increasing, but the revolutions of time are simply working over the stratified rocks again and again. But this is improbable in a high degree. There is no warrant whatever for such a belief, and therefore no justification for the inference that all eruptive rocks are derived from the secondary fusion of the metamorphics. But if it is probable that some of the lavas have emanated from primordial rocks, what are they? There is one great group of lavas which quickly furnish ground for suspicion.

Recurring here to the generalization that the materials composing the stratified rocks have been ultimately derived from primordial matter, it is but an identical proposition to say that the chemical constitution of that primordial matter ought inferentially to be such as would yield the materials of the sedimentary rocks. It ought to possess the same constituents, and ought also to contain them in substantially the same proportions as the average constitution of the stratified rocks taken as a whole category. In a word, it should be what some biologists might call a synthetic or comprehensive type of rock, from which the stratified materials might be differentiated by the known processes of sub-aerial decomposition and selection. Secondly, it ought not to conform in composition to any one variety of stratified rock, unless, perchance, in some rare exceptional cases. Thirdly, it ought to be a very abundant and voluminous rock, erupted at almost any geological age or period, from the present as far back into the past as we are able to discriminate the age of an eruption. Among the several groups or sub-groups of volcanic rocks do we find any one of them answering to this ideal type? This question does not admit of a very brief and decisive answer. We have no very accurate knowledge of the mean constitution of the stratified rocks. There is a statement, handed down, I believe, from Bischof, and passing current in the text-books, that silica constitutes very nearly 50 per cent. of the mass of all known rocks, and the estimate seems to be a very fair one. Its probable error is certainly small if the impressions of the geologists who have given much attention to lithology are to be trusted. This percentage of silica is substantially the same as that found in the basalts, and if there be a synthetic type of eruptive rocks this fact fastens suspicion at once upon the basaltic group. Probably no lithologist will hesitate to say that next to silica the most abundant constituent of the stratified rocks is alumina; but the exact proportions we do not know. Alumina is, however, known to be the second in quantity in the constitution of average basalt. But the third constituent of basalt in respect to quantity is iron oxide; in the foliated rocks it is unquestionably lime. Here is a discrepancy, and a well-marked one, which we cannot explain away without resorting to doubtful postulates and conjectures. Iron oxide forms at least 10 to 12 per cent. of normal basalt, and, while it is found abundantly in almost all foliated rocks, it cannot be admitted that it forms so large a percentage of their average constitution. With regard to lime, however, which forms about 8 or 9 per cent. of the basalts, the percentage is apparently in harmony with what we know of the constitution of the foliated rocks. With regard to the remaining important components—magnesia, soda, and potash—the same relative correspondence is found; but whether the correspondence be exact or not, we have not the data for determining.

Relative order of abundance of the oxides constituting basalts and the foliated rocks.

Basalts.	Foliated rocks.		
Silica.	Siliea.		Siliea.
Alumina.	Alumina.		Alumina.
Iron oxide.	Lime.		Lime.
Lime.	Magnesia. / Iron oxide.	or	Iron oxide.
Magnesia.			Magnesia.
Soda.	Soda.		Soda.
Potash.	Potash.		Potash.

With the single exception of iron oxide, therefore, the basalts, as nearly as we have the means of ascertaining, have a constitution representing approximately the average composition and proportions of the foliated rocks. There is no other known volcanic rock which approaches that relation so nearly; all others contain too much silica and alkali and too little lime. But so long as the iron oxide remains an outstanding anomaly we cannot be justified in pronouncing the basalts to be the exact synthetic type. It remains to be added that the basalts alone fail to show that agreement in chemical constitution with any known and abundant metamorphic rock which we find in all other volcanic groups In truth, its whole range of characters is indicative of an origin among magmas which have never passed through the reactions and mechanical processes which prepared and arranged the materials of the sedimentary strata. Lastly, the basalts are among the most abundant of eruptive rocks, and if we reckon with them the more ancient dolerites or diabases, they have always been abundant in all ages as far back as our knowledge extends.

But not only should we infer that the primordial masses of the earth (or "primitive crust") were basic like the basalts or dolerites, but that they were very nearly *homogeneous*. If we are at liberty to speculate at all upon the physical condition of an all-liquid planet, its molten surface exposed to radiation and to the action of its immense atmosphere, we should be led to infer that it would be agitated by disturbances similar in nature, though inferior in magnitude, to those affecting the sun, thus producing a thorough and homogeneous mixture of the compounds of silica with alumina, the earths, and alkalies. This admixture once formed would, so far as we can now see, remain unaltered until it cooled sufficiently for the reactions of the atmosphere. We know of no natural processes capable of separating the more acid parts of such a magma except the chemistry of the atmosphere acting at temperatures far below the melting-points of the silicates. We have the results of that process in the quartzites, granites, gneisses, and syenites among the siliceous rocks; and the limestones and dolomites among the basic rocks; with argillaceous rocks as the residuum of the decomposition. Yet if these rocks could be remelted together they would form one homogeneous magma. Every iron-smelting furnace is an experimental demonstration of the tendency of silica to take up and hold at fusion-temperature alumina, lime, magnesia, potash, and soda in proportions exceeding those which occur in nature. No facts are known to me which justify the conclusion that segregation into two magmas could occur in such a state of fusion. Nor would it be of any service in this connection to establish the possibility of such a segregation.* It is suggested by Mr. King that crystals might form in the liquid and sink by reason of their superior specific gravity. Although I hold it to be extremely doubtful whether any crystals are formed while the rocks are melted, and very probable that the greater part of them are formed during the viscous stage of cooling (especially the hornblendes and pyroxenes), there is one consideration which would prevent us from using this view to predicate a theory of a single magma separating into two or more of very different degrees of acidity. The low percentage of silica in basalt is due not

* Iron, however, might separate from such a compound, either as a regulus or as magnetic oxide, if the conditions were favorable and the oxide in excess.

only to the low percentage in the feldspar and augite, but also to an equally low percentage in the base. The high percentage in rhyolite and trachyte is due not only to the feldspar, but still more to the even higher percentage of silica in the base. If there has been segregation, it must, therefore, have affected not only the crystals, but the base even more than the crystals. Such a separation, therefore, does not seem explicable by supposing a precipitation of crystals.

Gathering together now the threads of this comparison, we are led to the conclusion that the constitution of the eruptive rocks forbids the belief that the acid varieties, or even the intermediate varieties, can be primordial masses from vesicles which separated in a liquid condition from the original earthmass and remained liquid up to the time of their eruption. Chemical considerations of a cogent character lead up to the inference that primordial magma ought to possess a constitution similar to rocks of the basaltic group, though perhaps somewhat less ferruginous (?), and that it should be nearly homogeneous. And in general our inference from the nature and constitution of the volcanic rocks, from their great variety, from the localization of eruptive phenomena, from the intermittent character of volcanic action, from the independence of the several vents, is that the lavas do not emanate from an earth-nucleus wholly liquid, nor from great subterranean reservoirs still left in a liquid condition "from the foundations of the world," but from the secondary fusion of rocks, a part of which may have formed the primitive crust, while the remaining part consisted of deeply-buried and metamorphosed sedimentary strata. No doubt some cautious philosophers may regard this inference as specifying a little too minutely the locus of volcanic activity—more minutely than a rigorous deduction from known facts will permit us to regard as positively proven. But at all events there is one proposition which may be laid down with no small degree of confidence, and it is this: We must at least admit that *the source of lavas is among segregated masses of heterogeneous materials.* This arrangement would be well satisfied by a succession of metamorphic strata resting upon a supposed primitive crust of magma having a constitution approximating that of the basaltic group of rocks.

II. The second general consideration has reference to the dynamical cause of volcanic eruptions, or the force which has brought them to the surface.

Not only are volcanic phenomena very local in respect to area, but the period of activity in any given spot is very limited in respect to duration. No region has always been eruptive, and we may be reasonably confident that none will continue to be eruptive indefinitely. Volcanicity has its inception, passes through its cycle, and lapses into final repose. We do, indeed, find localities which have twice been the scene of such devastations during the entire period of which systematic geology takes cognizance, just as battles have more than once been fought on the same plain with centuries between; but the intervals separating such visitations are so vast when measured even by the geological standard of time, that there is no obvious relation between them. It is not strange that a process which shifts its arena throughout the ages should occasionally revisit the scenes of former operations. This migratory character suggests to us that the normal condition of the nether regions is not one of unrest, but rather of quietude. What is the disturbing element which invades their secular calm, convulses them with earthquakes and explosions, and causes them to pour forth their fiery humors? With this problem geologists and physicists have wrestled in vain. Here speculation seems to be peculiarly unfruitful. To-day it looks promising; to-morrow turns it into ridicule. We do not know the determining cause of volcanic eruptions. Yet there are a few facts of a high degree of generality, around which we linger with inquiring, anxious minds, hopefully promising ourselves that light will shine out of them at some future day, and to these it may be proper to briefly advert.

We may contrast the explosive condition of volcanic products during an eruptive cycle with their quiet and inert condition before the cycle began. These same materials lay quietly in the earth for long periods, some of them, perhaps, since that imagined primordial epoch when a crust began to form. Some change has come over them, converting them into energetic explosive mixtures. The problem is to find an adequate cause for such a change and the nature of its operation. This statement of the conditions of the problem is in strong contrast with the view which regards lavas as primordial liquids charged with volcanic energy waiting for a convenient season to explode. It presents the case as a problem of energy acquired by some secondary forces, of which we are at present ignorant.

There is one general assumption which satisfies all the main requisites of volcanism. It is this: *Volcanic phenomena are brought about by a local increase of temperature within certain subterranean horizons.* This, indeed, is not a solution of the problem, for it throws us back instantly upon the ulterior question, What has caused the increase of temperature? All my efforts to find an answer to this ulterior question have utterly failed. But the proximate idea is suggested on every hand, and its reality takes deeper root in conviction the more it is contemplated. Around it the broader facts take form and coherence. It explains their secondary character as contradistinguished from the primordial. It explains the cyclical phases of volcanism; their beginning in a recent epoch of the world's secular history; their growth, decay, and extinction. It explains their intermittent character—why eruptions are repetitive instead of continuous. It explains the explosive and energetic character of the phenomena; and, lastly, it explains the lithological order of the eruptions, as will presently be shown.

But there is another and alternative assumption. We may suppose the deeply-seated rocks in regions of high temperature to undergo changes, one result of which is to lower their melting-points. This is not so strange as it might at first seem, for its accomplishment is conceivably within known physical laws. A relief of pressure is one conceivable mode. Probably another would be the absorption of water under great pressure and at high temperature. It can hardly be doubted that a rock charged with water and so confined that the water cannot readily escape is more fusible than the same rock in an anhydrous condition. The fact that lavas bring to the surface considerable quantities of water may be held to be evidence that water does find access to them from above. The only alternative view is that water formed a part of their original constitution. This is undoubtedly the case on the view that lavas are remelted metamorphic rocks; for the metamorphics all contain water, partly mechanically held and partly as water of combination in hydrous minerals. The amount of contained water is variable, but ordinarily more than one per cent. and sometimes much more This quantity, however, probably falls far below the volume of steam ordinarily given off by volcanoes. Unless the estimates of observers are altogether deceptive, the quantity of water blown out of volcanic vents must bear a far greater ratio to their lavas than one or two per cent., and we seem to be compelled to assume that the lavas derive their water from extraneous sources, and the penetration of surface water to regions of volcanic energy is by far the easiest explanation. The penetration of water, then, is a consideration of importance, but the precise nature of its effects we have no means of determining, and any attempt to follow them would lead us into discussions too purely speculative to be of value. The relief of pressure is another possible mode of liquefying rock. It is postulated by Mr. Clarence King as a basis of his theory of volcanic eruptions. This relief is effected through the removal of superincumbent strata by the process of denudation. Such removals have taken place upon a vast scale, and though geologists have possibly been suspected by other scientists of helping themselves very liberally to a supply of cause and effect of this kind, yet the surveys of our western domain have proven that they have been very modest and abstemious. But that such a process could have played a very important, much less a fundamental, part in causing volcanic eruptions seems to be negatived by facts. We do not find that eruptions always occur in localities which have suffered great denudation. We do not find even that they occur in such localities predominantly. Most of the existing volcanoes and most of those which have recently become extinct are situated in regions which have suffered very little denudation in recent geological periods, and many of them in regions of recent deposition. Ætna is built upon a platform of Post-Tertiary beds and Vesuvius stands upon late formations. The same is true, according to Dr. Junghuhn, of the volcanoes of Java, and this fact is repeated in the great volcanoes of the Cape de Verde and Canary Islands. The High Plateaus of Utah, which have been the theater of volcanic activity since the Middle Eocene, are localities of minimum erosion, while the denudation of the non-volcanic regions around them has been stupendous. It can hardly be supposed that the volcanoes of the Pacific have broken forth from denuded localities, unless the denudation took place at a considerable period of past time.

But whatever may be the effects of the relief of pressure, and however essential the presence of water may be to the total process of eruptivity, something more is obviously needed, and this additional want is apparently well satisfied by a local rise of temperature in the rocks to be erupted. For it cannot be insisted upon too strenuously that from a dynamical standpoint the problem to be explained is the passage of lava-forming materials from a dormant to an energetic condition. And when we resolve this very general statement into a more special and definite one, we find that it means the passage of solid materials into the liquid condition and (as will be indicated further on) a decrease of density. Whatever may be the ulterior cause of volcanicity, a rise of temperature in the erupting masses seems to be an indispensable condition, and in assuming it we are apparently doing nothing more than taking the most obvious facts and giving them the plainest and simplest interpretation.

III. The third general consideration has reference to the mechanics of eruptions. The fact that lavas are generated at the depth of several miles below the surface being given, how do they reach the surface? A study of the geological relations of eruptive masses furnishes a decisive answer to this question. The power of lava to penetrate and burrow into solid rock would never have been credited or even suspected had we not the proof of it in the rock exposures. The opening of fissures and the rise of lava into the gaps is one of the commonest and most intelligible methods. All volcanic areas are traversed by dikes, and near the centers of eruption they are exceedingly numerous. But what is most suggestive is the fact that many lavas, after rising part-way to the surface, suddenly tear open the strata and diffuse themselves between the beds, forming subterranean lakes at levels far above their original source. These intrusive lavas are exceedingly common, so much so, that they appear to have constituted in all ages a notable proportion of volcanic movements.

But when a vent is established through which lavas can find escape, we have still to consider the propelling force which urges them onwards or upwards. A very common view, long entertained by many geologists, is that the escape of lavas is analogous to what takes place when a bottle of warm champagne is suddenly uncorked. So comprehensible and plausible is this explanation that its wide acceptance is not surprising. In some cases, for want of ability to show the contrary, it may be accounted a sufficient explanation, and in general it cannot be questioned, that in most volcanoes this identical action plays a more or less important part. Scoria, pumice, and volcanic dust have unquestionably this origin; but the whole of the extravasation is not so accomplished. The outpour of lava is a very different matter. It is comparatively calm and quiet in its flow, like water welling forth from a spring; sometimes boiling, bubbling, and spurting a little, but never boisterous or obstreperous. It continues its flow for days and sometimes weeks, but at length ceases and comes to rest.

A careful examination of the details of volcanic eruptions leaves the impression that they are pressed up by the weight of rocks which overlie their reservoirs, and that their extravasation is merely a hydrostatic problem of the simplest order. The conception of a liquid inclosed in a cavity beneath the surface and opening to the outer air through a stand-pipe requires some discussion when we come to apply it to volcanic eruptions. Our conceptions of the constrained motion of liquids are derived from experiments upon small quantities of them in small vessels; but when we come to such enormous volumes as are disgorged by volcanoes, a consideration arising from mere magnitude enters into the scheme—a consideration which has no bearing in relation to small volumes. This is the strength of the receptacle. It is a well-known principle in mechanics that the *relative* strength of a body is inversely proportional to its size. Thus, where we have similar bodies subject to forces which are proportional to their own masses, the resistance to detrusion is proportional only to the square of their linear dimensions. It is this relation which limits the span of an arch or the length of a truss. Now, if we could conceive the contents of one of these subterranean lava reservoirs to be suddenly annihilated, so great must be their dimensions that the rocks above would instantly sink into the cavity, just as the rocks above a coal-mine do on small provocation. A small cavity, on the other hand, might persist. Now, the point I wish to illustrate is that the strength of the retaining-walls of a lava reservoir are relatively so weak, in consequence of the large dimensions, that their effect is very nearly the same as it would be if the lava were overlaid by another liquid with which it could not commingle. It is the gross weight of this overlying cover of solid rocks, I conceive, which presses the lava upward through any passage where it can find vent.

It will follow, then, as a corollary, that the lava will rise to the surface or not according to its density. If it be lighter than the mean density of the rock above its reservoir, it will reach the surface and nothing can keep it in; if it be heavier than the overlying rock, it will never reach the surface.

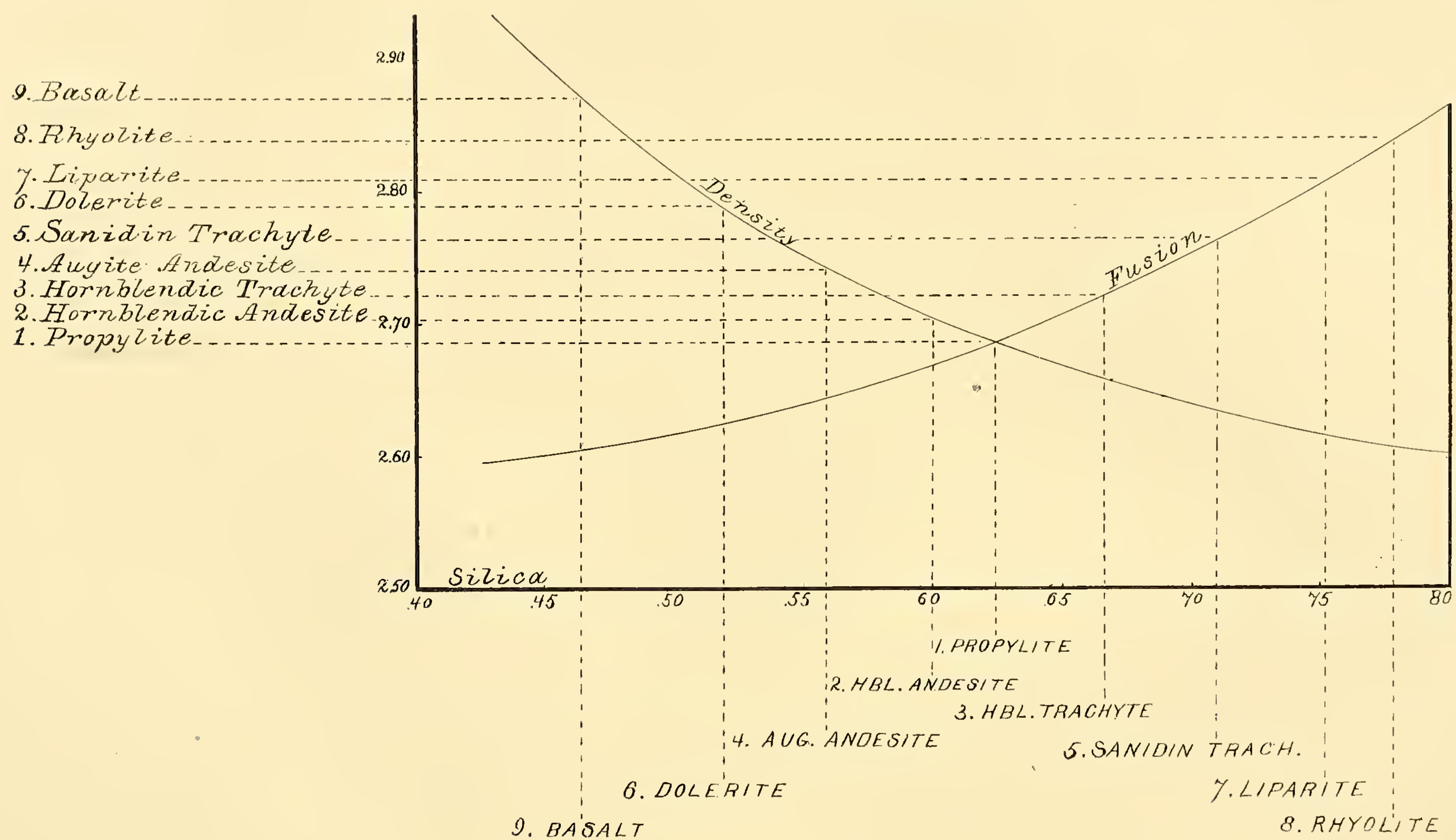
IV. We come now to the explanation of the sequence of volcanic rocks. In order that any eruption of lava may take place two preliminary conditions are requisite: First. The rocks must be fused. Second. The density of the lavas must be less than that of the overlying rocks. Having shown from independent considerations that the proximate cause of volcanic activity may be a local rise of temperature in the deeply-seated rocks, it only remains to follow the obvious phases of the process. We know that the volcanic rocks vary within tolerably ample limits as to their chemical constitution, and that associated with these chemical differences are notable differences of physical properties. Some are more fusible than others and some are heavier than others. We also presume that prior to eruption these different rocks were within the earth separated as if in strata or in *maculæ*. Imagining, then, a rise of temperature in a nether region where the constitution of the magma is variable—here very siliceous, there very basic, with many intermediate varieties, all arranged in any arbitrary manner and in each other's neighborhood—it is quite certain that not all of these magmas would be both fused and sufficiently expanded by heat to be ready for eruption at the same time. The more refractory rocks might not be melted or the heavier ones might not be sufficiently expanded. There would, therefore, be some selection as to the order in which they would become eruptible. But upon what principle would the selection be made? The acid rocks are known to have the highest melting temperature, but the basic rocks in the cold state have the highest specific gravity. It is just possible that the acid rocks may be light enough to erupt at an early stage of the process but are not yet melted, and that the basic rocks may be melted but must await a further expansion in order to reach the surface. The first selection would then fall upon some intermediate rock. Let us see if there be anything in the physical properties of the rocks to justify such a hypothesis. We can represent this best by a graphic expression of their physical properties regarded as functions of temperature and acidity.

Let the axis of abscissas, Plate 4, represent the proportions of silica characteristic of the various groups of volcanic rocks, the figures along that axis representing percentages from 40 to 80. Let the ordinates represent, first, the density of the rocks in the cold state. Considering now any one variety of rock, take the point on the axis of abscissas corresponding to its percentage of silica, and erect an ordinate proportional to its density. For all the varieties of rocks construct ordinates in the same manner and join their upper extremities. On the assumption that the density is rigorously correlated to the percentage of silica, a curve would be constructed representing the density as a definite function of the silica. This assumption, however, is not strictly true, being subject, indeed, to notable variations; yet in a general way it is more or less an approximation to the truth. The anomalies will be adverted to in the sequel.

It is known that the rocks of the basic and sub-basic groups are when cold considerably more dense than the average of the foliated rocks, and the same is true of some of the sub-acid rocks, and according to the doctrine heretofore laid down such rocks could not be erupted at all were it not for the fact that when intensely heated and liquefied, their density is notably diminished and reduced below that of the strata which overlie them. Hence the more basic the rock, the more it must be heated to reach an eruptible density. The ordinates, then, may be used to represent the relative increase of temperature which must supervene in order to render the rocks light enough to reach the surface, and as these increments of temperature are directly proportional to the density of the rock, the same curve may (in the absence of fundamental constants) be used to express the increments of temperature required by the various rocks to reach an eruptive density.

Again, let the ordinates represent the relative melting temperatures of the various sub-groups, the assumption still being that the fusibility is a definite function of the proportion of silica. This assumption is probably subject to still wider variations than that which postulates a dependence of

PLATE II.



9. Basalt
8. Rhyolite
7. Liparite
6. Dolerite
5. Sanidin Trachyte
4. Augite Andesite
3. Hornblendic Trachyte
2. Hornblendic Andesite
1. Propylite
2.90
2.80
2.70
2.60
2.50
Silica
.40
.45
.50
.55
.60
.65
.70
.75
.80
Density
Fusion
1. PROPYLITE
2. HBL. ANDESITE
3. HBL. TRACHYTE
4. AUG. ANDESITE
5. SANIDIN TRACH.
6. DOLERITE
7. LIPARITE
8. RHYOLITE
9. BASALT

density upon silica, but it is still known that there exists an approximation to such a dependence. This will also be subsequently alluded to. A curve may be constructed, as before, representing this dependence, which may be called the curve of fusion. Since both density and fusion have approximate relations to the quantity of silica present (and for present purposes such relations are assumed to be exact), they are functions of each other. We know that with increasing percentages of silica the density diminishes, while the melting temperature increases, and hence the two curves if indefinitely prolonged will somewhere intersect. It remains to determine, if possible, the point of intersection. Let us for the present arbitrarily assume that the point of intersection is such that both curves have a common ordinate erected from a point on the axis of abscissas corresponding to 60 per cent. of silica, which is very nearly the normal percentage of hornblendic propylite. I shall hereafter adduce reasons for believing that this arbitrary assumption is very nearly or quite true.

We have now (*ex hypothese*) two curves, one representing the temperature required to render the rocks light enough to rise hydrostatically to the surface, the other representing the temperature required to fuse them. Conceiving, then, a general rise of temperature to occur among subterranean groups of rocks, no eruption could take place at any temperature less than that represented by the ordinate drawn at 60. For the basic rocks would still be too dense, while the acid rocks would be unmelted. But when that temperature is reached, the propylite would be in an eruptible condition. By a further increase of temperature hornblendic andesite and trachyte would become eruptible, the former having passed the fusion point and the latter having passed the density point of eruption. And in general as the temperature increases the line of eruptive temperature cuts the two curves at points further and further from the lowest point of eruptivity, and these points correspond to rocks which become more and more divergent in their degrees of acidity; one set progressing to the acid extreme, the other to the basic extreme. If now our fundamental assumptions are true, or in essential respects conform approximately to the truth, then the sequence of eruptions which those assumed conditions would give rise to conforms to the sequence which we find in nature. Let us, then, examine these assumptions, with a view to ascertaining, as well as we are able, how nearly they approach the truth.

1st. It is assumed that the density is some approximately definite function of the percentage of silica. There are indeed considerable variations from exactness in this respect, and we may select two or more species of rock having the same silica contents, but which differ conspicuously in density. Yet nothing is more certain than the fact that as a general rule the assumption is very near the truth. This is so well known that further discussion is probably unnecessary.

2d. It is assumed that melting temperatures also bear an approximately definite ratio to the silica. Here the variations from exactness are no doubt somewhat greater than in the case of density. Still, we know that on the whole the law strongly prevails, and that the melting temperature diminishes with the acidity of the rock.* The blast-furnace slags present often very close approximations to many of the volcanic rocks, and these approximations are not infrequently so close as to be fairly comparable. In such cases it is familiar to those who are acquainted with the practical working of furnaces that the more basic slags are much more easily fused than the more acid ones. The absolute melting temperatures, however, are not accurately known.

3d. The assumption that the two curves (density and fusion) will ordinarily cut each other at the ordinate of 60 per cent. of silica is one which presents greater difficulty. Translating graphical terms into concrete language, the meaning of it is this: It assumes that rocks having a normal percentage of about 60 per cent. of silica, and corresponding lithologically to the hornblendic propylites are fused and rendered light enough to erupt at one and the same temperature; while rocks more basic are fused at a lower temperature, but require a higher one to be sufficiently expanded; and rocks more acid are sufficiently expanded at a lower temperature, but require a higher one to fuse them. Is there any independent evidence of the verity of this assumption? The point is a very important one; indeed, vital. For if the intersection of the two curves be elsewhere,

* See observations of Bischof on fusion of igneous rock, D'Archiac, vol. iii, and results of Deville and Delesse, Bul. Soc. Geol. France, 2d ser. iv. D. Forbes Chem. News, xviii.

the theory is fatally impaired. In the absence of evidence fixing the intersection here, we might have arbitrarily taken it to be at some other point—at a point, too, outside of the scale of acidity within which volcanic rocks are always confined, as in Figs. 1 and 2. In either of these cases the

Fig. 1.

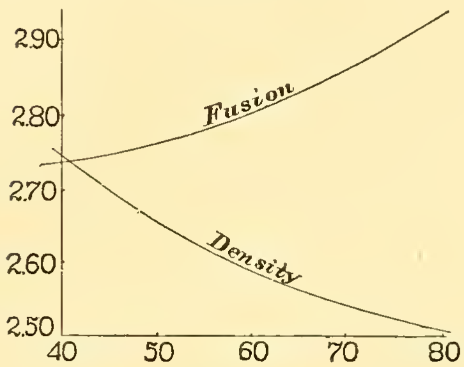
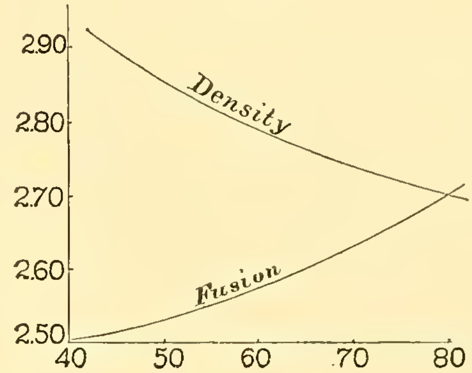


Fig. 2



rocks would have been, according to the terms of the theory, erupted strictly in the direct or inverse order of their densities throughout. But I believe we do possess some distinct evidence that the point of intersection is rightly chosen, and that this evidence may be read in the petrographic and mechanical characters of the rocks themselves. A very striking characteristic of the basaltic lavas is their perfect liquidity at the time of eruption and their power to flow in comparatively narrow and shallow streams to great distances. It is in the basalts that this property is most marked and conspicuous. *Coulées* only two or three hundred feet wide and only twenty or thirty feet thick are usually found flowing mile after mile with facility, and larger streams reach from thirty to fifty miles from their orifices. Very thin sheets of basalt flow on to great distances. No other rocks in streams of such small cross-sections reach distances so far from their origin. And when we recall the circumstances which favor a rapid cooling and solidification, this preservation of fluidity is remarkable. The experiments of Bischof and Deville agree in indicating that the latent heat of fusion is less in the basalts than in other rocks. The larger amount of surface which these thin streams or sheets expose, the disappearance of heat which is consumed in expelling in the form of vapor the included water, all combine to dissipate or render latent the contained heat of the lava with extreme rapidity. In the basaltic rocks we have thus, as I believe, most satisfactory evidence that when they reach the surface they are heated to a temperature much above that of mere fusion. In no other way are we able to account so satisfactorily for the persistency with which they retain their extreme liquidity and flow to such great distances. The same fact appears in the study of the minuter textural characters of the basalts. Under the microscope everything indicates an intense degree of ignition. The presence of glass particles and the absence of water cavities, the isotrope base, the exceeding compactness of the rock, its vitreous character, and (in the massive portions) the absence of all traces of viscosity or ropy condition, point to the same conclusion. All this is in strong contrast with rocks of the sub-acid group. The trachytes and propylites appear to have been erupted, in many cases, in a viscous condition, or in one which was not by any means thoroughly liquid. They are found in thick, cumbersome masses, and, unless the outpour was of excessive volume and mass, do not appear to have flowed far from their orifices. The trachytes, however, vary much in this respect; some appear to have been quite liquid, others exceedingly tough and pasty, with all intermediate consistencies, though in the most fluent ones there is no evidence of excess of temperature above the point of complete fusion. As a general rule their sluggish character is well pronounced. In the rhyolites there is evidence of intense ignition and thorough fusion; but the banded, ropy, and fibrolitic character is suggestive of a temperature just sufficient to melt them to a vitreous consistency, but without that perfect limpid liquidity of the basalts in which the rhyolitic texture would certainly be completely obliterated.

Now, the pyroxenic divisions—the basalts, dolerites, augitic andesites—all betray evidence of superfusion, or a temperature much in excess of that required to melt them. In the hornblendic andesites the same appearances are seen, though less in degree. In the propylites they have vanished, and are not discernible in the trachytes and rhyolites. This is in accordance with the assumption contained in the theory. All rocks more basic than propylite betray evidence of superfusion, and hence it is at propylite in the ascending scale of acidity that superfusion is presumed to cease.* If, then, these facts will bear the interpretation which I have placed upon them, we have in the rocks themselves the evidence required to show that propylite is a rock which at a certain temperature is just sufficiently fused and just sufficiently expanded to fulfill the mechanical conditions requisite for eruption.

It still remains to look at some points in the application of this theory to the succession of eruptions, which would at first sight appear anomalous if not inconsistent with it.

We do not always find the order of succession heretofore described to have been strictly followed; we find exceptional cases. Instances are not wanting where true basalts have outflowed prior to the eruption of rhyolites, and are even known to be overlaid by trachytes in the Auvergne district of France, or as Lyell has found to be the case in the Madeira Islands. These, however, seem to be exceptional instances. Even in the Auvergne and Madeiras the great preponderance of occurrences conform to the observed law of Richthofen, and so far as our knowledge of other regions extends the departures from this law are not common. But it may be asked whether a single unequivocal exception is not sufficient to seriously impair, if not wholly break down, the explanation of the sequence here given. So far are they from impairing it, that I think a little examination will show that not only ought we to look for exceptions, but we may even be surprised that exceptions have not been found more numerous than they appear to be. In the brief explanation given it has been assumed tacitly, that the rise of temperature has been uniform or followed some definite law of variation throughout the entire field of subterranean magmas. In its simplest or typical form the proposition assumes that in all typical or normal cases the rise of temperature affects all parts of this field alike. But this we could not expect. It is not probable that a uniform rise of temperature would take place in all parts of the field, but may vary

*It was when I was contemplating the great distances traversed by slender basalt streams in Southern Utah that this theory suggested itself to me. I could not doubt that such lavas must have been ejected at a temperature much more than sufficient to melt them. This seemed to contrast powerfully with the habits of trachytic masses. It occurred to me then that this high temperature might be absolutely essential to the eruption of so dense a rock as basalt, while a considerably lower one would suffice for lighter rocks. Immediately the higher melting temperature of the rhyolites and trachytes suggested itself, and almost as quickly as I write it the theory took form in my mind and the double function of density and fusibility associated itself with the double sequence.

horizontally in the amount of rise as we pass from point to point. It may also rise more rapidly in the lower part of the field than in the upper; and as between many fields, local circumstances may accelerate beyond the mean rate the fusion and expansion of one class of rocks or retard the same effects in others. Thus, while there is a normal or typical order of eruptions, it may become liable to not infrequent exceptions arising from want of exact homogeneity of conditions.

There are several sub-groups of rocks which present difficulties somewhat greater and have the appearance at present of being somewhat anomalous. These are principally quartz-propylite and quartz-andesite or dacite. These rocks are much more siliceous than the other members of the groups to which they are mineralogically most nearly allied, being about as siliceous as the more acid trachytes. They have apparently had their epochs of eruption coevally with the hornblendic members of their respective major groups, while according to the theory their epochs should have fallen much later. I am unable to harmonize these apparent anomolies with the main theory upon any considerations which at once carry with them a conviction of intrinsic probability and an obvious reason for their exceptional relations. They are comparatively rare rocks, and do not occur in very extensive masses; their physical constitution and properties are much less known than their chemical and mineralogical. Their inferior bulk, however, does not break the force of the anomaly if it be real. Considerations like the following, suggest themselves: The theory assumes that the physical properties (density and fusibility) have a definite relation and dependence upon the proportion of silica which a rock contains. Although this is approximately true, it is in all probability not rigorously so, and indeed the probabilities, so far as fusibility is concerned, are that the variations from *definiteness* in the dependence of fusibility upon the percentage of silica are in some cases very notable, though these variations may not impair the general law as an approximate expression of the truth. In spite of their high percentage of silica, therefore, these rocks may turn out to be exceptional in having a degree of fusibility corresponding very closely to that of the hornblendic members of the major groups to which they belong. While, therefore, we cannot claim the dacites and quartz-propylites as contributing their quota of support to the theory, we may still hold that they are not necessarily in conflict with it.

There is another conceivable mode in which the law here propounded theoretically may be modified in a manner which would yield results differing from the standard sequence to which it has been applied and give a somewhat different but still a definite succession. It might be affected by the depth at which the seat of volcanic activity is located, and also by the value of the mean density of the overlying rocks. Assuming our theory to be correct, let us call the depth at which Richthofen's succession becomes the normal one, unity. Suppose the depth to be considerably greater than unity, the melting temperature of the acid rocks would then be greater on account of the increased pressure. Recurring to the graphic diagram, the effect of this modification would be to transfer the intersection of the fusion and density curves to the left or toward the basic end of the scale, and rocks more basic than propylite would be first erupted and the succession would be more or less modified. The nature of the modification will readily appear by treating the modified diagram in the same manner as has been employed already. Or suppose the depth of eruptive activity to be less than the assumed unity: the intersection of the two curves would be transferred to the right and an inverse series of modifications would result. On the assumption that the secular cooling of the earth is gradually sinking the seat of volcanicity to lower horizons, it would follow that a corresponding modification is secularly proceeding in the normal order of succession in volcanic eruptions.

This theory has one important element of weakness which it is necessary to point out. The assumption that the proximate cause of volcanic activity is an increase of temperature is to a great extent an arbitrary one. Conclusive proof of it does not seem to be obtainable at present. There are numerous indications of it, many facts which seem to point to it; yet that strong, convincing evidence which can entitle such a proposition to absolute confidence is wanting. Hence the theory should be called rather a trial hypothesis, in which there is an important premise which remains to be proven. It is a frequent resort, however, in all sciences to adopt such premises provisionally, and they gain strength or the contrary in proportion as they are useful or otherwise in explaining a wider and wider range of facts. This was true of the hypothesis of a luminiferous ether and of gravitation. Neither of these postulates could be proven *à priori*, and have gained acceptance because they explain all facts to which they stand related. Following these precedents, we may inquire whether a rise of subterranean temperature is consistent with other categories of facts besides a succession in the order of eruptions and explains other phenomena.

I have endeavored to show that the whole tenor and purport of the phenomena of volcanicity point to the conclusion that lavas are not primordial liquids but secondary products derived from the liquefaction of solid matter situated below the surface in layers or maculæ. Of this statement of the case in its grosser aspect I believe the circumstantial evidence sufficient to convince a scientific and impartial jury. Taking a generalized view of the subject, the objections against primordial liquids are insuperable. If the whole interior of the earth below a crust a few miles in thickness is liquid, the stability of that crust is intelligible only on the assumption that the crust is less dense than the liquid, and if the reverse is true it seems inevitable that the crust would be speedily submerged. The same reasoning would be applicable to residuary vesicles or primordial reservoirs of great extent underlying states and empires. If we adopt the conception of a multitude of small vesicles left by the secular consolidation of the globe gradually squeezed out one after another, other difficulties equally palpable arise. These vesicles should, in the process of ages, become fewer and fewer, and show signs of exhaustion. But observation teaches us that the eruptions of Tertiary time are apparently as numerous, as varied, and as grand as any which have occurred in anterior ages. But, above all, the intermittent pulsating character of the eruptions in any volcanic cycle is at variance with such an assumption. If this primordial liquid has lain in its receptacle, possessing, from the beginning of the world, all the essential requisites of eruptibility except that it is waiting for some accident to open a vent for it, yet, when the vent is once opened, why does it not pour forth at one mighty belch all its lavas and then close up forever? Why should it require some hundreds or even thousands of eructations with intervals of years to completely exhaust it? Why, in the course of the cycle covering hundreds of thousands and even millions of years, should the same vent or cluster of vents yield so many different kinds of lava? So completely do the facts of volcanology antagonize the primordial character of lavas, that we seem driven to seek an opposite theory of their origin.

These difficulties cease to be such and become normal phenomena when we take the postulate of local increments of temperature. The refusion of rocks becomes a slow and very gradual process. But when the melted rock is ready for issue, it does not follow that a steady stream of lava would keep flowing as long as the temperature continues to rise. We must now take into consideration the mechanism by which the expulsion is effected. This has already been suggested as the weight of overlying rocks crowding in upon the reservoir, and as these rocks are rigid relatively to small reservoirs, there is a limit to the smallness of the eruption. As the quantity of melted rock increases, this rigidity relatively diminishes until rupture takes place and all the lava hitherto accumulated is expelled. The overlying masses are then soldered up for a time, during which more lava is melted, and when the quantity is sufficient a second eruption occurs, and so the intermittent character is established and for a long period maintained.

This assumption also explains the co-existence of vents at different levels, the presumption being that each vent derives its lavas from independent layers or maculæ, and that several maculæ or layers can successively find issue through the same vent when the magmas which they contain reach the eruptive condition.

There is, however, one comprehensive or generalized fact connected with volcanoes which this assumption does not explain by itself, though it is not in any obvious respect inconsistent with it. This is the geographical distribution of volcanoes. It is well known that existing and recently extinct vents stand in the vicinity of the ocean and large bodies of inland water; a few exceptions, however, being known. But it has been repeatedly remarked that the postulated rise of temperature is asserted to be a proximate cause, itself requiring explanation by the production of some ulterior exciting cause. If we were able to find this ulterior cause, we should then know why volcanoes have their present distribution. It may be proper to remark here that this distribution would lead us to look for that cause in occurrences which take place in waters and in their vicinity. It has long been held that water plays an essential part in volcanic eruptions, and it is quite natural that we should infer from the association that the penetration of water to the internal fires is after all the determinant; but, on the other hand, we cannot leave out of view the fact that there is water on the land as well as in the sea, and that every year from 30 to 50 inches of rain are ordinarily poured over the surface and the underground water-ways and fissures are kept full. An abundant penetration may, therefore, take place on land as well as under the sea. It does not seem justifiable, therefore, to conclude that the mere presence of water is the sole determinant. There is, however, one class of processes peculiar to bodies of water. It is beneath their surfaces that sediments are accumulated, often to the thickness of thousands of feet, until by their gross weight they subside. It may be that the ultimate cause of volcanism will eventually be traced to the shifting of vast loads of matter from place to place upon the earth's surface, but at present this subject has not been investigated from a mechanical standpoint with sufficient method and system to admit of safe generalization or even of legitimate speculation.

The assumption that a rise of temperature is the proximate cause of volcanic energy, then, is not a wholly arbitrary postulate, but is consistent with a wide range of facts; brings into order not only the broader but also the subordinate facts of volcanology, and apparently affords a working hypothesis.

CHAPTER VI.

STRATIGRAPHY OF THE DISTRICT.

Palæozoic formations.—The Shinárump.—Its strong lithological characters.—Constancy over wide extent of country.—Coloring.—Architectural forms.—Age of the Shinárump, either Permian or Lower Triassic.—Continuity with Red-beds of Colorado, New Mexico, and Arizona.—Triassic formation.—Vermilion Cliffs.—Cliff forms of the Triassic.—The Jurassic series.—Comparison of sections.—White sandstone.—Remarkable cross-bedding.—White Cliffs.—Architecture.—Jurassic shales.—The Cretaceous.—Alternations of sandstone and iron-gray shales.—Dakota Group.—Laramie Group.—Intervening formations not correlated.—Lignitic character of the Cretaceous.—Close of the Laramie period.—Unconformities.—Post-Cretaceous disturbances and erosion.—Tertiary formations.—Attenuation southward.—Pink Cliffs.—Tertiary lignites.

The study of the stratigraphy of the District of the High Plateaus and of the regions adjacent thereto has been chiefly the work of Messrs. Powell, Howell, and Gilbert. I have had little to do with it, except to take their results as starting points and add my own testimony in the way of elaboration. Mr. Howell rapidly traversed the district in 1874 and seized the salient features with remarkable rapidity and acumen. The geological horizons of the larger groups were determined by him, and all that was left to me was to ascertain their extent and distribution in greater detail.

PALÆOZOIC FORMATIONS.

The oldest strata of the district belong to the closing epochs of Palæozoic time; except, however, that upon the northwestern flank of the Tushar some crystalline rocks, supposed to be of Archæan age, are revealed in momentary exposures in the ravines where the overmantling rhyolite has been deeply scored by the mountain streams. On the northeastern flank of the Aquarius Plateau the summit of the Carboniferous is laid bare, the exposed area being about eighteen miles in length by six miles in width at the widest part. A remarkable dislocation, forming a part of the Hurricane fault, turns up a brief exposure of the same horizons southwest of the Markágunt Plateau. The western side and summit of the Pávant Range is composed almost wholly of Carboniferous strata, bent and faulted after the manner peculiar to the Basin Ranges. Although yielding characteristic fossils, none of these Carboniferous exposures present sufficient materials for special study. The great fields of Carboniferous rocks are found in the Kaibabs to the southward and in the basin to the westward.

THE SHINÁRUMP.

Resting everywhere upon the Carboniferous of the Plateau Country is a series of sandy shales, which in some respects are the most extraordinary group of strata in the West, and perhaps the most extraordinary in the world. To the eye they are a never-failing source of wonder. There are especially three characteristics, either one of which would render them in the highest degree conspicuous, curious, and entertaining. First may be mentioned the constancy with which the component members of the series preserve their characters throughout the entire province. Wherever their proper horizon is exposed they are always disclosed, and the same well-known features are presented in Southwestern Utah, in Central Utah, around the junction of the Grand and Green, in the San Rafael Swell, and at the base of the Uinta Mountains. As we pass from one of these localities to another, not a line seems to have disappeared nor a color to have deepened or paled. So strongly emphasized are the superficial aspects of the beds and so persistently are they maintained, that only careful measurement and inspection of each constituent seam can impair the *prima facie* conviction that these widely-separated exposures are absolutely identical. Detailed examination, however, does show some variation in thickness and slight changes in the constituent members; but, on the whole, the constancy is, so far as known to me, without a parallel in any formation in any other region. The sculptured cliffs of the Shinárump reveal the edges of the component layers as rigorously parallel as if a skillful stonemason had laid them down, and narrow bands can be followed for miles without any visible change in their aspect.

