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Diagenetic Relationships and Reservoir Quality Implications in Brookian Clastic Sequences, National Petroleum Reserve, Alaska

Thomas C. Mowatt
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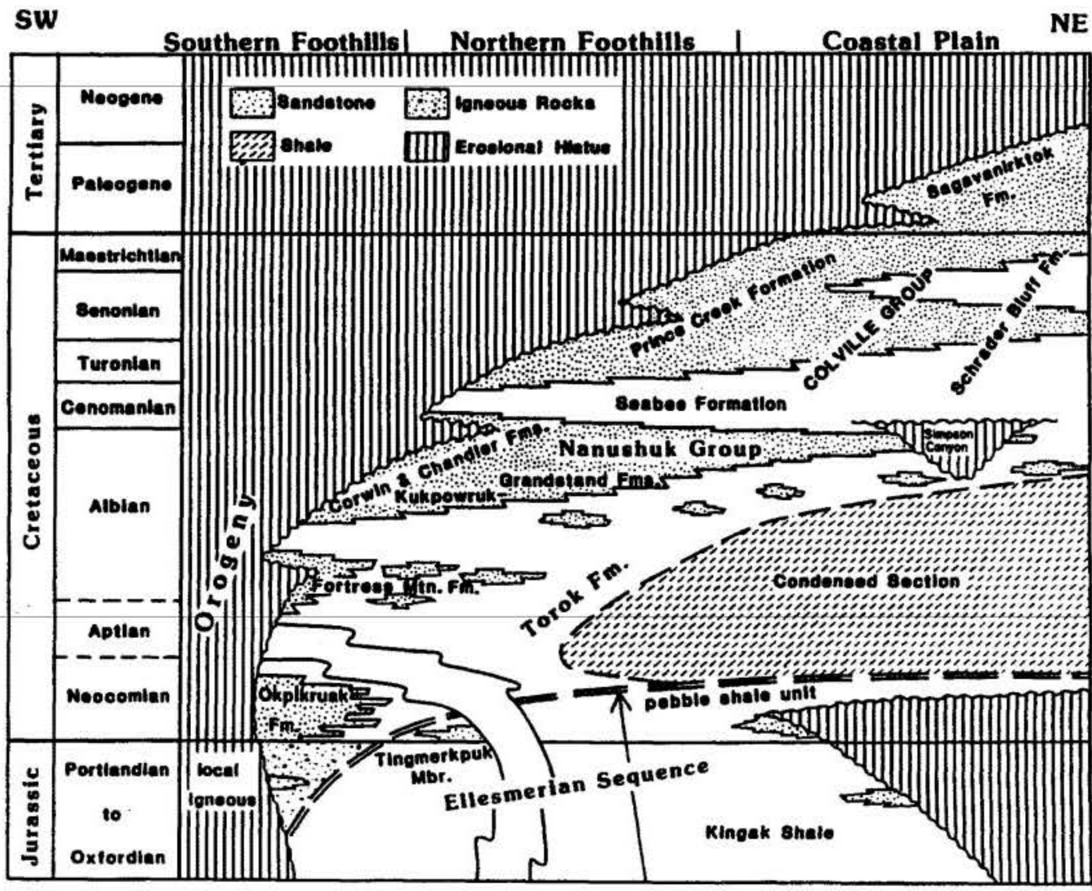

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Diagenetic Relationships and Reservoir Quality Implications in Brookian Clastic Sequences, National Petroleum Reserve, Alaska

Abstract

Petrologic and petrophysical investigations of Brookian sandstones and siltstones from wells in the National Petroleum Reserve in Alaska revealed new information about the diagenetic development of these rocks. Several kinds of labile materials are present, and secondary dissolution porosity has been developed to various degrees. Mineralogic, geochemical, and textural characteristics indicate the potential for development of appreciable porosity of this type in equivalent horizons and/or similar materials within northern Alaska.

Known regional geological, geochemical, and geophysical relationships are consistent with this view. Considerations of hydrocarbon resource potential should include concern for these relationships as integral to appreciation of the overall diagenetic evolution of the region.

Heretofore, the potential for the occurrence of significant reservoir rocks in these horizons has been considered to be rather low, based on primary petrologic characteristics. However, this should be reappraised.