A second striking feature is the powerful coloring of some of the beds. With the exception of the dark, iron-gray shales of the Cretaceous, the tints of the other formations are usually bright, lively, and often extremely delicate. In the Shinárump they are mostly strong, deep, and so rich as to become cloying. Maroon, slate; chocolate, purple, and especially a dark brownish-red (nitrous-acid color), are the prevailing hues, while one heavy sandstone bed is yellowish brown. At the base of the series is a thick mass of perishable shale not so conspicuous in its colors; it is in the middle members that they are so resplendent. Alternating horizontal belts of varying tones and shades, not merging into each other by gradation, but like ribbons joined at their edges, are seen wherever the formation is exposed in the same general vertical succession, and give the Shinárump Cliffs an aspect most constant, peculiar, and wholly unlike any others Here and there a thin line of white trenchantly separates the dark layers, emphasizing the distinctions, while the brown sandstone above heightens the contrasts. The effect upon the mind is impressive and oppressive.

Probably the most striking characteristic of this formation—one which is destined to make it one of the most notable of the freaks of nature in the popular estimation—is to be found in the architectural forms which have been carved out of it by the process of erosion. A common style of sculpture is represented by heliotype XI, taken from the southeastern flank of Thousand Lake Mountain. Probably the most striking forms are the buttes, which are often seen fringing the long lines of cliff bounding the Shinárump terraces in the San Rafael Swell, and again near the junction of the Grand and Green. These last have been described in glowing terms by Dr. J. S. Newberry and by Professor Powell.

The age of the Shinárump is either Permian or Lower Triassic. To which of the two periods it should be assigned is not yet free from doubt. Within the limits of the Plateau Country no fossils have yet been discovered which give a satisfactory solution to this question. Mr. E. E. Howell found in the shales south of Kanab, lying at the base of the formation, a small number of fossils which were so poorly preserved that only generic characters could be asserted with confidence. If any conclusion were to be drawn from them it would be that their general aspect is Jurassic. But the whole Triassic series, and most of the Shinárump itself, overlie the horizon from which they came, and, moreover, the types are well known to have a great vertical range.

Thoughout the region lying between the Great Plains of Colorado and Wyoming and the Basin area, wherever the horizons from the summit of the Carboniferous to the base of the Jurassic are exposed, there are usually found sandstones and arenaceous shales, distinguished by their rich red coloring, their tolerably constant texture and appearance, and the absence of fossils of distinctive character. In many places they may be imperfectly resolved into two groups, though ordinarily they show no well-marked plane of division between them; the distinction being somewhat vague and uncertain. The Triassic age of the upper portion is pretty well ascertained. Mr. Clarence King has found fossils in the lower portion which he believes to be sufficient to justify him in calling it Permo-Carboniferous. But the want of a clear boundary between the two divisions of these "Red-beds" has led many geologists to regard them provisionally as one formation, under the name of Trias. In the Plateau Country these beds appear to be conformable with each other, while the contact with the Carboniferous below is in several places distinctly unconformable. They gradually pass into the Trias above, and if a divisional plane is to be drawn, it is impossible to locate it within a belt of 500 feet of monotonous shales, and hence the tendency has been to regard the whole series as one group, and to use the names Upper and Lower Trias for the designation of different portions which, in reality, are not at present distinctly and precisely separable. Perhaps, also, some hesitation arises from the importance which must attach to a full recognition of the Permian age of these lower beds. The identity of the Shinárump of Utah and Arizona with the lower Red-beds of Colorado and Wyoming is unquestionable, and the formation, therefore, covers an area probably exceeding 250,000 square miles, with many exposures, and there is no intrinsic improbability that it is buried beneath a still greater area. If its age be Permian, then the Permian becomes a formation, ranking in importance stratigraphically with the Trias and Jura, and can no longer be considered as a merely local deposit coming in here and there to round off the majestic proportions of the Carboniferous. While the Permian age of these beds, therefore, is quite possible, there is good reason for laying a heavy burden of proof upon the advocates of that view.

The thickness of the Shinárump formation is difficult to determine, owing to the gradual transition into the Vermilion Cliff series above. Disregarding the doubtful horizons, the thickness along the Hurricane ledge is not far from 1,300 feet, and somewhat less at Kanab; and, in general, it attenuates very slowly and gradually as we recede southeastward, though it never sinks to small proportions anywhere within the limits of the Plateau Country. Besides the transitional shales above, there are three subdivisions. Commencing at the base, they are as follows:

1. Silico-argillaceous shales	450 to 650 feet.
2. Belted, highly-colored arenaceous and siliceous shales	400 to 500 feet.
3. Brown sandstone	150 to 250 feet.

The thickness of the transitional shales up to the base of the Vermilion Cliff sandstone may be reckoned from 550 to 750 feet. Within these shales there often appears a singular conglomerate. It consists of fragments of silicified wood imbedded in a matrix of sand and gravel. Sometimes trunks of trees of considerable size, thoroughly silicified, are found, to which the Piute Indians have given the name "*Shinárump*," meaning "the weapons of Shinav," the wolf-god. The conglomerate is found in many widely-separated localities, with a thickness rarely exceeding 50 feet. It occasionally thins out and disappears, but usually recurs if the outcrop be traced onwards, resembling the mode of occurrence common to the coal-seams of the Carboniferous coal measures. It is the most variable member of the Shinárump thus far observed. It is found on the west flank of the Markágunt and throughout the great circuit of cliffs south of the High Plateaus; it is seen at Paria, and again at the Red Gate between the Aquarius and Thousand Lake Mountain, the characters of the formation being quite the same in all these localities. The conditions under which it was accumulated would seem to have been remarkably uniform, and may have been similar in some respects to those attending the formation of coal. The subsequent silicification of the wood upon a scale so extensive and even universal is certainly a very striking phenomenon, and one for which no explanation suggests itself. It may be of interest to mention that at Leeds, in Southwestern Utah, the fragments of silicified wood were found to be strongly impregnated with horn-silver. Subsequent prospecting, which had been stimulated by this curious discovery, led to the finding of horn-silver impregnating the sandstones and shales in sufficient quantity to attract both miners and capital to the locality.

The Shinárump has but a few exposures within the District of the High Plateaus. The best example is seen at the Red Gate, at the foot of Rabbit Valley, where the Fremont River passes out into the desert waste in the heart of the Plateau Province. A belt of this formation is seen near the summit of the Water-Pocket flexure, flanking the northeastern part of the Aquarius a few miles from its base. It is brought up to daylight southwest of the Markágunt by the Hurricane fault, and the beds are there sharply flexed in the vicinity of the fault-plane, but quickly smooth out to the eastward and southward. The principal area of the Shinárump is south of the Vermilion Cliffs, in the northern part of the Kaibab District, around the junction of the Grand and Green and in the San Rafael Swell. Generally speaking, it is usually found as the first terrace above the Carboniferous in the areas of maximum erosion.

THE TRIAS.

Next above the Shinárump shales is found an extensive series of sandstones constituting the Trias. Probably no formation in Southern Utah is better exposed, but notwithstanding this, it has not in this part of the Plateau Province hitherto yielded a solitary fossil of any kind. Still we are not in doubt about the correlative age of the group for its continuity with beds found by Newberry in New Mexico, and yielding a distinctly Triassic flora; its further continuity and identity with Red-beds in the Uintas having a Jurassic fauna above and the unmistakable Shinárump shales below; and, lastly, its identity with the beds of Idaho, which furnished Dr. Peale a well-marked Triassic fauna, are sufficiently certain.

The contact with the shales below is usually conformable, but in the vicinity of the Hurricane fault, where the whole Triassic series is displayed, the junction is often unconformable. The separation, however, of the Trias into an upper and lower series, so far as Southern Utah is concerned, is based upon lithological grounds chiefly. It is also a matter of great convenience to effect this separation, since each division has its own topography, and their distributions differ notably. There is, also, a decided contrast in their respective aspects, and the geologist who studies them in the field is constantly reminded of the distinctions. The Upper Trias consists of many beds of sandstone with shaly partings. Usually the component members do not attain great thickness, but a few of them occasionally have a thickness exceeding 200 feet. Very many of them are cross-bedded in a beautiful manner, and although this feature is not so strongly marked as in the Jurassic sandstone, it is almost always conspicuous enough to attract attention. The whole formation is brilliantly colored, the predominant hue being a bright lively red, often inclining to orange. Occasionally, however, this color gives place to a strong yellow or bright brown. These are very distinct from the deep crimson, chocolate and purple of the Shinárump, and, furthermore, change from red to brown along the course of a single layer or bed, while in the Shinárump every layer preserves its color without a trace of change through many miles of exposure. The predominant red, approximating to vermilion, induced Professor Powell to give the local name of VERMILION CLIFFS to their grandest and most typical exposure.

The Upper Trias is in truth the great cliff-forming series of the Plateau Country. No other formation equals it in the extent and variety of cliff exposures. The Vermilion Cliffs extend from the Hurricane fault to Paria, more than a hundred miles in a straight line, and more than twice that distance if we follow the sinuosities of their escarpment. Throughout this distance they front the south with a succession of superposed ledges, rarely less than 1,000 feet in height and often exceeding 1,500 feet; throwing out great promontories, and deeply notched by estuaries and bays. Wherever exposed in more easterly regions the same tendency to form cliffs may be observed. These escarpments have their distinctive architecture and a structure quite as peculiar to the formation as those of the Shinárump below and the Jurassic above. Let us recall here that the series is composed of manifold layers of sandstone, with many shaly layers intervening. Usually three or four members are massive beds of very homogeneous sand rock, with a thickness of 100 to 250 feet. Recall, also, that the most effective attack of erosion is made primarily against these yielding shales, while the overlying and more obdurate sand rock is thereby undermined and cleaves off by its vertical joints. Take now a series of these alternating massive layers and softer shales, the long process of erosion gives a series of perpendicular walls, alternating with sloping taluses. This composite architecture is one of the most persistent features of the formation. Something like it is seen in the Carboniferous strata forming the walls of the Marble Cañon of the Colorado, but there are also many wide differences both of detail and *ensemble.*

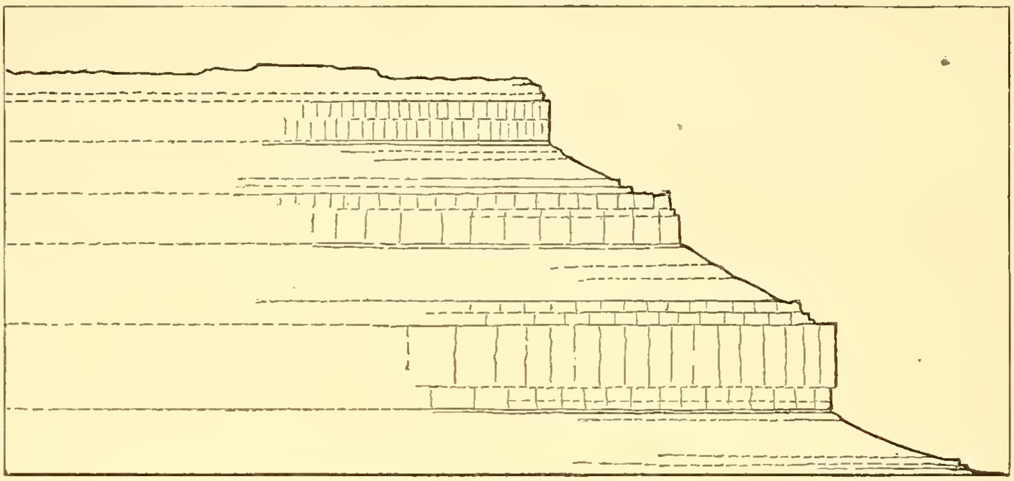


FIG. 3.—Generalized profile of Vermilion Cliff.

The thickness of the Upper Trias is from 1,100 to 1,800 feet, being greatest in the vicinity of the old shore line, and very slowly attenuating to the eastward.

THE JURASSIC.

The Jurassic series consists of two members, the lower being a massive sandstone of great thickness, the upper a series of calcareous and gypsiferous shales from 200 to 400 feet thick. Underneath the sandstone is a small group of shaly beds, which are presumed to be of Jurassic age, but no determinable fossils have been taken from them. It has been a long-standing and difficult question whether the Jurassic sandstone is not, after all, a mere upward continuation of the Vermilion Cliff beneath. Much color was given to this supposition by the fact that no unconformity between them has been detected in this vicinity, and still more by the fact that as we travel eastward and southeastward from the High Plateaus the distinction between them gradually fades, and the two seem to merge into one. Neither of them have yielded any determinable fossils. Nevertheless, I am convinced that the probable plane between the Jura and the Trias lies between these two sandstones. In the Uinta Mountains the Triassic sandstones have the same general features as they exhibit upon the southern flanks of the High Plateaus. Comparing the Jura-Trias section of the Uintas with that of the High Plateaus and Kaibabs, we find a concordance in the several members.

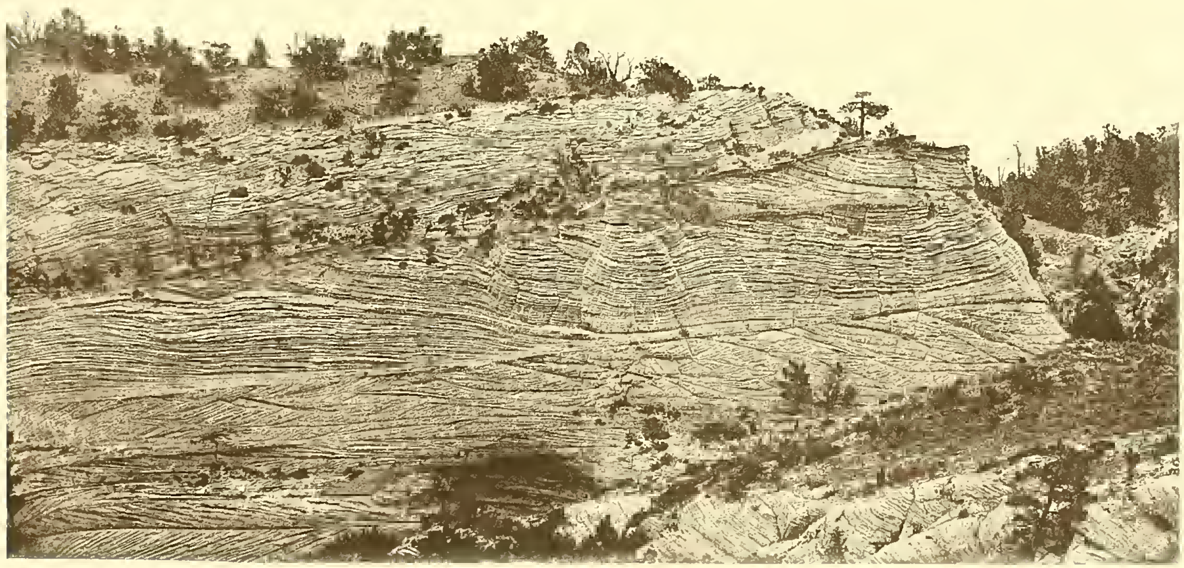
Uinta Section.		Kanab Section.	
	Feet.		*Feet.*
Calcareous, shales, limestone and gypsiferous shales	1,000	Calcareous shales, limestone and gypsiferous shales	500
Massive, cross-bedded white sandstone	1,100	Massive, cross-bedded white sandstone	1,400
Thin calcareous shale	100	Thin calcareous shale	50
Vermilion Cliff series	1,100	Vermilion Cliff series	1,500
Upper Shinárump shales and conglomerate	1,000	Upper Shinárump shales and conglomerate	750
Belted shales	400	Belted shales	400
Lower Shinárump shales	300	Lower Shinárump shales	500

A comparison of these two sections will lead to the conviction that the white sandstone of the Kanab region is identical with that of the Uintas. But the latter has Jurassic fossils above and below it, and hence we may conclude that the former is also Jurassic, although fossils of that age are found only above it, and none of any kind either in the sandstone itself or in the thin shales below.

Starting from the village of Cedar, west of the Markágunt, we find the sandstone in great force, and may trace it southward around the flank of that plateau, and thence eastward around the Paunságunt, and beyond the Paria River. In the Kaiparowits it is wholly lost beneath the Cretaceous, but east of the Kaiparowits it reappears. It skirts the southern and eastern slopes of the Aquarius, and is grandly displayed in the Water-Pocket flexure. It forms one of the terraces which lie west and north of the San Rafael Swell, but north of that area it dips beneath later formations, and is buried thousands of feet beneath the Cretaceous-Eocene deposits. A hundred miles north of the San Rafael it is turned up again upon the southern slopes of the Uintas with the same characteristics which it shows elsewhere. The line of outcrop with the intervals of concealment thus traced is nearly 500 miles. Wherever exposed along this belt the lithological characters are preserved without material change. But, on the other hand, if we trace the sandstone across this general line of strike and follow it southeastward into northeastern Arizona and New Mexico, its thickness slowly diminishes, its features lose force and individuality, and it seems to blend gradually with the Vermilion Cliff sandstones below. It is not certainly known at present whether the whole formation thins out in this direction or whether it forms a part of the beds which have been assigned by Newberry to the Upper Trias. Most probably it thins out altogether. A little way beyond the Glen Cañon in New Mexico the fossiliferous Upper Jurassic shales are seen to rest directly upon sandstones which are believed to be Triassic, and the Jurassic white sandstone of the High Plateaus is nowhere seen. A little farther on the Jurassic shales also disappear, and the Cretaceous touches the Trias. Thus the Jurassic sandstone appears to have been a littoral or off-shore formation thrown down along the coast of the Mesozoic mainland, which occupied the region now forming the Great Basin. Some doubt still attaches to the origin of those portions which flank the Uintas, but our ideas of a geography so ancient are very vague and our knowledge very fragmentary.

The lithological characters of the Jurassic white sandstone render it a very conspicuous formation. Through a thickness of more than a thousand feet, sometimes of nearly two thousand feet, it is one solid stratum, without a single heterogeneous layer or shaly parting. A few horizontal cracks are seen here and there, but inspection shows that they are merely the seams where two systems of cross-bedding are cemented together. In general, it is one indivisible stratum. This massive character has had its effect upon the cliff-forms that have been sculptured out of it. These forms are bold headlands and gigantic domes, usually without any minor details, but

HELIOTYPE VIII.



Heliotype Printing Co., 220 *Devonshire St., Boston.*

CROSS BEDDED JURASSIC SANDSTONE.

simple in the extreme, and majestic by reason of their simplicity. The color of the rock is almost always gray, verging towards white. Occasionally it is a very pale cream color, and again pale red. The red becomes more common as we recede from the old shore line towards the east. But of all the features of this rock the most striking is the cross-bedding. It is hard to find a single rock-face which is not lined off with rich tracery produced by the action of weathering upon the cross-lamination. The massive cliff-fronts are etched from summit to base with a filagree as intricate and delicate as frost-work. The same phenomenon is seen in the Vermilion Cliff sandstones below, often so rich and complex that it excites constant admiration. Dr. Newberry speaks of it with enthusiasm as presented in the Triassic sandstones of New Mexico. But it is far less wonderful than the cross-bedding which the Jurassic presents at every exposure. In the Colob Terrace, south of the Markágunt, the rock weathers into many cones and pyramids, and the details produced by the action of the weather upon the cross-bedding are grotesque and often ludicrous. A journey down the Upper Kanab Cañon is enlivened by ever-recurring displays of this phenomenon, presented with a profuseness and variety which extort exclamations of delight from the beholder. The Jurassic sandstone was deposited over an area which cannot fall much short of 35,000 square miles, and the average thickness exceeds 1,000 feet. The imagination is utterly baffled in the endeavor to conceive how a mass so vast and at the same time so homogeneous and intricately cross-bedded throughout its entire extent could have been accumulated.

Overlying the white sandstone is a series of beds which may be called shales with some reservation, and here we find for the first time an abundance of distinctive fossils. They are clearly of Jurassic genera and species, and enable us to correlate the horizon with confidence. They belong to a well-marked formation, which is represented not only throughout the greater part of the Plateau Province, but also in Colorado, Wyoming, and Northern New Mexico. From many large areas, indeed, it has been denuded, but throughout Utah it is never wanting from those exposures where its presence could be looked for.

That constancy of lithological character which is so conspicuous in older Mesozoic members does not prevail in this one, for it is highly variable not only in the mass, but also in the constitution of the beds. In some exposures it is more than a thousand feet thick; in others, it is less than two hundred. Where its volume is greatest it is more arenaceous, and where the volume is less the beds are shaly, marly, and calcareous. Usually several seams of limestone occur, and in these the fossils are found often abundantly. One notable feature is the small amount of cement in the arenaceous layers, which are, therefore, very poorly consolidated, and the rock weathers and wastes away with extreme facility. Gypsum and selenite occur abundantly in these beds, and especially noticeable is the latter mineral, which is seen sparkling and glittering in the sunlight in the badlands to which the decay of the strata gives rise.

THE CRETACEOUS.

Throughout the District of the High Plateaus and the broad terraces which flank it upon the south and east the Cretaceous system has the same relative magnitude and importance which distinguish it in other portions of the West. In absolute mass it is inferior only to the Carboniferous; but as the latter formation is usually covered by later ones over the greater part of the West, and especially of the Plateau Country, the Cretaceous exposures are everywhere the dominant ones and most conspicuous. The series consists of many beds of sandstone and argillaceous shale, the latter decidedly predominating. The number of beds is very great, but they show a tendency to form groups, here a series of sandstones with a few shales, there a series of shales with a few thin seams of sandstone. Two conditions, however, have combined to render the group a difficult one to study and to correlate with coeval groups in other regions. The first is the want of sharp and persistent divisional horizons; the second is the great variation of the lithological characters along the outcrops, and the changes which almost all the strata undergo as we trace them from place to place. No two sections show any close agreement in the bedding. Since the fossils are generally confined to a few of the many layers, it is frequently difficult to find a valid separation, and even when we discover one we cannot apply it to every locality. But while we are often at a loss to decide to what part of the Cretaceous system a particular exposure should be assigned, we are rarely in doubt about its Cretaceous age, for each member of the system possesses lithological characteristics only a little less emphatic and distinctive than those of the Trias and Jura. They consist of very heavy alternating masses of iron-gray argillaceous shales and bright yellowish-brown sandstones, which the observer will seldom be in danger of confounding with the members of any other group. The iron-gray shale sometimes gradually passes into a bluish-gray or light dove-color, especially to the eastward of the High Plateaus. At the base, or near the base of the Cretaceous system, is a conglomerate, the age of which is doubtful, since the horizon separating the Upper Jurassic has not yet been accurately determined, and the conglomerate may ultimately prove to be a part of the latter group.

The upper and lower divisions of the Cretaceous can be correlated with a very high degree of probability with the Laramie and Dakota groups of Colorado, respectively. Our inability hitherto to subdivide the intervening members prevents us for the present from asserting any exact correlations with the middle Cretaceous divisions of that State. The sandstone near the base of the system, with a few underlying shales, is without much doubt the extension of similar strata found in Southwestern Colorado and Northwestern New Mexico by Messrs. Holmes and Peale, and referred by them to the Dakota Group. The fossils found in this group are *Ostrea prudentia* (White), *Gryphea Pitcheri*, *Exogyra laeviuscula*, *E. ponderosa*, *Plicatula hydrotheca* (White), *Avicula linguiformis* (Shumard), *Camptonectes platessa* (White), *Callista Deweyi* (Meek and Hayden). In these lower Cretaceous beds are also found a good workable seam of coal and numerous Carbonaceous shales. The coal outcrops near Upper Kanab, south of the Paunságunt Plateau, and also in Potato Valley, south of the Aquarius.*

The equivalence of the Upper Cretaceous shales with the Laramie beds is founded upon their known continuity with strata of that age in Western Colorado and along the course of the Green River south of the Uintas. This continuity can be traced very clearly in the great cliffs west

*A good workable coal is found at several places on the southwest flank of the Markágunt, but I am not quite sure that it belongs to this horizon.

of Castle Valley, which swing around the north end of the San Rafael Swell and merge into the broad Upper Cretaceous mesas east of it. The fossils which are found in these shales are of brackish-water habits, and although the species are in many cases new or peculiar to the locality, yet their general facies and generic forms are clearly such as harmonize with this correlation. The mass of the Laramie beds is here very considerable, averaging about 1,800 feet. They contain many Carbonaceous shales, and workable seams of coal have also been observed which apparently lie near the base of the group.

Between the summit of the Dakota and the base of the Laramie beds lie from 2,000 to 3,000 feet of sandstones and shales which must represent the middle Cretaceous divisions. These are as yet not subdivided nor correlated with the divisions of Colorado and Wyoming.

The whole Cretaceous system of the High Plateaus and their encircling terraces is lignitic, and coal is found at many horizons. Nor does one portion of the series seem to abound in coal more than another. Carbonaceous shales are found along the great escarpments in many localities, and a considerable number of workable beds of coal are also known.

At the close of the Laramie period we come to a physical break in the course of the deposition. Prior to that epoch the disturbances and resulting unconformities appear to have been few and inconsiderable. The continuity of deposition from the base of the Trias to the summit of the Cretaceous appears to have been unbroken, and the only unconformities seen are local and usually slight. But at the close of the Laramie period extensive disturbances took place along the old Mesozoic shore line which now marks the boundary of the Great Basin. Considerable areas have been found from which the Cretaceous strata were extensively denuded before the deposition of the earliest Tertiary beds began, and where the lower Eocene is seen to lie across the upturned and beveled edges of the Cretaceous. In the locality now occupied by the Aquarius Plateau and Thousand Lake Mountain the lower Eocene rests directly upon the Jurassic, and the Cretaceous series is wholly wanting over a large part of the area. A great monoclinal flexure runs under the Aquarius from the south, and where it disappears beneath the great lava cap of that plateau the history of the unconformity is clearly revealed. The monoclinal involves the whole Cretaceous system, but not the overlying Tertiary, and fixes the age of the disturbance between the close of the Laramie and the beginning of the Tertiary. The northern extension of the Water-Pocket flexure indicates a precisely similar movement coeval with the one already recited. This flexure disappears beneath volcanic accumulations at Thousand Lake Mountain. The summit of that mass consists of lava-capped Tertiary strata resting upon the Jurassic, while to the northeast of the mountain the Cretaceous beds are rolled up towards it monoclinally, with patches of level Eocene beds lying unconformably across their edges. An unconformity of Tertiary and Cretaceous is also laid open to view in Salina Cañon. Around the flanks of the Markágunt Plateau many exposures of this unconformity are also seen. In truth, there appears to have been at this epoch a series of displacements having a north and south trend, breaking up the Mesozoic system into long blocks by well-defined monoclinal flexures, and the uplifted portions everywhere suffered denudation prior to the deposition of the Tertiary beds. On the other hand, very many of the contacts of the Eocene and Laramie beds are apparently conformable. This occurs wherever the older series escaped distortion, and throughout the central parts of the Plateau Province they usually did escape it. The great disturbances were for the most part localized in the vicinity of the old shore line, and only now and then extended far away from it. The disturbances, being also chiefly monoclinal flexures and faults, did not disturb very noticeably the horizontality of the strata except along the very narrow *locus* of the flexure itself.

The existence of these unconformities indicates a lapse of time between the close of the period of deposition of the Laramie beds and the beginning of the local Eocene. Nor could this period have been of very trifling duration, for there are instances of extensive erosion of the Upper Cretaceous prior to the deposition of the earliest Tertiary. In the Aquarius Plateau and in Thousand Lake Mountain the Lower Eocene rests upon the Jurassic, and in the southern amphitheaters of the Aquarius the Tertiary lies across the beveled edges of the whole Cretaceous system. Whether such an occurrence may be construed as meaning a temporary emergence of land from the water, or whether it merely indicates a local exposure to denudation, it is not possible at present to say.

TERTIARY LACUSTRINE FORMATIONS

The history of the Plateau Country which is at present best known is the history of its Tertiary formations. This remains to be written; but materials for it have been widely collated, and are in the possession of Professor Powell, who will, it is believed, discuss the subject at an early day. A more promising and instructive one probably is not to be found in the entire range of North American geology. Nothing more is needed here than a mere summary, which may serve as a guide and index to the meaning of the terms employed in this monograph.

The Tertiary system of the Plateau Country is lacustrine throughout, with the exception of a few layers near the base of the series, which have yielded estuarine fossils. The widely varying strata were accumulated upon the bottom of a lake of vast dimensions, and were derived from the waste of mainlands and mountain platforms, some of which are still discernible. The region of maximum deposit was in the vicinity of the Wasatch and Uintas, where in the course of Eocene time more than 8,000 feet of beds were laid down. As we proceed southward, these heavy deposits attenuate, partly by a diminution in the thickness of the individual members and partly because the period of deposition ceased earlier the farther southward we go, until in the southern part of the province only the lower Eocene is found, or, indeed, was ever deposited. The High Plateaus occupy the belt through which this diminishing bulk and successive elimination of upper members is well seen. In the Wasatch Plateau, at the extreme northern part of the district, we find the two lower divisions of the Eocene present in great volume; and in the valley of the Sevier and San Pete we find what is undoubtedly a still higher division. At the southern portion of the district only the lower division can be clearly made out, though some of the upper beds may prove to belong to a later period. The present weight of evidence, however, seems to me to place them in one division, the "Bitter Creek" of Powell.

In the southern plateaus, the Markágunt and Paunságunt, we find the following members of the Bitter Creek, which are much the same in all exposures:

SOUTHERN BITTER CREEK.	Feet.
1. Upper white limestone and calcareous marl (summit of series)	300
2. Pink calcareous sandstone	800
3. Pink conglomerate (base of the series)	550
	1,650

In the northern part of the district we have a larger development of the Bitter Creek series, and resting upon it some heavy masses of the Lower Green River shales, and probably a considerable portion of the Upper Green River Group is also represented. There is, however, no exact correspondence in the lithological or stratigraphical succession of the component members of the Bitter Creek when the northern and southern portions of the district are compared. A series of sections from the northern part is given in the following chapter.

The Pink Cliffs, which form such a striking feature in the scenery of the southern terraces, are exposures of the fine-grained calcareous sandstone forming the middle member of the Bitter Creek. The same exposures are exhibited in the southern and southwestern flanks of the Markágunt around the entire promontory of the Paunságunt and in the circuit of the Table Cliff. In the Aquarius Plateau the Lower Eocene is found, but in smaller volume than elsewhere, and it is decidedly diminished in mass upon the summit of Thousand Lake Mountain. But it resumes its normal thickness farther north, and then grows more and more massive throughout the extent of the Wasatch Plateau.

In their general characteristics these Tertiary strata are similar to the Laramie beds upon which they generally rest, being shaly and marly and sometimes lignitic. It is noteworthy, however, that in the southern part of the district of the High Plateaus no lignite or carbonaceous material has yet been discovered in the Tertiary beds. But in the northern part of the district the lignites are found abundantly not only in the Lower Eocene (Bitter Creek), but even in the Lower and Upper Green River (?) beds. In the San Pete Valley coal has been mined for local use for several years, and taken from what appear to be seams of Green River age. A more detailed description of the Northern Tertiaries will be given in the next chapter.

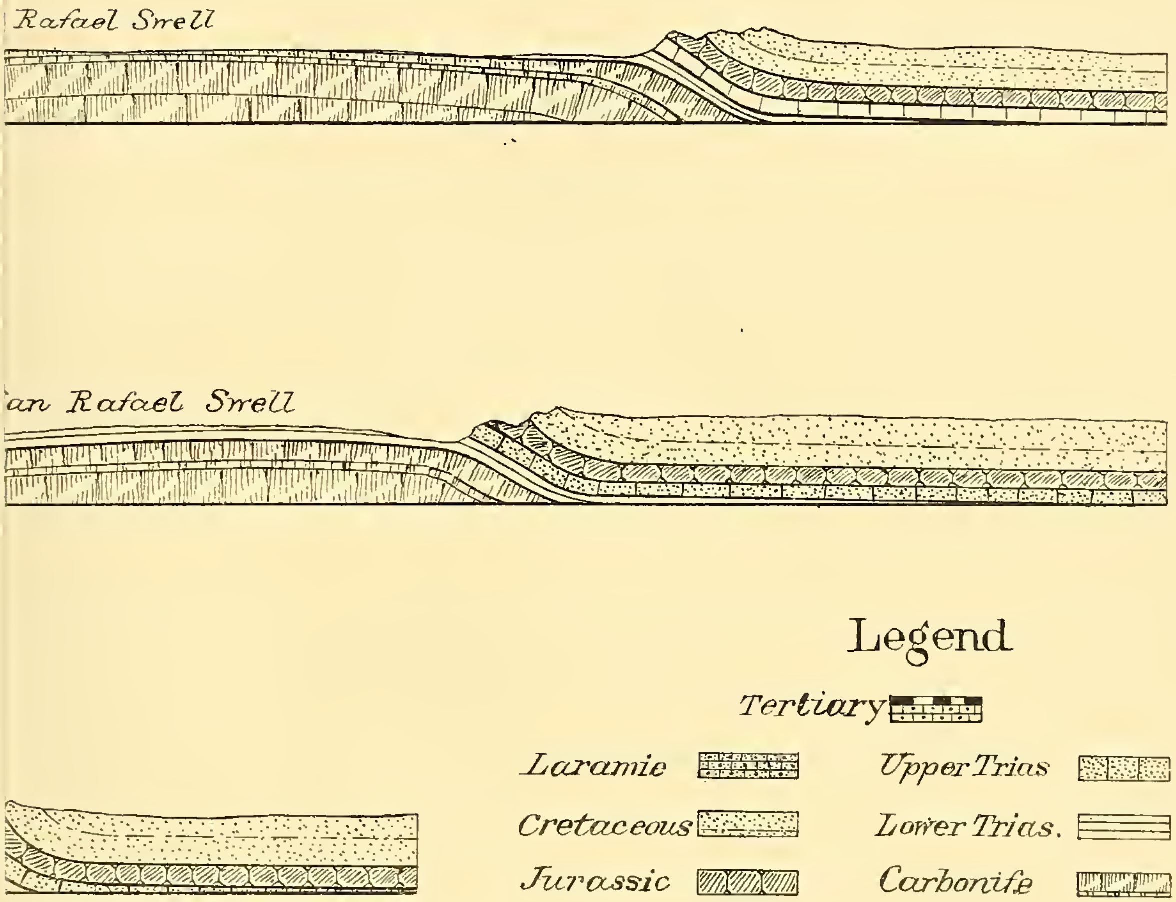
CHAPTER VII.

THE WASATCH PLATEAU.

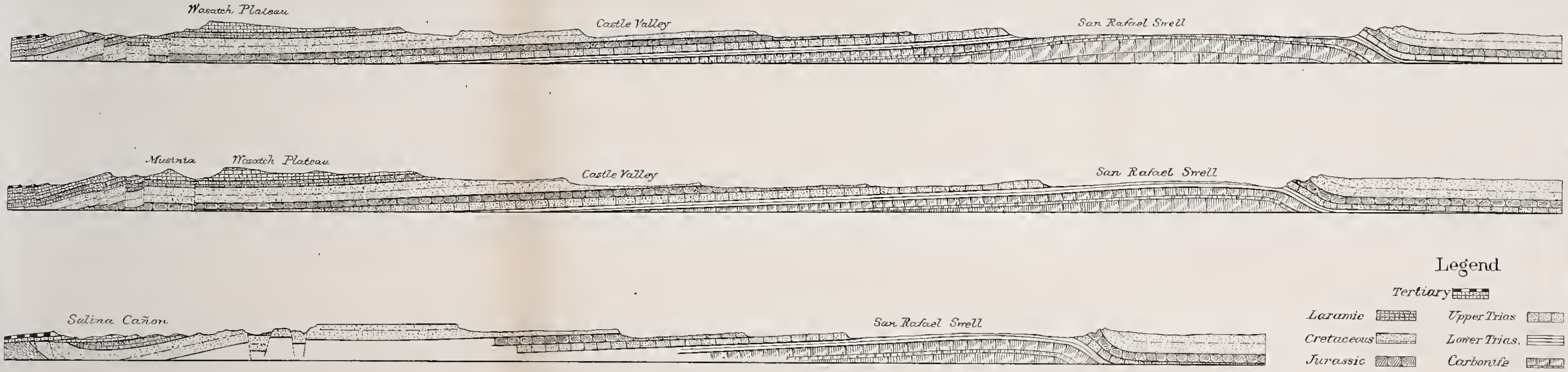
Situation and structure of the Wasatch Plateau.—Of what strata composed.—The great monoclinal.—The Cretaceous platform south of it.—Salina Cañon.—The Jurassic Wedge.—East and West Gunnison faults.—San Pete Plateau.—Sedimentary beds composing the Wasatch Plateau; Bitter Creek, Lower Green River, and Upper Green River beds.

The name of Wasatch Plateau has been given to the northernmost of those highlands of tabular form which are the subject of the present monograph. It is in some sense an outlier of the group, and presents features peculiarly its own, though sharing with them a common history and many similar features. It slightly overlaps at its northern end the main range of the Wasatch Mountains, and stands *en échelon* to the southeast of Mount Nebo, the last great mountain of that beautiful chain. The interval between Nebo and the plateau is about 15 miles, and is filled partly by a medley of low hills and partly by a depression called San Pete Valley, which lies along the base of the table. The western flank of the uplift is a monoclinal flexure of the grandest proportions. Along a base line nearly 50 miles in length the Tertiary strata bend upward to the summit in a single sweep, diversified by minor inequalities arising partly from minor fractures, partly from erosion, but never of such magnitude as to mask the general plan of the uplift, nor even to greatly disfigure its symmetry. The minor features, though elsewhere they might seem of considerable moment, are mere ripples upon the great wave. At the summit the strata suddenly flex back to horizontality, and when we reach it we find ourselves upon a long narrow platform, nowhere more than 6 miles in width, usually much narrower, and here and there reduced to a knife-edge or even eaten through by erosion. To the eastward the profile at once drops down, often by a great cliff, always abruptly, by a succession of leaps across the edges of the sensibly horizontal strata, to lower terraces, succeeding each other at intervals of 3 to 6 miles, and consisting of older and older formations.

PLATE I.



the San Rafael Swell.



Sections from San Pete and Sevier Valleys across the Wasatch Monoclinal to the San Rafael Swell.

Scale 4 Miles : 1 inch

The eastern front of the plateau is simply a wall left standing by the erosion of the region which it faces. The Tertiary beds upon the summit, as well as the Cretaceous beneath, once spread, unbroken and undisturbed, as far to the eastward as the eye can reach, and thence far beyond the limits of vision. From the strange land which that summit now overlooks at an altitude of 11,500 feet, more than 8,000 feet of Tertiary and Mesozoic strata have been swept away, and the region which has been thus devastated is large enough for a great kingdom. The Wasatch Plateau is a mere remnant of that protracted process, and, so far as it extends, is a mere rim standing along a portion of the western boundary of the Plateau Province.

The western front of the plateau, then, is a great monoclinal flexure, and its eastern front is a wall of erosion. To the northward the beds which compose it stretch far up toward the Uinta Mountains, still ending in lines of great cliffs or bold slopes gradually swinging to the eastward until, after a course of nearly a hundred miles, they cross the Green River, where Powell named the Tertiaries the Roan Cliffs, and the Upper Cretaceous the Book Cliffs. Southward the Tertiaries forming the summit of the plateau end abruptly in a precipice extending east and west, while the underlying Cretaceous beds continue, forming a lower terrace overlooking the still lower level of Castle Valley. The average altitude of the table is about 11,000 feet, and it stands from 5,500 to 6,000 feet above San Pete Valley on the west and about the same height above Castle Valley on the east. To gain an adequate conception of the great monoclinal, which forms the western flank, we must recur to the consideration that the upward curvature and reflection to horizontality leaves the Lower Tertiary beds full 5,500 feet above still more recent ones in the valley below. If the latter were now continuous across the summit, as they once probably were, the altitude would be from 1,500 to 2,000 feet greater than at present. Thus the total rise of the monoclinal appears to have been more than 7,000 feet, and the uplift has occurred with a near approach to equality along a line of strike of 50 miles. The transverse structure will be seen by referring to Plate 3, sections 6 and 7.

The platform of the summit is rugged, the irregularities being due mainly to erosion, the degradation of 1,500 to 2,000 feet of beds having proceeded unequally, although the stratification still retains its sensible horizontality. Upon the southwestern shoulder there is considerable complication of the displacement. Two or three sharp faults, running north and south, include between them a long block from 2 to 3 miles in width, which has dropped, the amount of the fall varying from 600 to 1,700 feet. The length of this block is at least 27 miles and may be greater. It is much complicated by minor fractures, and a portion of its southern extension into the Cretaceous terrace south of the Wasatch Plateau has been described and illustrated by Mr. G. K. Gilbert* as an instance of a "zone of diverse displacement." The general appearance and relations of this complicated downthrow suggest that the upper recurving branch of the great monoclinal was subject to tension during the uplift, and the beds, being unable to stretch, were rent apart, allowing the block to sink.

The Cretaceous terrace, upon which we may look down while standing upon the southern terminus of the Wasatch Plateau, is no doubt, from a structural point of view, a part of that plateau; but the loss of its Tertiary beds by erosion has reduced its altitude to a level 1,500 to 2,000 feet lower. It continues the structural features southward to plateaus next in order, forming a kind of connecting-link between the northern and southern uplifts. Its chief deformation is due to the sunken block already described. The two faults between which it has fallen increase for a time their throw as they continue southward, reaching a maximum of nearly 3,000 feet, and then decreasing to zero at points about 18 and 20 miles, respectively, south of the Wasatch Plateau. The structural depression thus produced has been called Gunnison Valley, but, this name being preoccupied, it should be used provisionally. It contains abundant evidence of its origin, for the Tertiary beds are seen to abut against the Cretaceous along the lines of faulting, and the latter beds tower far above them. The drainage of this valley is to the westward, through a deep cañon called Salina Cañon, which is a clearly defined, but by no means uncommon example of a general fact, which is repeated so frequently throughout the entire Plateau Country that

*Amer. Jour. Science; also, Geol. Uinta Mountains, J. W. Powell. The minor fractures are too small to appear effectively upon the stereogram, and have been omitted, but the main faults are introduced.

it has now become a generalization of great importance. Its formula is exceedingly brief. *The principal drainage channels are older than the displacements.*

Salina Cañon cuts through the southern continuation of the great monoclinal at a point where its rise is a minimum, and nearly midway between the Wasatch Plateau on the north and the Sevier and Fish Lake Plateaus on the south. Even here it plunges into a wall forming the uplifted side of a great fault of which the shear could not have been much less than 3,000 feet, though fully 2,000 feet of upper beds have been removed from the uplift by erosion. After a course of about 23 miles the cañon opens into the Sevier Valley. It carries a fine stream, whose waters join the Sevier at the town of Salina. Along the descent of this stream the beds dip more rapidly than the stream descends. This relation between the course of a drainage channel and the inclination of the strata is not the usual one in the Plateau Country; on the contrary, the strata much more frequently dip upstream, and rivers usually emerge from cliffs instead of entering them. In this respect Salina Cañon is an exception, though not an isolated one.

A remarkable displacement is found along the eastern side of the Sevier Valley, between Gunnison and Salina. A narrow belt of rocks of Jurassic age is thrust up, forming a chain of foot-hills and bad lands, and the later Tertiaries are seen to flex upward against their western sides and terminate in a "hog-back," while they abut almost horizontally against their eastern sides. A small remnant of Tertiary beds is here and there found as a thin capping lying upon the Jurassic beds unconformably, and patches of volcanic rock farther southward are also seen to cover them. The belt of Jurassic rocks nowhere exceeds two miles and a half in width, but its length is nearly 40 miles, extending from a point about 7 miles south of Manti along the base of the great monoclinal and the throw of the Sevier fault as far as Monroe, where it ends, to all appearances, somewhat abruptly, or perhaps disappears under the great mass of volcanic rocks which form the loftiest part of the Sevier Plateau. These older beds dip eastward, always at a high angle, which sometimes passes the vertical. This inclination was attained, without doubt, in part before the commencement of Tertiary time, and probably during the Cretaceous epoch. It may belong to a class of flexures produced near the close of the Cretaceous, of which several instances are found in the district, chiefly in its southeastern portions. They all involve the Cretaceous beds in the displacements whenever they are present, but not the Tertiaries, which, when found in contact, overlie them unconformably. After the upturning of this flexure it may have stood as a long narrow ridge near the western shore line of the great Cretaceous-Eocene lake and been subject to a considerable amount of degradation, which removed the Cretaceous beds and finally planed down the whole mass until it stood but little above the common level. In the oscillations of the shore line during the Green River epoch it would seem to have been overflowed by the waters of the lake during the last stages of its existence, receiving a thin deposit of the beds of that period, which have since been nearly all removed, though just enough traces of them are left to render it certain that they once extended over it in a sheet which is locally very thin. At some epoch subsequent to that of the latest deposition a fault occurred, cutting along these Jurassic beds, throwing up the western side into a great "hog-back." By the subsequent denudation of the overlying Tertiaries the highly-inclined Jurassic beds are left projecting above them and also above the continuation of these Tertiaries on the eastern or thrown side of the fault. Thus they form a narrow belt between the interrupted Tertiary formations. The fault is directly in the prolongation of the Sevier fault, but the throw is reversed relatively to it. It is designated on the stereogram as the East Gunnison fault, and its northern continuation is found on the west side of San Pete Valley, extending nearly and perhaps quite to the base of Mount Nebo, though its details have not been examined in that vicinity. The sections across this *Jurassic Wedge*, as I have termed it, will be found in Mr. Howell's delineations (Plate 3), sections 1 to 13.