1. Introduction

Background Comments

This report was originally prepared in 1982, but was not completed in finished form. Since then, several oral presentations have been made on the subject. Due to subsequent inquiries, it was felt appropriate to release this information at this time, essentially unmodified in open-file form, since development of interest in, and knowledge pertaining to the topics presented have increased significantly. At the time of the original work, appreciation of secondary dissolution porosity was not particularly widespread within the government agencies concerned.

Although no systematic attempt has been made to incorporate any appreciable additional material from either the literature or other sources, including our own work, subsequent to 1982, occasional comments have been inserted.

General Considerations

Petrographic studies were made of Brookian (Cretaceous) sedimentary rocks from a number of selected wells from the National Petroleum Reserve in Alaska (NPRA). *Figure 1* shows the location of NPRA. *Figure 2* shows well locations. The original work was carried out (1977-1979) during the course of interagency land use planning/resource appraisal investigations of NPRA (U.S. Department of the Interior, 1979). Available core samples from selected wells within NPRA were examined visually and with a hand-held scintillometer, as part of the mineral resource assessment aspects of this program. Selected portions of horizons of particular interest were sampled, with the intent of characterizing the materials petrographically, mineralogically, and/or chemically, as appropriate. Due to subsequent changes in program emphasis, however, only preliminary petrographic studies, together with limited X-ray diffraction, scanning electron microscopy, and chemical analyses were carried out.

In recent years, there has been an increased awareness and appreciation of the development of secondary dissolution porosity in sedimentary rocks, attendant to the general course of diagenetic events subsequent to the deposition of the sediments of which these rocks are constituted. Among the numerous published accounts of various aspects of this, the early work of Schmidt et al (1977), Schmidt and McDonald (1979 a, b), Hayes (1979), Pittman (1979), Galloway (1979), Curtis (1978, 1981), Lindquist (1976), Loucks et al. (1979), and Land and Milliken (1981) have been particularly useful in facilitating recognition and interpretation of observed petrologic characteristics, in the broader context of diagenetic trends and relationships.

The voluminous subsequent technical literature provides ample testimony as to the continued interest in this. Increasingly sophisticated techniques and concepts have combined to furnish more detailed and substantive insights in terms of rock-fluid interactions attendant to diagenetic events. The large number of technical publications on this theme essentially defies citation here; the literature is replete with examples (cf. McDonald and Surdam, 1984). The presently recognized magnitude and extent of secondary porosity development worldwide, together with the implications for hydrocarbon migration and accumulation (as well as for geothermal and mineral resources in certain instances) combine to make this a topic of interest in exploration, development, and research.

The presentations by Schmidt and McDonald (1979a, b) were particularly relevant, as the present NPRA work resulted in the recognition of sedimentary rocks with mineralogic and textural characteristics apparently amenable to the development of secondary dissolution porosity under appropriate geological conditions. Current concepts of diagenetic processes, together with those concerning the origin, migration, accumulation, and preservation of petroleum, collectively suggest that the reservoir properties and hydrocarbon potential of these rocks ought to be investigated further.