On the west side of the Sevier Valley runs another fault parallel to the foregoing and presenting similar and even homologous features, but with the throw on the opposite side. Both in linear and vertical extent the dimensions of this displacement (termed the West Gunnison fault) are less late Part 1

OLOGICAL SECTIONS

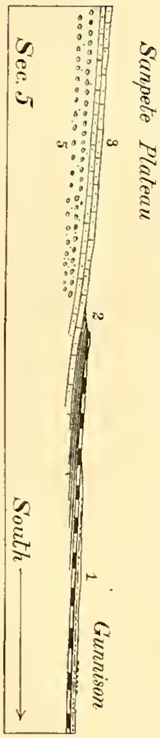
HE VICINITY OF

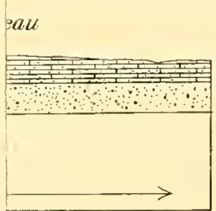
AND SALINA, UTAH

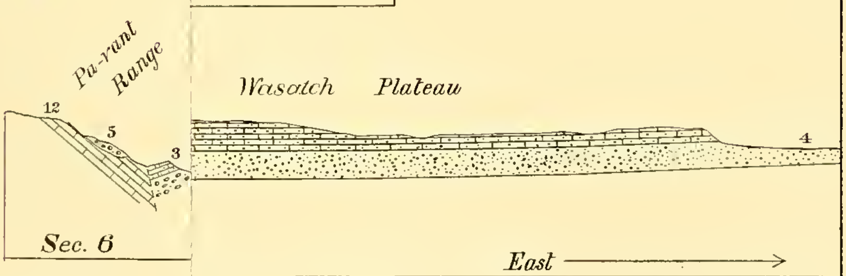
BY

VIN E. HOWELL.

umbered in order from north to south
d that points in the same longitude
tical line. Their geographic
on a map included in part 2 of this plate.
section is the level of the sea.
ertical scales are the same.







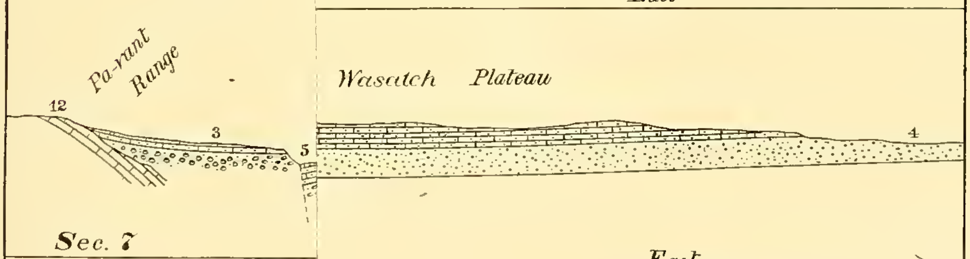


Plate Part 1

GENERAL GEOLOGICAL SECTIONS IN THE VICINITY OF GUNNISON AND SALINA, UTAH

BY

EDWIN E. HOWELL.

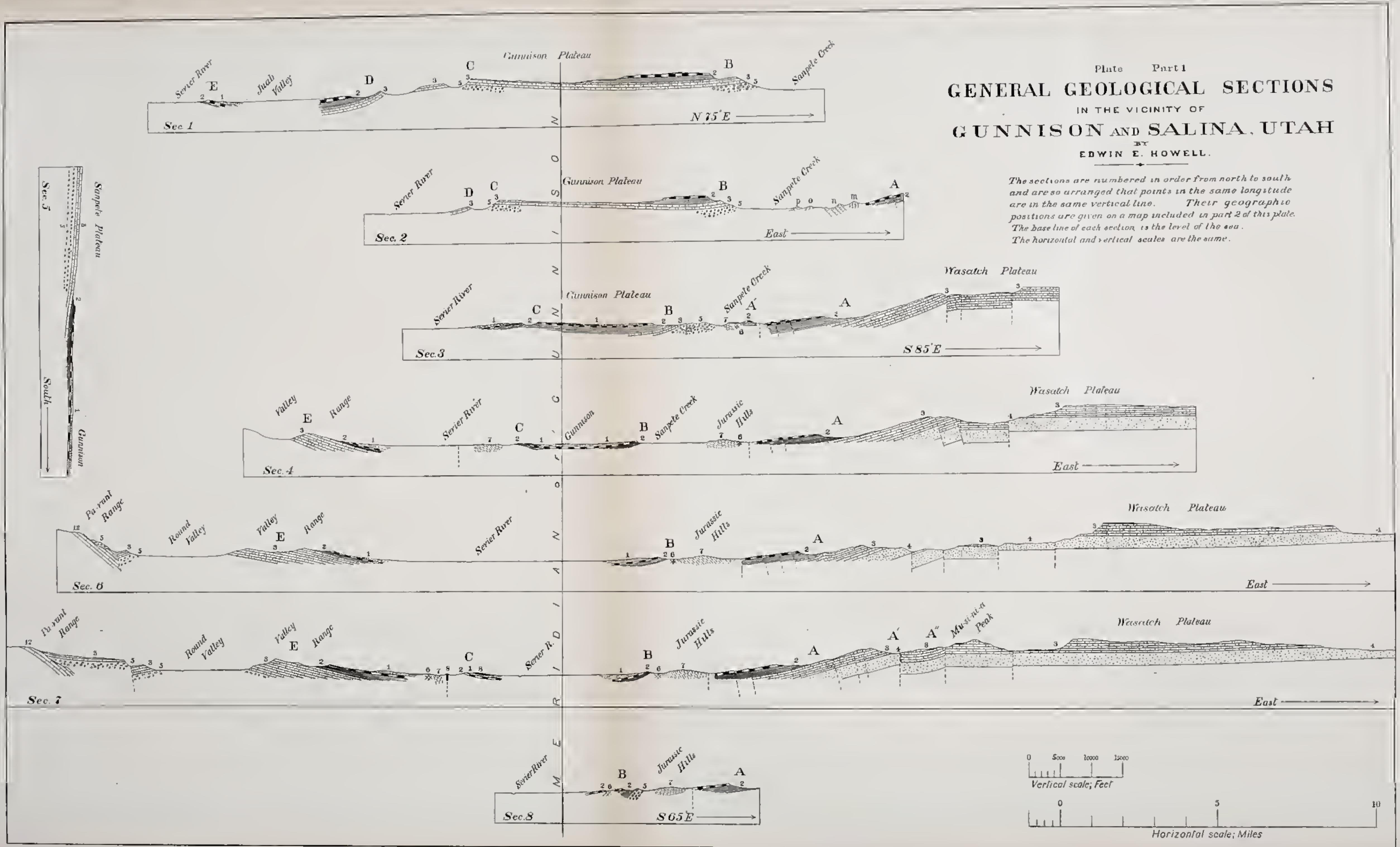
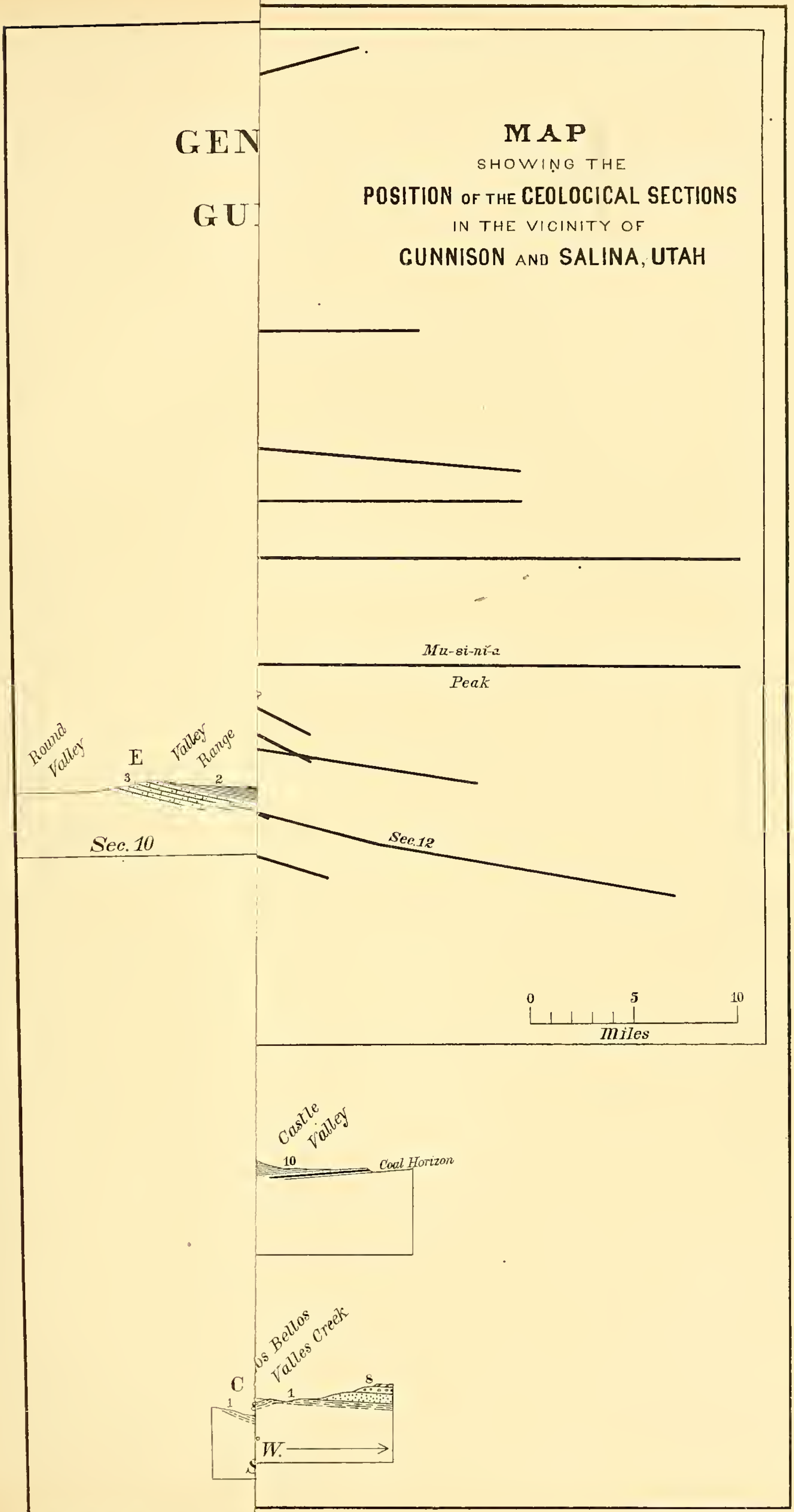
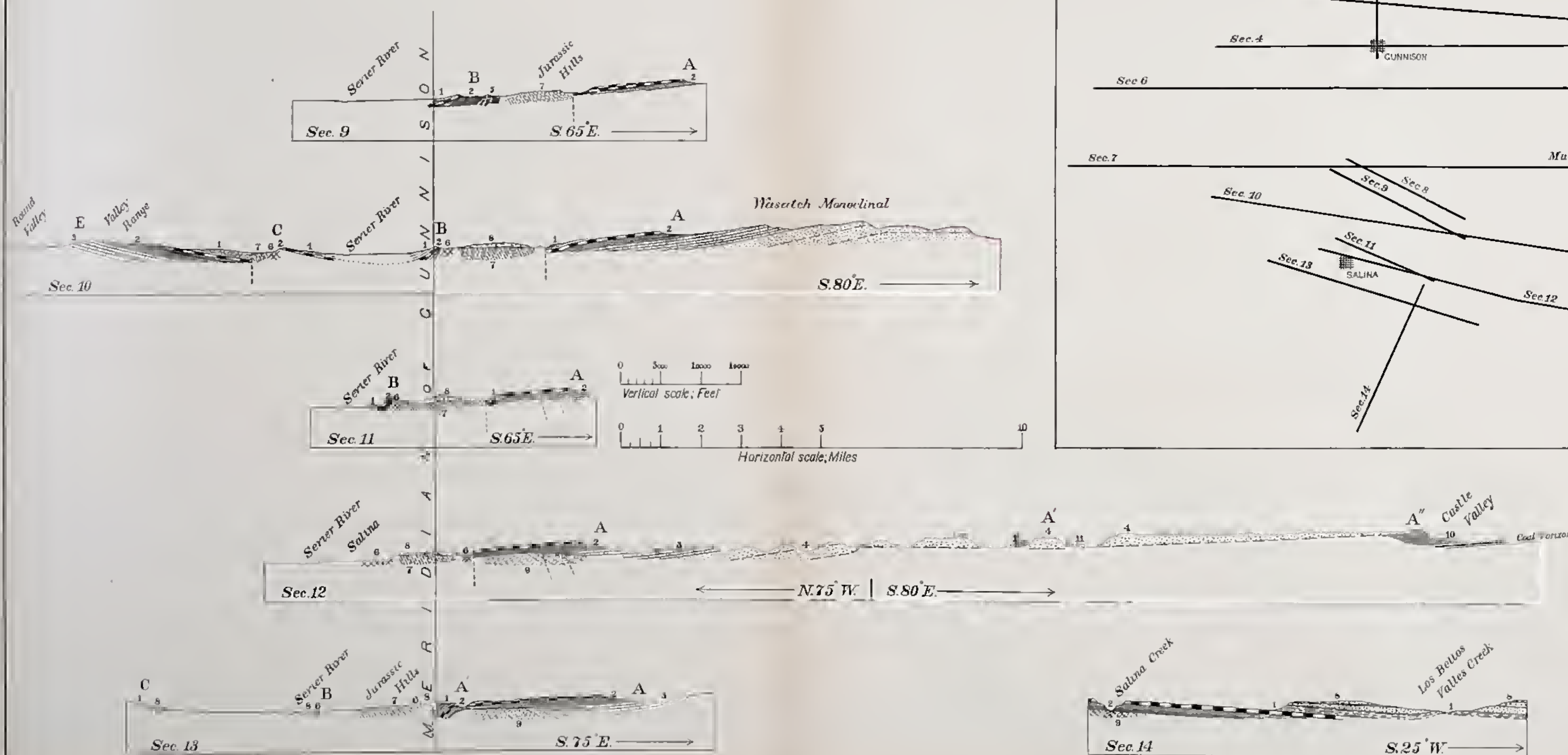
The sections are numbered in order from north to south and are so arranged that points in the same longitude are in the same vertical line. Their geographic positions are given on a map included in part 2 of this plate. The base line of each section is the level of the sea. The horizontal and vertical scales are the same.


GEN
GU
MAP
SHOWING THE
POSITION OF THE GEOLOGICAL SECTIONS
IN THE VICINITY OF
GUNNISON AND SALINA, UTAH
Mu-si-ni-a
Peak
Round Valley
E
Valley Range
3
2
Sec. 10
Sec.12
0
5
10
Miles
Castle Valley
10
Coal Horizon
os Bellos
Valles Creek
C
1
1
8
W.

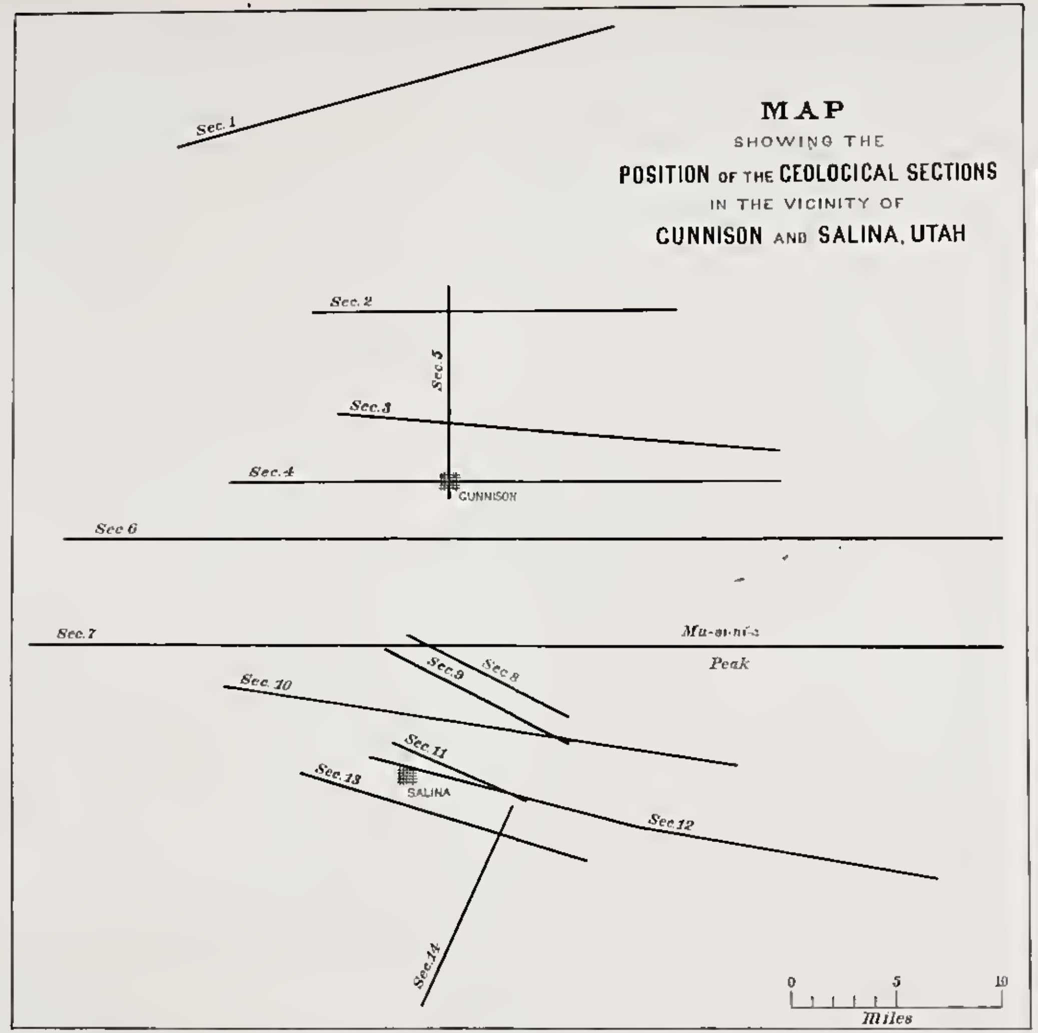
Plate Part 2

GENERAL GEOLOGICAL SECTIONS
IN THE VICINITY OF
GUNNISON AND SALINA, UTAH

BY
EDWIN E. HOWELL.

The sections are numbered in order from north to south, and are so arranged that points in the same longitude are in the same vertical line.
The base line of each section is the level of the sea.
The horizontal and vertical scales are the same.





than those of the East Gunnison fault. Its position and relations are shown in the stereogram and in the sections above referred to.

Between the East and West Gunnison faults is an uplift, qualifiedly tabular in form, which may be called the San Pete Plateau. Its northern end is separated from the base of Mount Nebo only by a cañon, which emerges near the town of Nephi. Eastward it looks down upon San Pete Valley, westward upon Juab Valley, which may be regarded as the northern continuation of Sevier Valley. Southward the plateau slopes slowly as far as the town of Gunnison, where it becomes the floor of the Sevier Valley. Its altitude is insufficient to warrant its admission as a member of the group of High Plateaus. Its general form may be illustrated as follows: If from a point situated about six miles south of Gunnison we travel north 30° east, our course would lead us up into San Pete Valley; if we travel north 30° west, it would lead us down the Juab Valley; if we travel due north, we shall ascend the easy slope of the plateau to its summit at its northern end. Its transverse structure is shown in the sections. Plate 3; sections 1, 2, and 3.

SEDIMENTARY BEDS COMPOSING THE WASATCH PLATEAU.

The Wasatch Plateau consists of beds of Upper Cretaceous and early Tertiary age, the latter being correlated, as well as any lacustrine beds of the Rocky Mountain region can be, with the Lower Eocene. In the lowlands immediately adjoining are found, on the east the Lower Cretaceous, and on the west a singular occurrence of the Upper Jurassic. There is found also in the Sevier and San Pete Valleys, and in the low uplift between them, a series of strata of later age than the Tertiaries of the plateau, though from many considerations it appears that their age is with great probability early Tertiary and immediately subsequent to that of the strata upon which they rest. They are believed to be local deposits only, and to have accumulated here and there after the commencement of the general disturbance and uplifting which resulted in the drainage of the great Eocene lake.

The principal Tertiary series is provisionally divided into two; the lower can be referred with confidence to the same horizons as those occupied by the beds which Powell has called Bitter Creek, lying upon the southern slopes of the Uinta Mountains. This determination does not rest upon identical fossils, for the two localities do not yield the same species; but upon the most decisive of all evidence, the known continuity of the beds. Between the Bitter Creek beds of the Uintas and those here assigned to the same epoch is an unbroken exposure along which the identity can be traced. The fossils found are *Viviparus trochiformis* (White), *Hydrobia Utahensis* (White), several undetermined species of *Physa*, *Planorbis*, and *Limnæa*, and some plant remains. The total thickness of this series is about 2,200 feet, but varies a little in different sections. The following section was measured by Mr. E. E. Howell at the southwest angle of the plateau, and very well represents the general character of the whole formation.

	Feet.
(*a*) Shaly limestone, containing *Physa*, *Limnæa*, and *Planorbis*	250
(*b*) Gray and cream-colored limestone with *Physa*	400
(*c*) Pale pink arenaceous limestone	250
(*d*) Gray limestone, shaly and green at base, with *Hydrobia*, *Physa*, and *Viviparus*	350
(*e*) Cream-colored calcareous sandstone	350
(*f*) Gray limestone with *Viviparus*	600
	2,200

This series has been designated No. 3 in the various sections, and though it has not been connected with the Lower Tertiary beds in the southernmost of the High Plateaus its identity is probable in a high degree, so much so that it is taken for granted. The beds which overlie it are separated by a distinct plane of demarkation in the principal sections and by lithological characters. They are much more variable in their constitution and in their bedding. Its members are designated as series No. 2, and the following sections by Mr. Howell illustrate their characters:

Series No. 2 (Tertiary), section No. 7 A:	Feet.
(*a*) Cream to gray shaly limestone, with fishes, *Planorbis*, *Viviparus*, and indistinct plant remains	350
(*b*) Greenish calcareous shale	750
(*c*) Pale red, purple, and slate-colored marls, with occasional bands of calcareosu gray sandstone, fish-scales being found in some of the more calcareous members	400
	1,500

Series No. 2 (Tertiary), section No. 7 B:	Feet.
(*a*) Cream and gray limestone, containing a few fish-scales; bed of chert at top..	300
(*b*) Greenish calcareous shale	300
(*c*) Pale red marly shale	300
	900

These beds are assigned provisionally to the Lower Green River epoch. Unlike the series below them, they cannot be directly connected with the strata lying at the base of the Uintas, nor are their fossils a satisfactory guide to a decisive correlation, though the presence of fishes resembling those of the Green River beds might be regarded as indicating such a relation. They have not, however, been identified as belonging to the same species as those of the latter formations. The beds in question are found only in the Sevier and San Pete Valleys, in the uplift between them, and extending a short distance up the great monoclinal flanking the west side of the Wasatch Plateau. That they formerly extended over that plateau, and for an indefinite distance eastward, is very probable. In this portion of Utah they are the last lingering remnants of a series which was nearly and in many large areas quite the last to be deposited and the first to be attacked by the general process of degradation which has swept away such vast masses of strata. From the snmmit of the Wasatch Plateau this whole group of beds has been eroded and about 300 feet of the Bitter Creek beds immediately beneath, and this amount of denudation is probably the minimum of the whole Southern Plateau Province, except where the sedimentary beds have been protected by volcanic rock or have enjoyed uninterrupted protection in gravel-covered valleys between great uplifts.

The uppermost series of Tertiary beds has been alluded to as consisting probably of a series of local deposits accumulated after the general upward movement of the whole Plateau Province had commenced, though it seems probable that this movement was then in its earlier stages. The beds contain fossils very similar and perhaps in some cases identical with the species of *Planorbis Physa Helix* (?), and *Viviparus*, which are found in the series upon which they rest. Lithologically they are much more variable. Some of them are conglomerates, which are apparently of alluvial origin, and none of them are found to be continuous over a large area.

They all lie near the ancient shore line of the great Eocene lake, and cases of unconformity, not only with the underlying series, but among themselves, are not uncommon. Their physical characters are, in general, indicative of an epoch of gradual displacement in the several tracts which they occupy. It would be obviously extremely difficult to correlate such a group with any such formations as those which are found on both flanks of the Uintas, forming the comparatively regular and systematic strata of the Upper Green River series, though general considerations may warrant a provisional reference of these local deposits to that period.

The unconformities just spoken of are probably in some cases apparent rather than real. It is easy to see that while deposits are accumulating along the slope of a flexure which is in process of formation, the two going on *pari passu*, there may result a want of parallelism in successive layers as well as other irregularities which produce collectively the appearance of unconformity. This differs, however, from that type of real unconformity which is usually relied upon as proof of an interval of time between contiguous formations in which the record is interrupted by a blank of unknown duration. Where the exposures are satisfactory the apparent and real occurrences may be distinguished, but in a majority of cases the distinction is not easy to find.

The thickness of the formation is highly variable, ranging from 300 to 750 feet. It consists of alternating marls and sandstones, the latter being sometimes coarse-grained, with here and there a patch of conglomerate.

CHAPTER VIII.

THE TUSHAR.

Sevier Valley from Gunnison southward.—The Pávant.—Salina.—Grandeur of the plateau fronts.—The northern end of the Tushar.—General structure of the northern part of the range.—Its intermediate character between the plateau and basin types.—Rugged and mountainous aspect of the higher parts.—Mounts Belknap and Baldy.—Eastern front.—Bullion Cañon.—The Tushar fault.—Rhyolites and their numerous varieties.—Basalt upon the summit.—Succession of eruptions and the intermissions.—Southern portion of the Tushar.—The great conglomerate.—Progressive growth of the range.—Alternations of volcanic activity and reposo.—Southern termination of the Tushar.—Midget's Crest.—Dog Valley.—Succession of eruptions in the southern part of the range.—General history of the Tushar.

The road leading southward from Gunnison up the valley of the Sevier River lies along a smooth plain between the Pávant Range on the west and the great monoclinal on the east. The interval separating these uplifts is about 30 miles from summit to summit and about 8 miles from base to base (see Plate 3, sections 4 to 13). To the east and northeast from Gunnison is seen the Wasatch Plateau, just distant enough to afford a fine view of its grand proportions. Its southwestern angle is decorated with a huge butte perched upon a lofty pedestal and crowned with a flat, ashlar-like block, which is a conspicuous land-mark from every lofty point to the southward. This mass is called Musinia, and at once arrests the attention by its peculiar form, whether seen from far or near. Southward, at a distance of nearly 30 miles, loom up the high volcanic plateaus. The Fish Lake and northern portion of the Sevier tables present their transverse profiles towards us, and are seen to be separated by a depression called Grass Valley. Far to the south-southwest is seen a portion of the Tushar, the main mass being hidden by a very obtuse salient of the Pávant. The absence of Alpine forms and the predominance of the long and slightly-inclined profiles of the plateau type rob these great masses of their grandeur and beauty; for they produce an optical deception which carries the horizon up near their summits, while in reality it is far below. Yet some sense of the reality is awakened when from the plain below, in the torrid heat of July, we see the fields of lingering snow light up their gloomy crests. To the westward rises the Pávant, its eastern flank ascending with a smooth swell to a crest line which looks down into Round Valley; and beyond that rise to still greater altitudes the mildly sierra-like summits of the range. The broad valley of the Sevier is treeless, and supports but scantily even the desert-loving Artemisia. It is floored with fine loam, which, under the scorching sun, is like ashes, except where the fields are made to yield their crops of grain by irrigation. As we ascend the valley to the southward the scenery is impressive, for every object is molded upon a grand scale; though it is only by long study and familiarity that the huge proportions are realized. The absence of details, the smoothness of crests and profiles, at first deceive the eye and always tend to belittle the component masses. A stretch of 10 miles from Gunnison throws to the westward the salient of the Pávant and reveals the southward extension of the valley for 35 miles, beyond which rise the summits of the Tushar in full view. Right opposite this point the Pávant has now changed its aspect to one contrasting strongly with the view we had of it from Gunnison. There we saw a dull, monotonous slope; here we behold a splendid array of cliffs, showing the edges of Tertiary strata gently sloping towards us, carved and broken after the usual fashion of the Plateau Country, and lit up with flaring colors—red, white, and yellow. The individual cliffs and crags are neither very high nor very long, but rise above each other terrace-like, after the manner of a rambling series of fortifications, with tier upon tier and with numberless salients and curtain walls. To one viewing plateau scenery for the first time this portion of the Pávant would be a source of surprise and enthusiasm; to one familiar with the colossal walls in the heart of the Plateau Province it is tame and almost insignificant.

Fourteen miles south of Gunnison is the little Mormon village Salina, a wretched hamlet, whose inhabitants earn a scanty subsistence by lixiviating salt from the red clay which underlies the Tertiary beds in the vicinity. Around and beyond this village is a dismal array of bad lands of great extent, presenting a striking picture of desolation and the wreck of strata, while beyond and above them rise the northern volcanic sheets of the

Sevier Plateau. The lava, the desolation, and the salt strongly suggest recollections of Sodom and Gomorrah. At this point Salina Creek emerges from its cañon through the great monoclinal—a fine, large stream. To the south-southwest the valley of the Sevier becomes considerably narrower and the Pávant lower, but the slope of that range gives place to an abrupt wall, due to a fault. A few miles south of Salina commences the great Sevier Plateau on the east side of the valley, its northern end gradually and steadily sloping upwards as we proceed south and its western wall becoming more and more abrupt, until it becomes a cliff of grand dimensions. From the town of Richfield, 18 miles south of Salina, we may behold it in all its grandeur, rising 5,800 feet above the plain below; its upper third a sheer precipice, the lower two-thirds plunging down in steep buttresses which thrust their bases beneath the level floor. Its aspect is dark and gloomy from the dark gray dolerites and trachytes which make up its whole mass Right at our backs are the lively tints of the Tertiaries in the Pávant; beds of pink, carmine, and cream, alternating with almost pure white, and with a rigorously even stratification. A stronger contrast it is difficult to imagine. Yet a mile or two beyond Richfield these rainbow beds suddenly give place to a black rhyolite,* which has spread from some unknown vent and covered the Tertiaries.

Moving still southwards along the flank of the Pávant, which slowly but steadily diminishes in altitude, we reach its junction with the Tushar about 16 miles southwest of Richfield. Here a lateral valley from the west joins the Sevier Valley, the upward continuation of the latter being due south between the towering heights of the Sevier Plateau on the east and the Tushar on the west. The separation of the Pávant from the Tushar is merely a low divide or saddle, or, if the idea is more acceptable, the former may be regarded as the northern continuation of the latter at a lower altitude. The lateral valley, as we ascend, narrows rapidly to a mere cañon, and from is southern brink rise the great spurs of the Tushar.

The northern portion of this uplift is crowned by volcanic peaks,

* This is a somewhat exceptional rock; very little feldspar, much free quartz, and the vesicular specimens have the elongated, wiry, and fluctuated vesicles which are eminently characteristic of rhyolite. The black color, almost equal to that of basalt, is apparently due to the presence of an unusual quantity of magnetite.

which reach higher altitudes than any other summits in Utah excepting a few in the Uintas. There are three points which reach above 12,000 feet, viz: Delano, 12,160 feet; Belknap, 12,080 feet, and Baldy, 12,000 (?) feet. There is nothing in the aspect of this portion of the Tushar mass to suggest to the eye a plateau structure; on the contrary, the appearance is in a high degree sierra-like, and it is quite possible that this portion of it should be regarded as belonging rather to the basin than to the plateau type of uplift. But so far as the structure depends upon vertical displacement, it is much obscured by the enormous series of volcanic floods which have been poured over it by numberless eruptions. Frequent indications, however, are seen of a general and moderate dip of the whole series to the west, leading to a presumption that the whole Tushar mass has a tilt in that direction. But while the exposures are numerous, there are no extended ones among them. The process of erosion has here wrought out a sculpture differing utterly from that presented by the sedimentaries, and one calculated to conceal the frame-work of the mountains instead of laying it bare. The degradation has here been very great; greater certainly than in some of the other volcanic plateaus. Instead of great cliffs, we find only slopes covered with *débris* and soil, with here and there a projecting ledge, which is soon lost beneath a talus. The best exposures are seen along the eastern front, facing the Sevier Valley, and in the deep gorges opening into it and heading far back in the heart of the range. These all concur in indicating a general slope of the beds to the westward, which is strongest near the eastern flank and smaller in the central portions and western flank. The northern portion is also deeply scored with grand ravines, well calculated to kindle the enthusiasm of the mountaineer and task his energy. The exposures which they contain, so far as they have been examined, accord with those in the eastern gorges in presenting a westward inclination. It is quite possible that many faults complicating the structure have escaped detection, but it is not probable that any subordinate displacements yet to be discovered will seriously impair the conclusion adopted regarding the general structure.

But while the plan of the entire uplift seems to be most nearly allied to the plateau type, it is equally apparent that there is a strong tendency toward the basin type. The latter may be represented by conceiving the strata forming the platform of a given tract to be rent by a long fault, and upon one side of it to be lifted and tilted at a considerable angle. This inclined mass is usually further fractured by smaller faults rudely parallel to the principal one, and complicated by more or less warping. The plateaus also are usually tilted, the Aquarius and Kaibab being most nearly horizontal. But there is a marked difference between the two types in the amount of inclination. In the plateaus it seldom exceeds three degrees; in the basin it is rarely less than ten. In the plateaus the warping and minor displacements are seldom important, and the whole aspect is calm and even; in the basin they are extensive, and the aspect is wild and distorted. In the plateaus, the obvious characteristic features are the broad platforms of the tables, the gently sloping terraces and the majestic repose of the mighty cliffs which bound them; in the basin, they are the sharp ridges, cusp-like teeth, and tumultuous slopes of sierras. Probably the correct view to be drawn from a comparison of the two structures is that the basin type represents an advanced stage of an action which has been imperfectly developed in the plateaus. Had the tables been pushed up higher, they might have been as much inclined as the sierras and as much comminuted and distorted.

The Tushar is in some portions at least, and so far as observed in most portions, more inclined than any other of the High Plateaus, but so far as can now be discerned it approaches more nearly to the tabular than to the sierra type. Lying within the geographical limits of the Great Basin, it is not surprising that it should show an approach to the structure of the latter province. It may be regarded as indicating a transition between the two forms, though more nearly allied to those peculiar to the Plateau Province.

It is difficult, however, to realize this conclusion as being a true one when we stand upon the southern termination of the Pávant, and look at the cluster of peaks which crown the summit of the Tushar. Two noble cones ending in sharp cusps stand pre-eminent, while behind them numerous dome-like masses rise to nearly the same altitudes. The two peaks are Belknap and Baldy, which reach above the timber-line, and are very striking on account of the light cream-color of their steep slopes and the ashy-gray tips of the apices. These pyramids are not apparently the remains of craters, but mere remnants of the uppermost sheets, which have been almost wholly removed by erosion. From their bases radiate profound gorges separated by huge buttresses, which extend to the lowest valleys and plains, while beyond them rough crags and shattered domes rear their bald summits to the clouds. But all this grand detail of mountain form has been carved out of the vast block of the tabular mass by the ordinary process of erosion. The lavas accumulated sheet upon sheet, the subterranean forces uplifted the block and tilted it, and the rains and torrents have done the rest.

The eastern front of the Tushar is far more rugged and mountainous than the western, and the explanation is obvious. The western slope is along the dip of the strata, which, though considerable near the crest, is slight as we recede from it westward. The eastern slope is across the upturned edges, and from the nature of the case is very abrupt. The power of water to corrade and carve rapidly increases with the slope, and the resultant sculptural forms are correspondingly bold and craggy.

The loftiest, boldest, and most diversified portion of the Tushar fronts the Sevier Valley in the vicinity of a little hamlet called Marysvale, situated about 27 miles south of Richfield. The great mountain wall leaps at once from the narrow platform of the valley to nearly its greatest altitude. Immense ravines, rivaling those of the Wasatch in depth, but narrower and with steeper sides, have deeply cleft the great tabular mass, and subdivided it into huge pediments, which from below appear like individual mountains. The finest gorge is named Bullion Cañon, in the jaws of which the little village of Marysvale is situated. Ascending it, we may gain some information concerning the structure of this portion of the Tushar mass. The lowest beds forming the base courses of the uplift are quartzites resulting from the metamorphism of sedimentary strata, which are believed to be of Jurassic age. They are considerably disturbed, yet not excessively so. The prevailing dip is to the west, though it is by no means uniform. The main fault, which has thrown down the platform of the Sevier Valley, runs north and south along the base of the mountains, but the whole displacement is probably by a series of parallel repetitive faults. I have seen but one of the faults west of the principal displacement, but have inferred their existence by the recurrence of beds, which seem to be identical both individually and serially, at higher and higher levels up the cañon.

As we ascend Bullion Cañon from Marysvale we observe on either side a hard quartzitic rock well bedded in massive layers, exhibiting considerable metamorphism. It is also somewhat variable in the dip. The strata incline upward at first, but soon flex easily back until the dip is westward. The thickness of the series seems to be very considerable, though the apparent thickness may be partly due to repetitive faults of small shear. At a distance of about 3 miles from Marysvale and 2,600 feet above that village, we come upon the volcanic series. A mass of dark-colored liparite rests upon the quartzite, having a thickness of about 450 feet. About 500 feet higher the quartzite reappears, being probably the same bed as below, but thrown up by a minor displacement, and it is covered by the same or a similar sheet of liparite. The quartzite, however, is more altered than the portion of it below, and in general as we ascend from Marysvale through the quartzitic beds the signs of increasing alteration are unmistakable. From this point upwards eruptive rocks alone are seen. The lower masses are dark liparites, with abundant quartz and monoclinic feldspar and decomposed hornblende. Still higher rocks of a porphyritic texture and a dark purplish hue lie in great volume. They have a striking resemblance superficially to the argilloid trachytes of the central and eastern plateaus, but contain abundant quartz, and the microscope confirms their rhyolitic character. These two groups of eruptions are separated by local conglomerates derived from the older of them, and the surface of the latter is seen to have been much eroded, indicating a considerable interval of time between the periods of activity. The summit of the series consists of a group of rhyolites (proper rhyolite), which contrast strongly with those beneath. They are very light colored, without crystals, and yet not hyaline. They are highly siliceous, and exhibit in the thin sections a fibrolitic or spherolitic groundmass of beautiful texture and very interesting. Some of the specimens are exceedingly siliceous, and are resolved under the microscope into an aggregation resembling very fine-grained quartzite and appear to be quite abnormal. The light-colored masses are generally true rhyolites of no uncommon kind. This rock forms the lofty peaks crowning the northern summit of the Tushar mass, and occurs in several outlying knobs and small crests to the east and northeast of Belknap. But the northwestern slope of the range has been mantled by great floods of it, which have poured in massive sheets from summit to base, burying the antecedent topography of the mountain and generating a new one. The individual eruptions making up this rhyolitic mass appear to have been numerous, some very voluminous, others very small. The smaller ones are seen to fill up old ravines and to mold themselves upon uneven preexisting surfaces, while the grander floods pour over everything and spread out over great expanses of mountain side. Although this lava is, with the exception of a few minor basaltic streams around the western base of the Tushar, the most recent of all the outbreaks, yet absolutely it is of considerable antiquity. Since the extinction of the vents from which it was emitted there has been a long period of erosion. Belknap and Baldy, together with the eastern outliers, are mere remnants of piled-up sheets, which were perhaps once continuous, but are now separated by profound ravines, which have been excavated by erosion.

The indications are abundant that the period separating the earliest from the latest eruptions was a very long one. The contact of the earliest liparites with the Jurassic quartzites shows heavy floods of lava pouring over a very uneven surface and piled up in layers by successive eruptions to a thickness of more than 2,000 feet. These, in their turn, show a subsequent degradation by erosion not only in the sculpturing and carving of the beds, producing an unconformity in some of the contacts, but also in the existence of local conglomerates composed of the water-worn fragments of the dilapidated rocks cemented by finer detritus derived from the decomposition of the feldspathic materials.

These earlier eruptions appear to have been followed by a long period of calm, during which they were attacked by the degrading force and slowly wasted by decay. In many places the beds were cut through down to the quartzite and a fresh topography was carved out by erosion. Afterwards the activity was reopened with fresh eruptions of a different character. These second eruptions were grander than the first, some of the beds being many hundreds of feet in thickness, spreading over great areas, and

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VOLCANIC CONGLOMERATE. THE TUSHAR.

extending far to the westward, expanding as they extend. Of this rock, a dark purplish porphyritic rhyolite, the great central mass of the Tushar is composed.

The second period of activity was followed by another interval of repose. During this interval the greater part of the uplifting of the range took place. The faults traverse and dislocate both the first and the second series of eruptions. It was also a period of great erosion, during which the turmoil of mountain peaks, domes, and spurs were carved on the eastern flank, and that side of the range devastated in a striking manner by the slow ravage of time. The third epoch of eruption was the least of all and most local, being confined to the portion around Belknap and Baldy, and furnishing the cream-colored rhyolite and a few small outbreaks of basalt.

The southern portion of the Tushar contrasts with the northern portion in many respects. It exhibits a totally different group of eruptive rocks. In the northern part the extravasated rocks are rhyolites; in the southern part they are trachytes, augitic andesites, dolerites, and basalts. The form of the southern part of the uplift is distinctly tabular or plateau-like, while the northern part has the sierra aspect.

About 3 miles south of Belknap, standing upon the brink of an old *coulée*, we look southward over a broad expanse of comparative calm lying at a slightly lower level. In this expanse the tabular form of the Tushar mass is no longer doubtful. A lofty plain diversified by ridges of erosion is spread out before the gaze, clad with spruce and aspen and opening in grassy parks. The abundant streams have carved gently-sloping ravines and pleasant knolls, where the dark lavas may occasionally be detected dipping very gently to the west, but near the eastern rim rising more boldly to the timber line (11,500 to 12,000 feet), where they are suddenly cut off and present their truncated edges to the eastward in the boldest of mountain slopes. This part of the plateau summit is about 22 miles in length, 8 to 10 miles in width, and the mean altitude about 10,000 feet. Erosion has given to this lofty watershed a surface very similar to that which may be observed in any well-watered country, and which is in strong contrast with the peculiar forms observable at lower levels where the precipitation is much smaller

The eastern front of the Tushar preserves that rugged mountainous aspect already described throughout two-thirds of its extent. The southern third is a wall of imposing grandeur, presenting to the eye the effect of a perpendicular escarpment, though really it is inclined at a slope of 60° or more. It is a magnificent object as seen from Circle Valley, rising nearly 2,000 feet above its base, and its base standing at the summit of a long slope which rises 2,000 feet above the valley bottom. This great cliff is a conglomerate composed of the ruins of older volcanic rocks. It is stratified, but not so conspicuously as most of the similar formations so abundant throughout the district. The finer material which incloses the rocky fragments is a light-gray pulverulent detritus, evidently resulting from the decomposition of feldspathic materials and highly aluminous. Some of the members of this series of heavy beds consist chiefly of this finer material, holding comparatively few fragments; in others the fragments are much more abundant, constituting the greater part of the mass. The fragments are usually somewhat rounded at the edges, but in most cases the amount of attrition is small, though seldom wholly unrecognizable. The mode of origin of this and similar conglomerates will be discussed in detail in a subsequent chapter. It is a sub-aërial formation throughout, and the mode of accumulation may be seen and studied hard by in all the valleys of the district. (See Heliotype II.)

These beds are of ancient origin, having been formed prior to the great displacements which have given the Tushar its present structural features. The inclosed fragments are wholly variable in character. None of the rhyolitic, trachytic, and basaltic rocks of later age are seen among them, and the inference is irresistible that its formation was completed before these last-named masses were erupted. The source of these materials seems to have been the adjoining mass of the present Tushar table to the northward. To realize how this may have been we are obliged to go back in time to the later Eocene or early Miocene, when, in all probability, these great outbreaks occurred, and endeavor to reconstruct the country. At that time the centers or *loci* of eruption were doubtless in the very heart of the range, and stood considerably higher than the adjoining part of the country, just as they do now, though more recent movements on a grand scale have produced new features by uplifting the range *en masse.* But as these recent movements apply to the whole uplift, the relative altitudes of the loftier portion, which furnished the *débris*, and the less lofty portion, which has received it, have not been much, if at all, changed with respect to each other. But erosion has apparently effected what displacement has not; it has nearly equalized the levels of the two portions. The volcanic masses near the *foci* must have been very voluminous, for the conglomerates derived from them extend with great thickness over a large area, rivaling in bulk, if indeed they do not surpass, the enormous masses yet remaining. Wherever we find strata composed of clastic materials, the present methods of reasoning in geological science compel us to acknowledge that they have been derived from the degradation of masses of even greater magnitude.* In the case of a great sub-aerial conglomerate, formed under conditions which are still existing and a process still operating, we naturally look to the vicinity or border of the conglomerate itself for the source of the materials. We find a very obvious source to the northward. The structure of the great uplift of which the conglomerate forms a part and large masses of eruptive strata *in situ*, composed of materials agreeing with those found in the clastic beds, confirm this view so strongly, that there seems no room for question. But the mass of the conglomerate argues an enormous degradation. To supply so vast an accumulation the older eruptive area in the central part of the Tushar must have been piled thousands of feet high with successive sheets no longer visible, or have been the theater of eruptions separated by long intervals of erosion, which in the long run removed the lavas as fast as they were erupted. A view which is a compromise between these two I regard as decidedly preferable, and most fully sustained by the general tenor of the evidence throughout the entire district. We may look back to a period somewhat earlier than Middle Tertiary, when the volcanic eruptions built up Ætna-like highlands of eruptive materials, not by rapidly succeeding outpours, but by alternating emission and quiescence. Between the outbreaks many years or centuries may have elapsed, but the accumulation was much more rapid for a time than

*Except in cases where pulverulent and fragmentary materials have been ejected and scattered, which is not the case in the present instance.

degradation, and the altitudes of the eruptive centers increased. Now and then came a long interval of repose, indicated by the quiet accumulation of considerable, though very local, masses of stratified conglomerate here and there. Again the energy was renewed and fresh outbreaks occurred, followed by a long rest. After a protracted series of alternating eruptions and unequal intervals of rest there came a very long period of repose to be reckoned by a geological standard of time, during which these massive conglomerates accumulated and the huge volcanic piles were razeed—a period in which there may have been eruptions, but in which, on the whole, the ceaseless erosion leveled down the highlands and leveled up the lowlands.

But the building of the conglomerate beds did not close the volcanic cycle. After they had acquired their enormous bulk there came another period of outbreaks, some of them in the old localities, others in new ones, pouring fresh sheets over the wasted centers and over their scattered and stratified *débris*, piling up fresh mountains of lava and generating a new topography. This second series of eruptions differed strikingly in lithological character from the first. The earliest series in the Tushar, so far as known, is andesitic and trachytic; the second is rhyolitic and basaltic. In the northern part of the range the dominant rock of the second series is rhyolite, with a limited occurrence of basalt. In the southern part of the range the relative abundance of the two groups is reversed, rhyolite being uncommon, and in most areas being replaced by true trachyte. These beds cover both the central part of the Tushar and the conglomerates at the southern end. They lie upon the eroded surface, filling old ravines and spread out in broad sheets over the tabular summit, obliterating upon the surface the definition between the conglomerate and the degraded mass which furnished its materials, though the junction is exposed in the eastern front of the range by the great fault which at a later epoch was formed by the general uplifting of the whole mass.

The southern termination of the Tushar is marked by a group of lofty summits a few hundred feet lower than Belknap at the northern end and Delano near the center, but full 1,600 feet higher than the wall and tabular summit which connects them with the central part of the table. They are superposed masses of volcanic beds resting upon the great conglomerate. Here the faulted wall of the range swings around to the southwestward and rapidly dies out. (See stereogram.)

The lofty crest at the southern end of the Tushar has been named Midget's Crest, and it presents to the southeast three bold salients, standing about 5,600 feet above Circle Valley, which lies at the base of its great spurs east-northeast. Its absolute altitude is about 11,600 feet. It is a volcanic mass, built by the accumulation of andesitic, trachytic, and basaltic sheets. The three salients are from 1,400 to 1,600 feet higher than the summit of the conglomerate cliff to the north of them and their superior eminence is due to this accumulation of lavas. The conglomerate passes beneath them though its outcrop is masked by the talus.

The sheets which compose Midget's Crest belong to a later period than those which occupy the central part of the Tushar range, and which were broken down to form the great conglomerate. *Coulées* of the same period are found north of this crest, upon the summit of the tabular part of the Tushar, where they are mainly trachytic. Upon the extreme summit of the southern crest lies a true basalt, highly vesicular upon its surface, and the first impression is that it is a comparatively recent eruption—Post-Pliocene or Quaternary—the rocks on which it rests being certainly very much older. It is of small expanse and thickness and is abruptly cut off at the crest-line of the ridge. Its origin cannot easily be conjectured. There are no indications of a vent in the vicinity and, notwithstanding the freshness of its appearance, it may be as old as early Pliocene. But the beds on which it lies are less doubtful. They face southeastwardly, forming the salients already mentioned, and have been wasted greatly by the general degradation. When the period of dislocation and uplifting set, in they extended as far to southeast as the principal fault which runs around this angle of the plateau with a throw of about 3,500 to 4,000 feet, and the entire mass between the crest-line and the fault has been denuded to a corresponding depth. The origin of the lavas I believe to have been to the southeast and east of the ridge in the vicinity of the faults, where evidences of great contortion and considerable chaos are still visible, and where rocks apparently identical with those upon the summit of the table and near the summit of the crest are still discernible, though now they lie at least 3,000 feet below them.

Immediately south of Midget's Crest lies Dog Valley—a pleasant moderately diversified platform—with an absolute altitude of about 7,500 feet or 1,500 feet above the Sevier at Circle Valley. It is a part of the last-mentioned focus of eruptions of the second or middle epoch, but erosion has leveled down most of the ancient irregularities, and left it a field of rolling hills, well covered with soil, loam, and sharp gravels. Its real history might not have been suspected, were it not for the vast floods of lava which spread out from it in all directions for many miles, growing thinner and broader as they recede.

Southwest of Midget's Crest the altitude of the plateau gradually diminishes until its summit at last is lost in the next region. The fault which originated the escarpment of the plateau suddenly becomes a monoclinal which dies out in the space of about 6 miles. This monoclinal is composed of conglomerate of unknown thickness, but not less than 1,500 feet in the vicinity of the flexure. It turns up at an angle of 28° to 30° against the diminishing wall of the plateau, but soon straightens out towards the south and decreases rapidly in thickness. It is composed of basaltic (doleritic) materials chiefly, quite similar to, and perhaps identical in part with, the remnants of that kind of rock forming the extreme summits of the salients on Midget's Crest.

The western base of the Tushar I have seen in part only, and have given that part merely a cursory examination. It is possible that there exists a fault of about 1,200 feet along this base with a throw to the west; a continuation of the Hurricane fault, which appears in great force about 15 miles south of the southwest slope of the Tushar. But I have not verified the existence of such a fault in this locality, and such an occurrence may not be necessary to explain the features presented, so far as observed. The summit of the table, after maintaining for about 10 miles an easy slope to the west, suddenly increases the descent of the profile to the broad plain below. The surface contour here cuts across the ends of the lava sheets, which are seen to be considerably attenuated when compared with the huge masses exposed upon the upturned eastern flank of the range.

Whether the somewhat abrupt western boundary is due to the faulting suggested above or to the termination of the old *coulées* it is not possible to say with confidence, but the former view seems to furnish the easiest explanation.

At the western base of the Tushar, near the town of Beaver, is seen a very recent basaltic crater in a very perfect state of preservation. Farther northward are others, some of them so recent that we may easily suppose that their eruptive activity has ceased within a few hundred years. Many of the basaltic craters throughout the Plateau Country seem to be equally recent, though many others have considerable antiquity. On the whole, however, the true basalts are the most recent of all eruptions. They are seldom found in the heart of the older eruptions—indeed, I am able to recall but few such instances—but they occur around the outskirts of older volcanic districts, and often at a considerable distance from them. In respect to magnitude of eruptive mass, the basalts are here decidedly inferior to every other class of rocks.

THE BUILDING OF THE TUSHAR.

To go back to the commencement of the series of events and processes which have combined to rear this majestic range to its present altitude and proportions and give it its present details is no easy task. But while there is much room for conjecture, there are many facts which appear, after careful analysis, and which are sufficient, when properly arranged, to give a connected history, even though it be but a faint outline.

It is necessary to find, in the first place, some initial epoch marking the beginning of the train of events which have been directly concerned in the construction of the range, and this is the same epoch which forms the starting-point probably of the processes which have built all of the High Plateaus. This is the close of the Upper Green River epoch. The direct evidence that the Tushar had its birth-throes at this period is not so clear as in the others, but the cumulative indirect evidence is very strong and will become apparent as the discussion proceeds. It may be sufficient to remark just here that this view harmonizes with all known facts and all observations, and is in conflict with none.

The Tushar stands upon the course of the western shore line of the great Eocene lake. This shore line may be traced, with a very close approach to exactitude, from the southern base of Nebo across Juab Valley to the Pávant, and through that range longitudinally as far as the northern flank of the Tushar. For the whole series of lacustrine beds may be seen abutting sharply against the disturbed beds of Carboniferous and early Mesozoic age along this line, excepting where their junction is concealed for a short distance by the alluvia of the Juab Valley. Through a portion of its extent this fragment of the coast was rockbound; for in the Pávant, at least, plicated and contorted Carboniferous rocks still overlook the Tertiary beds, with every indication that this relation has remained unaltered throughout Tertiary time, though general movements of displacement involving the entire range have otherwise modified its topography. Like all rockbound coasts it had its sinuosities—here an estuary, there a peninsula; here a bight, there an outward swing of the shore. This coast line strikes the Tushar near its northwestern angle and is instantly lost beneath floods of rhyolite. Nothing is seen of it until nearly 50 miles south-southwest it is revealed in the Iron Mountains by Tertiary beds cut off against the Trias. If we suppose a straight line joining the broken ends to represent the mean position of the coast line, the whole of the Tushar would stand within the Eocene lake; but this supposition is not tenable. On the eastern flank of the range, near Marysvale, and thence southward for 10 miles, we find the base of it to be composed of metamorphosed quartzites, upon which a few patches of limestone rest, holding *Pentacrinus asteriscus*, a highly characteristic Jurassic fossil, and upon this quartzite and limestone immediately rest the lavas. No trace of a Tertiary or even Cretaceous stratified rock is to be seen. The uneven eroded surface of these beds, with hills and valleys and rocky eminences, was thus sealed up at the very epoch of which we speak and broken open at an epoch long subsequent by the shearing of a great fault and by the cutting of ravines, thus revealing in a manner which cannot be mistaken the existence of a land area. It lies at least 15 miles to the eastward of the straight line joining the broken ends of the lake coast. Either, then, we have a peninsula or an island in the lake to mark the nucleus of the future Tushar. The Tertiaries are seen lapping around both the northern and southern extremities of the range, and it is probable that they are concealed not far from its eastern base.

Such was the relation of the area to its surroundings when the earliest eruptions (so far as they have been observed) took place. They broke forth at first along the course of the present eastern front, a little east of the main divide as it now stands, and along a line nearly 30 miles in length, having a general trend north and south. They were not continuous along this line, but were massed in at least three places: one near the northern end of the Tushar, one (and this the principal one) near the central part of the front, and the other near the southern end, but a few miles southeast of it. The location of this latter center of eruption cannot be fixed at present with exactitude, and may have been more remote than I was at first led to suppose. The interval between the southern and middle sources is greater than that between the middle and northern, and it is not certain that this second or northern interval was well marked, though the southern interval is very distinctly so. What other vents existed, or even whether any others existed at all, it is not now possible to determine, on account of subsequent accumulations which have buried the surrounding country. This period of eruptive activity was certainly a long one; for between the outbreaks erosion went on, leaving traces of its action in the eroded surfaces of its sheets and in the many small local conglomerates formed out of their decay. But the accumulation by successive outpours was far more rapid than the waste, until there came a long period during which these vents were sealed up and degradation proceeded. At the commencement of this period of repose the eruptive masses must have been piled up to a great altitude and covered an extensive area, for the conglomerates which were formed by their dilapidation are of immense extent and thickness and sufficient in mass to build a goodly range of mountains. The southern interval was almost wholly filled up by the fragments washed into it and stratified, and the conglomerate thus formed stretches far to the southwest, always maintaining a great thickness. At least 2,000 feet of it occupy the southern interval, and it is still many hundreds of feet thick 8 or 10 miles away.

In many respects the relations of the eruptive masses to the country they occupied at the close of the earliest volcanic period presents a very strong analogy to those of Central France, as described by Sir G. Poulett Scrope in his work upon that region.* In point of magnitude the earliest eruptions of the Tushar were probably comparable to those of the Cantal, covering perhaps a larger area but with a greater thickness.

After a long period of comparative quiet, during which the greater portion of the mass of these earlier eruptions was broken up by erosion and scattered over the adjoining lowlands and intervening valleys, came the second period of eruption, upon a scale grander than the first. The *foci* of activity were in close proximity to those of the first period. The outpours at the northern portion still remain in great bulk and are chiefly rhyolitic. But the grandest floods of all are in the center of the range, where they are laid open by several deep gorges, the largest of which is Bullion Cañon. The course of the streams was here to the westward chiefly, where they widened out and grew thin as they receded from their origin. The total thickness remaining of these rhyolitic masses probably exceeds 2,000 feet, and there is good evidence that a considerable amount has been lost by erosion. What floods may be hidden beneath the floor of the Sevier Valley at the eastern base it is impossible to say or even to conjecture. Thus for the second time the Tushar was built up by extravasated materials and to an altitude greater probably than at first.

A second period of comparative calm now followed, during which erosion was at work cutting deep gorges, carving out pediments, and leaving a rugged series of peaks and domes along the eastern flank. But another agency in mountain structure also intervened. This was an extensive vertical movement of the whole mass. At what precise epoch the faults which now separate it from the platform of the Sevier Valley were started it is impossible to say with precision. It is clear, however, that the commencement of the displacement was subsequent to the deposition of the great conglomerates which were formed by the destruction of the older Tushar, and it is almost certain that the displacements had not attained any great magnitude or a magnitude comparable to the present during the second eruptive period. The principal part of the uplifting has apparently

* The Geology and Extinct Volcanoes of Central France, by G. Poulett Scrope, 1858.

been accomplished since the close of this second activity, though some of the movement may, in the absence of evidence to the contrary, be assigned to this period.

The second period of cessation in the eruptions was broken at a comparatively late epoch by a third outbreak at the northern end and at several localities on the eastern flank in the vicinity of the faults. To this third eruptive period belong the whitish rhyolite and the basalts, together with several masses in the Sevier Valley which have emanated from the foot of the range, and which will be discussed when we reach in regular order the description of that valley.

The history of the Tushar, therefore, comprises five tolerably distinct periods since the commencement of the various activities which have brought it to its present stage.

1st. An older eruptive epoch, building up an ancient volcanic mass.

2d. A period of decay, in which the mass thus built was nearly leveled down, and its fragments scattered far and wide and reconstructed in the form of conglomerates and alluvial beds.

3d. A second eruptive period, more extensive than the first, rebuilding the dilapidated mass.

4th. A second cessation of eruptions and the introduction and progress of extensive uplifting and faulting, accompanied by considerable erosion.

5th. A third series of minor outbreaks of much smaller extent than either of the others, some of which (around the bases of the range) are very recent.

In this history we perceive the combination of most of the important forces and agencies of geology: eruption, displacement, erosion, and accumulation; all performing their parts in the general work, and yielding an intelligible result in the erection of a grand uplift.

CHAPTER IX.

THE MARKÁGUNT PLATEAU.

Description of its general features and relations.—Dog Valley.—One of the principal eruptive centers of trachytic masses.—Characters of the lavas.—Basaltic eruptions and conglomerates.—Bear Valley.—Little Creek Peak and Bear Peak.—Tufaceous beds.—Overlying lavas.—Degradation of the plateau.—View from the summit of Little Creek Peak.—Journey over the Markágunt.—Succession of eruptions, andesites, trachytes, rhyolites, basalts.—Central group of ancient basaltic cones.—Their dilapidated condition.—Panquitch Lake.—Exposures of contact between the lavas and sedimentaries.—Modern basaltic outpours.—Other basaltic fields.—Relative recency of the basalts.—Surface changes since the eruptions.—Connection of the Markágunt basalts with those of more southern regions.—Sedimentary formations of the Western and Southern Markágunt.—Tufaceous deposits.—Pink Cliff beds.—Correlation of local Tertiaries with those of the Wasatch Plateau.—The Cretaceous.—Jurassic and Triassic formations.—The Shinárump.—The Southern Cliffs of the Markágunt.—Outlook to the far southward.

The Markágunt Plateau lies southwest of the Tushar. From the southern salient of Midget's Crest a considerable portion of its expanse may be seen, though the view is not a very good one. In truth there is nowhere to be obtained a good panoramic overlook of the Markágunt, for there is no stand-point sufficiently lofty. The observer on this summit, standing more than a mile above the neighboring lowlands, will find it difficult to realize that the most distant verge visible along the southwestern horizon has an altitude about equal to his own. With the exception of two respectable masses shooting up in the middle-ground of the picture, there are no peaks nor strongly individualized summits; nothing, in fact, to suggest mountains. It is a broad expanse of rolling hills and ridges, rarely exceeding 600 feet in altitude. The whole platform has a slight dip to the eastward; being, however, not an inclined plane, but dish-shaped. The eastern base of the plateau lies at the foot of the southern Sevier Plateau, being the thrown side of the great Sevier fault. From this line it rises by a very slow ascent, not exceeding $2\frac{1}{2}°$, westward to its summit. The character of the gradients will be understood by a reference to the stereogram. (Atlas sheet, No. 5.) The general relations of this plateau to the country at large may be comprised in the statement that it is an excellent illustration of what Powell has called the Kaibab structure. The length from north to south cannot be definitely given until we can fix its northern boundary, which, if done at all, must be done arbitrarily, for it fades out so gradually that no real demarkation exists. The same may be said of its eastern boundary. But assuming the plateau to extend northward to the base of the Tushar and eastward to the Sevier Plateau, the length would be about 50 miles and the breadth about 28 miles.

The greater part of this area is covered with ancient eruptions resting upon Tertiary lacustrine beds. Around the southern and western sides of the plateau the sedimentary strata project several miles beyond the volcanic sheets and end abruptly in giant cliffs, facing the south and west, and deeply scored by erosion. The western wall of the plateau is formed by the northward prolongation of the Hurricane fault, while the southern wall consists of cliffs of erosion without any known dislocation of great magnitude. These southern cliffs are the lingering remnants of Tertiary and Cretaceous beds, which once extended over the entire region to the southward beyond the Colorado, but have throughout Tertiary time receded by waste to their present boundary.

The detailed description will begin at the northern portion. At the foot of the lofty summits which crown the southern end of the Tushar lies Dog Valley, inclosed south and west by rolling and somewhat rugged volcanic hills and by remnants of a great volcanic conglomerate. Similar hills are found to the eastward, and the whole tract is a center or focus of eruptions of the trachytic epoch. The cones and craters which may once have existed are no longer visible, having been wasted to a medley of hills by a period of decay which stretches far back towards middle Tertiary time. Soil and gravel, with a rich growth of wild grass and shrubbery, now mantle these degraded remnants, giving them a rather pleasant and gentle aspect. Yet the outcrops of volcanic sheets around the borders and away from the valley betray its history in spite of the effort of nature to hide it. East, west, and south the old floods are seen to radiate away for many miles from this center, spreading out and growing thinner as they were poured along over the ancient inequalities of the land. They also flowed northward in great volume, but since their eruption the eastern Tushar fault, swinging westwardly, has uplifted full 3,000 feet the extension of the sheets in that direction. The lavas which flowed eastward are all trachytic, but represent two groups of trachytic rock, one being highly hornblendic, the other being almost pure feldspar and granitoid in appearance, with a very few small but well-defined crystals of biotite. The hornblendic variety is exhibited in much greater quantity than the other, is very coarse-grained in texture, and lies in masses of great thickness. In several places single floods are seen between 300 and 400 feet thick, as if erupted in a highly viscous state, and appearing to have moved with great slowness and much internal resistance. This appearance is not only common, but is highly characteristic of the most typical trachytes, and gives rise to the exceeding coarseness and roughness which the etymology of the name implies.

Upon the western side of Dog Valley many masses of coarse dolerites and some basalts are found. Being among the latest outbreaks of the locality, they have suffered most from erosion, and their *débris* are widely distributed in the form of conglomerates over the surrounding regions. These conglomerates are well stratified, and when the exposures are viewed at a distance great enough to render the rocky fragments no longer distinguishable, they reveal a lamination quite as conspicuous as a succession of sedimentary strata. These conglomerates lie in the heaviest masses in the northwestern portion of the valley, and turn up against the southern end of the Tushar at an angle of 22°, showing a thickness exceeding 1,500 feet, without exposing its entire extent. No individual mass of conglomerate has been observed to extend over any large area, but they seem rather to have filled up depressions They increase and diminish rapidly in thickness, and obviously represent many local accumulations, which are not continuous among themselves. This arrangement is to be expected upon the theory that their origin is alluvial, a theory which (if it needs any special support) will appear to be abundantly sustained when we come to the examination of their formation at the present time in the larger valleys of the district.

The elevation of this valley above that of the Sevier on the east is about 1,400 feet. It cannot be regarded as a part of the Markágunt, but occupies an intermediate position between that plateau and the Tushar. It is interesting chiefly as being the locality from which emanated a large portion of the lavas of the trachytic eruptive epoch. Probably it was the scene of eruptions of the first epoch also, though the lavas which it may have there poured forth are deeply buried beneath the great extravasated masses of the second period, and are revealed only in the fragments of andesite which are seen in the older conglomerates and by the lower beds at the base of the Tushar, which are brought up to daylight by the fault at its base.

Crossing the southern rim of Dog Valley we descend into another valley of a little lower altitude, called Bear Valley. The divide between the two consists of a low range of hills, which are the degraded remnants of old volcanic piles which were once, no doubt, of imposing magnitude, giving vent to the huge sheets of lava which diverge from them, but are now reduced to mere hills and discrete masses of dolerite and basalt. Reaching the bottom of Bear Valley, we find a smooth, park-like inclosure of ample dimensions, with high hills of trachyte on the east and the brilliant rosy red of the Eocene (Bitter Creek) on the west. It has already been stated that the Markágunt has a fringe or border of sedimentary rocks upon its western and southern sides, and this border is from 2 to 6 miles in width. In other words, the volcanic beds which cover its central and eastern portions do not extend to the western and southern margins of the uplift. Bear Valley lies at the foot of a broken crest which is formed by the sudden termination of these eruptive masses. This boundary is a very irregular one, having westward projections and eastward recesses. But it is necessary to keep in mind one important relation. The vents stood near this western margin. The main flow of the erupted materials was towards the east, in which direction they extended probably as far as the Sevier Plateau, or until they are lost beneath more recent sub-aërial accumulations. Towards the west their progress was arrested by the rising slope of the country, and they do not appear to have extended more than a very few miles in that direction. Then, as now, the face of the country sloped downward from west to east, though the gradient was considerably smaller than at present. A few large eruptions, however, reach out westward, producing the sinuous course of the boundary which marks their termination. One of these westerly projecting masses separates Bear Valley into two portions, connected by a narrow gorge cut through it by erosion.

Overlooking Upper Bear Valley from the eastward stand two conspicuous mountain masses called Bear Peak and Little Creek Peak, of which the respective elevations are 9,870 and 10,040 feet. Although of moderate altitudes, they present, in consequence of their isolation, a very commanding appearance and attract the attention from every point of view in the surrounding country. They are also interesting on account of their structure and the masses which constitute their bulk. The beds which lie at their foundations merit some description.

Wherever we examine the contact of the volcanics with the sedimentary beds along the western verge of the eruptive rocks of the Markágunt, we usually find a series of strata composed of finely comminnted volcanic materials. Sometimes it is a fine sandstone; sometimes an argillaceous rock with minute fragments of feldspar and mica; sometimes a calcareous or marly deposit. Often rolled and rounded fragments of notable size are included, and the beds have then a coarse or gravelly texture, the grains being fragments of some eruptive mass so much decomposed that it is difficult to determine its exact variety. These beds are always well stratified and have clearly been deposited by water, and do not differ from ordinary sedimentary beds, except in the fact that the materials which make up their mass have been derived from eruptive rocks. The individual beds are usually of small snperficial extent and small thickness, and are often seen running out with "feather-edges." They always overlie the systematic lacustrine Tertiaries of early Eocene age. Similar formations are found at the northern and southern extremities of the Sevier Plateau and in the East Fork Cañon, where they have been more or less metamorphosed. They are exhibited on the west side of Bear Valley and again along the base of the great trachytic wall of the Markágunt in considerable variety. Wherever found they seem to constitute a group by themselves of more recent age than the uppermost Tertiaries of the Wasatch

Plateau and Lower Sevier Valley. As these last-mentioned formations have been inferred provisionally to be of Green River age, the beds of volcanic sand, &c., may form an upward continuation of the same group, or may even be considerably more recent, though many circumstances seem to indicate that they were deposited in immediate succession to the definite Green River beds without any protracted interval to separate them. Their significance is purely local. They indicate that the eruptive activity had commenced and had given vent to large masses of lava before the extravasation of the older volcanic masses now remaining, and that these most ancient ejections had been wasted and either utterly swept away or buried where they have not up to the present time been laid bare. These beds are seen in considerable mass on both sides of Upper Bear Valley, and on the southeast side they constitute the lower courses of the two mountains which tower above it and the long curtain wall which connects them. Resting upon them is a sheet of lava of very interesting character. It is identical in constitution with a sheet exposed in East Fork Cañon, and which will be described in detail in the chapter on the Sevier Plateau. Upon this lava rests a layer of coarse rhyolite, which is evidently much more recent in age, and forms the summit wall of the west side of Upper Bear Valley. This layer is not seen on the eastern side, but in place of it numerous trachytic beds are found alternating with conglomerate.

At the bases of the two mountains these same beds of volcanic sand are seen and the succession of trachytes and conglomerates. The upper masses of the mountains are mostly trachytic, though between the flows there is one prominent conglomeritic mass. The stratification is remarkably even throughout, considering the volcanic nature of the components, but it is not horizontal. In both mountains there is an east or east-southeast dip, and they present the general aspect of great buttes left by the denudation of the surrounding country, though the similitude is not exact. A portion of their eminence, however, is due to a fault of about 800 feet displacement which runs along their western bases, and the remainder of their relative altitude is probably due to the denudation of the general platform to the east of them and to the dip of the beds. These eruptions are all very ancient (Miocene?), and since their extravasation they have been uninterruptedly exposed to erosion, and it is by no means surprising that the average degradation should have been many hundreds or more than a thousand feet. There is no evidence that they are old cones piled up of eruptive matter around local vents, but are unmistakably carved out of a mass of interstratified lava sheets and bedded fragments, like great cameos, and their altitudes notably augmented by local uplifting.

The summit of Little Creek Peak gives a fine view of the surrounding country, though the altitude is insufficient to command the great expanse of the Markágunt to the southward, which is higher than the peak itself. But north and east the prospect is excellent. As soon as the firs and spruces are cleared the Tushar is in full view to the northward, the grand pyramids of Belknap and Baldy stand out in splendid relief against the horizon, and the inclined plateau, whose summit they crown, is seen in detail. It may be recalled that this plateau slopes to the west, while the Markágunt slopes to the east. The Hurricane fault bounds the western front of the Markágunt, while the Tushar has a great fault upon its eastern front. The two plateaus gradually merge into each other through the intervening area of Dog Valley. The shifting of the displacement from the west front of the Markágunt to the east side of the Tushar is an interesting structural feature and worthy of a careful study, for it is often repeated in the Basin ranges, and constitutes one of the most important modifications of that type of structure. We may for present purposes regard the Tushar and Markágunt as a single block, of which the length is nearly 80 miles and the width a little more than 20. The southern portion is tilted eastward (Markágunt) and the northern portion is tilted westward, while the intervening or middle part is warped and otherwise flexed. Now if this great block were a simple warped surface, the middle portion would be synclinal. In reality it is an anticlinal area. An anticlinal axis leaves the Hurricane fault at a very acute angle, and crosses the block obliquely to the commencement of the Tushar fault. These structural features may be discerned distinctly from the summit of Little Creek Peak.

Looking westward from the same point we behold in the foreground a scene eminently characteristic of the western border of the Markágunt.

It is a valley of erosion carved into the plateau by a plexus of streams. The proportions are grand, and the abrupt slopes which wall it about on every side are very impressive. It is a vast Coliseum, opening to the westward by a deep and narrow cañon leading to the floor of the Great Basin near Parowan. The walls west, south, and north are all Tertiary (Bitter Creek) and luminous with colors, which are all the more conspicuous from contrast with the dark trachytic beds which overlook them from the eastern side. Several great valleys of similar aspect and excavated in the same manner occur elsewhere in the sedimentary belt which borders the western portion of the Markágunt. The plateau is there yielding slowly to the destroying agents, and the continuance of the process through indefinite time will at last destroy its eminence. It taxes the credulity to think that this work has been gradually accomplished by the feeble action now in progress; but the results here witnessed sink into insignificance when compared with those which are forced upon the conviction when we look upon the regions drained by the Colorado.

Eastward from the foot of the mountain the plateau slopes almost insensibly to the base of the Sevier Plateau, which rises against the eastern sky. The country is rough with hills and rocky valleys, though these inequalities upon so vast an expanse as the back of the Markágunt are as mere ripples or waves upon the bosom of a great lake. In this direction none but old volcanic rocks and conglomerates are visible. To the southward the view is not extensive. The plateau slowly increases in altitude in that direction until it becomes more lofty than the peak. So much of it as is visible presents a pleasant but rather monotonous appearance, with rolling hills and ridges, grassy slopes and scattered groves of pines.

A journey over this broad surface is a pleasure excursion, but not remarkably instructive to the geologist. The explorer will enjoy the luscious camps beneath the shade of century-old pines, beside sparkling streams of the purest water, and will see with pleasure the keen relish with which the animals devour the luxuriant wild grass. Nature is here in her gentle mood, neither wild nor inanimate, neither grand nor trivial, but genial, temperate, and mildly suggestive. A few cañons which it is a pleasure to cross; long grassy slopes which seem to ask to be climbed; hill tops giving charming pictures of shaded dells and sloping banks, with distant views of the Tushar and the mighty wall of the Sevier Plateau, combine to produce a medley of pleasant scenes and experiences which will always be looked back to with refreshment. As a field of geological study it is in great part meager. Now and then a bit of local curiosity is excited by a curious result of rain sculpture, by remains of small lake deposits, by the curious weathering of rocks, by some strange freak of the old lava flows, none of which will find places here. Broad facts are comparatively few.

Among the most noteworthy is the succession of eruptions. In the central part of the Markágunt the oldest eruptions observed were andesitic. These are displayed in a disconnected way in the deeper ravines of the central and northern portions, but are elsewhere so masked by subsequent floods that their extent and the circumstances of their extravasation are not fully intelligible. Whether they were generally distributed over the face of the plateau or represent a number of local eruptions it is not possible to say with certainty. Wherever deep cañons are found in the central part of the area they lay open great masses of dark andesitic lava, and areas are occasionally found where surface erosion has removed the later rocks and laid the andesite bare. In any event, whether generally or discontinuously distributed, the mass of this rock is very great. No propylitic eruptions have been observed in the Markágunt.

Next in order are found great masses of trachyte. Over the greater portion of the expanse of the Markágunt these are the surface rocks. In reality their volume may not exceed that of the andesites, which they usually cover, but being more frequently seen they appear to be the dominant rock, and I incline to the opinion that they are so. On the whole, the varieties of trachyte are less numerous in the Markágunt than in the more eastern plateaus of the district; but their number is still very great. The least common variety is the hornblendic; but the augitic trachytes are abundant, and the commonest of all is a highly porphyritic argilloid variety. The latter consists of a reddish or purplish fine base, resembling a rather rough argillite, holding crystals of white opaque orthoclase. One of its most persistent characteristics is its fracture, which is very peculiar. Most volcanic rocks, when broken, present a tolerably even or gently rounded though

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TUFA. MARKAGUNT PLATEAU.

rough surface; but this trachyte breaks with an exceedingly jagged, angular, and irregular fracture, so that it is impossible to hammer out a neat and shapely specimen. The grandest masses of trachyte, not only in the Markágunt but in the other plateaus, consist of this variety. It lies in immense beds, often two or three hundred feet in thickness, spreading out over many square miles with remarkable regularity and homogeneity. In the Markágunt it forms mesa-like platforms, ending in low precipices, where the shallow cañons and ravines have cut into it. It breaks up or rather crumbles with unusual facility for an eruptive rock, producing a coarse gravel, which floors the ravines below. This rock is so distinct in its characters that it seems almost to justify a separate name, but I shall content myself with a purely descriptive designation, and call it *argilloid trachyte.*

The augitic varieties of trachyte are found in sheets, which are usually much thinner and cover smaller areas, though the number of them is much greater. The total bulk is less than that of the argilloid variety, though absolutely it is very great.

The rhyolites are the third group of eruptives found in the Markágunt. They are seen in large masses along the very highest part of the plateau, from the crest of which they poured out in massive sheets. They are probably as ancient as the older liparitic masses of the Tushar, but always overlie the trachytes whenever they are in contact with them. They belong altogether to the liparitic sub-group, with an abundance of porphyritic crystals of feldspar and quartz. None of those hyaline fluent rhyolites which characterize the northern Tushar are seen here. Although their volume is very great, it is far less than that of the trachytes, and the areas which they cover are much smaller.

The fourth group is the basaltic. Among the High Plateaus the Markágunt and Tushar alone present extensive outpours of rocks of this class. A few small eruptions are found in the eastern plateaus and notably in the intervening valleys, but they are not comparable in extent to those of the Markágunt. Here they are confined to the southern half of the plateau. A little south of the center is a large tract in which are still preserved remnants of a considerable number of basaltic craters, though so much degraded that they are not immediately recognized. They form a large cluster of rolling hills, rarely exceeding 300 feet in altitude above the platform on which they stand, covered with soil mingled with decayed vesicular cinders. Their true nature is disclosed by the scoriaceous character of the fragments which constitute the greater portion of their mass. It will be remembered that basaltic craters, when well preserved, are rather symmetrical truncated cones, with conical or funnel-shaped depressions at the summit, and the entire mass is composed of vesicular fragments blown out by the escaping steam and gases and falling with approximate uniformity around the orifice. The spongy character of these fragments renders them an easy prey to the chemical forces of the atmosphere, and they are readily decomposed. After thousands of years of weathering these cones are literally dissolved, losing their lime, iron, and alkali, while the alumina and silica remain, and the cone gradually loses its form and is reduced to a shapeless heap of soil with commingled cinders in every stage of decay. Around the bases of these ancient cones we find half-revealed sheets of basaltic lava. Any eruption may be followed by the building of a cinder-cone, and most basaltic outbreaks are so supplemented (at least in this district); but it is not always so. A considerable number of the basaltic sheets have been disgorged where no trace of a cone remains, and some of these are so recent that the last thousand years may have witnessed the catastrophes.* It is notable that the most extensive outpours are most frequently without them. Among the basalts of the locality of which we are speaking are many cinder-cones in an advanced stage of decay. The floods of basalt which have emanated from them lie in many sheets, none of which individually present great thickness, but by superposition have built up this part of the plateau from 500 to 800 feet above the normal platform. They are for the most part concealed by their own ruins, but numerous ravines have been cut into them, showing in many places their edges and giving a general idea of their mass and distribution. They rest upon older trachytes and occasionally andesites which had been scored by ravines before the basaltic outbreaks, and in a number of places the uneven surfaces of contact are clearly revealed.

*I am speaking in general terms of the basalts. Those of the locality just spoken of are all probably older than the Quaternary.

A few miles southeast of this basaltic field is a picturesque lakelet, occupying a depression in the plateau, called the Panquitch Lake—a sheet of water about a mile and a half in length and a mile in width It is a delightful locality, both for the tourist and the geologist. Around it stand forests of pine (*P. ponderosa*), while farther up the slopes of the plateau are thickets of spruce and aspen. Broad and stately ravines, bearing sparkling streams from the higher levels open near its margin, and the traveler, weary of the desert wastes below, revels in the rank vegetation which clothes their rocky slopes. Through the brief summer the longest and richest grass carpets their floors and every knoll and sloping bank is a parterre of the gayest flowers.

Around this lake the volcanic strata are seen resting upon the sedimentaries; in short, it is a locality where the eruptive rocks have diminished in thickness, and they gradually disappear southward and southeastward. To the west and southwest they continue still in immense bulk, with greater variety and stronger contrasts than in the northern part of the plateau. Here the oldest eruptives are trachytic. They are finely displayed upon the northern side of the lake, where they form low cliffs or steep slopes, and an abrupt cañon entering from the northwest still more clearly lays them open to view. As we approach the lake from the northeast (the usual route), the instant we reach the summit of the hill from which we first see the expanse of its surface, a most conspicuous object upon the south side of the lake immediately attracts the attention. It is a flood of basalt so recent and so fresh in its aspect that we wonder why there is no record or tradition of its eruption. It is dense black, and its ominous shade is rendered still more conspicuous by the lively colors of the sedimentary rocks and soil around it. We see at first only the end of a grand *coulée*, but beyond it rise rough, angry knolls and mountainous waves as black as midnight, telling of more beyond. Riding to the base of it, we find it to be composed of numberless fragments, ranging in size from a cubic foot to many cubic yards, piled up in strange confusion. A continuous bed or sheet is nowhere to be seen; nothing but this coarse rubble, looking like an exaggerated pile of anthracite dumped from the cars at the terminus of a great coal railway. A close inspection confirms this impression of recency given by the first view. The surfaces of the fragments are not affected by weathering to any notable extent, and it is only by comparison with surfaces fractured by the hammer that we can find an assurance of an exceedingly slight impairment of its original freshness. No doubt this is largely due to the fact that this portion of the mass is not in the slightest degree vesicular. In other parts of the *coulée* highly vesicular fragments were encountered; but where I first approached it every stone was as compact as a dike. But even the vesicular specimens show so little weathering, that it is hard to believe that this eruption is as old as the discovery of America. Such appearances, however, may be very deceptive. I am not aware that there is any authentic record of a volcanic eruption within the present limits of the United States, though it is quite possible that a number of them have occurred since the conquest of Mexico by Cortez. In this region it may have easily escaped the chronicles of the Spanish priests, even if such a dire event had occurred only a hundred years ago, and two hundred years would have destroyed all reliable tradition of it among the Indians.* This basalt came from a vent situated about 3 miles southwest of Panquitch Lake, and from the same source flowed a considerable number of large streams all presenting the same appearance of recency. An attempt was made to reach the crater, but the climbing over the rough angular blocks piled up in the worst conceivable confusion proved to be so perilous, that after several misadventures it was abandoned. From surrounding eminences several overlooks were obtained, from which it was inferred that there are several vents clustered near each other, and from three of them at least there have been a number of eruptions. Nothing like a cinder-cone, however, was distinguishable. The lavas appear to have reached the surface and overflowed like water from a spring, spreading out immediately and deluging a broad surface around the orifice, and sending off into surrounding valleys and ravines deep rivers of molten rock. One flood rolled northeast towards Panquitch Lake, but came to rest before reaching it. A second flowed eastward down a broad ravine situated about 3 miles from the lake. The largest streams went to the southeast into

* There is said to be a tradition among the Mohave Indians that their ancestors were driven out of Central Arizona by volcanic eruptions, and though very recent basalts are found there, many circumstances combine to oppose such a tradition even if there be one.

the tributary ravines of Mammoth Creek (the main fork of the Sevier River), and reach a point about 6 miles from their origin.

Besides this field of very recent basalt, remains of much more ancient basalt are found in the vicinity and in much larger amount. In truth, the basaltic eruptions go back to a period sufficiently remote to have permitted important changes in the configuration of the country to take place in the interval separating the present from the earliest eruptions of this class. During that interval a considerable number of outbreaks, separated by many centuries (probably hundreds of centuries), have occurred. Basalt fields of different ages are readily distinguished. Among the oldest, probably, are the first basalts spoken of in this chapter. Of an antiquity which may be quite as great are two large masses, lying respectively southeast and southwest of Panquitch Lake. The southwest field is much eroded, and consists of a tabular mountainous mass immediately overlooking the very recent basalt field just spoken of. The edges of the sheets composing this tabular mass project in bold cliffs around its flat summit in the same manner as is frequently seen in lower regions, where buttes of sedimentary rocks owe their origin and preservation to a protecting mantle of lava. On all sides it is girt about by a talus of blocks, which have fallen by the sapping of the foundations of the mass through untold ages. Since this lava was disgorged broad valleys and deep ravines have been scored in the platform of the Markágunt, and the minor details of topography arising from the general process of surface sculpture have been carved out, and an older topography has been swept away or so completely remodeled that it cannot now be reconstructed.

Southeast of the lake a wide expanse of country has been covered with ancient basalt, but only remnants are now left, covering mesas and buttes of sedimentary rocks and overlying fields of still older trachytes and volcanic conglomerates. Ravines of considerable magnitude and broad valleys have been cut into the country which they once covered, and these excavations have in several instances given passage to more recent floods of basalt, some of which extend as far east as the Sevier River. These later basalt fields are in an excellent state of preservation, but soil has accumulated upon them, and the face of the rocks shows deep weathering.

The different stages of the decay are readily discerned, and it is easy to see that the various basaltic eruptions, though they may, in a certain geological sense, be considered as belonging to one epoch, and that a very recent one, have occurred at intervals which, measured by a historical standard of time, have been very long. The lithological characters also vary to some extent; the more ancient floods being less heavily charged with magnitite, and on the whole less basic and a little lighter-colored, also less finely textured, than the most recent ones, and of a little lower specific gravity.

Finally, the largest basalt field of all and, with the exception of that one nearest to Panquitch Lake the most recent, is found near the southwest margin of the plateau, covering about 25 square miles, with a considerable number of cones, from which a large number of eruptions have issued. This field I have had no opportunity to examine in detail, and it is not easily accessible on account of the exceedingly rough character of its surface. Much of it is clothed with dense forests of spruce, which alone render it almost impenetrable, and prevent the observer from obtaining a satisfactory view of it. Its mean altitude is more than 10,000 feet.

The basaltic eruptions of the Markágunt are a portion of a belt of such eruptions, which extends along the course of the Hurricane fault and the country adjacent to it far southward across the Colorado River into Arizona. Eruptive rocks older than basalt within this belt are very few and of small magnitude. The volume and number of basaltic eruptions increase as we proceed southward, and reach a great development near the Grand Cañon, where more than a thousand square miles are covered with it and more than a hundred cones are still standing. South of the Colorado many large basalt fields are known to exist, but they have not been thoroughly studied. Throughout the Hurricane belt they occur in patches, often small, but frequently extensive. It is a notable fact that by far the greater portion of them occur upon the uplifted side of this great displacement; indeed those upon the thrown side are comparatively trivial. This fact seems to be generally true throughout the District of the High Plateaus and also throughout the country to the south of it. It is, moreover, so strongly emphasized, that it suggests the possibility of a correlation between these basaltic eruptions and the greater upward displacements.

On the other hand, an equally striking fact is the apparent independence of basaltic eruptions of the minor or local inequalities of a country. They have broken out, with seeming indifference, upon hill-tops and slopes, in valley bottoms, upon the brinks of great cliffs of erosion, upon buttes, and upon broad mesas. The only localities where I have not seen them are in cañons and at the bases of cliffs of erosion.*

SEDIMENTARY FORMATIONS OF THE MARKÁGUNT.

Around the western and southern borders of the Markágunt extends a broad belt of sedimentary formations almost wholly unencumbered with volcanic emanations. The volcanic cap ends always abruptly upon the highest part of the plateau several miles from the plateau limits, and usually presents to the westward a line of cliffs looking down into the great valleys and amphitheaters where the ravines and cañons of the sedimentary belt begin. The destroying agents have wrought terrible havoc in the strata, cutting chasms which have laid bare in grand sections the series of sedimentary strata from the Eocene to the base of the Trias inclusive.

The most recent deposits are those local accumulations first encountered in Bear Valley, consisting of the sands and marls derived from the decay of volcanic rocks. We seldom miss them from their proper place at the base of the volcanic cap, and they attain considerable thickness (200 to 350 feet) in numerous exposures along the western margin of the trachyte. From what rocks they were derived it is impossible to say; no lavas older than themselves have been detected. They rest everywhere upon the Eocene limestones, frequently shading downwards into sandstones undis-

* Perhaps I ought to qualify this assertion of seeming indifference to minor topographical features by saying that basaltic vents occur very often upon the brink of cliffs of erosion, and never (within my own observation) at the base of one; often upon the top of the wall of a cañon and never within the cañon itself, though the stream of lava often runs into the cañon. So numerous, indeed, are the instances of cones upon the verge of a cliff of erosion or cañon-wall, that I was at one time led to suspect that it was a favorite locality. This is very conspicuous in the large basaltic field near the Grand Cañon in the vicinity of Mount Trumbull, where 10 large cones stand upon the very brink of the great abyss and have sent their lavas down into it. Away from the cañon a considerable number of craters are seen upon the various cliffs near the Hurricane Ledge, and far to the northeastward half a dozen are found upon the crests of the White Cliffs. Out of rather more than 300 basaltic cones of this region, I have noted 33, or nearly 11 per cent., occupying such positions. Whether this is accidental it is difficult to say, but when it is remembered that they do not occur at the bases of such cliffs, nor in the cañons (so far as I have observed), the fact is certainly a remarkable one. In our present ignorance concerning the nature of the forces and chain of causation which lead up to and precipitate volcanic phenomena, it would be vain to speculate upon the reasons for this apparent preference of locality.

tinguishable in composition and texture from ordinary sediments derived from ordinary materials. Nor is their exact age assignable, since they have yielded no fossils, but the probabilities are great that they are not far from middle Eocene age.

Beneath them lies what is called the Pink Cliff series, which is known to be Lower Eocene.* At the base brackish-water fossils are found, which give place as we ascend to a fresh-water fauna. The upper members are limestones, which are usually more or less siliceous, and the silica increases in the lower members, where gravelly beds, layers of sandstone, and even conglomerate are found. The highly calcareous members strongly predominate. The coloring is always striking and vies in brilliancy with the Triassic beds. The highest member is frequently almost snow-white, with a band of strong orange-yellow beneath it. But the great mass of color is a pale rosy-pink. When the sun is low and sends his nearly level beams of reddish light against the towering fronts and mazes of buttresses, alcoves, and pinnacles, they seem to glow with a rare color, intensely rich and beautiful—flesh-of-watermelon color is the nearest hue I can suggest. Some of the beds do not naturally possess this color, but have been painted superficially by the wash from the beds above them, or possibly have taken on the color through exposure, while they are yellow within.

The identity of these beds with the Bitter Creek of the Wasatch Plateau and of the Uintas seems clear. The connection by actual continuity is, indeed, wanting, but the fossils, though few, are convincing, and the relations to the Cretaceous beneath are strictly homologous to those which prevail farther north. Some doubt arises whether the white limestone which caps the series should be referred to the Bitter Creek or to the Green River beds. Mr. Howell, whose opinions are of great weight, inclined to the latter view, and thought that one of the members of the Wasatch Plateau (No. 2), which I have referred to the Lower Green River period, was wanting, and that the white limestone should be correlated to those beds which I have referred doubtfully to the Upper Green River. It is true that two

*I use the term Eocene in its local sense. It may or may not be coëval with the European Eocene. Probably it is very nearly so.

or three species of fresh-water mollusca seem to sustain his view, but the fresh-water forms of the Plateau Province so frequently have a very great vertical range, that they are apt to mislead in just such cases, and require collateral evidence to justify such a conclusion. On the other hand, there is no indication in the appearance of the rocks of such a break of the continuity, and the whole of the Tertiary here exposed seems to belong to one series without unconformity and without any break in the conditions necessary to continuous deposition. It has, therefore, seemed to me unadvisable to intercalate a vacant horizon in a series which to all appearances is continuous.

The white limestone at the summit of the formation is a very conspicuous member and forms the surface of the plateau for a considerable distance south of Panquitch Lake, where it is laid open by ravines and exposed in buttes capped by basalt. It reaches a thickness of rather more than 300 feet in some places, but is usually much less. It is very impure; sometimes very siliceous, holding agate or chalcedony, and is also sometimes marly. The total thickness of the Eocene beds is from 1,100 to 1,200 feet.

The epoch of final emergence from the lacustrine condition seems to have been earlier here in the southwestern part of the Plateau Province than in the middle or northern portions. This is indicated by the earlier age of the most recent lacustrine beds; for as we proceed northward later and later members gradually make their appearance. In the south, not more than the lower third of the Eocene is present; in the middle district, barely more than one-half; while around the southern slopes of the Uintas nearly or perhaps quite the whole of it is revealed. It may be conjectured that the Lower Green River beds once existed here and were eroded and wholly removed before the volcanic eruptions began. This cannot be wholly disproven, but the view is extremely improbable; for in the epoch immediately following the final emergence the conditions were not favorable to a rapid erosion; the region was not at that time an elevated one; it could scarcely have exceeded a few hundred feet in altitude above sea level, and there were no important displacements nor dislocations. The Bitter Creek beds cover many hundred square miles of continuous territory with splendid exposure, and have in many places been thoroughly protected from destruction since early Miocene time at least, but nowhere have they been seen to be covered with any more recent sedimentary formations, excepting the local beds of volcanic sand. It is not probable that every vestige of such a formation, had it existed, should have been so completely destroyed, nor that an erosion of such magnitude should have been withal so uniform as to stop everywhere at the summit of the very perishable limestone which forms the uppermost member of the Bitter Creek.

Here, as elsewhere, the volume of Cretaceous beds is very great, probably attaining more than 4,000 feet. The valleys and gorges which reveal them descend to the westward, while the rocks dip at varying angles to the eastward; thus in the course of 5 or 6 miles the water-courses pass through the entire series. The Cretaceous mass is composed of alternating sandstones and dark-gray shales, which are usually very heavily bedded, uniformly stratified, and have strong and persistent lithological characters.

The subdivision of the Cretaceous rocks and their correlation with those of the Plateau Province at large I have not attempted; the study of them has been too superficial and the number of fossils collected is much too small, while the series itself is enormous and highly variable. It is evident at once that, though the series as a whole possesses the same general characteristics as prevail elsewhere, it is very inconstant in details, and comparatively few of the subordinate members can be strictly correlated over extended intervals. The great beds of shale are the most striking members, attaining many hundreds of feet of thickness, with slight interruptions of arenaceous layers, which hardly mar the uniformity of their aspect. Coal of good quality is found in workable beds in the lower half of the series. There is a strong family likeness in all the Cretaceous exposures of the Plateau Province, and their features are as characteristic of the formation as the peculiarities of the Trias; but the wonderful persistence over great areas which marks the Triassic members cannot be affirmed of the Cretaceous.

No series of rocks can be more strongly marked by their lithological characteristics than the Mesozoic formations which here underlie the Cretaceous. Quite as strongly individualized are the topographical features which have been sculptured out of them. The great marvels of surface sculpture found throughout the lower Plateau Province, the grand cliffs with strange carvings and elaborate ornamentation, the wonderful buttes and towering domes, the numberless shapes which startle us by their grotesqueness owe their peculiarities as much to the nature of the rocks themselves as to the abnormal meteoric conditions under which they were produced. Each formation has its own fashions—its own school of natural architecture. The Gray Cliffs, the Vermilion Cliffs, the Shinárump (Lower Trias)—each has its own topography, and they are as distinctly individualized as the modes of building and ornamentation found among distinct races of men.

The uppermost member of the Jurassic series is fossiliferous, and has yielded a fauna which, though not very abundant, is still highly characteristic and sufficient to fix its age with certainty as Upper Jurassic. Immediately below it is the Gray Cliff sandstone, so wonderful for its cross-bedding, for the massiveness and homogeneity of its stratification, and for its persistence without any notable change of character over great areas. This formation has been assigned to the Jurassic solely on the ground of its infra-position to the fossiliferous member just mentioned. The Gray Cliffs have not yielded a solitary fossil hitherto of any kind. Next below is the Vermilion Cliff series, characterized by beds of sandstone built up in many layers, with a tendency towards shaly characters, though seldom or never a true shale. It is as persistent as the Gray Cliffs above, and in color it contrasts powerfully with it. The Gray Cliffs are nearly white, and are merely toned with gray; the Vermilion Cliffs are intensely, gorgeously red. The latter also is destitute of fossils, except a few obscure fish-scales, though great search has been made for them. Beneath lies the Shinárump. It consists of a very remarkable conglomerate above and a series of shales below. The conglomerate is made up chiefly of fragments of *silicified wood*, cemented by a light-colored matrix of sand, lime, and clay, out of which the woody fragments weather and are scattered over the plains below. The shales below consist of a succession of layers, each a few feet or a very few yards in thickness, preserving that thickness with remarkable uniformity over miles of exposure and contrasting with each other by their varying shades of chocolate, dark red, and purple, producing an effect of colored bands of small thickness individually but great collectively, and with a perfect regularity or parallelism. (See Heliotype No. XI.)

The Lower Mesozoic series (Jura and Trias) is found in the Markágunt only in the immediate vicinity of the great Hurricane displacement, which defines the western boundary of the structure, and is only seen there along the southern portion of the west flank. I have not visited them, but Mr. Howell has examined them somewhat cursorily, and the results of his observations, in the form of notes, are before me. There is a general agreement of the sections he there found with the general section of the Plateau Country to the eastward, though there are minor differences which might be worthy of future study. All of the notable Mesozoic groups and beds are present and seem to be on the whole somewhat thicker than they are to the eastward, but the thickness is more variable and the deposition generally more unequal. In close proximity to the great fault, the beds are in some places flexed abruptly upwards on the uplifted side of the fault, but in passing eastward they speedily recur to the general east or east-northeast dip of 1° to 2° which prevails throughout the plateau. Nowhere in this vicinity does the Carboniferous seem to be exposed, though in several localities it must be very near the surface in the immediate line of the fault. Where these upward flexures occur, the plane of denudation between the summit of the plateau and the fault cuts across the entire series of Mesozoic and Cenozoic formations more than 10,000 feet in thickness.

From the southwest salient of the Markágunt we behold one of those sublime spectacles which characterize the loftiest standpoints of the Plateau Province. Even to the mere tourist there are few panoramas so broad and grand; but to the geologist there comes with all the visible grandeur a deep significance. The radius of vision is from 80 to 100 miles. We stand upon the great cliff of Tertiary beds which meanders to the eastward till lost in the distance, sculptured into strange and even startling forms, and lit up with colors so rich and glowing that they awaken enthusiasm in the most apathetic. To the southward the profile of the

HELIOTYPE IX.

Heliotype Printing Co., *220 Devonshire St., Boston.*

CROSS BEDDED JURASSIC SANDSTONE.

country drops down by a succession of terraces formed by lower and lower formations which come to the daylight as those which overlie them are successively terminated in lines of cliffs, each formation rising gently to the southward to recover a portion of the lost altitude until it is cut off by its own escarpment. Thirty miles away the last descent falls upon the Carboniferous, which slowly rises with an unbroken slope to the brink of the Grand Cañon. But the great abyss is not discernible, for the curvature of the earth hides it from sight. Standing among evergreens, knee-deep in succulent grass and a wealth of Alpine blossoms, fanned by chill, moist breezes, we look over terraces decked with towers and temples and gashed with cañons to the desert which stretches away beyond the southern horizon, blank, lifeless, and glowing with torrid heat. To the southwestward the Basin Ranges toss up their angry waves in characteristic confusion, sierra behind sierra, till the hazy distance hides them as with a vail. Due south Mount Trumbull is well in view, with its throng of black basaltic cones looking down into the Grand Cañon. To the southeast the Kaibab rears its noble palisade and smooth crest line, stretching southward until it dips below the horizon more than a hundred miles away. In the terraces which occupy the middle ground and foreground of the picture we recognize the characteristic work of erosion. Numberless masses of rock, carved in the strangest fashion out of the Jurassic and Triassic strata, start up from the terraced platforms. The great cliffs—perhaps the grandest of all the features in this region of grandeur—are turned away from us, and only now and then are seen in profile in the flank of some salient. Among the most marvelous things to be found in these terraces are the cañons; such cañons as exist nowhere else even in the Plateau Country. Right beneath us are the springs of the Rio Virgin, whose filaments have cut narrow clefts, rather than cañons, into the sandstones of the Jura and Trias more than 2,000 feet deep; and as the streamlets sank their narrow beds they oscillated from side to side, so that now bulges of the walls project over the clefts and shut out the sky. They are by far the narrowest chasms, in proportion to their depth, of which I have any knowledge.

All the Tertiary strata of the Markágunt, together with the entire Mesozoic series, with the possible exception of the Gray Cliff sandstone, once extended over the vast expanse before us and far beyond the limits of vision to the south and southeast. One after another they have been swept away by the ordinary process of erosion, and the great expanse of desert around the Colorado has been denuded down to the Carboniferous. Here and there an insulated patch of the Trias remains, fading remnants of formations which were once continuous and without a break; but the whole of the vast Cretaceous system and the heavy Eocene beds have not left a single butte upon the denuded portion. Sixty to eighty miles to the east of us the Cretaceous still extends uninterruptedly from the southern slope of the Aquarius Plateau to the Colorado and thence into Arizona. A little farther westward and the Upper Trias similarly stretches across the interval. But from the eastern wall of the Kaibab to the mouth of the Grand Cañon the Carboniferous forms the floor of the country, and no later beds are found within 50 miles of the river except a few outliers of the Shinárump.

CHAPTER X.

SEVIER VALLEY AND ITS ALLUVIAL CONGLOMERATES.

The headwaters of Sevier River.—Upper Sevier, or Panquitch Valley.—Panquitch Cañon.—Circle Valley.—Origin of the Sevier Valley.—Conglomerates.—Their various kinds.—Sources of the materials.—Transportation of coarse *débris* and the natural laws governing it.—Action of rivers upon transported materials.—Action of the sea.—Alluvial conglomerates.—Formation of alluvial cones at the openings of mountain gorges.—Their structure.—Alluvial cones now forming in the valleys of the district.—A comparison between the modern alluvial formations and the ancient conglomerates.—Identity of the process which formed both.

The South Fork of the Sevier River heads in the Markágunt near its southwestern crest, the springs being scattered among the basalt fields, which cover a considerable area in that vicinity. Two fine creeks flow eastward in broad valleys, meandering down the slopes of the plateau until they meet the opposite slopes which descend from the western wall of the Paunságunt. Here the southernmost creek (Asa's Creek) is deflected northward, and 6 miles below, Mammoth Creek joins it, the two forming the South Fork of the Sevier. Thence northward the stream flows for more than 50 miles, receiving a few insignificant tributaries, until at the foot of Circle Valley it is joined by the East Fork issuing from a mighty chasm, which cuts from top to bottom the great Sevier Plateau. Still northward it pursues its course nearly a hundred miles more, receiving one important affluent at Salina and another at Gunnison, until it suddenly springs westward at the Pávant and cuts a chasm through it; then turning south-southwest, it meanders through a forlorn desert for about 60 miles, and ends at Sevier Lake, a large, nauseous bittern of the Great Basin. The site of this lake was at a recent epoch covered by a southward extension of Lake Bonneville. It is interesting to reflect that as late as Post-Glacial time the waters which fell upon the crests of the Pink Cliffs of Southern Utah were there divided; a part to flow southward into the Grand Cañon, the remainder to flow northward into Lake Bonneville,* and thence through the Snake River into the Columbia.

Where the upper tributaries of the South Fork reach the foot of the Markágunt slope the altitude is about 7,000 feet. At the junction of the East Fork it is 6,000 feet, and where the river enters the Pávant it is 5,000 feet.† In any ordinary region the Sevier would not be dignified by the name of a river. In the early part of July its flow is a little less than 1,000 cubic feet per second, and this volume diminishes to about half that in September. Nevertheless it is the largest stream between Great Salt Lake and the Colorado.

The name *Sevier Valley* might with propriety be given to the entire trough of the stream, but local names have been given to different portions of it which are well separated by transverse barriers through which the river has cut narrow passages. The most important of these is encountered by the Southern Fork, about 17 miles north of (below) the town of Panquitch. The great outbursts of trachytic lava which flowed eastward from Dog Valley here stretch athwart the course of the stream and wall against still more ancient *coulées*, which broke forth from vents situated in the southern half of the Sevier Plateau, and over them have accumulated large masses of conglomerate derived from their ruins. There has also been local uplifting of a few hundred feet transversely to the greater structure-lines, so that now the confused masses of trachyte and conglomerate form a barrier from 800 to 1,000 feet high and 10 miles in width across the valley. Through this mass the fork has cut a noble cañon, called Panquitch Cañon. Above this barrier (southward) lies a large valley-plain, having on the east long alluvial slopes, which rise gently to the base of the Sevier Plateau, and on the west the still longer and gentler slope of

*Although all American geologists are well aware of it, it may not be generally known that the name "Lake Bonneville" has been given to a vast body of fresh water which during the Glacial and Post-Glacial periods, occupied the eastern part of the Great Basin. This lake had an area about three-fourths as great as that of Lake Superior, and its greatest depth was about 1,000 feet. This lake outflowed to the north into the Snake River and thence into the Columbia. The increasing aridity of the climate since the close of the Glacial epoch has dried up most of the sources of the lake and evaporated the waters of the lake itself, so that now only a few remnants are left. Of these, Great Salt Lake is by far the most important. Utah Lake is a body of *fresh* water, and has an outlet through the Jordan River into Great Salt Lake. Sevier Lake is another remnant of Lake Bonneville.

†These altitudes are probably within 50 feet of the exact truth.

the Northern Markágunt, crowned by the Bear Peak and Little Creek Peak in the background. From Panquitch Cañon the stream emerges into Circle Valley, which is much smaller in area but far grander in scenery—indeed, the grandest of the High Plateaus. On the east rises the long palisade of the Sevier Plateau 4,300 feet above the river; on the west the wall of the Southern Tushar, which opposite the valley is 4,200 feet above it, and from 5,000 to 6,000 feet above it in its northern and southern extensions. The Tushar shows rugged peaks and domes planted upon a colossal wall; the Sevier Plateau shows a blank wall without the peaks. Very grand and majestic are these mural fronts, stretching away into the dim distance calm, stern, and restful. Yet they fail to impress the beholder with a full realization of their magnitude. This is true of mountains in general, but pre-eminently so of great cliffs. If one-third of the stuff in the Sevier Plateau, east of Circle Valley, had been used to build a range of lively mountains, they would have seemed grander and possessed what no palisade can ever possess—beauty and animation. It is otherwise with the Tushar. There the great wall has magnified the mountains by giving them a noble sub-structure on which to stand, and the mountains have magnified the wall by giving it something to support.

Twenty miles south of Circle Valley and just below the hamlet of Marysvale another considerable barrier lies across the valley of the Sevier. It consists of a mass of rhyolitic lavas, which broke out in the valley bottom in many eruptions, and now remain as a chaos of tangled sheets stretching from wall to wall. The river has maintained a cañon through the mass right at the base of the spurs of the Tushar, whose front here is not mural but mountainous. Emerging from this barrier the river flows unobstructed through its main lower valley between the Pávant and Sevier Plateau until it darts into the former 70 miles to the northward.

The valley of the Sevier is due to structure, and owes to erosion only the cañons which are cut through the two barriers of volcanic rocks which have poured across it. The upper valley (Panquitch Valley) lies along the great displacement which has lifted the wall of the Sevier Plateau. Below Panquitch Cañon, from Circle Valley to the mouth of Marysvale Cañon, the valley platform is a block between two faults, with the Sevier Plateau on the east and the Tushar on the west. Farther northward to the Juab Valley a similar relation prevails. So far is the entire trough of the Sevier, except at the barriers, from being due to erosion, that its floor has been built up by the growth of alluvial formations of considerable magnitude. They are of special interest because of the light they throw upon an interesting problem in dynamical geology.

THE FORMATION OF CONGLOMERATES.

There are several kinds of conglomerate, formed by processes which, though they may have some features in common, are on the whole strikingly different. Glacial drift, though it undoubtedly falls within the usual conception of a conglomerate, has an origin wholly different from that of a littoral or alluvial conglomerate. Yet in respect to the source from which its materials are derived—the disintegration of the harder rocks by water and frost—the distinction is not well marked. The great difference is in the methods and agents of transportation and final distribution. Alluvial conglomerates agree with the littoral in having the same origin for their materials, and the same transporting agent, moving water, but the two differ in respect to the conditions under which the transporting power is exercised and the materials distributed. Thus these three kinds have something in common and each has some features peculiar to itself.

Sources of materials.—The stones and pebbles included in these formations are derived from the break-up of the hardest classes of rocks, which are usually metamorphic or volcanic. Ordinary sandstones, limestones, and clays, and shaly rocks in general seldom contribute to the mass of fragments found in conglomerates. Attrition, weathering, and solution utterly destroy them before they reach a resting-place. A few remnants of rock not usually reckoned as metamorphic nor volcanic are sometimes inclosed, but they come from sedimentary strata as hard and enduring as the others, and such strata are rare. Hard masses, originally contained in softer beds, are sometimes found, but they owe their preservation to their excessive durability, such as the flints of chalk, the chert, and many forms of amorphous silica occurring in limestones. The localities from which the stones come are no doubt very near those where they are deposited, as compared with the distances traveled by finer detritus. Instances where stones weighing from two to five pounds have traveled 50 miles are common. Where ice is the vehicle, the distance may be almost indefinitely great. It would seem to require extraordinary circumstances to justify the belief that a conglomerate could be formed as far as 50 miles from the sources of its fragments, and it is probable that most of the stratified beds are formed in the very neighborhood of those sources, though beds of small gravel, graduating into coarse and then into fine sandstone, may extend away much farther.

Transportation.—Transportation by ice, whether floating, or moving upon the land, forms a subject by itself, and has no analogy to the agency of water in moving *débris*. It will therefore be passed over, since it takes no part in the operations which are the object of this discussion. The movements of the coarse materials which build up conglomerates differ from those of the finer sediments, though they have something in common. The greater portion of the fine silt, much of the fine sand, and the whole of the chemical and organic precipitates are carried by moving waters in suspension, and are thrown down when the waters come to rest. The coarser materials are impelled along the bottoms of rivers and the shelving floors of the ocean and lakes near the beaches. Here the want of habitual observation and common experience is apt to mislead us and render difficult the obtaining a just apprehension of the nature and magnitude of this impulsion. Any day we may see the rivers turbid with earthy matter, and it is an easy step from this observation to the great generalization that the land is wasting away and heavy strata accumulating beneath the ocean. But it is not so easy to see what goes on beneath the water. The times when the processions of stones are on the move are times of high water, and flooding rains, when geologists are as prone as other people to seek the kindly welcome of roofs and closed doors; times when the deep and murky waters prevent us from seeing and the roar of the torrent from hearing the movement, even if we ventured out to watch it. Thus, the process is not a matter of common and direct experience; nay, experience might seem at first to lead us to a contrary conclusion. When a stream is low and clear we may note the stones which pave its bed, and after a flood has passed and the stream again is clear we may find that there has been little change in them; but to conclude that no stones have passed in the interval would be a mistake. Those which retain their places have lodged there and been fastened to the bottom by a packing of sand or wedged together like the cobbles of a pavement. If the sources of the materials continue to furnish them, doubtless many stones have been hurried along over this pavement during the flood, a few finding a resting place, but more of them passing on to be ground into silt or to find resting-places in deeper waters below.

But there is another method quite different from this precipitate one, and by which it is very probable that much larger movements are effected, though much more slowly. It never happens that the materials to be moved are of uniform grain. Mud, sand, gravel, shingle, and cobblestones always accompany coarser *débris* in varying proportions, and form a matrix in which the larger fragments are imbedded. An acceleration of the current removes the finer stuff and retardation replaces it with fresh. The washing out of the matrix of sand and grit which holds a pebble in its place leaves the pebble to the unobstructed energy of the current. If that energy is sufficient it will be carried along until the current slackens or until it finds a lodgment. If the energy is too small, the pebble will remain until the ceaseless wear of attrition reduces it and brings it within the power of the stream to move it. Nor are these movements dependent solely upon periodical floods. Any cause which alternately accelerates the movement of water may produce them, and these causes are many. Every stream and every shore current is affected by numerous rhythmical movements which produce these alternations in many ways and many degrees. The waves and surf, the undertow, the tides, the shifting of shore currents, the storms and monsoons, the ripples of the brook, the numberless surgings and waverings of rivers, the shifting of channels, the building and destruction of sand bars, the freshets—all are causes by virtue of which any spot at the bottom of the water is subject to alternate maxima and minima in the velocity of the water which passes over it. Sooner or later, then, the pebble must move on, provided any maximum of velocity in the water is sufficient to move it when subject to no other resistance than its own weight.*

Thus whatever a stream receives it carries along, whether it be water or solid rock. Certainly much of the matter rolled into it is in the form of coarse fragments, but it urges them onwards, grinding them to silt as they move. Nothing which it receives does it retain, except in places here and there where its current is suddenly checked, and here for a time coarser materials accumulate. But in the secular life of the river even these local accumulations may in turn be removed by subsequent changes of relative level along different portions of its course.

The distance which a fragment may ultimately travel is independent of its original size. Large stones, being moved with difficulty, are detained at numerous halting places and subjected to long attrition until they are sufficiently reduced to be within the power of the current, and at length become no bigger than those which were originally smaller. In truth, all fragments, in a certain sense, travel the same distance ultimately, for they all pass the mouth of the river in the form of silt and dissolved constituents. Viewed in another aspect, however, the size of the fragment determines in a general way its amount of progress. The larger ones have at any given stage moved a shorter distance and the smaller ones a greater distance—on the average.

The action of a current upon rocky fragments, then, is to sweep them along and to grind them to powder as it sweeps. It never accumulates them except in a limited way and under circumstances which will be hereafter described at some length. Whether the detritus which a river discharges shall be in the form of pebbles, gravel, or silt, depends upon the length of the stream and the power of its current. A long stream with a low slope and sluggish current along its lower course, but with more rapid tributaries above, will have dissipated its fragments and discharge nothing but silt. A short stream with a rapid descent may readily discharge coarse

*Where a sudden retardation of the velocity of a stream occurs, as by the sudden widening or deepening of a channel, and where this change predominates over all other changes from maxima to minima, there will occur a persistent accumulation of coarser *débris* without any great admixture of finer. * * * Concerning the power of water to move pebbles, it will be merely necessary to refer to Dr. Hopkins's well-known theorem.

fragments, shingle, and gravel. The latter may build up a conglomerate at its outlet; the former never.

The action of the sea upon coarse materials has a very close analogy to that of rivers. Currents are generated by the tides and winds along coasts. The surface-waters are rolled in waves upon the shore and flow outwards along the bottom. But their directions are frequently vacillating, trending both ways along the coast with varying obliquity. These currents are usually fast enough to move gravel, shingle, and pebbles as large as those ordinarily seen in marine conglomerates, and may transport them several miles. The general effect of the agitation produced in littoral waters by tides and winds is to seize upon the loose materials of the shore within reach and distribute them over the bottom with an approach to uniformity, and this distributive action prevails wherever the influence of that disturbance exists.

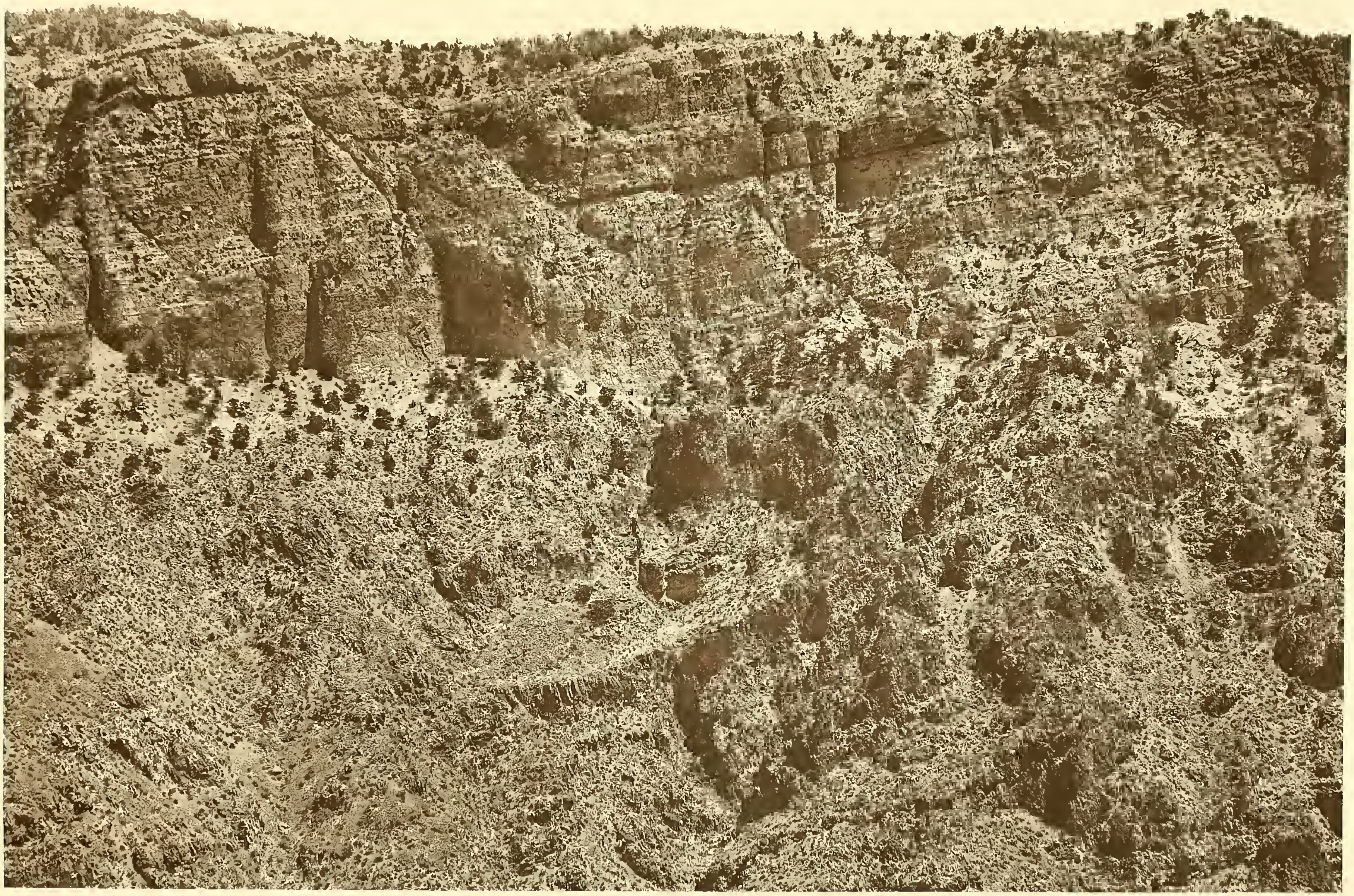
The distribution of the materials.—It is sometimes a little difficult to realize the agency which has, in the stratification of conglomerates, scattered the fragments over considerable areas and arranged them harmoniously in beds. The stratification of conglomerates is often as conspicuous as that of finer strata, though in general it is less so In the case of marine conglomerates, which are usually formed in the vicinity of the shores, and at no great distance from the sources of their materials, the problem is not difficult. Currents of no mean intensity are perpetually generated along the bottom, near the coast, by tides and the outward flow of water, which has been blown landwards at the surface by winds. These currents, though having at any given locality an average direction, in the long run are never constant in direction from hour to hour, nor from day to day, but sweep hither and thither. But the average flow at the surface is generally landwards, while at the bottom it is seawards. In any case, however, the general trend is oblique, with reference to any given portion of a coast, and never, or at least very seldom, normal to it. These vacillating movements are highly conducive to a harmonious and definite arrangement of the materials upon which the currents act, ever tending to sift and to sort them, and finally to stratify them. The power of these currents to transport is perhaps greater than we are apt to imagine. The drift of sand along coasts is a process which has often awakened the surprise of engineers who are called for the first time to deal with the problems of harbor protection and is ever revealing wonderful things. Not only does the finer loose material move in grand procession under the influence of unseen, though still comprehensible, agencies, but very coarse detritus is carried slowly with it. The tendency of the process, however, is not towards an indiscriminate mixing of all sorts and sizes, but towards the grouping into layers, here of coarser, there of finer, stuff, according to the variations in the power of the moving water.

But there is another class of conglomerates which claims our special attention. These are of alluvial origin, formed, not beneath the surface of the sea nor of lakes, but on the land itself. They do not seem to have received from investigators all the attention and study which they merit. They are usually called gravels—perhaps are sometimes or even frequently mistaken for glacial drift—but their homology to the ordinary stratified conglomerates of the systematic strata is not always recognized. Throughout great portions of the Rocky Mountain region they are accumulating to-day upon a grand scale and have accumulated very extensively in the past.

The processes of degradation are far more energetic and effective in mountains than upon plains. The agents which disintegrate rocks—frost, rain, chemical solution—have the greatest freedom of action upon the steep slopes of the numberless ravines, and are continuously breaking off fragments and reducing them to sand, gravel, and clay. Not only is the greater part of the finer mold gathered up by the swift rills and torrents, but fragments of considerable size, attaining, under favorable circumstances, the weight of several tons, are caught and urged downward in rushing rapids with an energy which must be seen in order to be realized. The many streamlets and filaments of a mountain amphitheater gradually unite, as we descend from the crest of the mountains, generating a creek, which attains its greatest flood near the mountain base, and when the snows melt in the spring its swollen current sweeps onward a mass of clastic material of every description from impalpable clay to bowlders. Within the mountain masses the descents are rapid and the streams are torrents. Reaching the valleys or plains, their velocity is at once checked by the diminished slope and the coarser *débris* comes to rest. These streams lie (within the mountains) in ravines usually profound, with steep flaring sides, and opening upon the valley bottoms or plains through magnificent gateways, and every long range or ridge has usually many such gateways opening at intervals of a very few miles along its flank. At the gateway the stream begins to surrender a part of its freight and to build up its channel. The check given to the velocity of the stream here is marked, indeed, but less incisive than might at first be supposed. The profile of the bed of the stream does not have an angle at this point, but is curved very gently, and is concave upward. Indeed, it is so throughout the entire course of the stream outside the gate and generally for a considerable distance inside the gate. Thus the velocity of the stream slows down gradually and not suddenly. As the velocity gradually diminishes so the stream gives up more and more of its load. But the stuff which it drops along any small part of its course is by no means of the same size; that is to say, there is no rigorous sifting of the material in such a manner that the stones or particles at any given place are of uniform size, while finer ones are carried on to be scrupulously selected where the slope and velocity are less. On the contrary, all sorts are deposited everywhere. Nevertheless there is a tendency to sorting. Higher up the slope there is a greater proportion of coarser deposit; lower down there is a larger proportion of finer deposit; but everywhere the coarse and the fine are commingled.

Where the stream is progressively building up its bed outside of the gate, it is obvious that it cannot long occupy one position; for if it persisted in running for a very long time in one place it would begin to build an embankment Its position soon becomes unstable, and the slightest cause will divert it to a new bed which it builds up in turn, and which in turn becomes unstable and is also abandoned. The frequent repetition of these shiftings causes the course of the stream to vibrate radially around the gate as a center, and in the lapse of ages it builds up a half-cone, the apex of which is at the gate. The vibration is not regular, but vacillating, like a needle in a magnetic storm; but in the long run, and after very

HELIOTYPE IV.



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VOLCANIC ALLUVIAL CONGLOMERATE ON TRACHYTE, PANQUITCH CANON.

many shiftings, the stream will have swept over a whole semicircle with approximately equal and uniform results.

The formation thus built up is an "Alluvial Cone." As we travel over these cones their forms are usually recognized by the eye, though sometimes with difficulty. The slant of the cone (of which more will be said hereafter) is usually quite small, though sometimes very conspicuous. It varies greatly but not capriciously, depending much upon the nature of the materials of which it is composed. Most frequently these cones are so large and so flat, that it is only by very close scrutiny and comparison with surrounding objects that their forms are optically recognized, and many cases occur where we become aware of their true figures and relations only by the use of our pocket instruments. There is one feature which the eye seldom recognizes or even suspects. The profiles are not (even typically) truly conical, but are slightly curved instead of having a rectilinear slope. They are concave upwards, the slope being a little greater near the apex and slightly or sometimes notably diminishing towards the periphery. The slopes near the circumference usually lie between 1° and 2°; those near the apex between 2° and 3½°. The lengths of the radii of the bases often exceed 3 miles, sometimes exceed 4 miles, and seldom fall below 2 miles. Perhaps 3 miles would be a fair average for those found in the valleys of the District of the High Plateaus. So nearly together are the gateways along the mountain and plateau flanks, each having its own alluvial cone, that the cones are confluent laterally; giving rise to a continuous marginal belt along the base of the plateau flanks consisting of alluvial slopes which are sensibly nearly uniform.

The conical form of these accumulations is ordinarily tolerably accurate and often remarkably perfect. It is a surprisingly harmonious result of a process which in its elements is apparently irregular, but becomes regular only by averaging the results of its constituents. Not only is the regularity seen in the external form of the cone, but it is found whenever an opportunity occurs to examine its interior structure. This is sometimes revealed to us. In the vicissitudes to which a stream so conditioned is subject it occasionally happens that indirect causes have set it at work cutting into its cone; dissecting it, so to speak, by a deep cut and laying bare its anatomy. Our surprise is often great at finding the cone wonderfully well stratified, but in a peculiar way. The most perfect stratification is presented when the dissecting cut is made radially. But when a cut transverse to the radius is made by excavations of another stream, the stratification, though still conspicuous, is much less uniform and harmonious. The cone appears to be built up of long radial or sectoral slabs superposed like a series of shingles or thatches.

There are marked differences between the cones formed by streams which have their entire descent within unaltered sedimentary strata and those running among volcanic and metamorphic rocks. The fragments resulting from the decay of sandstones, limestones, and shales are much more susceptible to the influence of weathering and are more readily worn-out by the abrasion of travel. Even when they escape destruction by the wear of the torrent and reach a resting-place upon the surface of the cone, the gentler but more insidious action of meteoric forces gradually crumbles them to sand or dissolves them, and they at length disappear. But the compact volcanic and metamorphic rocks are much more durable and do not yield so readily either to mechanical or chemical forces; more of them reach the cones, where they survive long enough to be buried beneath later accumulations and thus receive final protection from dissolution. Hence the cones derived from the waste of sedimentary strata seldom contain much coarse *débris*, while those from harder rocks are largely composed of it. This difference in texture in turn produces some difference in the proportions of cones. The sedimentary cones are usually very slightly flatter and broader. The difference in this respect is on the whole quite small, but the measurement of a considerable number of both kinds seems to indicate that it really exists.

In consequence of the flatness of the cones and their lateral confluence, the general result of their serial aggregation is a long and thick *stratum* made up of many subordinate folia. In process of time it may also become consolidated and hardened into a rock mass resembling in all essential respects the stratified conglomerates usually reckoned among the members of a stratigraphic series. That distinctions between such a conglomerate and one deposited littorally would be readily detected after close inspection of favorable exposures we may well believe; yet it is highly probable that the two kinds would be confounded on a hasty examination, and the distinction would be difficult to verify even by careful study, unless the exposures were extensive and conspicuous enough to display very fully and clearly their respective characters. These doubts generally would prevail in those cases where a decision would have to turn only upon the intimate structures of the deposits. Collateral circumstances, however, may often decide the question.

Throughout the volcanic portions of the District of the High Plateaus the conglomerates are present in prodigious masses. They constitute a large proportion of the rock masses of the plateaus, and form many miles of escarpment more than a thousand—sometimes more than 2,000—feet in thickness. In the central and southern portions of the plateaus they cannot fall much short of one-half of the masses now open to observation, and taking the volcanic portion of the entire district, a rough estimate would place their volume at least at a third of the whole eruptive material. They are well stratified, and though the distinctness of the bedding is somewhat variable, the stratification never becomes obscure. Indeed, on the whole, these conglomerates seem to be about as well stratified as the average of those which are attributed to sub-aqueous deposition. The individual beds are not so thick and massive and show partings more frequently or at shorter intervals.

The occurrence of large stratified accumulations of pyroclastic materials in regions or districts which have been the theaters of protracted volcanic activity is a fact of common observation. They abound throughout the State of Colorado and along the more or less volcanic ranges of Northern Wyoming, Montana, and Idaho. They excited the admiration of Scrope in Central France, and are conspicuous in Sicily and around Vesuvius. Indeed, every volcanic region will doubtless be found to display them to a greater or less extent. Where large bodies of water wash the flanks of volcanic mountains and ranges we may expect to find large bodies of sub-aqueous conglomerate formed from their *débris*. Volcanic tuffs are formed by the mechanical projection of dust, ash, *rapilli*, and small fragments from vents blowing out gases and steam, and falling at considerable distances from the orifices. Want of opportunities for observing such formations of unquestionable origin prevents me from having any just conception of the nature, extent, and texture of such accumulations. But it seems sufficiently clear that there could be no difficulty in distinguishing them from such as are with equal certainty attributable to sub-aqueous or alluvial deposition. I have observed but few exposures which I can attribute to such an origin. That the great mass of conglomerates of the High Plateaus were accumulated from the *débris* derived from the erosive destruction of volcanic beds cannot be doubted. The only question is whether they are alluvial or sub-aqueous, and of the former origin I entertain no doubt. The fragments seldom fail to reveal traces of attrition and weathering, never preserving sharp angles like those produced by fresh fracture. But, on the other hand, the attrition is not ordinarily extreme. In most cases there is enough of it to indicate distinctly that the fragments have really been abraded, though with no great loss of substance. The stones of sub-aqueous conglomerates, on the contrary, are almost always much worn and rounded. Again, the sizes of the stones range from a fraction of a cubic inch to several cubic feet; in rare instances to more than a cubic yard.

In whatsoever manner we compare the great conglomerates now forming solid rock masses and uplifted as plateaus with the alluvial conglomerates now forming in the valleys, we cannot fail to be impressed with the evidence that both were formed by essentially the same process. The only differences of any appreciable moment which are now discoverable arise from the fact that the older conglomerates have been consolidated into rock-masses, while the later ones have not.

CHAPTER XI.

SEVIER AND PAUNSÁGUNT PLATEAUS.

General structure and form of the Sevier Plateau.—Sculpture.—Ravines.—Superposed features and details.—Northern portion of the plateau.—A gigantic cliff.—Monroe Amphitheater.—Lava beds exposed within it.—The Gate of Monroe.—Propylitic masses.—Clastic volcanic beds at the base of the series.—Hornblendic andesites.—Intervening period of erosion of the propylites.—Hornblendic trachytes and augitic andesites.—Argilloid and granitoid trachytes.—General succession of the eruptions.—Comparison with the succession found in the Auvergne.—Eastern side of the Sevier Plateau and Blue Mountain.—Great extent of the emanations from the principal volcanic centers of the northern part of the plateau.—Eroded lava-capped mesas around Salina Cañon.—The Black Cap.—Augitic trachytes.—Lava sheets south of Monroe Amphitheater.—Central vents of the Sevier Plateau.—Volcanic conglomerates.—An ancient cone, buried in lava and exhumed by erosion.—Conglomerates south of the central vents.—Southern focus of eruptions.—Andesitic conglomerates.—Southern termination of the Sevier Plateau.—General succession of eruptive sheets.—Sections.—East Fork Cañon.—Effect of the Sevier fault.—Tufaceous deposits exposed in East Fork Cañon.—Their transitional characters.—Their metamorphism and the resemblance of the metamorphs to lava sheets.—Phonolite hill.—Grass Valley, its structure and origin.—Existence of an ancient lake in Grass Valley.—The causes which produced it.—Tufaceous deposits of Mesa Creek.—Their recent formation.—Their transitional characters.—Alluvial cones of Grass Valley.—The Paunságunt.—Lower Eocene beds.—Faults.—The southern terraces.—Paria Valley.—A grand erosion.—The scenery of Paria Valley.—Table Cliff and Kaipárowits Peak.—The Pink Cliffs and architectural forms sculptured from them.—A recent basaltic cone.—Scattered basaltic craters of the southern terraces.

The SEVIER PLATEAU is next to be described. It is a long and rather narrow uplift, having a fault along its western base and inclining to the eastward; at first very gently, then with a stronger slope, which grades rapidly down into Grass Valley. The length of this table is about 70 miles, and its width varies from 10 to 20 miles. It is, therefore, long and narrow like the general ground-plan of a mountain range. But its structure has very little analogy to ordinary mountain uplifts. It has no sharply upturned strata upon its flanks reclining against a core of metamorphic rocks—no summit ridge marking the axis along which granitoid and schistose rocks have been protruded, nor even the monoclinal ridge which characterizes the Wasatch and Basin Ranges. It is a tabular mass very like the inclined blocks of the Kaibab region to the southward. The inclination is very small, seldom exceeding three or four degrees upon the summit, though reaching a considerably greater slope upon the eastern flank. The eastern side, indeed, suggests a monoclinal flexure, but the bending of the profiles is so small and their sweep is so gradual that we may forbear to call it such. It is hardly pronounced enough to justify such a designation.

Standing in the Sevier Valley and looking at this barrier there are many stretches along its western front which appear quite like a common mountain range. Profound gorges, V-shaped, heading far back in its mass, have cut the table from summit to base and open through magnificent gateways into the valley. The residual masses between these gorges present their gable-ends to the spectator, who cannot see what is behind them, and they look exactly like so many individual mountains, while in reality they are merely pediments carved by erosion out of a gigantic palisade. Other long stretches of the western front are unbroken and present to the valley of the Sevier a wall of vast proportions. The summit of the plateau is not smooth, but carved into rolling ridges and vales, deepening eastward into cañons, while at several places volcanic ridges cross it transversely. These last are the remnants of old volcanic piles worn down and half obliterated by long ages of decay, for they belong to the middle epoch of volcanic activity, which may be as old as the Middle Miocene. They present from a structural point of view a peculiar relation to the table on which they now stand. In almost every great mountain range of ordinary type the axes of those minor ridges or superimposed features which had their origin in general causes which built the entire range lie roughly parallel to the main uplift in the relation of superimposed waves of displacement. But here it is otherwise. The volcanic ridges which are planted upon the Sevier Plateau run not along its major axis, but across the table from side to side. The movement which hoisted the plateau *en masse* was not sensibly embarrassed by such trifles as a few ridges of volcanic piles. The features impressed by erosion, on the contrary, conform to the usual law which prevails in mountain ranges. The streams pour down from the summit along whatever slopes may have been generated by the details of the uplift, and have carved their vales, gorges, and cañons accordingly. Since these run across the table or perpendicular to its major axis they have sculptured ridges of erosion which trend that way. If we view the Sevier Plateau from the north, its transverse profile is alone seen, and the tabular summit slightly inclined is conspicuous to the eye. But if we view it from the east or west, its long summit is seen in many places to be somewhat rumpled and even serrated by the ridges of erosion and by the old volcanic remnants viewed endwise.

The northern end of the Sevier Plateau is not well defined. A long, gentle ramp, deeply scarred and much wasted by erosion, begins a little south of Salina and ascends southward to the summit. It is best appreciated as we journey up the Sevier Valley from Salina to Richfield. We then observe the whole platform of the country to the east of us gradually gaining in altitude through a distance of 20 miles, until from being a thousand feet above us at Salina it becomes 5,800 feet above us opposite Richfield, and there presents to the west a stupendous battlement of nearly vertical wall above and abrupt spur-like slopes below, thrusting their buttresses beneath the valley plain. For nearly 10 miles this tremendous escarpment is quite massive and unbroken, simple in form and more than a mile in height. Opposite Monroe a large amphitheater has been excavated in the plateau by a plexus of streams, and may be likened to a huge bowl filled with mountains. From this point southward the plateau wall is notched repeatedly by profound ravines heading far back in the table, until, at a distance of about 32 miles south of Monroe, the plateau is cut completely in twain by the East Fork Cañon. From this gap southward 30 miles the southern division of the plateau presents a very few inconspicuous breaks, and terminates in a low wall at a rather lofty and broad transverse valley known as the Panquitch Hayfield. The eastern front of the table looks down into Grass Valley, but from a much smaller eminence, both because the eastern front is absolutely lower than the western, and because Grass Valley is absolutely higher than Sevier Valley. The descent into Grass Valley along the northern and central parts of the plateau is rather abrupt, frequently precipitous; but along the southern part it is very gradual.

The Sevier Plateau is composed chiefly of volcanic sheets of grand dimensions and enormous cumulative thickness, and of immense beds of alluvial conglomerate derived from their degradation. Only at the northern and southern ends are the sedimentaries clearly seen in mass lying beneath the old lavas. At a few intermediate points, however, and especially in East Fork Cañon, some metamorphosed beds of peculiarly interesting character are exposed, and these will receive special attention in the latter part of this chapter.

The eruptions which compose the plateau mass belong to several well-separated periods, which for the most part had their locations at the same centers or axes. Of these centers or axes there are in the Sevier Plateau three—one at the loftiest part of the table at the summit of its northern slope, the second about 20 miles farther south, the third in the southern section of the plateau, right abreast of Panquitch Cañon and about 30 miles south of the second. They may be distinguished as the northern, central, and southern eruptive centers respectively. Of these the largest and most voluminous is the northern one; in truth it is apparently the most important one of the entire district.

Immediately opposite the Mormon town Monroe the great wall of the plateau rises more than a mile above the valley plain, presenting the edges of the volcanic beds, which appear to be very nearly horizontal and more than 4,000 feet in thickness. How much more is impossible to say, for the lowest sheets are concealed. Upon the summit of the wall a transverse ridge runs across the table to the eastern side and ends in a high knob overlooking Grass Valley and named the Blue Mountain. It was in the vicinity of this ridge that the grander eruptions had their origin.

The great amphitheater near Monroe has laid open the table to its foundation, but the promise of information conveyed by such a section is not fulfilled. It has revealed a bewildering maze of earlier rocks lying in all possible positions and having but few intelligible relations to each other. Upon them rest later floods in rather regular bedding, which succeed each other to the summit. I have revisited this locality repeatedly, but have generally found at each visit more questions than answers. The confusion among the lower rocks is indescribable, and the exposures of any given bed so fragmentary that I have been compelled to abandon the effort to unravel the knot, and can give an account of only the most general relations presented. The most conspicuous rock of the oldest series is a ridge of hornblendic *propylite* extending across the opening of the amphitheater. The stream which drains the amphitheater has cut a cleft 20 or 30 feet wide and more than 500 feet deep through this barrier (Heliotype I), and the gorge has received the name of Gate of Monroe. The length of this chasm between propylitic walls is about half a mile. Following it downstream the massive propylite gives place suddenly to beds of conglomerate and clay, baked and altered by heat, which abut in the natural section against the propylite. They are probably younger than the volcanic rock and may have been derived from its waste. At the upper end of the gorge the propylitic mass ends suddenly—a lateral ravine parallel to its precipitous face hiding its mode of exit. On the other side of the ravine is a mass of andesite succeeded by trachyte, both apparently younger than the propylite. The propylitic mass may have been erupted at as early a period as Middle or Late Eocene, for the stratified beds which abut against its western flank have evidently been water-laid, and there is no evidence of the existence of any considerable body of water in this locality later than the epoch referred to. Moreover, beds of similar nature, sometimes altered, sometimes not, are found around the eruptive centers in many localities, and have been derived from the destruction of some unknown volcanic rocks. Fragments of similar altered rocks are brought down by the stream from some of the forks above, showing that on both sides of the propylitic mass these peculiar sediments were deposited. Very partial exposures of propylitic rock are also found elsewhere in the deepest part of the ramifying gorges, cut by the many streams that unite in the creek which cuts the cleft in the larger barrier of the amphitheater.

These propylitic rocks are interesting, inasmuch as they furnish another instance of that priority in time among Tertiary eruptions which Richthofen has claimed for them. Here they are not only older than all other eruptives, but they appear to speak of an epoch in which they alone were erupted, and that epoch probably goes as far back as the Middle Eocene. They certainly do no appear among the later or the middle eruptions. A period of rest from volcanic disturbance succeeded their extravasation, and during that quiescent period they were much ravaged by erosion. Patches of conglomerate, formed of their fragments, were accumulated and are here and there brought to light where erosion has deeply excavated the still grander masses of subsequent lavas overlying them So completely were these most ancient rocks overwhelmed, that erosion has only revealed a very small portion of them and left us to conjecture what may be the extent of those portions now concealed. It is not improbable that the clastic beds, formed of the waste of volcanic rocks, and which underlie the great lava caps of the plateaus and in turn rest upon the Bitter Creek and Green River beds, may have derived their sands and clays from the decomposition of some of these propylitic masses.

These ancient eruptions are succeeded by those of a middle epoch, lying across the surface of an eroded country, which they overwhelmed. These second lavas are much less chaotic in their arrangement and much less affected by erosion during the intervals between the eruption of successive floods. They are, therefore, more intelligible, and some idea of their sequences has been obtained, though less definite than is desirable, because the exposures are so partial and so much obscured by *débris* and soil. These outpours were upon a very large scale, the masses being often several hundred feet in thickness and spreading out over large areas. The lower masses are andesitic and show but little variety. They all belong to the hornblendic group and are characterized by triclinic feldspar, with a moderate proportion of hornblende, with some augite and magnetite, and are very compact and rather fine-grained. Higher up, these give place to coarse-grained trachytes, with both monoclinic and triclinic feldspars and abundant hornblende. These occasionally intercalate with sheets of dolerite. Still higher, a totally distinct group of trachytes is found. They consist largely of the argilloid variety—a fine-grained, highly ferritic, reddish paste, holding porphyritic crystals of opaque monoclinic feldspar. There is probably no eruptive rock within the district more abundant. It forms the summit of the series of middle-aged eruptions in many localities. Very nearly coeval with it is a group of trachytes, having an appearance faintly resembling a fine-grained syenite, though not by any means wholly crystalline. It varies in color from iron gray to light gray. It shows a tendency to break up into slabs or tiles from an inch to four or five inches thick, the cleavage being sometimes parallel with the bedding, sometimes making a large angle with it, like slate. Hornblende, augite, and black mica, in very small crystals, are sparingly disseminated through it. Associated with these are masses of doleritic lava. I use this designation to indicate a rock more basic than andesite, but less so than basalt; and though more nearly approaching the latter, is distinguished from it both in mode of occurrence and in aspect. It is associated with the middle eruptions and I believe never with the later. Its feldspars are triclinic (Labradorite), frequently in large crystals, which have a conspicuous glassy luster, resembling sanidin. It never contains olivin. Usually it is blackish and nearly as dark as basalt, but in some cases it is red, even in compact specimens.

We have, then, in this great amphitheater more than 4,000 feet of volcanic rocks, belonging to at least two periods, and possibly more, separated by long intervals of erosion—the oldest going back into the latter part of the Eocene, the younger belonging to I know not what period exactly, but from general considerations, am disposed to regard them as Miocene or early Pliocene, covering a long period in their totality, which may extend throughout the entire range of Miocene and Pliocene time. At the base of the series we find large bodies of rock, consisting of plagioclase, with considerable quantities of accessory hornblende, and also having the habit of hornblendic propylite and hornblendic andesite. These were much eroded after their eruption and before the extravasation of the later *coulées*. They are succeeded by heavy masses of rather fine-grained augitic andesite in great sheets, reaching a thickness of 300 and even 400 feet, and are followed by equally heavy masses of trachyte, sometimes augitic, sometimes with no great or notable amount of any accessory mineral. With these last doleritic eruptions intercalate

Scrope, in his work on the "Volcanoes of Central France," repeatedly mentions the occurrence of "basalts" intercalating with the trachytic masses of Mont Dore and the Cantal. He was particular to call attention to the fact that in that region no confirmation was found of the view which had been entertained by some geologists that the basalts were erupted at a later period than the trachytes, and notes many instances where "basalt" was overlaid by trachyte. It is clear, however, that Scrope included under the name basalt nearly, if not quite, the whole category of dark-gray and black augitic rocks of rather fine-grained texture, high specific gravity, and more or less conchoidal fracture. To the range of variation which is now known to extend through this class both in respect to chemical and mineralogical constitution he appears to have attached little importance, and, indeed, was unacquainted with such distinctions as have been established by later researches. It has seemed to me possible that the earlier rocks which he has called basalt may prove to be augitic andesite, while the most recent ones are the most basic of their class, and therefore identical with the rocks now assigned by more recent classification to basalt in the more restricted sense of the term, and finally that intermediate varieties may there exist, which are equivalent to those rocks which I have here designated as dolerite. At all events, there is this correspondence—both localities present the intercalation of augitic-plagioclase rocks with trachytes.

Let us now examine the east side of the plateau directly across from the great amphitheater. Another grand exposure is presented here. There is no fault on this side of the table—at least, none has been observed—but a large valley has been excavated not perpendicularly inwards towards the axis of the plateau, but very obliquely, cutting off the gable-like end of Blue Mountain. This name is given to that high knob which stands upon the eastern verge of the plateau, at the end of the transverse ridge which now marks the locus of one of the centers or axes of eruption. The excavation of the valley has cut off the eastern face of this ridge and laid open the structure and arrangement of the various beds. This arrangement is quite similar to what would be expected and to what has often been observed in great volcanic piles. From the central axis the sheets are seen dipping away in both directions at variable angles never very great. On the northern side they descend towards the northeast and on the southern side to the southeast, the lower beds dipping more than the upper ones. All of these lavas seem to have welled up in mighty floods without any of that explosive violence which often characterizes volcanic action, and so great was the volume of extravasated matter, that it at once spread out in wide fields, and deluged the surrounding country like a tide in a bay flowing over all inequalities. How far these floods extended it is difficult to say. To the westward they are cut off in the great wall which faces Sevier Valley with an altitude of nearly 6,000 feet above the river. To the east they are likewise cut off by the oblique valley, though they reappear at lower altitudes on the other side, and are instantly lost again under soil and waste, but evidently descend into Grass Valley, and may commingle with the equally grand floods emanating from the Fish Lake Plateau to the eastward. But south and north they are displayed in immense volume. Those which flowed north and northeast are spread out in the vicinity of Salina Cañon and one great *coulée* stretched beyond the cañon, which now cuts off a portion of it, leaving it as an outlier. Large portions of these old lavas have been swept away. The *mauvaises terres* south of Salina village were once covered with it. Standing prominent among these bad lands is a conical butte-like mountain of singularly perfect form. It is a remnant left by circumdenudation, and upon its summit is a "tip" or cap about 250 feet thick, consisting of this same lava reposing upon the sedimentary strata, out of which the peak has been carved in *cameo*. This mountain is called the Black Cap. The augitic trachyte,* of which its summit apparently forms a remnant, is the same as that which extends across the Salina Cañon. This flow reached a distance of 30 miles from its source. South of the cañon and nearer the source sheets of argilloid trachyte rest upon the augitic and hornblendic, and heavy beds of conglomerate derived from the ruins of both kinds of rock are interspersed. To the northeastward, extending as far as 25 miles, similar aggregates of massive superposed *coulées* are displayed, having a thickness of nearly a thousand feet and increasing in bulk as we approach the Sevier Plateau. The hornblendic trachytes are in the larger proportion, but the lighter gray trachytes, and especially the 'argilloid' varieties, are almost as voluminous. They are much degraded by erosion, and several fine cañons have been cut, ramifying into broader ravines, with big rough swelling hills between them.

* This rock is a conspicuous one. It has many crystals of sanidin, but the less conspicuous plagioclase is very abundant. The line is difficult to draw—perhaps impossible—between some andesites and augitic trachytes. The texture is sometimes the only basis of a distinction, and this should be used with great caution, and never without reservations. Still the textures of the two groups are usually distinct and characteristic, and the rock assumes in most cases the one aspect or the other even when the mineralogical constitution is doubtful. In the very few cases where there is no means of forming a decided distinction it would seem as if the old term "trachydolerite" might be useful. It has the advantage at least of being non-committal.

Southward from the northern center of eruption of the Sevier Plateau the floods are piled up in grand succession sheet upon sheet. No narrow streams or rivers of lava were here, but great deluges, which welled up and rolled majestically over vast Phlegræan fields, and, spreading out in broad lakes, left after their congelation an even stratification, which may be read miles away from distant summits. Standing upon the verge of the Awapa Plateau and looking across Grass Valley, these old floods are seen lying calmly and evenly with an outward resemblance to dark stratified rocks cut by ravines and terraced off into trappean ledges. Ten or fifteen miles southward they have commingled by intercalation with the *coulées* from the middle eruptive focus of the plateau.

The eruptions from this middle locality were inferior in magnitude to those from the northern vents, though absolutely they were by no means small. Its lavas differ somewhat in character from those derived from the northern vent. Trachytes are present in considerable volume, and here as elsewhere alternate with dark doleritic lavas. They succeeded the andesites in the order of eruption. Here we find also the same inclination of the pseudo-strata which is observed in the Blue Mountain, the layers dipping away from the central mass in opposite directions.

Around this eruptive locus we find also those great beds of conglomerate which are so conspicuous throughout the entire district and especially in its southern portions. A mighty wall of this material is presented towards Sevier Valley, just north of the middle vent, and extends for about 8 miles in that direction, where it thins out; but before being quite lost by attenuation is cut off by erosion. It is well stratified and weathers into an abrupt cliff. Here, as elsewhere, it was formed in an ancient valley, lying between the two vents, and has the alluvial-cone structure. The great Sevier fault has cut the formation, and its continuation is seen upon the eastern slopes of Sevier Valley, 3,000 feet below. Upon the southern side of the vent the conglomerate is seen in still greater mass. In truth, its magnitude here becomes astonishing.

Upon the Grass Valley side of this central eruptive locality is seen what is undoubtedly a remnant of a very ancient volcanic cone, afterwards completely buried in the seas of lavas which were poured out around it. At a later date it has been excavated by the erosion of Grass Valley and one side of it exposed. This is a large tufa cone, which must once have been nearly 1,800 feet high, and was formed by showers of small fragments blown from the orifice. They are seen dipping to the southeastward in a large ravine recently excavated in the side of the plateau, and the angle of dip is from 28 to 30 degrees near the summit, but decreases towards the base. The fragments are mostly augitic andesite and are closely compacted with very little cementing material. They are very sharp and angular, showing no evidence at all of attrition The stratification is quite perfect and the entire mass is thoroughly consolidated into a coherent body of stratiform layers. It is noticeable that the fragments are seldom of large size, rarely exceeding in weight ten or fifteen pounds. Only a small segment of this cone is now exposed, and such portions as have been excavated have been ruthlessly attacked by the waters, which have incised deep ravines, which are destroying the cone almost as fast as they are unearthing it. Far above it rise the massy sheets of trachyte and the pediments formed in the projecting sheets lap around it on both sides. Probably it is a very common thing in the history of a volcanic pile for its earlier cones and monticules to be overwhelmed and buried by later outpours. But it may give some notion of the magnitude and grandeur of the eruptions of the Sevier Plateau to see a cone of this magnitude inclosed in rock, as if it were a mere trifle.

The conglomerate forms the principal mass of the plateau south of the central vents for a distance of nearly 20 miles, where it becomes confluent with similar beds derived from the volcanic masses disgorged from the southern vents. It is frequently intercalated with enormous sheets of hornblendic trachyte, erupted during the long period occupied by the accumulation. The conglomerate forms the intervening summit of the plateau between the eruptive localities, and has a thickness never less than a thousand feet and several exposures show more than 1,600 feet of it. Into its composition enter all the varieties of the andesitic and trachytic rocks forming the series of eruptive masses to the northward, which are cemented together by volcanic sand and decomposed fine detrital matter. The degree of consolidation is always considerable and is quite sufficient to enable the edges to stand in great mural fronts many hundreds of feet in height. In this respect it is as consistent as any of the calcareous sandstones of the region. It is, however, more easily attacked by the rains and frost than the volcanics or even than the more massive kinds of sandstone. The included fragments exhibit all degrees of roundness by attrition; are often quite sharp and angular; most frequently a little worn by current-action; sometimes greatly so. Where the fragments are least worn they are most abundant In many places the amount of cement is much less than others, while in some places the fragments are relatively few. In size, the fragments vary from a mere granule to two or three tons. The conglomerates are seen upon the slopes of Sevier Valley at the foot of the western front of the plateau usually flexed upward a little and then cut off by the great fault. On the east side of the plateau they slope down towards Grass Valley (which is in great part a valley of erosion), and are cut off in some places and dip beneath its floor in others, but reappear in the western front of the Awapa Plateau. Whether these beds which are seen in the Awapa are continuations of those in the Sevier Plateau is not absolutely certain, but I think they are.

About midway between the middle and southern eruptive centers the Sevier Plateau is cut completely in twain by a mighty gorge called the East Fork Cañon. It is the old story—erosion. The plateau rose athwart the course of the stream and was sawed in two. It is not a narrow chasm, but a valley walled by ledge upon ledge. The dissevered beds above stand a couple of miles or more apart facing each other across the depths; below, the walls are from 1,000 to 2,000 feet assunder. The total depth varies in different parts from 1,400 to 3,700 feet. The structure of the plateau is thus clearly revealed. The upper rocks are volcanic conglomerate of immense thickness, with intercalary sheets of coarse trachyte, the former well stratified. The lower rocks are of a highly exceptional character, and will be treated of at length in the latter part of this chapter.

The third eruptive focus of the Sevier Plateau stands east of the head of Panquitch Cañon. It bears a strong resemblance in its features and the character of its emanations to the northern vent (Blue Mountain). It is not, however, so well exposed, and much less can be said about it. A grand ravine has eaten its way into it from the western side and disclosed at the base propylite and hornblendic andesite in great masses, and exhibiting evidence of an early period of great erosion followed by the eruption of augitic andesites and many forms of trachyte, which buried the ancient piles beneath their floods. A few fragmentary exposures of old conglomerate, consisting of the ruins of the most ancient lavas, are also revealed near the base. Some of these have been so thoroughly metamorphosed that they form almost a homogeneous mass, in which the cement has an aspect closely resembling the fragments it envelops, and is shot through with minute crystals of feldspar and secondary hornblende. When broken, the surface of fracture cuts the pebbles and cement indifferently. The propylites and hornblendic andesites are more profusely charged with hornblende than those of the northern vent, and the propylites are rather finer in texture. The great mass of rocks now visible in this part of the plateau are of the trachytic series and later in age. They are mostly of the 'argilloid' varieties, but contain fewer porphyritic crystals of orthoclase than are usually found in such lavas, and are heavily charged with ferritic matter, giving them a dirty brown appearance. Those eruptions which flowed westward commingled with those which emanated from Dog Valley, about 12 to 15 miles westward. Of those which flowed eastward I know but little. I have no doubt that they are well exposed in many of the ravines which descend from the crest of the plateau towards the foot of the Aquarius. I have hastily crossed them once, but have no conception of them sufficiently clear to justify me in attempting to describe them. My field-notes indicate a broad expanse of trachytic and andesitic rocks interbedded with volcanic conglomerate sloping gently towards the east and appearing to emanate from the above-mentioned source.

The eruptions from this source did not extend more than 6 or 7 miles southward. On the west side of the Sevier Plateau the last that was seen of them was in a deep cañon-like ravine, called Sanford Cañon, opening into Panquitch Valley about 6 miles south of the head of Panquitch Cañon. Here the strictly eruptive part of the plateau ends, and the continuation of it southward is composed of Tertiary beds of the Bitter Creek group, overlaid by an enormous mass of volcanic conglomerate. Between the two are thin layers of those fine-grained marls and sandstones which have been derived from the decay of ancient lavas, and which were evidently deposited in water. Of the age of these intermediate beds it is possible to say but little. They are apparently conformable to the Bitter Creek below, but the conformity is no proof of continuity of deposition. They contain no fossils. The finer marly and arenaceous deposits are often of an exquisite apple-green color, and in some of the exposures the color is most charmingly delicate. The larger masses are from strong gray to white, when the grain is fine, and brown when it is coarse. Small decayed granules of volcanic sand, hornblendes, mica, and a green mineral, which may be epidote or "viridite," are intimately commingled. Veins of chalcedony and agate often cut the beds, and the fragments strew the soils and badland at the foot of the cliffs.

The fault which uplifts the plateau has not been affected in any noticeable manner by its passage from the volcanic to the sedimentary region. It cut through a country which had apparently been long in repose; where time had been gradually smoothing down the inequalities which had been produced by volcanic activity. When this new disturbance set in it seems to have laid out its line of operations regardless of existing inequalities, splitting whatever it found in its way. In the southern part of the Sevier Plateau it has sheared the old volcanic pile, and passing southward among the sedimentaries and conglomerates it treated them in the same fashion.

The termination of the Sevier Plateau southward is effected by cliffs of conglomerate fringed with buttes. The conglomerate attenuates in that direction, and when its thickness has diminished to about 600 feet it is cut off by the undermining of the sedimentaries upon which it rests. At the end of the plateau the Sevier fault has diminished its throws to less than a thousand feet, and farther southward the throw reaches a minimum of about 600 feet, and thenceforward it increases again. This has produced a very slight sag, in which lies the Panquitch Hayfield, a broad valley-plain having an absolute altitude of a little less than 7,000 feet.

SUCCESSION OF ERUPTIONS IN THE SEVIER PLATEAU.

The following successions of volcanic beds were observed in the Sevier Plateau. An effort was made to obtain some good sections in the Monroe amphitheater, but proved unsuccessful, partly owing to the difficulty of scaling the rock faces and penetrating the clefts, and partly to the fact that the chaotic condition of the rocks in many places makes the section of doubtful value. Thus lavas of later age, filling ravines scoured in older floods, occupy lower positions than the latter, and the contacts are lateral instead of by superposition. Some present thick lenticular outcrops, some recur (probably) at different altitudes. There is much local shattering and faulting which cannot be restored, and many masses vary so much in thickness that it would be misleading to state it without qualification. Most of the heavy masses are presumed to consist of several distinct *coulées*, but the separation is rarely visible or accessible. These difficulties and many others increase towards the base of the series and are troublesome near the summit. The chief value of a collection of sections is the illustration it furnishes of the secular order of eruptions of the various groups of rocks and their intercalary character.

SECTION I.

Commencing at the summit of Mount Thurber and descending southwest; altitude, about 11,160 feet.

	Feet.
1. Granitoid trachyte, composed of layers, ranging from 30 to 80 feet in thickness, the number of which is unknown, and varying but little in lithological character	280
2. Coarse dolerite, several layers	60
3. Somewhat finer dolerite, but with well-marked porphyritic plagioclase	35
4. Argilloid trachyte, reddish brown	140
5. Gray granitoid trachyte	40
6. Dolerite, very fine-grained and compact	12
7. Argilloid trachyte, several layers	110
8. Very coarse and porphyritic dolerite, dark gray, many layers	85
9. Granitoid trachytes, several layers, thickness unknown; only 60 feet measured	60

SECTION II.—MONROE AMPHITHEATER.

Beginning at the verge of the upper amphitheater and descending west-southwest; altitude, about 10,100 feet.

		Feet.
1.	Argilloid trachyte, reddish brown, with large orthoclase crystals	27
2.	Granitoid trachyte, very coarse and somewhat hornblendic, three layers and probably more	100
3.	Fine-grained dolerite	13
4.	Fine-grained dolerite, perhaps two layers	23
5.	Hornblendic trachyte, rather fine grain	80
6.	Granitoid trachyte	45
7.	Light red trachyte, brick-like texture	30
8.	Argilloid trachyte, light gray, with small crystals and grains of magnetite, and probably six or seven layers	220
9.	Augitic andesite, very massive and in many sheets	190
10.	Hornblendic trachyte	40
11.	Granitoid trachyte, coarse grain	175
12.	Dolerite	20
13.	Granitoid trachyte, unknown thickness.	

SECTION III.—MONROE AMPHITHEATER.

Beginning near the base of the great upper cliff on the northern side of the amphitheatre and descending south-southwest; altitude, about 9,800 feet.

		Feet.
1.	Granitoid trachyte, light reddish-brown, with crystals of magnetite	38
2.	Granitoid trachyte, light gray, coarser than the foregoing, containing magnetite	65
3.	Argilloid trachyte, very heavy masses, probably several layers but divisional lines not readily made out, dark-colored porphyritic crystals, much weathered on all surfaces	230
4.	Dolerite, large plagioclase crystals, dark-gray color	40
5.	Augitic trachyte (?), several layers	70
6.	Hornblendic trachyte (?)	150
7.	Argilloid trachyte, light reddish color	115
8.	Augitic trachyte	30
9.	Dolerite	50
10.	Granitoid trachyte, slightly hornblendic, several layers, not readily separable	200

SECTION IV.—MONROE AMPHITHEATER.

Beginning near the central part of the upper verge of inner amphitheater; altitude, about 9,400 feet and descending west.

	Feet.
1. Granitoid trachyte	80
2. Dolerite, brownish gray, much weathered on the surface, much shattered and splintered and falling apart in slabs and tiles, probably numerous layers, not distinctly separable	160
3. Granitoid trachyte, rather dark gray, slightly hornblendic, and somewhat fine grained	35
4. Granitoid trachyte, finer than above and rather lighter in color	30
5. Granitoid trachyte, like No. 3	50
6. Granitoid trachyte, a little darker and coarser than the preceding	65
7. Dolerite	15
8. Argilloid trachyte, numerous sheets very massive and not distinctly separated	420
9. Dolerite	50
10. Argilloid trachyte	50
11. Argilloid trachyte	60
12. Argilloid trachyte	55
13. Trachytic conglomerate	140
14. Granitoid trachyte, dark colored, coarse grain, very hard and compact, and in very massive layers	180
15. Dolerite or augitic andesite (?)	100
16. Hornblendic trachyte, dark and rather fine grained	110
17. Hornblendic trachyte	40
18. Hornblendic trachyte	50
19. Dark granitoid trachyte	50
20. Hornblendic trachyte	95
21. Granitoid trachyte, light brown	33
22. Hornblendic trachyte, dark, coarse grained. This and the preceding numbers below 15 probably consist of several layers each, not well separated	75
23. Augitic andesite in many layers, hard, compact, fine grained, and all very similar in appearance	260
24. Conglomerate, containing fragments of hornblendic trachyte and hornblendic andesite	60
25. Hornblendic trachyte, numerous layers	(?)350
26. Hornblendic andesite, no good estimate possible, but not less than	200

SECTION V.—MONROE AMPHITHEATER.

In the middle gorge of the amphitheater, beginning at 7,750 feet altitude and descending to the west.

	Feet.
1. Granitoid trachyte	110
2. Augitic andesite, in layers varying much in thickness along the exposure	200
3. Hornblendic trachyte, very rough and coarse in texture, probably four or five layers	330
4. Augitic andesite	80
5. Hornblendic trachyte	40
6. Hornblendic trachyte	40
7. Hornblendic trachyte	70
8. Conglomerate, with fragments of hornblendic andesite and trachyte and augitic andesite	55
9. Hornblendic andesite of unknown thickness in numerous layers, with very uneven divisional lines.	
10. Modern alluvial or torrential deposits of unknown thickness.	
11. Tufas, water laid, of unknown thickness.	
12. Hornblendic andesite, possibly forming a part of the same mass as No. 9, lying upon the eroded and highly-inclined surface of propylite; thickness unknown.	
13. Hornblendic propylite, rising in a precipitous wall or barrier far above the last-named mass, but also extending beneath it and unquestionably of greater antiquity	775

SECTION VI.—SEVIER PLATEAU.

In a large ravine about 3½ miles south of Marysvale Peak, beginning on the south side of the ravine and descending westward; altitude, 7,700 feet.

	Feet.
1. Hyaline trachyte, with a few porphyritic crystals, somewhat resembling a liparite, but no free quartz	35
2. Granitoid trachyte, rather dark gray	22
3. Granitoid trachyte, dark gray and coarser than preceding	20
4. Granitoid trachyte	32
5. Granitoid trachyte	28
6. Dolerite, with large crystals of plagioclase in a very fine base	15
7. Hyaline trachyte, similar to No. 1	25
8. Hyaline trachyte, bright reddish color	37
9. Argilloid trachyte, in several layers, varying slightly in character	90
10. Dolerite in several layers, similar to No. 6, with smaller crystals of plagioclase	75
11. Argilloid trachyte, in numerous layers	160
12. Tufas of unknown thickness, but a visible exposure of	220

EAST FORK CAÑON.

East Fork Cañon is a great chasm cut through the Sevier Plateau transversely at its narrowest part, dividing that uplift into two portions. It is wholly the work of erosion, and is an excellent example of the persistence of a river channel in spite of the great displacements of the country along its course. The East Fork of the Sevier River carries the entire drainage of Grass Valley, and has evidently done so through several long geological periods. Grass Valley, as will be seen by the map, is the long narrow depression lying at the eastern base of the Sevier Plateau, and is parallel to Sevier Valley, lying west of the plateau. Between the *loci* of these two valleys the plateau has been, through the later periods of geological time, gradually hoisted several thousand feet. The uplift has been greatest upon the west side of the table, which is bounded by the great Sevier fault. From the western crest-line the plateau slopes eastward; at first very gently, then with a more pronounced descent as far as the wall of the Awapa Plateau. There is no fault on the east side of the Sevier table, but in some portions there is a cliff or abrupt slope caused by long ages of erosion.

Ten or twelve miles north of the cañon are the central vents of the Sevier Plateau, already described as of very ancient date. Twelve or thirteen miles south are found the great andesitic and still greater trachytic centers of eruption. Far back in Pliocene time this fork flowed between these volcanic piles from east to west, joining the main stream of the Sevier River at the foot of Circle Valley. The great changes of topography produced by the elevation of the Sevier Plateau have in no manner affected the location of the fork, which has only sunk its channel as the table slowly ascended. Very grand and imposing is the valley which it has carved through this uplifted mass. It is not one of those deep, narrow chasms cut into the earth, but a terraced valley of notable width, a distance of 2 to 5 miles separating the summit walls, with only a narrow bottom below. In the natural section thus made nearly 4,000 feet of beds, composed wholly of volcanic materials, are exposed. The river near the point of maximum cutting just grazes the top of the yellow Tertiary lacustrine beds, exposing only a few acres, but enough to assure us that we have here the entire volcanic series.

As we enter the lower gateway of the gorge ascending from Sevier Valley we at once recognize the nature of the displacements which have occurred. On the north side are seen immense beds of volcanic conglomerate dipping at angles varying from 12° to 25° to the westward. There is much repetitive faulting here. Again and again the beds have sheared

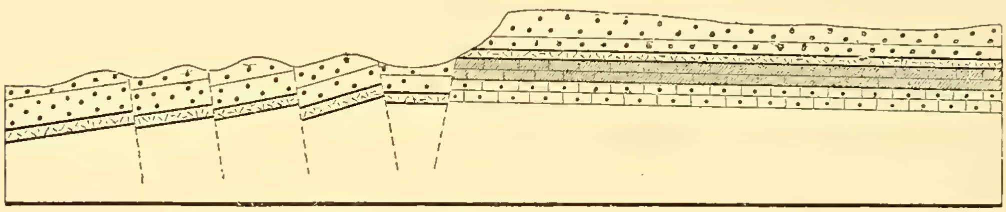
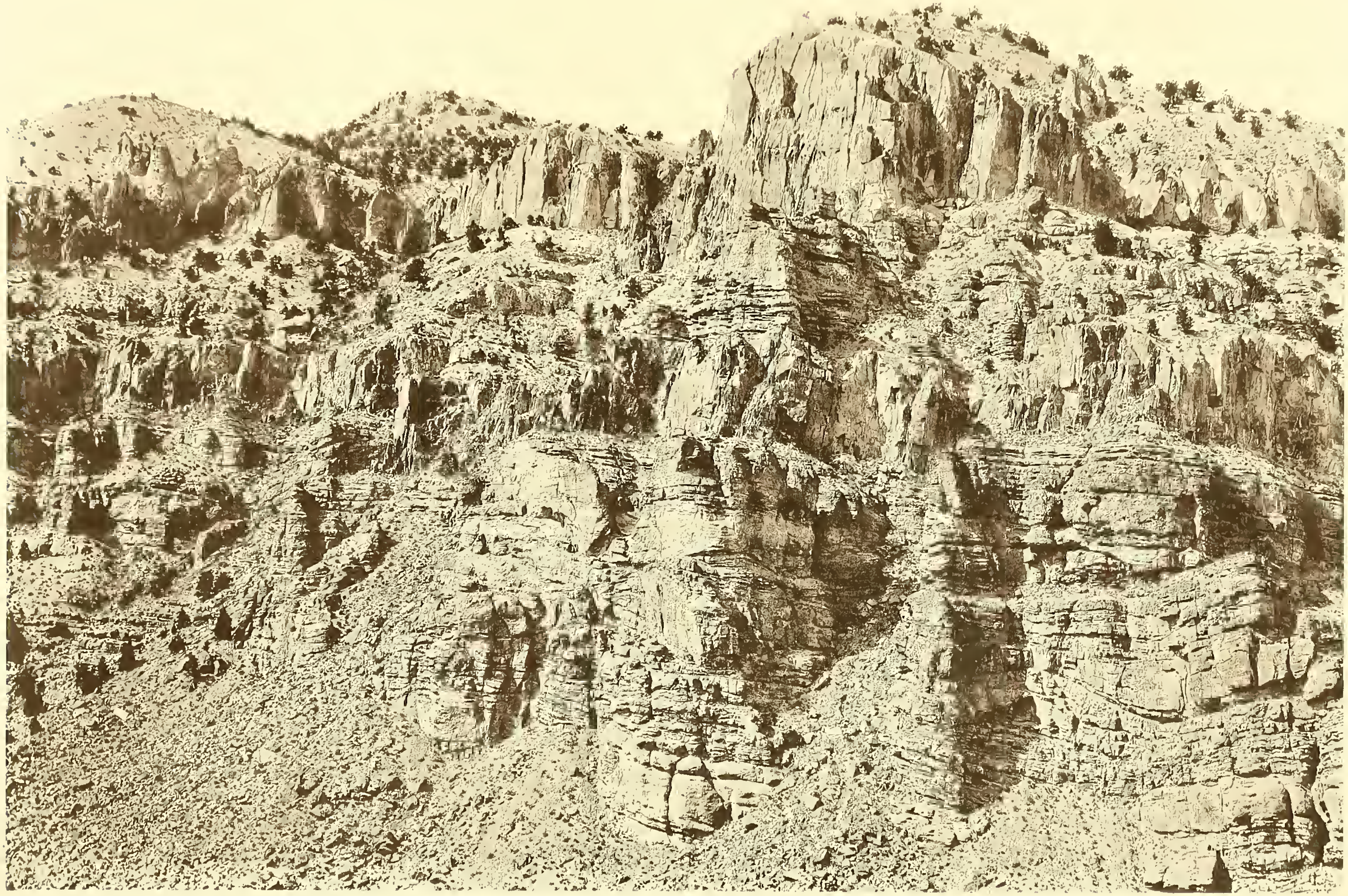


FIG. 4.—FAULTS AT LOWER END OF EAST FORK CAÑON.

and slipped, the throws varying from 200 to 350 feet, all of them being thrown to the eastward. More than 2,000 feet of conglomerate, beautifully stratified in huge massy layers, with intercalations of dark hornblendic trachyte of the roughest description, are exposed in this part of the gorge. Suddenly we miss the conglomerates. They appear to end abruptly at a lateral ravine which enters the main cañon from the north, and on the opposite side of the ravine the rocks are of a totally different character. Through that ravine runs the main throw of the great Sevier fault, here of about 2,500 feet of displacement. As we look beyond it and up to the towering crags of the principal plateau mass, we again recognize the continuations of the conglomerates in the palisades bounding the tabular summit. Beneath them another series of strata has been brought to light by the lift of the fault and the erosion of the cañon. These are tufaceous deposits, presenting features of great interest.

The general aspect of these beds is shown in Heliotypes V and VI.* It is obvious at once from their very aspect that they are water-laid, yet when closely examined all of them are seen to have been subject to alteration in varying degree, which gives them the appearance of massive volcanic rocks. There is one member about 120 feet in thickness which has the character of a volcanic rock so pronounced that no person would doubt that

*The summit of the plateau is not visible from the points where the photographs were taken, as the upper walls of the cañon are beyond the summits of the lower walls.



Heliotype Printing Co., *220 Devonshire St., Boston.*

TUFA BEDS METAMORPHOSED. EAST FORK CANON.

such is its real nature, if confining his examination to a hand-specimen and unaware of its mode of occurrence. It has, however, some peculiarities not common in lavas, though not sufficiently marked to justify their exclusion from that category. It is an acid rock, carrying as much silica as some rhyolites or extremely siliceous trachytes. Feldspar, chiefly monoclinic, is very abundant and in conspicuous, though not very large, crystals. The most notable peculiarity is the abundance of accessory minerals, which is not a common character in volcanic rocks so highly charged with silica. Although they are seldom destitute of accessory minerals, my own observation has given me the impression that they are almost always scantily supplied with them. These minerals are chiefly mica, hornblende, and plagioclase. There is also an unusually large quantity of peroxide of iron in a diffused state, which has given the rock a strong reddish or pink color. It is excessively hard and compact, and one of the most difficult to fracture of any in the whole district. Its chemical composition allies it most nearly to rhyolite, but in texture and in mineral constituents it does not conform so nearly to that group. The base, when examined microscopically, is similar to that which is seen in rocks with a well-marked porphyritic habit. None of these peculiarities would be alone sufficient to affect the conclusion that it is a volcanic rock. My doubts have arisen from other considerations. Both above and below it are thin beds composed of materials which more or less closely resemble it, some so nearly that no appreciable distinctions can be drawn, and these are surely sediments deposited and stratified where they lie and altered by metamorphic action, some more, some less. A transition can be traced, by selecting from the different layers, ranging from tufas which have been but little altered to the extremely hard rock of pronounced volcanic appearance. All of the little altered tufas show that they are composed of water-worn volcanic sands and gravel, and in some which are greatly altered the original pebbles are still visible.

The strata which are composed of volcanic *débris* seem to be extremely susceptible to metamorphism. This is true not only of fine tufas, but of conglomerates which have a pulverulent matrix. But what is most remarkable is that the result of the alteration is not a wholly crystalline rock, like gneiss or diorite or hornblendic schist, but one consisting of an amorphous base holding porphyritic crystals, which is the dominant and distinctive characteristic of a volcanic product. Not only are the various stages of this alteration displayed here, but they may be seen in many other localities within the district; and I infer that similar occurrences are found in many other portions of the western mountain region.

Immediately beneath these tufas, in the heart of the cañon, there is a very small area of common sedimentary beds. Their age is not known, since no fossils have been taken from them, but judging from their litho logical character, they resemble the Upper Bitter Creek Tertiary; and lithological correspondence here is of much more value than is elsewhere attributable to it. They show no trace of alteration, which is all the more remarkable when we find so much change in the beds which overlie them. This relation of altered volcanic clastic beds to underlying unaltered Tertiaries is also presented in the southern part of the Sevier Plateau. These facts appear to emphasize still more strongly the assertion that tufaceous deposits are extremely susceptible to metamorphism. Perhaps this ought not be regarded as surprising. Ordinary sediments consist of materials which have not only been comminuted, but also chemically decomposed and separated into aggregations much simpler than those constituting eruptive rocks, and their chemical correlatives among the metamorphics. Among the common sedimentaries we find chiefly siliceous, argillaceous, or calcareous deposits, with these ingredients commingled; but only now and then presenting such components as would yield by metamorphism rocks corresponding chemically to the volcanics. They are very poor in alkali. The tufas, on the other hand, consist of materials which, though thoroughly comminuted, are not so thoroughly decomposed as those constituting the common sediments, and contain the constituents which by mutual reaction are capable of yielding feldspars, hornblende, and mica.

The geologist in the field is often called upon to note instances of local metamorphism for which he can discover no adequate local cause. On the other hand, he often finds occurrences where metamorphism has not operated, though the conditions seem to be identical with those which are elsewhere believed to have produced it. The phenomena of contact metamorphism have been sufficiently studied to enable us to say confidently that the proximity of heated magmas or the prevalence of high temperature within a mass of strata are not the only conditions requisite for the activity of that process. Strata traversed by eruptive dikes are sometimes altered for many hundred feet from the contact and sometimes are wholly unaffected. This fact alone indicates that something besides high temperature is required to produce such an alteration. Nor do all the conditions appear to be fulfilled when strata containing suitable constituents are subjected to a high temperature, for cases are common where rocks so constituted and conditioned are not altered. Although we do not know all the requirements of metamorphic action, we may feel confident that they are somewhat complex and numerous. One inferential condition is that of a high degree of molecular mobility in the constituents, whereby a free interchange of molecules among the clastic particles or fragments is made possible But precisely how this is effected is a matter of conjecture. It may be by the permeation of heated waters or other liquid or vaporous solvents which may not require a very high temperature, and which may even be effectual at quite moderate temperatures. How far we are required to postulate the absorption of foreign constituents (alkalis and earths) by the entire metamorphosed masses or the elimination of constituents which the masses originally contained are problems too conjectural in their nature for present discussion. That the tufas of East Fork Cañon should have been metamorphosed while the Tertiary (?) strata upon which they rest are wholly unchanged is not a matter so wholly surprising. In the former beds all the conditions precedent have been satisfied, in the latter they have not.

An examination of the heliotypes (V and VI) will show one member more massive than the others which is about 120 feet in thickness. Under ordinary circumstances this would have been pronounced an eruptive sheet without much hesitation. But such a decision would raise some difficult questions. Other layers much thinner, and in some cases not exceeding one or two feet in thickness, are composed of rock very similar to it. Others show a transition from material apparently identical into unaltered or very little altered tufa. In most of the beds rolled pebbles are found, and as the varieties become more and more metamorphosed these pebbles become less and less distinct; and in the massive sheet itself some of these pebbles may still be discovered upon weathered surfaces, though in fresh fractures they appear to have gained an aspect very nearly homogeneous with the general mass. This phenomenon of the gradual vanishment of pebbles is not confined to the tufas, but is frequently seen in the conglomerates, some of which have been greatly altered and converted into a hard semi-crystalline rock strongly resembling andesite and hornblendic trachyte. Moreover, the inferior boundary of the larger sheet is indefinite in many places, and near the fault it appears to have passed lower down and involved beds which are not so much affected farther up the cañon. The lines of bedding near the fault are nearly obliterated, and the thickness of the lava-like mass has greatly increased. I entertain very little doubt that the sheet is not a lava, either contemporaneous or intrusive, but is a metamorphosed tufaceous deposit.

Farther up the East Fork Cañon, upon the north side, stands an isolated mass, consisting of phonolite, represented in Heliotype No. XI. It is a hill about 1,400 feet high, with steep flanks, covered with talus. Near the summit the cleavage of the rock in vertical planes is exhibited with clearness. Upon closer inspection a secondary cleavage, perpendicular to the foregoing, is also disclosed, and the viscous vitreous character of the lava is very conspicuous. Under the microscope it discloses very few crystals, and these are very small, consisting of nephelin. No feldspar was detected. The specimens brought home, though fair in appearance, proved to be much weathered and hardly suitable for microscopic or chemical investigation. The plateau mass around this hill was much eroded, and the eruption of the phonolite appears to have occurred after the erosion had far advanced, for it is an isolated mass, and its lavas flow over rugged ridges and ravines upon its northern side.

GRASS VALLEY.

Separating the second and third ranges of tabular uplifts is a broad depression, named Grass Valley; a name which has done great service in the West, for it may be found in every State and Territory. It is properly an appendage of the Sevier Plateau, from the platform of which it has been in part eroded. The eastern wall of the valley is the uplifted side of the third plateau range, comprising the Fish Lake table at the north, the Awapa in the middle, and the Aquarius at the south. This wall is everywhere due to displacement. The western side of the valley is a wall of erosion formed by the river sinking its channel and the subsequent decay of the mesas by secular waste. The origin of the valley apparently antedates the last general uplifting of the plateaus by a very long period, and its course and general arrangement were probably determined by the configuration of the country which was made at the close of the trachytic epoch of eruptions. The valley then lay between two long lines of volcanic vents, one in the Sevier Plateau, the other in the Awapa, with a broad lava field between them. The vertical movements which subsequently upheaved those tables did not displace the course of the drainage, which only established itself the more immutably in its original position.

The lowest point of the valley is not at either end, but a little south of its mid-length, opposite the head of East Fork Cañon. To this point two streams flow, one from the north, the other from the south, and their waters, here uniting, pass through the cañon to join the Sevier. It was evidently so from a remote epoch. The great cañon itself was at first a mere depression between the central and southern trachytic vents of the Sevier Plateau, but as that mass was upraised, the fork persisted in holding its thoroughfare and cut the rising platform in twain. At one epoch the rate of elevation was sufficiently rapid to dam the fork and create a lake in the valley, which may have been 15 or 20 miles in length. Remnants of old lake beaches are still visible on the southern and eastern sides of the valley, and these possess considerable interest. They are best displayed where Mesa Creek merges from its gorge in the northwestern angle of the Aquarius. They consist of beds which are composed of a mixture of the ordinary detritus which comes from the waste of sedimentary sandstones and that which is derived from the decay of volcanic rocks. Where the former greatly preponderates, the resulting strata have the usual aspect of the lacustrine Tertiary deposits; and where the latter is in great excess the beds have the same appearance and characters as the stratified tufas elsewhere described as of middle or late Eocene age. The case is also presented where the same stratum, traced horizontally along its exposure, passes gradually from one kind into the other. These beds are probably of greater antiquity than the Bonneville beaches around the shores of Great Salt Lake, being in a much more dilapidated condition and only occasional remnants being preserved. Near the head of East Fork Cañon, a large "meadow"* or bog, formed by the accumulation of the finest river silt, deposited by slack water, still indicates the recency of the same struggle between the uplifting of the plateau tending to dam the stream and the agency of the running water in carving its channel and lowering its outlet.

Perhaps the most striking phenomena which may be seen in Grass Valley are the great alluvial cones now forming in the northern and middle portions of it. The great gorge of the Fish Lake Plateau opens into it near the northern end, and a very flat cone, with a radius nearly 3½ miles in length, has been built of the detritus brought down from that chasm. Viewed from the summit of that table, which rises 4,300 feet above it, the periphery of the cone is seen to be very nearly circular through an arc of about 120°, becoming confluent with another great cone south of it. Many others of equal magnitude and quite perfect in form are displayed down the valley, most of them sloping from the Sevier side. They are composed of fragments which are not much abraded or rounded by attrition, and whatever waste they have suffered seems to be due as much to slow weathering as to abrasion. They are held in a matrix of soil which is highly fertile when watered, but too stony for the plough. They vary in size from a few ounces to a few pounds, and near the apices of the cones they are found weighing many hundreds of pounds. At numerous places the shiftings of the streams have enabled them to cut into the cones locally, and the sections always reveal a pronounced stratification. Comparing them with the ancient conglomerates now exposed in the plateau walls on either side of the valley, it is impossible to doubt the identity of the processes which have accumulated both.

No sedimentary formations are found in the northern part of Grass

*In the West, a marshy locality formed by the accumulation of vegetable mold and river silt, yielding a peculiar wild grass, is called a "meadow." In a moister country it would be simply a bog.

Valley. In the southern portion, the lift of the Awapa fault has brought up the Tertiary strata and exposed them in the wall of that plateau. The rocks exhibited in the valley proper are all volcanic. They are chiefly trachytic, and only here and there project above the masses of alluvial matter which is gradually burying them. Just south of East Fork Cañon a few large *coulées* of basalt are seen, and they appear to have emanated from the vicinity of the Awapa fault. They form broad terraces, rising one behind another, and ending in cliff and talus 60 to 80 feet in height. They have been much battered by erosion and are no doubt of considerable antiquity. Basalts of similar character are found overspreading considerable tracts upon the summit of the Awapa Plateau near its western verge and upon the northwestern edge of the Aquarius.

PAUNSÁGUNT PLATEAU AND PÁRIA VALLEY.

Crossing the Panquitch Hayfield we reach the foot of a very gentle slope, which rises almost insensibly to the southward, forming a plateau of the ordinary type called the Paunságunt.* Its length is about 25 miles and its width from 8 to 12 miles. It lies in the southward prolongation of the major axis of the Sevier Plateau, from which it is separated by the shallow depression of the Panquitch Hayfield. Its western front is formed by the uplifted side of the Sevier fault. Its eastern front is a cliff of erosion looking down into the Upper Pária Valley; a valley of erosion draining into the Colorado. There is a fault a little distance from the eastern wall running north-northeast, but the Paunságunt is upon the thrown side of it. So great has been the erosion in Pária Valley that, notwithstanding the greater altitude of the strata within it than the altitude of their continuations in the plateau, the valley is from 3,000 to 3,500 feet below the plateau summit. If the denuded strata could be restored, they would make the locus of the valley nearly 2,000 feet higher than the plateau.

The Paunságunt is composed wholly of sedimentary beds: Eocene resting upon Cretaceous. The stratification is sensibly horizontal, though at several localities on the eastern flank the junction of the two series is

* Paunságunt means the "place of the beavers."

unconformable. In the cliffs of the eastern and southern margins the following series is presented:

	Feet.
1. Gray ealeareous sandstone	180
2. White limestone	160
3. Red marly limestones and ealeareous shales	300
4. Red pinkish limestone	450
5. Conglomerate, with small pebbles and gravelly sandstone	190
	1,280

Below these are the characteristic gray Cretaceous shales, somewhat arenaceous, forming long spurs and foot-hills. They do not here form cliffs, but long slopes, descending into the lower regions adjoining. From the southern extremity of the Paunságunt they rise with a slight inclination towards the south and are beveled off by erosion. At one point the section crosses (southward) a decided monoclinal flexure with a maximum dip of about 10° to 12° trending east and west, but quickly reflexing back to a dip of 3° to 4°. One after another the formations end in cliffs and ledges, and the profiles drop at each crest-line upon lower beds, until at a distance of about 23 miles from the southern end of the plateau the carboniferous forms the final platform, and rises gently but continuously to the Grand Cañon.

The western side of the plateau looks down from its northern half upon the valley which carries the upper waters of the South Fork of the Sevier River. Across this valley the gentle slopes of the Markágunt rise towards the west. Along this base of the Paunságunt runs the Sevier fault, but before reaching the end of the plateau its course changes from south to the southwest. Just where this change occurs is the divide between the valley of the Sevier and the headwaters of the Virgin, a tributary of the Colorado. The wall of the plateau thenceforward becomes a cliff of erosion gradually swinging to the southeast, then around the end of the table (which projects southward like a great promontory), and finally trends to the northward. The summit of the table has a central stream which gathers all the drainage and carries it northward to the Panquitch Hayfield, thence into the East Fork by the way of Grass Valley, and finally through East Fork Cañon into the Sevier River.

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Pink Cliffs. Lower Eocene. Paunsagunt Plateau.

From the southern cape of the plateau we look southward over an immense expanse. The Kaibab is in full view, stretching away southward until its flat summit and straight palisade is lost in illimitable distance. To the southwest Mount Trumbull is seen nearly a hundred miles away. To the southeast a farrago of cliffs and buttes of strange forms and vivid colors breaks up the monotony of the scene. But the eastern and northeastern view is one which the beholder will not easily forget. It is the great amphitheater of the PARÍA.*

An almost semicircular area, with a chord 30 miles in length, has been excavated into a valley by numberless creeks and brooks, which unite into one stream named the Paria. This stream is at present a mere thread of water flowing southward to the Colorado, which it reaches at the head of the Marble Cañon. During nine months of the year so feeble is the stream that it sinks in the sands before reaching the Colorado, but it is a raging torrent during the months when the snows are melting. The many tributaries which ramify in all directions are generally dry during the greater part of the year, but a few of them are perennial. Every one of these little streamlets has cut its cañon, and nearly all of them are abrupt and impassible save by very difficult and tortuous trails made by Indians and preserved from obliteration by the few herdsmen who pasture cattle in the vicinity. Yet it seems that at a comparatively late geological epoch the climate may have been much moister than at present, and these many water-ways carried perennial streams. Such a climate in all probability prevailed during the glacial period and during the Miocene age. The amount of erosion which has here been produced is very great. By reference to the stereogram it will be seen that the *locus* of the Paria Valley is constructed as a great uplift. The strata which are found within its confines occupy much higher horizons than their continuations beneath the Kaiparowits Plateau on the east and the Paunságunt Plateau on the west. In these two plateaus the erosion has been small for some reason, while in the Pária Valley it has been very great, approaching in extent the vast erosion which has taken place to the southward in the Kaibab district.

* In the pronnnciation of this name the vowels have the German sound, and the accent is on the middle syllable (Pah-rí-ah). It is the Ute name for elk.

From the center of the great Pária Valley or amphitheater the dip of the strata is semi-quaquaversal; that is, towards the east, north, and west, and all intermediate directions; but towards the south the strata incline upwards. The erosion has been greatest in the center of the amphitheater, and has proceeded radially outwards just as in the San Rafael Swell. This process has left the strata in terraced cliffs facing the center of the amphitheater, and as we look across from the southern cape of the Paunságunt to Table Cliff and Kaiparowits Peak, more than 30 miles distant, we behold the edges of the strata, sculptured and carved in a fashion that kindles enthusiasm in the dullest mind. At the base of the series the vermilion sandstones of the Upper Trias are seen in massive palisades and gorgeous friezes, stretching away to the southward till lost in the distance. Above them is the still more massive Jurassic sandstone, pale gray and nearly white, without sculptured details, but imposing from the magnitude and solidity of its fronts. Next rises in a succession of terraces the whole Cretaceous system more than 4,000 feet in thickness. It consists of broad alternating bands of bright yellow sandstone and dark iron-gray argillaceous shales, the several homogeneous members ranging in thickness from 600 to 1,000 feet. But the glory of all this rock-work is seen in the Pink Cliffs, the exposed edges of the Lower Eocene strata. The resemblances to strict architectural forms are often startling. The upper tier of the vast amphitheater is one mighty ruined colonnade. Standing obelisks, prostrate columns, shattered capitals, panels, niches, buttresses, repetitions of symmetrical forms, all bring vividly before the mind suggestions of the work of giant hands, a race of genii once rearing temples of rock, but now chained up in a spell of enchantment, while their structures are falling in ruins through centuries of decay. Along the southern and southeastern flank of the Paunságunt these ruins stretch mile after mile. But the crowning work is Table Cliff in the background. Standing 11,000 feet above sea-level and projected against the deep blue of the western sky, it presents the aspect of a vast Acropolis crowned with a Parthenon. It is hard to dispel the fancy that this is a work of some intelligence and design akin to that of humanity, but far grander. Such glorious tints, such keen contrasts of light and shade, such profusion of sculptured forms, can never be forgotten by him who has once beheld it. This is one of the grand panoramas of the Plateau Country and typical in all respects. To the eye which is not trained to it and to the mind which is not inured to its strangeness, its desolation and grotesqueness may be repulsive rather than attractive, but to the mind which has grown into sympathy with such scenes it conveys a sense of power and grandeur and a fullness of meaning which lay hold of the sensibilities more forcibly than tropical verdure or snow-clad Alps or Arcadian valleys.

The Amphitheater or Upper Valley of the Pária seems from the summit of the Pink Cliffs to be a slightly rugged basin, but like most of the Plateau Country it is found to be a difficult field to traverse. A network of sharp cañons several hundred feet in depth ramifies through it, and the traveler is apt to become entangled in their mazes, and find himself confronted every few miles with an impassable chasm, never seen until he is almost upon the point of driving his mule into it. A few tortuous traits wind deftly among them, leading by break-neck paths into their depths and out again, and finally into the broad and grotesquely picturesque bottom of the Pária River.

The Paunságunt is the southernmost extension of the system of the High Plateaus, and is a promontory thrust out into the terraces which step by step drop down to the Kaibab district. In this series of terraces are exposed the edges, almost always cliffwise, of the entire Mesozoic system of the region. Just here the Cretaceous does not form such conspicuous cliffs as it presents farther east, but the Jurassic and Triassic series are seen to the southward in their most typical forms. The exposures are truly magnificent. While the cliffs front southward, presenting in naked walls their entire thickness and disclosing every line, they are also cut from north to south and sometimes diagonally by cañons, which reveal their dip and structure. But as these terraces are more properly a part of the Kaibab system, no detailed description will be given of them here. The Paunságunt itself is a simple tabular block of Lower Eocene beds, of which a section has just been given. It is exceedingly simple in its structure, and, further than has been already described, presents very little matter for special remark. It is destitute of eruptive rocks, except at its northern end, where a number of basalt streams appear to have burst out of the western wall near the summit and poured down upon the talus and slopes below. They are of small extent and mass, and are noteworthy only as an instance of the peculiar positions from which basalt sometimes breaks out.

A few miles to the south of the southern cape of the plateau is another small field of basaltic eruption. It is located in the bottom of a rather broad valley or basin. A large cinder-cone is still standing singularly perfect in symmetry and perfect also in its preservation. The cup at the summit is not broken down, but still preserves a continuous rim. From this cone streams of basalt flow southward, and entering a cañon in the Jurassic sandstone reach the front of the White Cliffs nearly 12 miles from their source. The individual streams have spread out very thin, and are in some places very slender, with every indication of extreme fluidity at the time of their passage. In the cañon the basalt is nearly all swept away by erosion, only a few small patches (*in situ*) being left to indicate its former existence. But beyond the cañon larger remnants are seen, and these evidently formed the terminations of the *coulées*. It is impossible to affirm anything as to the age of this basalt, though I have little doubt that all the damage it has suffered from weathering and erosion might surely have been accomplished in the period of a thousand years and perhaps in a shorter time. On the other hand, it may be several thousand years since the vent became silent. Four miles to the west of this cone stand half a dozen others, perched high upon cliffs or mesas, and sending their streams into the upper cañon of Kanab Creek. These appear to be older and more weather-beaten, though evidently belonging to the most recent geological history of the country.

CHAPTER XII.

THE FISH LAKE PLATEAU.—THE AWAPA.—THOUSAND LAKE MOUNTAIN.

Southern extension of the Wasatch monocline across Salina Cañon.—Its bifurcation into the Sevier and Grass Valley faults.—Strawberry Valley.—Ascent of the northern slopes of Fish Lake Plateau.—Summit Valley.—Tertiary exposures.—Fish Lake Plateau.—Its summit.—The great gorge and cliffs.—Sources of the volcanic sheets.—Origin of the gorge.—Fish Lake.—Moraines.—Reversal of the course of the drainage.—Alcoves in the plateau wall.—Succession of beds.—Trachytes and dolerites.—Augitic andesites.—Location of the vents and sources of the lavas.—Outlet of the lake.—Mount Terrill.—Mount Marvine.—Origin of Summit Valley.—Isolation of Mount Marvine from its parent mass.—Moraine Valley.—Exposures of Tertiary beds.—Mount Hilgard.—Gilson's Crest.—Lavas of Mount Hilgard.—The Awapa.—Its general configuration and structure.—Its desolate character.—Great variety of rocks displayed in the Awapa.—Hornblendic and granitoid trachytes.—Conglomerates.—Propylites.—Basaltic fields of ancient date.—Rabbit Valley.—Its structural origin.—Erosion of the lava sheets around the borders of the valley.—Accumulation of modern alluvial conglomerates.—Exposures of Tertiary beds in Rabbit Valley.—Thousand Lake Mountain.—A remnant of the grand erosion of the Plateau Province.—Lava Cap.—Underlying Tertiary.—Absence of the Cretaceous and unconformity of the Tertiary with the Jurassic.—The Water Pocket flexure and its age.—Jurassic sandstone.—Triassic beds.—The Shinárump and its sculptured cliff.—The Red Gate.—The separation of the mountain from the Aquarius Plateau.

The third range of plateaus, including the Fish Lake, the Awapa, and the Aquarius, are not inferior in interest to those already described. Connected with them are the masses of Mounts Marvine and Hilgard with the intervening valleys. Far to the northward, in the extension of the same line, is the Wasatch Plateau, of which the structure has already been described. The great monoclinal slope which forms its western flank splits gradually into two displacements in its southward extension, one of which forms the Sevier fault, and the other, passing gradually from a monoclinal into a sharp dislocation, forms the Grass Valley fault on the eastern side of Grass Valley. The uplifting along the course of the Sevier fault has produced the Sevier Plateau. The uplifting along the other branch or Grass Valley fault has given rise to the Fish Lake table and the Awapa Plateau.

As we go southward from the Wasatch Plateau, crossing Salina Cañon near its middle, we at once begin to ascend the northern slopes of the third chain. We are among the sedimentaries, which dip gently to the westward; and descending from the south, a noble valley opens into the middle of Salina Cañon, with the edges of the lowest Tertiary beds walling it abruptly on the west and the surface of the Upper Cretaceous rising gradually on the east. This lateral valley is named, locally, Strawberry Valley—a name which recurs with great frequency throughout the mountain regions of the West. As we move upward towards the south the dip of the beds increases, and the very long and gentle inclination of the strata at length becomes wrinkled into a monoclinal of large proportions. We perceive this readily when, at a distance of 4 or 5 miles south of Salina Cañon, we climb the western wall of Strawberry Valley, and see directly in front of us to the southward the Tertiary beds covered with immense sheets of old lava, but exposed beneath in a deep ravine. We see them rising monoclinally from the west and smoothing out eastwardly to a sensibly horizontal position at a high altitude. The underlying sedimentaries are well exposed, for erosion has carved away much of the country to the northward and given admirable sections transverse to the main structure lines and axes. Three days' inspection of these northern flanks will convey a full conception of the general features of the structure, for they are very easily read.

Climbing the western wall of Strawberry Valley, we reach a platform about 2 miles wide, from which start the long slopes leading up to higher levels. Immediately in front is the Fish Lake Plateau, full 4,000 feet above us. To the south-southeast is an easy ramp leading up to Summit Valley, an elevated interspace between Fish Lake Plateau and Mount Marvine. As we ascend this grade, we have on the right a deep ravine carved into the general plateau mass, laying bare, in an admirable manner, the sweeping curves of the Tertiary beds, overlaid by trachyte, both being bent into typical monoclinal form. The strike of this monoclinal is visible, extending south-southwest nearly 15 miles, giving origin to a slope varying in inclination from 18° to 20°, and with no other ravines than the one just mentioned. It conveys to the eye an impression of singular smoothness—like a vast roof. The slope we are ascending is much more uneven; and, at an altitude of about 9,300 feet, brings us upon the floor of Summit Valley. Upon the west is a sharp crest-line, constituting the eastern verge of Fish Lake Plateau, which overlooks the valley from an altitude of 11,000 to 11,400 feet. Upon the east side rise two conspicuous masses—Mount Terrill and Mount Marvine. This valley is an excellent starting-point, from which we may make excursions radiating in many directions, and study in detail the diversified objects which compose the surrounding country. And, first, let us look at the nature of the valley itself.

Not the smallest among its attractions for the geologist is the fact that it is a most eligible summer camping-place. In the daytime, throughout July, August, and most of September, it is mild and genial, while the nights are frosty and conducive to rest. The grass is long, luxuriant, and aglow with flowers. Clumps of spruce and aspen furnish shade from the keen rays of the sun, and fuel is in abundance for camp-fires. Thus the great requsites for Western camp-life, fuel, water, and grass, are richly supplied, while neither is in such excess as to be an obstacle to progress and examination.

The valley floor is, for the most part, Lower Tertiary. For a considerable portion of the length the edges of these beds are exposed upon the eastern side of the valley, forming the lower slopes of Mounts Terrill and Marvine. They are also seen at the base of the Fish Lake slopes; but a little higher up they are covered with ancient lavas. Northward, however, lavas form the floor of the valley. Proceeding in that direction a few miles, the mountain-walls which inclose the valley rapidly decline in altitude and die away in steep slopes, while the platform on which we travel at length becomes the summit of a plateau, having an altitude about 2,000 feet lower than the neighboring tables; and projecting 4 or 5 miles farther northward, it ends in abrupt volcanic cliffs, from the crests of which we overlook all the space which intervenes between them and the Wasatch Plateau, 20 miles distant. The thickness of the lava at these cliffs is about 700 feet, and is composed of hornblendic trachytes in very massive sheets, alternating with augitic andesites, which are much thinner. Retracing our steps and traveling to the southern end of the valley, we find its floor undulating with little hills, a part of which are Eocene beds and a part are old terminal moraines, of which more will be said hereafter. A fine stream runs along the valley, and at the southern end is joined by a still larger one, issuing from Fish Lake, a few miles to the south-west.

FISH LAKE PLATEAU.

An easy way of reaching the top of this plateau is by ascending its northeastern angle from Summit Valley. If the route be well chosen, we may reach the highest point without once dismounting. The summit is about 12 miles in length and 2 miles in width; is nearly level, or very slightly undulated; and stands about 11,600 feet above sea-level. On every side it is bounded by precipitous cliffs, except along a part of its southwestern flank, but here and there the walls are broken and notched. Along the side facing west-northwest runs a cliff of vast proportions, second only to the western front of the Sevier Plateau in magnitude and grandeur. Upon the very brink of this wall is the highest point of the plateau, from which, in a clear day, we may easily discern the peaks of the Wasatch around Salt Lake City and beyond. These are more than 150 miles distant. Mount Nebo, 70 miles northward, seems like a near neighbor, and the gray peaks of the Tushar are seen towering beyond the heights of the Sevier Plateau. To the southward looms up the grandest of all the plateaus—the Aquarius—its long straight crest-line stretched across the whole southern horizon, and seeming but a few hours' ride away from us. Here we do not feel that sense of being upon a plain which impresses us while traveling upon the other plateaus, but we realize that this summit is at a great elevation; for we may look afar off in every direction to valleys and plains which lie thousands of feet below us, and beyond which we perceive other summits rising to altitudes nearly or quite equal to our own. But perhaps the most impressive feature of the scenery lies almost beneath our feet. It is a grand amphitheater, eroded deep into the plateau mass. Its dimensions and grandeur are surpassed only in the great amphitheater in the Sevier table near Monroe. It is less rugged and diversified than the latter, but is more picturesque, chiefly because the eye can command the whole of it at once. The summit upon which we stand is upon the edge of a straight unbroken wall 4 miles long and nearly vertical for 1,200 feet, then descending in steep slopes to the central line of depression, which declines to the westward until the gorge opens into Grass Valley, 4,300 feet below. Across the abyss rises the other wall, somewhat less lofty and abrupt than this, and we can look over it to the great irrigated farms of the Lower Sevier Valley, 40 miles away. In this gorge a grand section of volcanic rocks is exposed, of which the total thickness now visible will aggregate very nearly 4,000 feet. The exposure, however, is not so advantageous for study as might be desired, since the upper third is inaccessible cliff and the lower two-thirds are heavily mantled with soil held in place by forests of spruce and aspen, or are hidden beneath huge banks of coarse talus. The disconnected exposures, however, are very many; and, so far as each one individually extends, it exhibits distinctly the local attitudes of the rocks.

The first inquiry which arises is, whence came all these lavas? The question is not easy to answer satisfactorily, for they were erupted far back in Tertiary time, and the changes which the country has undergone since their outpouring are very great. The nearest great centers of eruption which we are now able to identify with certainty are Blue Mountain, nearly 12 miles distant across Grass Valley, and Mount Hilgard, nearly as far in the opposite direction. As for the Fish Lake table itself, it does not furnish very decisive indications of being an eruptive center. In the cliff wall which faces the great amphitheater the successive sheets are seen to lie nearly horizontal, parallel, and continuous over great distances. Although they cannot be reached from below, yet they can be distinguished by their colors, which are apparently identical with those in the great west wall of the Sevier table overlooking Monroe. The beds are very massive and are dark iron-gray (hornblendic trachyte), alternating with a number of shades of red (augitic andesite, argilloid trachyte, and dolerite). No distortion or confusion of the layers and no dikes were observed. None of those signs of a volcanic core or center which are seen in Blue Mountain or in portions of the Monroe amphitheater are here apparent. Nevertheless, it seemed to me that the source of these lavas could not be far distant. Since the face of the great cliff is parallel to the general course of the structure lines, it is not surprising that the evidences of an eruptive center should be few and inconspicuous, or even escape notice altogether.

The gorge itself is the work of erosion, and its apparent history is worthy of passing mention. The course of this valley cuts obliquely across the great monoclinal flexure which forms the western flank of the Fish Lake Plateau, and was in process of excavation before that flexure was formed. Like almost all other valleys, its position and direction are quite independent of the structural features of the country, and when the final uplifting took place it did not divert here the course of the drainage. Its only effect was to increase the amount of excavation to be done. The position of the great gorge upon the shoulder of the monocline and running obliquely across it is very striking, and might have given rise to a great deal of speculation as to its origin, were we not able to apply to it the exceedingly simple solution of the antecedence of drainage courses to the structural features of the country and their persistence in spite of changes of great magnitude. At first the interior of the gorge suggests a vast *caldera*, like those described by Lyell in the Cape de Verde Islands or the Val del Bove at Ætna. But it is neither a *caldera* nor a Val del Bove, as a study of the surrounding country abundantly proves.

Passing across the nearly level summit a distance of 2 miles we reach the southeastern verge of the plateau, whence we may look down upon the beautiful surface of Fish Lake. This sheet of water, about 5½ miles in length and a mile and a half in breadth, is walled in by two noble palisades. The one on which we imagine ourselves to stand—the plateau summit—is about 2,600 feet above the water; the other is nearly a thousand feet less lofty. The lake itself is about 8,600 feet above the level of the sea. No resort more beautiful than this lake can be found in Southern Utah. Its grassy banks clad with groves of spruce and aspen; the splendid vista down between its mountain walls, with the massive fronts of Mounts Marvine and Hilgard in the distance; the crystal-clear expanse of the lake itself, combine to form a scene of beauty rarely equaled in the West.

The subjects of geological interest to be found in the vicinity are numerous. First may be mentioned the origin of the lake itself. Mr. Howell's first impression was that glaciation had played an important part in its excavation. Mr. Gilbert expressed the opinion that it might have been caused by the sinking of a block between two faults. But I have been unable to discover sufficient evidence to sustain ether view. Although the traces of ancient glaciers are conspicuous in the vicinity, nothing can be more sharply defined than the places where they terminated; and we are able to affirm confidently, by a comparison of places in close juxtaposition, that in one place the sculpture is due to glaciation and in another it is not. It does not appear anywhere in this part of the plateaus that the glaciers ever extended much below the 9,000 feet level, for at about that level the terminal moraines cease and give place to other forms of sculpture. As regards the possibility of a sunken block between two faults, it seems to me that the evidence is not sufficient to establish it, and there is decided evidence that it is an ancient valley of erosion, having its main features marked out and partially developed before the present elevation of the country had been reached. At the southwestern extremity is a low divide, scarcely 30 feet above the water level, which forms the local watershed between the Colorado drainage system and that of the Great Basin. At present the lake drains into the Colorado system; but at no distant epoch it apparently drained into the basin system, flowing over this low divide. Its ancient channel, leading down into Grass Valley (tributary to the Sevier River), is as distinct and unmistakable as if it had dried up only a few years ago. Mr. Howell, who recognized this channel and its obvious meaning, supposed that the barrier now forming the divide had been produced by morainal *débris* brought down from the Fish Lake Plateau and deposited athwart the channel. More careful scrutiny, however, shows that the barrier consists of volcanic rock in place. Hence it appears that the course of the drainage has been reversed. Originally it flowed out of the lake to the southwest; but as the gradual uplifting went on the whole lake basin was tilted, so that it began to flow out of the opposite end and over a low barrier to the east and southeast. A very slight tilting only was required to effect the change; and a drop of 40 or 50 feet on the western side would again reverse it to its original channel and pour it down the Awapa wall into Grass Valley.

A journey along the bank of the lake towards its outlet is instructive as well as entertaining. The trail (I believe there is now a wagon-road) leads along the base of the plateau wall, rising more than 2,000 feet above us and notched deeply here and there by great recesses of peculiar form and appearance. These alcoves are half a mile or more in width, and set back into the plateau mass a mile or two. They are filled with coarse broken rubble or talus, over which it is extremely difficult to make progress, but still practicable. These alcoves are the work of ancient glaciers, and extending from the opening of each of them is a pile projecting out towards or even into the lake basin and forming a terminal moraine. Near the lower end of the lake is a moraine a projecting a mile and a half from the plateau, and consisting of soil, rubble, and bowlders piled in a confused mass to the height of nearly 200 feet and having a width of nearly a mile. It almost divides the lake into two. The summit of the moraine holds many pools of water embowered in aspens and bushes of many kinds, inviting to lovers of the picturesque, but disappointing to him who accepts the invitation. This is the largest moraine in the vicinity, though absolutely it is not a very extensive one. It is instructive chiefly because it indicates how small a part glaciation has played in the sculpture of this country. There is never any difficulty in distinguishing the work which has been performed here by ice from that which has been accomplished by the more usual processes of degradation. The effects of glaciation are distinct and peculiar, and cannot easily be confounded by a skilled observer with the results of any other action. Doubtful cases do not seem to occur; at least I cannot recall any which conveyed doubt to my own mind. The ice which formed the ancient glaciers of course accumulated upon the summit of the plateau. That summit is about 12 miles in length and 2 to 3 miles in width. It is very nearly level and is not deeply scored by ravines in the central parts, but only upon the edges of the walls which bound the table on nearly all sides. The ice may have accumulated to a considerable thickness upon this summit, so broad and so nearly level, before attaining sufficient mass to flow readily. Most of the effects were exerted upon the eastern and south-eastern walls of the plateau, for such inclination as it possesses is in those directions. The grander wall, which overlooks the great gorge, is not perceptibly affected by glacial action, and it is not probable that the ice flowed over it to any considerable extent.

In the glacial gorges the rocks are very accessible for study. They form a great aggregate thickness of trachytes, alternating with augitic andesites and some dolerites. The intercalary relations of the trachytes with the augitic sheets is conspicuously marked, as is also the transition from hornblendic trachytes near the base of the exposures to argilloid, granitoid, and even hyaline trachytes at the summit of the exposures. These older trachytes are dark gray, sometimes with a greenish or olive tinge, suggestive of the andesitic group, but retaining a predominance of the trachytic characters. Among them are found what appear to be augitic trachytes, but they have not yet been studied very critically, and they differ notably in their macroscopic facies from the more abundant and voluminous augitic trachytes lying at lower levels around Salina Cañon. About the middle, or a little below the middle, of the mass are found very heavy beds of argilloid trachyte. Throughout the northern part of the district there is no single variety of rock which occurs in such massive beds or with such frequency. Its texture and habit are strongly individualized and peculiar. It varies somewhat in color, ranging from dull red to a dark purplish hue; in fact, having the same range of colors as common clay-slate. It is soon recognized in the great walls of the plateaus by its color, especially at sunset, when the cliff faces the west, or in the morning when the cliff faces the east. At such times the color characters come out strong and clear, and the greater thickness of the beds also adds confidence to the recognition. Higher up many varieties of light-gray trachyte are found, belonging to the sanidin-trachyte group. Many of these have the characters of clinkstone (not phonolite), being resonant and foliated in a peculiar manner. Some of the sheets are broken up by a system of cleavage joints into regular tiles an inch or two in thickness, and having from one to three square feet of surface in the broader faces. In other sheets the cleavage, though conspicuous, is not so regular. Upon the extreme summit of Fish Lake Plateau is a small remnant of an ancient *coulée*, which was once no doubt of large proportions. It is of the granitoid variety, and all that now remains are some large blocks (as large as cottages), looking like huge bowlders clustered together. Several of these are poised upon smaller blocks, and during a keen blast of hail and snow I had once an occasion to feel grateful for the shelter afforded me when I crept beneath one large mass supported upon four corner-stones. Where lavas are disjointed into large blocks of this kind it is not uncommon to find them, in the last stages of decay, taking the aspect of a heap of gigantic bowlders. Granites and massive sandstones sometimes exhibit the same behavior. The companions of these blocks have in this case probably been carried off by ice into the gorges, and thus, instead of being erratics, they are the source from which many erratics have probably emanated.

In addition to the trachytic rocks of Fish Lake Plateau, many flows of augitic andesite and dolerite are also found. These occur as intercalations between the trachytes, and are very numerous; but as they lie in much thinner sheets their aggregate mass is much less. The augitic andesites are older than the dolerites, and are seen in greatest frequency at the lower horizons. They vary considerably in character, some being hardly distinguishable from the augitic varieties of trachyte, and having a grayish color, while others merge into dolerites. Several varieties were found, which were of a bright red color, and which might, upon hasty examination, have been very deceptive. The iron contained in these varieties appears to be largely in the form of peroxide, and both the magnetite and augite have been altered, not by ordinary weathering, but by some metasomatic change which I have not met with elsewhere. It does not appear to be identical altogether with that alteration which reddens the scoria of basaltic cinder cones, though the two changes may have much in common. In these varieties the plagioclase crystals are well developed and retain their lively polarization, and are exquisitely striated.

No particular portion of Fish Lake Plateau could be designated as a focus of the very many eruptions which constitute its mass. Nothing like a cone or crater is anywhere discernible, unless in some spot there may yet remain the ruins of such a feature so nearly obliterated as to escape ordinary or cursory observation. The several beds appear to lie in well stratified sheets, somewhat irregular in form, occasionally highly so, but on the whole decidedly like a series of coarse sedimentary strata in their general grouping. This, however, does not necessarily involve the inference that the lavas came from a distant source or were not erupted from numerous fissures and orifices in the vicinity and within the plateau mass itself. In truth, it seems little doubtful that the Fish Lake Plateau is a great center of eruption. A general fact in support of this view is that in three directions—north, south, and east—and in all intermediate directions, the mass of erupted material attenuates gradually. Whether this be true also of the west side it is impossible to say, because the great monocline carries everything down beneath the alluvium of Grass Valley. But in the other directions we can form a fair notion of the general arrangement of the total extravasation, and the attenuation and radiation from a central locality is sufficiently clear. The most probable view of the original arrangement is that the lavas emanated from many orifices and fissures scattered over the surface of an extensive volcanic pile, not unlike that of Mauna Loa, but on a smaller scale.

From the outlet of Fish Lake, at its northeastern end, we may pursue our way down the noble valley which carries the effluent stream. About 4 miles from the outlet we again enter Summit Valley, and, turning northward, we may ascend it to the first camping-ground from which we started to ascend the plateau. On the trail thither we pass two great terminal moraines projecting from the openings of gorges cut back into the plateau mass. Like the one projecting into the lake, they are well preserved and quite typical in their features.

MOUNT TERRILL AND MOUNT MARVINE.

Upon the eastern side of Summit Valley rise two conspicuous masses, which present to the eye nothing suggestive of a plateau. The northern one is Mount Terrill, the southern is Mount Marvine, both being in the prolongation of the same axis. Although in external form they are great mountain piles, their origin is due to circumdenudation, just as a great butte owes its individuality to the removal of the strata around it. They consist of lavas, resting upon Lower Tertiary calcareous beds, and both the lavas and the sediments are nearly horizontal so far as stratification is concerned; but the lavas were obviously outpoured over a much eroded surface, with hills and valleys of some magnitude. The volcanic sheets may have been continuous with those of Fish Lake Plateau., since they have the same lithological characters and varieties as the more striking trachytic members, but are less numerous and of less thickness in the aggregate. Whether once continuous or not, it seems evident that the separation of these two mountains from the plateau was effected by the gradual excavation and enlargement of Summit Valley. As we view the objects on the ground and try to reconcile ourselves to this notion, the magnitude of the process seems to make it incredible. Yet, as a common cañon valley is the self-evident result of erosion, so may such a valley as this be produced by the operation of the same general process, if sufficiently long continued. And this valley is very ancient. It is a remnant of a topography existing before the general uplifting of the platform on which the plateau and mountains stand. The volcanic rocks are probably as old as the Miocene, and the inception of Summit Valley may have occurred late in that age or in the early Pliocene. Judging comparatively by the effects of erosion here and in the adjoining country, the isolation of such a mountain as Mount Marvine is by no means a disproportionate work, when the duration of the process is considered. This view is abundantly confirmed when we examine the positions of the Tertiary strata beneath the lavas. There has been no downthrow sufficient to cause the valley, and the beds are seen to curve gradually downwards towards the west in their normal attitudes on the shoulder of the great monoclinal. (See Section 3, Atlas sheet, No. 6.)

Mount Terrill is a long narrow ridge, consisting of trachytic lavas, resting upon calcareous beds of Lower Eocene age. The trachytes are rather thin, their aggregate thickness being from 250 to 450 feet only. The varieties are very similar to those of the Fish Lake Plateau. The extreme summit is a remnant of a light-gray clinkstone (not phonolite, but a sanidin-trachyte), which weathers into slabs about 3 inches thick by horizontal planes of cleavage and by vertical joints. Underneath is a large mass of light-red argilloid trachyte and several bodies of light-gray trachyte, and one dark mass which may be an augitic variety. The sedimentary beds upon which they lie are not well exposed. As is almost always the case at such high altitudes (over 10,000 feet), they are covered with soil and talus. No fossils were discovered, but their continuity has been traced with strata of known age, and these are found in the ravine under the northeast corner of the Fish Lake Plateau. They are Lower Eocene, equivalent to the Bitter Creek of Powell.

The altitude of the ridge forming Mount Terrill declines towards the south until a lofty *col* or "saddle" is reached, which divides it from Mount Marvine. The latter is one of the most striking features of the region. It is a long ridge reduced to a mere knife-edge at the summit, and having rocky fronts on either side, sloping about 60°. A transverse section of the upper 2,000 feet of the mountain would be an equilateral triangle. For several years it was named by our parties The Blade. When seen from the south or north it has a most abrupt and peaked appearance, which becomes more pronounced the nearer we approach it. Viewed laterally from Summit Valley at its base, it presents a serrated summit, notched with many gaps and bristling with many cusps. The altitude of the mountain above the valley is about 2,700 feet and 11,400 feet above the sea. It consists of alternating trachytes and augitic rocks, resting upon Lower Eocene strata. The thickness of the volcanic beds is, in the aggregate, from 1,200 to 1,800 feet, being least at the northern end, and increasing towards the south. There is a succession of beds having the same general lithological characters as those in Fish Lake Plateau, except that the augitic members seem to be less numerous but more massive. Here, also, the dominant rock is the argilloid variety of trachyte.

The origin of this mountain becomes quite apparent when studied from both sides. It has been isolated, like a gigantic butte, from the adjoining country by the erosion of the valleys upon either flank. The inception of this work is very ancient, since it undoubtedly antedates the uplifting of the platform on which the mountain stands, and may therefore be referred to any epoch more ancient than the latter part of the Pliocene and more recent than the Eocene.

MOUNT HILGARD AND MORAINE VALLEY.

Before proceeding southward it is desirable to look briefly at Mount Hilgard and at the intervales which separate it from Mounts Terrill and Marvine. From Summit Valley we may easily cross the *col* which separates the two latter summits, and descending the other side we find ourselves in a broad valley parallel to the one just left. This has been named Moraine Valley, from a rather large and conspicuous relic of glacial times, which could not escape observation because it is so well preserved and tells its story so plainly. It fills a lateral valley, heading near the summit of Mount Terrill and extending eastward into the broader expanse of Moraine Valley. It is covered with pools and lakelets bowered with aspen and spruce, and has the ordinary terminal character where its proper bed opens into Moraine Valley; beyond which no traces of glaciation are recognizable. The altitude of the termination is very nearly 9,000 feet, showing the same general fact which has already been spoken of, that the glaciers did not, in this part of the country descend to low levels, but were confined to the highest parts of the region.

In the northern part of Moraine Valley the sedimentary beds are occasionally revealed in insulated exposures surrounded by trachytic and andesitic beds in an advanced stage of decay. They are of Tertiary age and are found on the western side of the valley, where considerable spaces are uncovered. They dip slightly towards the east, being, in fact, the eastern branch of an anticlinal swell, while the beds of Summit Valley form the western branch and Mount Terrill occupies the summit. (See Sec. 3, Atlas Sheet No. 6.) Their Tertiary age is inferred from their position, but no fossils have been obtained from them. The volcanic rocks of the northern part of the valley seem to have been of much greater volume formerly than at present, and to have been much wasted by erosion, though it is also inferred that they were never so extensive and massive here as to the southward. They are all, so far as observed, trachytic; some of them belonging to the dark hornblendic division, others to the sanidin division, the latter predominating upon the western side of the valley.

The principal drainage is to the southward, running parallel for a considerable distance to that from Summit Valley, and at length the two unite and form a noble stream as large as the Sevier, which has volume enough to reach the Colorado. The northern part of the valley is drained by a few rills, which find their way into Gunnison Valley to the northeast and thence through Salina Cañon to the Sevier. Thus the divide between the

Colorado and Basin drainage systems crosses the upper part of Moraine Valley transversely, and the same is true of Summit Valley.

Mount Hilgard is a lofty headland, rising upon the eastern side of Moraine Valley to an altitude of about 11,000 feet. Towards the north and east it presents inaccessible battlements of dark volcanic rock, consisting chiefly of hornblendic trachyte and augitic andesite. Towards the west it presents an abrupt face, which, however, is easily scaled. To the south it extends in a long ridge of diminishing altitude until it reaches the vicinity of Thousand Lake Mountain. To the eastward are seen the sedimentary formations stretching away indefinitely. They are Cretaceous, with a thin fringe of Lower Eocene capping them just at the base of the volcanic wall of which Mount Hilgard forms the loftiest part. To the northward the volcanic wall extends at an altitude 2,000 feet lower than the mountain top, and gradually swings westward until it nearly joins the wall which forms the northern salient at the head of Summit Valley, being divided from it only by a narrow ravine heading near Mount Terrill. This northern extension of the volcanic battlement has been named Gilson's Crest. This, together with the great ridge formed by Mount Hilgard and its southern extension, forms the eastern boundary of the great eruptive masses which cover almost the entire expanse of the District of the High Plateaus. There are, however, two or three outlying patches to the eastward of small extent, evidently independent centers of eruption, but no special significance seemed to attach to them.

The ridge of which Mount Hilgard is the culmination is evidently a chain of volcanic vents along a fissure, and the extravasation appears to have taken place along its entire extent. There are no individualized peaks or cones suddenly springing up at various points of the chain, but a broad summit platform, slowly and pretty regularly diminishing in altitude through a distance of nearly 20 miles, and it is difficult to point to any particular spot as possessing a more distinctly focal character than the others. The outpours appear to have occurred all along the line, with an approximation to uniformity, or possibly with a gradual increase of magnitude and frequency, as we approach the summit of Mount Hilgard. From that headland southward the top of the platform widens out, becoming 4 miles wide at a distance of 8 miles south. The mass of lavas appears to be of great thickness, and the sedimentary beds are not seen beneath them until we approach the vicinity of Thousand Lake Mountain. The eruptions were of the most massive character, being in some instances more than a hundred and twenty feet thick, and presenting ledges of rock several miles in length.

The eruptive materials are of the same general character as those observed in the Fish Lake Plateau. They are mostly trachytic, with subordinate though considerable masses of augitic andesite and dolerite intercalating. All of the trachytes have a dark, somber appearance, and belong to both of the divisions of that group. The older varieties are hornblendic, with considerable plagioclase, and among them are also found augitic trachytes. The younger members are chiefly of the argilloid varieties, and, as elsewhere, they occur in immense beds.

THE AWAPA PLATEAU.

The Awapa and Aquarius Plateaus have not been studied in detail, and my knowledge of them is such only as has been derived from a few rapid transits across the former in different places, and about three weeks spent upon the flanks of the latter. Their area is very great, and, in order to acquire sufficient data to give any detailed account of them, much more labor and travel is necessary. I have been much indebted to some notes prepared by Mr. E. E. Howell, whose observations have supplemented my own in some very important particulars, and have prepared the way to the determination of many points; especially those relating to the stratigraphy and structure of the Aquarius Plateau.

The separation of the Awapa from the Fish Lake Plateau is probably more justifiable on the ground of convenience of discussion than of reality, for the latter passes directly into the former. A sudden descent across a steep slope brings us from one to the other. For a short space the lake may be regarded as a natural barrier, but east of the lake it is not practicable to say where the one ends and the other begins. The Fish Lake table has an altitude of more than 11,000 feet, and where its southern end drops down upon the Awapa the altitude of the latter is less than 9,000 feet; and generally the altitude of the Awapa is the least of the several masses constituting the High Plateaus. The slopes of the entire mass all converge towards a central depression called Rabbit Valley. It is not an inclined plane or roof, but the segment of a dish. Everywhere the general inclination is very slight, though undulating with low hills. The western boundary is a wall from 1,800 to 3,000 feet high, plunging down into Grass Valley, sometimes by a grand precipice, sometimes by a steep, difficult slope and always abruptly. The length of the plateau, though its boundaries are for the most part difficult to locate with precision, is about 35 miles and its breadth about 18 miles.

It is a dreary place. Upon its broad expanse scarcely a tree lifts its welcome green, save a few gnarled and twisted cedars. Its herbage consists only of the ubiquitous artemisia and long nodding grasses. Not a spring or stream of water is known upon all its area, except at the lowest part, where its slope merges into the floor of Rabbit Valley. And yet most of its surface is at an altitude where verdure and moisture abound, and where the summer is like the spring of more favored regions. But here the snows of winter are melted early, and the summers are nearly as hot and dry as those of the plains below. A ride across it is toilsome and monotonous in the extreme. It takes us over an endless succession of hills and valleys, clad with a stony soil, usually just steep enough to worry the animals, but not enough so to require us, or to even encourage us, to dismount. Here and there a sharp cañon opens across the path in an unexpected manner, compelling a long detour to find a crossing. These are usually shallow, rarely exceeding 400 or 500 feet in depth, but are as typical in their forms or sections as the cañons in the sedimentary strata.

The whole mass of the Awapa consists of volcanic materials. The only localities where sedimentary beds are seen are in Rabbit Valley and low down in the western flank opposite East Fork Cañon in Grass Valley. In the latter locality the great fault has brought them to daylight, and the ravines have still further opened them to view. They are Lower Tertiary, corresponding to the Bitter Creek beds of the northern plateaus. Above them are 3,000 feet of volcanic conglomerates and lavas. In Rabbit Valley beds presumed to be of the same age are also discovered beneath thin cappings of trachyte and basalt. Hence it appears that the lavas gradually attenuate from west to east, or rather from the periphery of the plateau towards its central depression.

The variety of the rocks displayed is truly astonishing. It seems as if two exposures rarely presented the same description of lava. The great majority of them belong to the trachytic group, and it is surprising to see what numberless changes can be rung upon materials which vary so little in their ultimate composition. This manifold variation is displayed in the Sevier Plateau and in the Markágunt; but for some reason I was more profoundly impressed with it in the Awapa than elsewhere, though, possibly, it may be no greater in the latter than in the former. But assuredly the number of distinct *coulées* is extremely great, and it is hard to find two precisely alike. Some of the trachytic beds are quite thin, being not more than 20 to 25 feet thick, and successions of these variegated layers are frequently met with. On the other hand, some of the grandest and most massive sheets in the High Plateaus are found here. On the north side of Rabbit Valley the plateau slope ends in a low wall about 100 to 120 feet in height and nearly 4 miles in length, which seems to be one individual sheet of argilloid trachyte. Some very grand sheets of hornblendic trachyte are also displayed hard by, having the exceedingly rough, coarse texture which is so characteristic of that variety. In the large *coulées* of hornblendic trachyte, and sometimes also in the granitoid variety, may be seen that rough, broken aspect of the lava suggestive of flowing in a very viscous and almost solid state, as if the whole mass were continually rending itself into fragments, as it crept along like a huge glacier, while more fluent portions from within the flood worked their way into the rifts, and there congealed. In the smaller and thinner sheets this phenomenon is not seen; but a more mobile character is indicated. The grander flows generally belong to the granitoid and argilloid varieties, while the smaller and more fluent ones are sometimes hyaline and sometimes augitic trachyte. Vitreous products also are common, and at the parting of the beds trachytic obsidian is found in abundance. No rhyolites have been detected in this plateau, but a few pitch-stones, with the trachytic character rather than the rhyolitic, were observed. This indicates a considerable range in the chemical constitution, and is accompanied with a corresponding range in the superficial aspects of the beds. In the northern part of the plateau the dark argilloid and hornblendic trachytes predominate. They agree in their characters and aspects with those which occur in the Fish Lake Plateau and Mount Marvine. There is also decided evidence that the main sources from which they outflowed were around the southeastern borders of the lake. This evidence is substantially the fact, that the sheets increase in thickness and become more rugged in that quarter, and all the phenomena of flow indicate movement from that direction. The supposed location of the vents, however, was not visited. No augitic andesites were noticed intercalating with the northern trachytes of the Awapa, though large bodies of them may have escaped observation, owing to the superficial and cursory character of the investigation.

No conglomerates or tufas were seen in the northern part of the Awapa, and these would have been noticed if they really exist there in masses of any importance. As such bodies are usually very bulky and conspicuous, it is hardly possible to overlook them. In the western part of the plateau, however, they are found in great volume. They are stratified in the usual manner, with nearly horizontal bedding or with that peculiar cross-bedding which may be seen in Panquitch Cañon (Heliotype No. 4). In the western wall of the plateau, a little north of East Fork Cañon, these conglomerates form a grand cliff and talus rising about 3,400 feet above Grass Valley, and the total thickness of the fragmental beds is roughly estimated at 1,600 feet. Large masses of hornblendic trachyte are found beneath them, and granitoid trachyte above them. These beds of conglomerate stretch north and south from this point, forming the most conspicuous part of the plateau wall, for a distance of 21 or 22 miles. Their degradation gives rise to a precipitous escarpment, broken in several places by ravines and gorges. They are also found in great bulk in the cañons which cut into the heart of the plateau. They are believed to be alluvial in their origin. The fragments which they contain are exceedingly varied in their composition and texture. Hornblendic andesites and trachytes are commingled in the same stratum, and of each kind there are very many varieties. In one of the deeper cañons some propylitic fragments were found, but whether they were derived from conglomerates or from rocks *in situ* farther up the gorge was uncertain.

A considerable number of basalt fields are found upon the surface of the Awapa. In no instance was any considerable mass of this lava encountered, and wherever found it formed only a rather thin local veneer rarely so much as 100 feet thick, and generally much less. These basaltic sheets have been greatly ravaged by erosion, and their fragments scattered far and wide. No trace of a basaltic cone or monticule was anywhere seen. If any such ever existed it has been totally demolished. I incline to the opinion that none were ever built in those portions of the Awapa which were visited, but rather that the basalt quietly outflowed in the same manner as it did from some of the very recent vents on the Markágunt. From the orifices it seems to have spread out at once in thin, diffuse pools or lakes, where it has slowly weathered away. Wherever it occurs, it is the most recent of the eruptive masses. None of it belongs to so late an epoch as those of the Markágunt or the southern terraces overlooked by the Pink Cliffs. In some localities the sheets of basalt are wasted to mere heaps of disjointed blocks, thickly strewing the platform and partly buried in soil. In others, the continuity of the sheets is tolerably well preserved. It is impossible to fix the age of those eruptions, though I infer that none are as old as Middle Pliocene; perhaps not so old as the close of that age. They seem to have been erupted after the movements of displacement which blocked out the plateau had well advanced, and these are held to be among the most recent events of Tertiary time.

I have not attempted to delineate these basalts upon the geological map, being uncertain as to their extent and outlines.

RABBIT VALLEY.

The slopes of the Awapa all converge towards a central depression called Rabbit Valley. The trachytic beds descending towards it end suddenly, sometimes in low cliffs, sometimes in steep slopes. The eastern side of the valley is walled by the great uplift of Thousand Lake Mountain. Along the western base of that mass runs one of the great faults of the district, with a maximum throw of more than 4,000 feet. On every side the valley is girt about by imposing masses; on the north and west by the slopes of the Awapa, and on the south by the Aquarius. Its floor is a broad alluvial plain, receiving the wash of all the surrounding uplifts, and carrying a noble stream, which is fed from all directions by rivulets which have brought down their loads of *débris* and, reaching the nearly level bottom, have deposited it. Those coming from the Awapa are always dry in summer, excepting one which heads near the foot of the slope, but the other tributaries from the north and south are perennial. The accumulation of detritus through the ages has produced a broad expanse of alluvial plain through which the Fremont River meanders, and nothing but a moist atmosphere is wanting to make this valley an Eden.

It is somewhat unusual to find so large an area in this elevated region in which the accumulation is in excess of the power of the rivers to carry it away. But this exceptional condition appears to have prevailed in Rabbit Valley for a considerable time. It was apparently brought about by the last stage in the uplifting to the eastward across the great fault, or, what is the same thing, the downthrow of the valley itself; for these vertical movements must be considered in a purely relative sense and as meaning simply the difference of elevation between the lifted and thrown sides, respectively, of the displacement. The Thousand Lake fault cuts across the outlet of Rabbit Valley, which passes between Thousand Lake Mountain and the northern salient of the Aquarius, and it has had the effect of an increasing barrier to the outflow of the Fremont River and has slackened its waters within the valley. Hence the loads of ditritus which its affluents bring down from the plateaus on every side are thrown down in the valley. Since the last paroxysm of uplifting the river has taken to meandering, in consequence of the progressive building up of its channel and has repeatedly shifted its bed over different parts of its flood plain. Old cañons in the borders of the lava sheets coming down from the Awapa have been partially filled up and the river has abandoned them. In truth, a considerible number of low cañons of this sort are still discernible in the lower portions of these old trachytic beds, and it is apparent at a glance that they have nothing in common with the cañons and ravines which descend the slopes of that plateau, except to form the old trunk channel into which the latter debouched. The Fremont River, however, still maintains its course in one of those old cañons for a distance of 4 or 5 miles. It leaves the low flats of the valley to enter the rising slopes of the Awapa and flows through a rocky gorge which becomes four or five hundred feet deep. Thence it emerges into the valley plain again and pursues its way to the foot of the valley, where a salt marsh, covered with saline pools, has been built up by the accumulation of fine silt.

It is interesting to pursue this subject further and to view it in relation to future instead of past time. The river leaves the valley through the great gap between the mountain and the Aquarius, and the passage has been named the Red Gate. Thence it flows off into the heart of the Plateau Country, reaching the Colorado by a profound cañon. Throughout the greater part of this distance the river is a rapid stream and is slowly sinking its channel. Its rapid descent begins half a mile beyond the point where it crosses the great fault, and it is apparent that here, too, it is lowering its bed; for old terraces of river gravel and loess are seen at different levels within the Red Gate in an excellent state of preservation, and the river has cut a broad and deep channel through them. It is only a question of time how deep the channel may be cut, for where it leaves Rabbit Valley the altitude is almost exactly 7,000 feet above sea-level, and the junction of the river with the Colorado is less than 4,500 feet. Estimating the course of the stream between the two points at 100 miles, the average descent is not far from 25 feet to the mile, which is about the same fall as prevails in nearly all the tributaries of the Colorado in this part of the country. All of them are evidently corrading their beds. Here and there local flood plains are formed, occurring along stretches of the streams where the fall is slight; but such flood plains are merely temporary in the secular life of the river. They are succeeded by rapids which are gradually eating their way backwards, and in a brief period the stretches of still water will become rapids in turn. In time, then, the Fremont River will cut down its channel at the outlet of Rabbit Valley unless the fault at the Red Gate increases its throw. In the absence of such increase in the fault the stream will ultimately carry back the excavating process into the valley and the extensive alluvial beds will be gradually attacked and eroded away.

These alluvial masses are partly conglomeritic in texture, especially near the borders of the lava sheets and at the foot of the plateau slopes. Towards the middle of the valley they become finer, shading into sandy or fine gravelly deposits. They are instances of the formation of conglomerates upon a considerable scale by the alluvial process, but under conditions somewhat different from those disclosed in Sevier and Grass Valleys. The included fragments upon the western and southern portions are always volcanic and exceedingly varied. The *débris* derived from Thousand Lake Mountain on the eastern side consists mainly of fine quartz sand coming from the decay of the Jurassic and Triassic sandstones of that structure.

In the northwestern part of Rabbit Valley a few exposures of Tertiary beds are found beneath the terminal trachytic sheets. Upon the eastern side of the valley are still better exposures upon the lowest slopes of Thousand Lake Mountain. In the latter locality they are soon cut off by the great fault, and reappear nearly 4,000 feet above, beneath the lava cap upon the summit. Below they abut against the Lower Trias. Laterally they run beneath extensive outpours of basalt, which, though not of very modern origin, are still comparatively recent.

THOUSAND LAKE MOUNTAIN.

Thousand Lake Mountain is an exceedingly interesting object. The name was given by the Mormons who pasture flocks in the valley below. They derived it from a group of pools of glacial origin upon the summit. Structurally and morphologically it is a small plateau, in some respects very similar to the other and larger members of the district, but possessing, also, features peculiar to itself. The country to the west of it is thrown down by a profound fault forming the depression of Rabbit Valley, The country to the east of it is the inner region of the Plateau Province, from which thousands of feet of strata have been removed by the grand erosion of Tertiary time, while the mountain itself has been left like a gigantic butte or cameo upon the border of the region. Upon its southern flank the Fremont River has cut a wide passage, which has separated it from its mighty parent, the Aquarius Plateau.

Upon the summit is a lava cap from 400 to 500 feet in thickness and quite flat, giving a tabular summit to the mass about 5 miles long and nearly 2 miles wide. An almost impassable talus surrounds the scarped edges of this cap, and renders the ascent difficult except at a few points upon the eastern side. The lavas are hornblendic trachytes and augitic andesites, heavily interbedded and made up of numerous flows. These rest upon a layer of Lower Tertiary, of which the thickness is not precisely known, but which cannot well exceed 700 feet. Whether the diminished volume of the Tertiary here is due to an originally small amount of deposition or to an erosion of the upper members prior to the volcanic overflow is not yet determined, but I incline to the former explanation. And the general indications seem to be that over the area occupied by the eastern part of the Aquarius and Thousand Lake Mountain the Tertiary deposition was locally much thinner than elsewhere. Immediately beneath is the Jurassic white sandstone. The Cretaceous is absent from its place in the stratigraphical series. Yet a few miles to the northeastward the whole vast Cretaceous system is rolled up and cut off on the slopes of a grand monoclinal.

This monoclinal is the *Water Pocket Fold*, which is probably the grandest feature of the kind in the Plateau Country, so far as known, and perhaps the most typical. Its first appearance is beneath Thousand Lake Mountain (see Atlas Sheet No. 4), where the trend is east-southeast and it gradually swings around towards the south-southeast, reaching to the Colorado River, in the heart of the Glen Cañon. It crosses the river into unknown regions. Upon the northwestern side of the mountain it is covered up by Tertiary beds and lava sheets and is wholly concealed, so that neither its northern nor its southern terminations are at present known. The great fault upon the west side of the mountain cuts across this monoclinal nearly at right angles, and has dropped the platform to the west several thousand feet. The age of the great flexure is evidently older than Tertiary time, for the Lower Eocene beds lie nearly horizontally across the upturned edges of the whole Cretaceous system and upon the deeply-eroded surface of the Jurassic sandstone. Inasmuch as the entire body of Cretaceous strata, including the Laramie beds, appear in succession as we cross the strike of the flexure and as they are all upturned upon its flanks,

Heliotype Printing Co., *220 Devonshire St., Boston.*

The Red Gate. Lower Trias. Shinarump.

the first conclusion seems to be that the movement took place after the Laramie beds were deposited and before the Tertiary strata were laid down. The contacts, however, between the Tertiary and Laramie beds have not yet been studied and analyzed, nor have any good exposures of those contacts in this vicinity been discovered. It is not impossible that through a large portion of Cretaceous time this area was a part of an island undergoing a slow erosion, while just beyond the flexure to the eastward the later Cretaceous members were accumulating upon an island coast; that at a later epoch the island was submerged, and received a deposit of Lower Eocene beds. This supposition has considerable support in facts which will be brought forward in the next chapter, and leads to the conclusion that a long interval of disturbance and erosion separated the Cretaceous from the Tertiary throughout this part of the Plateau Province. The absence of more than 5,000 feet of strata between the Lower Eocene and the formation upon which it reposes is a very striking fact, and the simplest explanation is here the best.

The Jurassic white sandstone is disclosed all around the mountain. It has the same familiar *facies* which has been adverted to in the preceding chapters upon the Markágunt and Paunságunt Plateaus—a grayish-white massive sandstone, wonderfully cross-bedded, and weathering into inaccessible domes of peculiarly solid and bold aspect. The upper Jurassic shales appear to be absent, at least they were not detected, and the eroded condition of the sandstone at the time of the deposition of the Tertiary is a sufficient reason for presuming that if the shales once existed here, and I doubt not that they did, they have been swept away.

Beneath the Jurassic appear in normal order and relations the Vermilion Cliff sandstones (Upper Trias) and the Shinárump shales. These formations have the same aspect as in the lower terraces which front the Kaibabs in the Grand Cañon District. The Vermilion Cliff series has the same succession of sandstones and siliceous shales, usually bright red, but sometimes patched with bright yellowish brown. They are best exposed upon the southern flank of the mountain at the Red Gate. The Shinárump has the same band of conglomerate, consisting of fragments of silicified wood imbedded in white sand, which is seen in the vicinity of the Hurricane fault, 150 miles to the southwest. The shales also present the same striking and constant appearance as if in all that interval not a layer or line had lost its identity. At the base of the mountain, upon the southern side, the Shinárump shales form a broad platform or terrace skirting the south-eastern flank, and ending in a beautifully sculptured cliff about 600 feet high, eminently characteristic of the formation. The architecture is represented in Heliotype X, but the colors are such as no pigments can portray. They are deep, rich, and variegated, and so luminous are they, that light seems to glow or shine out of the rock rather than to be reflected from it.

The *Red Gate* has already been alluded to as the passage by which the Fremont River leaves Rabbit Valley and flows off into the heart of the Plateau Country. As we approach it from the west the flaming red of the Trias is seen reaching out southward from Thousand Lake Mountain in a rocky wall which has been breached by the river. These beds curve downwards on the south side of the gate and disappear beneath the spurs of the Aquarius. The great fault along which Thousand Lake Mountain has been upheaved continues southward across this passage, cutting into the mass of the Aquarius. The downward flexure of the Trias is simply the effect of diminished uplift on the south side of the gate. The passage itself has been cut by the river, which has occupied its present *locus* for an immense period, which may reach back as far as Miocene time. Some changes may have occurred in its course through the repeated outflows of lava across and into its valley. But there are independent considerations which lead to the conclusion that the Fremont River is one of the more ancient tributaries of the Colorado, born with the country itself far back in Eocene time, though its upper branches may have been much modified by the violent changes accompanying the great volcanic activity of the Middle Tertiary. Beyond the Red Gate the relations of the river to the structural features of the region through which it flows, and also to the imposed sculpture of the country, are such as to compel the conviction that the river must antedate the Tertiary deformations of the strata which are there found, and also antedate the great erosion of the Plateau Province. Through all those vast changes by displacement and erosion the river has ever maintained its thoroughfare. The passage through the Red Gate is part and parcel of the same history.

We may in imagination look back of an immense geological period to an epoch when the platform of the Aquarius reached far beyond its present boundaries and included the whole mass of Thousand Lake Mountain and the whole country as far as the eye can reach to the eastern and southern horizons. The cutting of the passage through the Red Gate is but an insignificant factor in the total process, and falls far short of what we know has been accomplished in other portions of the wonderful country of which it is the portal.

CHAPTER XIII.

THE AQUARIUS PLATEAU.

Distant views and the approach to the Aquarius.—Its grandeur.—Its summit.—Scenery and vegetation.—Glacial lakes.—The lava cap.—The southern slopes.—Panorama from its southeastern salient.—View to the northeastward.—The Water Pocket fold.—Inconsequent drainage.—View of the Henry Mountains and La Sierra Sal.—The Circle Cliffs.—A labaryuth of cañons.—Cañons of the Escalante River.—Exposures of the Jura and Trias.—Navajo Mountain.—The great wall of the Kaiparowits Plateau.—Distant view of Table Cliff and Kaiparowits Cliff.—The great southern amphitheater of the Aquarius.—The grand erosion.—Former extension of the Cretaceous and Eocene strata over the Plateau Country.—General structure of the Aquarius.—Faults in the central portion.—The Escalante monocline and its Pre-Tertiary age.—A Cretaceous island.—Western wall of the Aquarius.—Trachytes, andesites, and basalts.—Complicated faulting.—Table Cliff.—Kaiparowits Peak.

The Aquarius should be described in blank verse and illustrated upon canvas. The explorer who sits upon the brink of its parapet looking off into the southern and eastern haze, who skirts its lava-cap or clambers up and down its vast ravines, who builds his camp-fire by the borders of its snow-fed lakes or stretches himself beneath its giant pines and spruces, forgets that he is a geologist and feels himself a poet. From numberless lofty standpoints we have seen it afar off, its long, straight crest-line stretched across the sky like the threshold of another world. We have drawn nearer and nearer to it, and seen its mellow blue change day by day to dark somber gray, and its dull, expressionless ramparts grow upward into walls of majestic proportions and sublime import. The formless undulations of its slopes have changed to gigantic spurs sweeping slowly down into the painted desert and parted by impenetrable ravines. The mottling of light and shadow upon its middle zones is resolved into groves of *Pinus ponderosa*, and the dark hues at the summit into myriads of spikes, which we know are the storm-loving spruces.

The ascent leads us among rugged hills, almost mountainous in size, strewn with black bowlders, along precipitous ledges, and by the sides of cañons. Long detours must be made to escape the chasms and to avoid the taluses of fallen blocks ; deep ravines must be crossed, projecting crags doubled, and lofty battlements scaled before the summit is reached. When the broad platform is gained the story of "Jack and the beanstalk," the finding of a strange and beautiful country somewhere up in the region of the clouds, no longer seems incongruous. Yesterday we were toiling over a burning soil, where nothing grows save the ashy-colored sage, the prickly pear, and a few cedars that writhe and contort their stunted limbs under a scorching sun. To-day we are among forests of rare beauty and luxuriance; the air is moist and cool, the grasses are green and rank, and hosts of flowers deck the turf like the hues of a Persian carpet. The forest opens in wide parks and winding avenues, which the fancy can easily people with fays and woodland nymphs. On either side the sylvan walls look impenetrable, and for the most part so thickly is the ground strewn with fallen trees, that any attempt to enter is as serious a matter as forcing an *abattis.* The tall spruces (*Abies subalpina*) stand so close together, that even if the dead-wood were not there a passage would be almost impossible. Their slender trunks, as straight as lances, reach upward a hundred feet, ending in barbed points, and the contours of the foliage are as symmetrical and uniform as if every tree had been clipped for a lordly garden. They are too prim and monotonous for a high type of beauty ; but not so the Engelmann spruces and great mountain firs (*A. Engelmanni, A. grandis*), which are delightfully varied, graceful in form, and rich in foliage. Rarely are these species found in such luxuriance and so variable in habit. In places where they are much exposed to the keen blasts of this altitude they do not grow into tall, majestic spires, but cower into the form of large bushes, with their branchlets thatched tightly together like a great hay-rick.

Upon the broad summit are numerous lakes—not the little morainal pools, but broad sheets of water a mile or two in length. Their basins were formed by glaciers, and since the ice-cap which once covered the whole plateau has disappeared they continue to fill with water from the melting snows. Early in autumn the snows have disappeared and the lakes cease to outflow, but never dry up.

The length of the Aquarius from northeast to southwest is about 35 miles, and its breadth from 10 to 18 miles. Its altitude varies from 10,500 to 11,600 feet above sea-level. Over three-fourths of its periphery is bounded by massive cliffs, while along the remaining fourth it declines gently to its confluence with the Awapa. Its upper portion is a lava-cap of vast dimensions, varying from 1,000 to 2,000 feet in thickness. Its lavas are seen in greatest mass at the northwestern flank, overlooking the southern part of Grass Valley and the Panquitch Hayfield. Upon the southern and eastern sides, at the foot of the volcanic wall, the long slopes begin, which reach far out into the mesas of the inner Plateau Country. Their descent is slow and easy to all appearance, but they are deeply gashed with profound cañons and terrible gorges, among which it is dangerous to venture. To traverse these slopes it is necessary to keep high up near the base of the lava-cap, where the ravines head, and where they are sufficiently open to afford a practicable trail. Even here the journey around the base of the cliff is laborious, involving the constant ascent and descent of vast gorges and amphitheaters, and requiring many days to accomplish it. Yet the traveler who has abundant strength and perseverance will be amply rewarded, provided he has chosen his way with prudence and good judgment. Upon these slopes the structure of the plateau is revealed.

In truth, there is but little "structure." The plateau is simply a remnant left by the erosion of the country around its southern and eastern flanks. A few of its minor features are due to displacements, and its western wall originated in a great fault or rather in several faults. The rest of the mass owes its pre-eminence to circumdenudation. We may gain some notion of the stupendous work which has accomplished this result by taking our position upon the southeastern salient at the verge of the upper platform.

It is a sublime panorama. The heart of the inner Plateau Country is spread out before us in a bird's-eye view. It is a maze of cliffs and terraces lined off with stratification, of crumbling buttes, red and white domes, rock platforms gashed with profound cañons, burning plains barren even of sage—all glowing with bright color and flooded with blazing sunlight.

Everything visible tells of ruin and decay. It is the extreme of desolation, the blankest solitude, a superlative desert.

To the northeastward the radius of vision reaches out perhaps a hundred miles, where everything gradually fades into dreamland, where the air boils like a pot, and objects are just what our fancy chooses to make them. Perhaps the most striking part of the picture is in the middle ground, where the great Water Pocket fold turns up the truncated beds of the Trias and Jura, whose edges face us from a great quadrant of which we occupy the center. Where the strata are cut off in this way upon the slope of a monocline they do not present to the front a common cliff and talus with a straight crest-line, but a row of cusps like a battery of shark's teeth on a large scale. But even in this relation the Jurassic sandstone is peculiar, for it is here of enormous thickness and so massive that it is virtually one homogenous bed, and the great gashes cut across the fold or perpendicular to the face of the outcrop have carved the stratum into colossal crags and domes. By these tokens we can trace the Water Pocket fold from the eastern slopes of Thousand Lake Mountain around a quadrant, whence its course flies off in a tangent far into the south and is lost to view beyond the Colorado. Its total length thus displayed must be about 90 miles. Across this monocline run the drainage channels which head in the amphitheaters along the eastern front of the Aquarius. It is interesting to note how completely independent are these streams of the structural slopes of the country. They rush into a cliff or into a rising slope of the strata as if they were only banks of fog or smoke. It matters not which way the strata dip, the streams have ways of their own. The Fremont River and the creeks which flow down from Thousand Lake Mountain present a very striking relation to the strata. They at first run very obliquely into the fold, and thence by an equally oblique course run out of it again. Nearer to us Temple Creek plunges right into the flexure perpendicular to its strike and in the somewhat uncommon relation of a stream running *with* the dip of the strata. Still nearer, Tantalus Creek runs across the fold in the same general relation but meanders about within it.

In the first chapter I have explained this independence of drainage channels of the structural slopes and attitudes of the strata by the general proposition that the rivers are older than these structural features, that their courses were initially determined by the configuration of the surface when the region emerged from its lacustrine condition in Middle Eocene time, and have persisted in holding those initial positions in spite of all changes. It happens, however, that in the cases before us the flexure is much older than the rivers. The age of the Water Pocket monocline is Pre-Tertiary, at least in the northern part, and we infer that the whole monocline is of one age. This seems at first to be in contravention of the law. But the anomaly is apparent only and not real. For we have seen that in Thousand Lake Mountain the Tertiary lies nearly horizontally across the denuded edges of the Cretaceous and Upper Jurassic and rests upon the Jurassic white sandstone. The same relation is found in the Aquarius. In the eastern half of the plateau the Cretaceous is wanting and the Tertiary rests upon the Jura. A little west of the middle of the plateau upon the southern flank is seen another ancient monocline with its throw in an opposite direction to that of the Water Pocket flexure. This, too, is of Pre-Tertiary age, and upon its slopes the Cretaceous again comes in with full force, and across its beveled edges lies the Lower Eocene horizontally. Thus while this pair of flexures was forming the intervening uplifted block was undergoing erosion, and at a later epoch it was submerged to receive a blanket of Lower Eocene strata. If now we attempt to replace the beds which have been stripped off by the later erosion of Miocene and Pliocene time, we must extend the Tertiary beds eastward (and southward) indefinitely, so as to cover the Water Pocket flexure unconformably, and also to cover the Cretaceous mesas which lie beyond it. Thus, after the Middle Eocene, the locus of the flexure was covered with a sensibly horizontal stratum of Lower Eocene beds upon which the local drainage system was laid out. As the erosion went on the streams sank their channels and the upper strata were denuded. The Water Pocket fold was in time exhumed and the streams cut down into it from above. And since its exhumation it has been greatly ravaged by erosion.

Directly east of us, beyond the domes of the flexure, rise the Henry Mountains. They are barely 35 miles distant, and they seem to be near neighbors. Under a clear sky every detail is distinct and no finer view of them is possible. It seems as if a few hours of lively traveling would bring us there, but it is a two days' journey with the best of animals. They are by far the most striking features of the panorama, on account of the strong contrast they present to the scenery about them. Among innumerable flat crest-lines, terminating in walls, they rise up grandly into peaks of Alpine form and grace like a modern cathedral among catecombs—the gothic order of architecture contrasting with the elephantine. Beyond the spurs of Mount Ellen may be seen the northernmost summits of the Sierra La Sal, 120 miles distant; but the main range is hidden by the mass of the Henry Mountains.

The view to the south and southeast is dismal and suggestive of the terrible. It is almost unique even in the catagory of plateau scenery. The streams which head at the foot of the lava-cap on the southern wall of the Aquarius flow southward down its long slopes. The amphitheaters soon grow into cañons of profound depth and inaccessible walls. These passages open into a single trunk cañon, and their united waters form the Escalante River, which flows out of Potato Valley due eastward for 12 or 15 miles, and then turns to the southeastward, reaching the Colorado about 50 miles from the turn. It enters its cañon at the foot of Potato Valley (see map, Atlas Sheet No. 1), and at no point can its walls be scaled.* Numberless tributary cañons open into it along its course from both sides, so that the entire platform through which it runs is scored with a net-work of narrow chasms. The rocks are swept bare of soil and show the naked edges of the strata. Nature has here made a geological map of the country and colored it so that we may read and copy it miles away. The rocks exposed are Trias and Jura, each preserving emphatically its characteristic color and architecture.

The descending spurs from the southeastern salient terminate upon a spot which is about as desolate as any to be found on earth. It is a large plain, about 25 miles long and 10 miles wide, elliptical in shape and girt about by a circuit of cliffs of great altitude. On the eastern side are the

* Mr. Jacob Hamblin, of Kanab, entered this chasm and traversed it nearly to the Colorado River, but at length found it impassable on account of quicksands and fallen rocks. His journey was a terrible one, and he sought in vain to reach the country above. The depth of the Escalante Cañon where its river first enters the Monocline is about 1,600 feet, and increases as the river flows on.

domes and crags of the Water Pocket fold, huge promontories of red and white massive sandstone, separated by narrow clefts, many of which are cut down to the level of the plain and even lower, so that they carry a portion of the drainage from within the "Circle Cliffs" to the Water Pocket Cañon. On the west side of the plain the mesa which looks down upon it is slashed by many narrow and profound cañons, which wind about within it and open into the cañon of the Escalante. These carry the remaining drainage of the plain—*i. e.*, when there is any to carry, which I warrant is seldom enough. The floor of this cliff-bound area is Lower Trias (Shiná-rump), and the walls which inclose it upon the west are Vermilion Cliff Trias, and those upon the east are the same, with the Jurassic sandstone a little beyond them. The plain is barren, treeless, and waterless, so far as known. It constitutes one of the centers of erosion of this part of the Plateau Country, from which the waste of the strata edgewise has proceeded radially outwards. Probably the Cretaceous was eroded from its surface prior to the Eocene, and the Tertiary afterwards deposited upon the Jura in the same relation as is now seen high up on the flanks of the Aquarius. The late erosion has removed the Eocene, the Jura, and the Upper Trias.

Far to the southeastward, upon the horizon, rises a gigantic dome of wonderfully symmetric and simple form. It is the Navajo Mountain. Conceive a segment of a sphere cut off by a plane through the 70th parallel of latitude, and you have its form exactly. From whatsoever quarter it is viewed, it always presents the same profile. It is quite solitary, without even a foot-hill for society, and its very loneliness is impressive. It stands upon the southern brink of the Glen Cañon of the Colorado, at the junction of the San Juan River. Its structure is believed by Mr. G. K. Gilbert to be laccolitic. Its summit has not yet been reached by any exploring party, and the approaches to it from all sides are extremely difficult.* On the north side runs the profound chasm of the Colorado, on the east the cañon of the San Juan, and on the west another side gorge. South of

* Professor Powell, during his descent of the Colorado River, climbed out of the cañon and ascended about half-way to the summit. He believed that if time had permitted he could have gained the top of the mountain.

it, for 60 miles, the eountry is disseeted by a net-work of deep, narrow ehasms, among whieh are trails of a most intrieate and diffieult nature, known at present only to Indians. The mountain is inhabited by a band of renegade Indians, ehiefly Navajos, who are very jealous of all intrusion into their fastnesses, and great caution is requsite when venturning near their retreat.

Due northward rises the great wall of the Kaiparowits Plateau. This giant eliff is 60 miles in length and nearly 2,000 feet high. Throughout its eourse it wavers but little from a straight line. Almost all the great eliffs of the Plateau Country are very sinuous, being in faet a series of promontories, separated by deep bays, like the lobes of a "digitate" leaf. The eause is readily diseerned The bays are produeed by the widening of the cañons, whieh, in a great majority of cases, emerge from the cliffs and seldom run down into them. Erosion thus not only saps the main front of the cliff, but attacks it through these side-euts. But the Kaiparowits eliff has only a single eañon emerging from it, and this is near the northern end. From the very erest-line the drainage is to the southwest, while the cliff faces northeast, and thus the eroding agents ean attaek it only in front. Sinee the strata are homogeneous in their horizontal extensions, and heterogeneous vertieally, the effeet of erosion has obviously been to produce a straight wall, broken only at the point where the single eañon emerges from it. The beds of which the Kaiparowits is eomposed are Middle Cretaeeous. We ean see, from our standpoint, their eharaeteristie colors, which present a very striking appearance. Broad bands of bright yellow sandstone, alternating with the dark gray of the argillaeeous shales, produee a eontrast whieh is not only visible, but even emphatic, at a distanee of 60 miles. These belts of light and shade are 300 to 400 feet thick, and apparently quite horizontal.

To the southwest rise Kaiparowits Peak and Table Cliff, of which more will be said hereafter. Between those points and our own position is a great depressed area, of which the lowest part is Potato Valley. The altitude of its floor is about 5,600 feet above the sea. Towards it eonverges the drainage of all the highlands lying north, west, and southwest, and the eonfluence of the streams from those direetions forms the Escalante

River. The country which thus concentrates its waters into Potato Valley may be regarded as a vast amphitheater, with a radius vector varying in length from 12 to 18 miles, and of which the ramparts of the Aquarius and Table Cliff form the upper rim. The amphitheater is the work of erosion, being a westward extension of that vast denudation which has removed thousands of feet of strata from the whole region spread out before our gaze.

As we study the panorama before us, the realization of the magnitude of this process gradually takes form and conviction in the mind. The strata which are cut off successively upon the slopes formerly reached out indefinitely and covered the entire country to the remotest boundary of vision. Their fading remnants are still discernible, forming buttes and mesas scattered over the vast expanse. The same process of reasoning by which the mind joins the edges of strata across the abyss of a narrow cañon enables us to join their edges across wider intervals. The restoration of the Trias to its Pre-Tertiary condition is made almost at a glance, since the vacant spaces are few. The restoration of the Jurassic and Cretaceous is precisely the same in nature and equally simple, though the spaces to be covered by it are much wider. The Tertiary is wholly wanting to the eastward. There remains only a single outlier to the southward—Kaiparowits Peak. But its former extension over the whole of the Plateau Country admits of no serious doubt after we have once mastered the plan of the drainage system and of the Post-Eocene displacements. The rivers alone might not be sufficient to demonstrate the conclusion, nor would a restoration of the displacements, but the two together admit of no other interpretation. How far eastward and southward the lava-cap extended cannot be determined. Remnants of alluvial conglomerates, with large fragments of trachytes and augitic andesites, are found more than 20 miles eastward, and they are indistinguishable from the rocks now forming the summit of the plateau. But how far they have been carried is a question which it is impossible to answer.

The altitude of the eastern front of the Aquarius above the country which it overlooks is upon an average about 5,500 to 6,000 feet, and the thickness of the strata removed from its vicinity is probably about 4,000 to

5,000 feet. In some localities the denudation has been much greater, in others considerably less. The preservation of the Aquarius has no doubt been due to its immense roof of hard lava.

The eastern part of the plateau is the loftiest, being about 11,600 feet above sea-level. Its platform here is believed to be nearly horizontal, as indicated by the projection of its summit against the sky from every point of view around the horizon. When seen from Thousand Lake Mountain, which is very nearly as high, no peak, nor even a hill, breaks the monotony of the almost level crest. But the summit is so densely forest-clad that no effort was made to penetrate its interior spaces. The upper wall of dark volcanic rock is seen to extend completely around the eastern third of the plateau. A little east of the center of the plateau a fault throws down the platform west of it from 600 to nearly 1,000 feet. This fault is a southward extension of the one which runs along the western base of Thousand Lake Mountain and across the Red Gate. South of the Gate its throw gradually diminishes, and on the southern slopes of the Aquarius, a few miles south of the lava-cap, it runs out. This fault is comparatively recent for the most part, and is probably coeval with the other great displacements of the Pliocene-Quaternary system. On the northern slopes it splits into two branches, which reunite near the southern verge.* This movement has produced a sag in the central part of the plateau, but the altitude of the summit is nearly all regained towards the west by a gradual ascent.

Of the rocks upon the summit I can say but little, having traversed only the central part of the plateau. Those which were observed were chiefly dark hornblendic trachytes commingled with very extensive masses of augitic andesites. In their general aspect they resemble those which are found on Thousand Lake Mountain and northward as far as Mount Hilgard, but with a somewhat larger proportion of augitic lavas. The bedded lavas exposed edgewise in the upper cliffs are highly varied within their limits of chemical and mineral constitution. No acid rocks were observed, and only a few very basic ones. But the sub-acid and sub-basic

*Mr. Gilbert is of the opinion that the displacement is much more complicated. Ascending the face of this fault and reaching the summit, he found a narrow valley near and parallel to the fault, which valley he believes was caused by the sinking of a narrow wedge. He has also suggested to me several other minor features of inequality in the surface which he regards as due to minor faulting.

rocks present a great deal of variation in their aspect. A body of lavas so enormous as that which caps the Aquarius cannot be discussed with profit until it has been studied long and patiently, and inasmuch as my own observation has been extremely superficial, I do not feel justified in attempting to give any further account of them.

The structure of the plateau is best studied upon the southern slopes. Here the most striking feature is a large monoclinal, already alluded to as a companion to the Water Pocket fold. It comes up from the southeast, crossing the lower end of Potato Valley, and trends along the slopes northwestwardly, disappearing beneath the lava-cap. The throw of the monocline is to the westward. Upon its flanks the Cretaceous system is turned up and dips westward beneath the southwestward extension of the general plateau mass. The edges of its strata are truncated by erosion, and over them lies unconformably the Tertiary. (See Atlas Sheet No. 7, Section No. 7.) The upthrow of the monocline heaves up the Jurassic white sandstone, which is seen rolling up in a huge wave 1,200 to 1,800 feet high across the lower end of Potato Valley. The position of this flexure relatively to the plateau mass is peculiar and very striking; indeed, at first sight it appears altogether anomalous. We are accustomed in the western regions to see the strata rolled up on the flanks of a mountain range like a great wave urged onward towards a coast and breaking against its rocky barriers. But the Escalante flexure is like a wave sweeping along parallel to the coast, the crest-line of the wave being perpendicular to the trend of the shore. Its line of strike runs up the slope and disappears beneath the Tertiary near the summit of the plateau. A fine steam of water (Winslow Creek) runs upon this monocline parallel to its strike, precisely as Water Pocket Creek runs upon and parallel to the course of that flexure.

The age of the Escalante monocline is evidently Pre-Tertiary. It has been exhumed by the general erosion after having been buried beneath Eocene strata, and after these strata had been overflowed in great part at least by many hundreds of feet of lavas. The stream had its course laid out prior to this erosion, and held its position after it had cut through lavas and Eocene beds into the underlying Jurassic sandstones.

The area included between the Escalante fold on the west and the

Water Pocket fold on the east appears to have been, during the latter part of the Cretaceous age, an island. It is apparently possible to designate roughly the positions of large portions of its east and west coast-lines. In a word, those coast-lines may have been approximately coincident with the axes of those two flexures. The northern part of this island cannot at present be ascertained, because the lavas have deeply buried it, and there is not even sufficient basis for conjecture. But of the portions now indicated it is possible to infer that the length of this island must have been at least 90 miles and its maximum width about 35 miles.

The northwestern angle of the Aquarius is laid open by an immense gorge. A mass of lavas and conglomerate more than 2,000 feet thick is revealed, and beneath them lies the Tertiary. Near the opening of this gorge the Grass Valley fault cuts across it, throwing down the platform to the west Along the western base of the Aquarius the faulting becomes very complicated, and the displacements are great in their vertical extent. The faults are repetitive, or "stepped," with numerous instances of the dropping of large blocks between faults of opposite throw. These blocks usually sag in the middle, and there is occasionally some chaos produced in the component masses. An effort was made to find the proper restoration, but I am doubtful whether it has been very accurately done. (See stereogram.)

The western wall of the Aquarius, which looks down upon the southern portion of Grass Valley and the Panquitch Hayfield, is of great grandeur, rising more than 4,000 feet above the valley below. Apparently it is composed of volcanic materials from top to bottom, but the thickness of the volcanic masses is less than it seems at first. The wall rises by successive steps, and each step represents a fault, so that the aggregate thickness of lava and conglomerate probably will not exceed 2,000 feet on the average. The rocks are mainly trachytic, but a large proportion of augitic andesites is associated with them. At the summit of the plateau near the western crest and upon the thrown blocks which are successively passed as we descend, are numerous fields of ancient basalt much eroded, and presenting a similar appearance to the scattered basalts spoken of in the preceding chapter as occurring upon the surface of the Awapa. Their extent and distribution is not accurately known. They cover a considerable area, but in a disconnected way, and their eruption appears to have occurred prior to the principal epoch of faulting. The mass of conglomerates is very great. They are composed wholly of the *débris* derived from the destruction of the more ancient trachytes and andesites, and are well stratified in layers which are nearly horizontal.

The age of the principal eruptions of trachyte and andesite cannot be ascertained, but it is very ancient, going back probably into the early Miocene. The same indications of great antiquity are found here which have been observed in the Sevier Plateau and in the Tushar—eruptive epochs in which lavas in enormous quantities were outpoured with hundreds and perhaps even thousands of individual eruptions, epochs of erosion during which were accumulated heavy beds of conglomerate, periods of faulting and dislocation which have given a new topography to the country, periods of renewed activity of volcanic forces, and a long final period of waste and decay. All this conveys the impression of immense duration; how long the era may have been we do not know, even in terms of the geological calendar. But the interval which separates us from the Eocene must in some way be filled, and these operations are all that we have to fill it with.

The western front of the Aquarius, from the grand gorge of Mesa Creek to its southern termination, is about 17 miles in length. The lavas and conglomerates are heaviest at the northwestern angle, and diminish in bulk towards the south. The northwestern part of the plateau seems to have been one of the great centers of trachytic and andesitic eruption from which the extravasated masses flowed outward in all directions. No cones or mountain piles, however, are now visible. If any formerly existed they have been leveled down nearly to a common platform, and can no longer be distinguished from the rolling hills which have been sculptured by the protracted erosion. There is, however, this peculiarity in the locality: the lava-sheets are less stratiform and more chaotic than in localities where they are collectively thinner. They are also more varied in kind and in texture. As we recede from this locality the sheets become more uniform and even in their bedding, as if they had spread out and become thinner.

Many dikes are also visible around the gorge of Mesa Creek, while none were observed in the bedded lavas farther south.

TABLE CLIFF.

The southwestern cape of the Aquarius ends at a high pass separating the Escalante drainage from that of the Panquitch Hayfield. This pass is thus in the main divide between the drainage system of the Colorado and of the Great Basin. At this cape the lava-cap of the Aquarius terminates, but beneath it the Tertiary thrusts out a long peninsula to the southward. The altitude of these beds is very nearly 11,000 feet above the sea, and the peninsula which they form is Table Cliff. Upon its summit is an outlying remnant of lava a few hundred feet thick, which was once, no doubt, continuous with the lava-cap of the Aquarius. The table is practically a large butte left by the denudation of the surrounding country. I have explained in the first chapter how the degradation of the Plateau Country has to a great extent proceeded from a number of centers, extending radially outwards, wasting the edges of the strata, partly by direct attack upon the fronts of cliffs, partly by the interlacing of cañons, but each series of beds being gradually wasted backwards, and their terminations forming ever-expanding circles facing the center of erosion. The erosion of the Tertiary, which spread from the center now occupied and inclosed by the Circle Cliffs, has met the outward-spreading erosion from a center now occupied by Pária Valley, and the cusp formed by the meeting of the two circles is the locus of Table Cliff. The table is interesting on account of the splendid exposures of the Cretaceous system upon its western and southwestern flanks. While the beds in the mass of the table are nearly horizontal, the ledges of the Cretaceous projecting towards the west are turned upwards at a very moderate inclination, and in passing to the floor of Pária Valley we cross the whole Cretaceous system, of which the thickness here is 5,000 feet. The series consists of heavy members of bright yellow sandstone and gray argillaceous shales. Each member is from 300 to 500 feet in thickness. The cliff sculpture is about as fine as any in the Plateau Country. We have noted its appearance from the western side of Pária Valley at the foot of the Paunságunt slopes (Chapter XI), and a nearer view, though less pleasing, is no less impressive. None of the cliffs are lofty, but the grandeur of the spectacle consists in the great number of cliffs rising successively one above and beyond another, like a stairway for the Titans, leading up to a mighty temple. The Eocene beds which form the upper table are rosy red, and carved in a manner which is so suggestive of intelligence that it is difficult to persuade ourselves that the blind forces of nature could have achieved such a result.

KAIPAROWITS PEAK.

Kaiparowits Peak is a mountain-like butte south of Table Cliff, capped by Tertiary beds, with the Upper Cretaceous upon its flanks. It is obviously a mere remnant of the continuous Eocene formation which formerly stretched indefinitely southward. Its slopes descend to the platform of the Kaiparowits Plateau, which is composed of Middle Cretaceous beds. This plateau is properly a member of the Kaibab system, and is one of the most interesting. It is a broad causeway, reaching to the Colorado, where it is cut off momentarily by the Glen Cañon. Beyond the river the Cretaceous beds continue far into Arizona, and expand into the great mesas and terraces which cover a large part of that Territory. Along this plateau there are still preserved the unity and virtual continuity of the formations which constitute the District of the High Plateaus and the mesas of New Mexico and Arizona, while elsewhere throughout the heart of the Plateau Province they have been removed by the great erosion. The little remnant of Tertiary beds upon the summit of Kaiparowits Peak is one of the many indications that the Lower Eocene also once reached across the same interval.

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