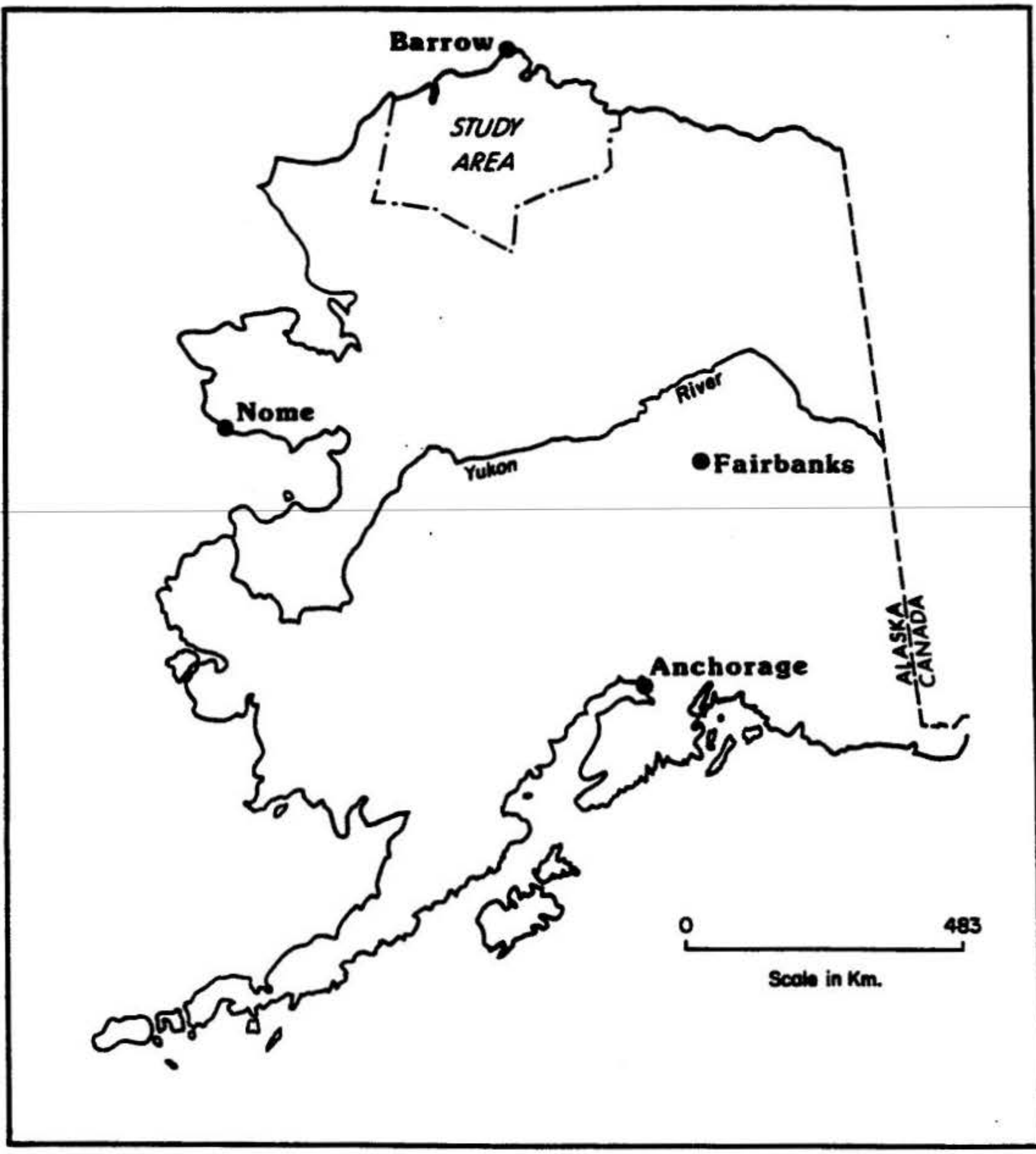

Figure 1.
Location map, National Petroleum Reserve in Alaska (NPRA).

LEGEND FOR FIGURE 2

1. Avak - 1	17. South Barrow - 3	33. Peard - 1	*49. Knifeblade - 1, 2A
2. East Simpson - 1	18. South Barrow - 16	34. South Meade - 1	50. Lisburne - 1
3. East Simpson - 2	19. South Barrow - 12	35. Topagoruk - 1	51. Seabee - 1
4. Iko Bay - 1	20. South Barrow - 14	36. Tunalik - 1	52. Square Lake - 1
5. North Simpson - 1	21. South Barrow - 17	37. Atigaru Point - 1	*53. Titaluk - 1
6. Simpson - 1	22. South Barrow - 19	38. Cape Halkett - 1	54. Umiat - 1
7. South Barrow - 1	23. South Barrow - 20	39. Drew Point - 1	55. Umiat - 2
8. South Barrow - 2	24. South Simpson - 1	40. East Teshekpuk - 1	56. Umiat - 3
9. South Barrow - 4	25. Walakpa - 1	*41. Fish Creek - 1	57. Umiat - 4
10. South Barrow - 6	26. West Dease - 1	42. Ikpikpuk - 1	58. Umiat - 7
11. South Barrow - 7	27. East Oumalik - 1	43. J.W. Dalton - 1	59. Umiat - 11
12. South Barrow - 8	*28. East Topagoruk - 1	44. North Kalikpik - 1	*60. Wolf Creek - 1
13. South Barrow - 9	29. Kaolak - 1	45. So. Harrison Bay - 1	*61. Wolf Creek - 2
14. South Barrow - 10	30. Kugrua - 1	46. West Fish Creek - 1	*62. Wolf Creek - 3
15. South Barrow - 11	*31. Meade - 1	47. W.T. Foran - 1	63. Grandstand - 1
16. South Barrow - 13	32. Oumalik - 1	48. Inigok - 1	64. Gubik - 1
			65. Gubik - 2

*Wells examined petrographically in present study.

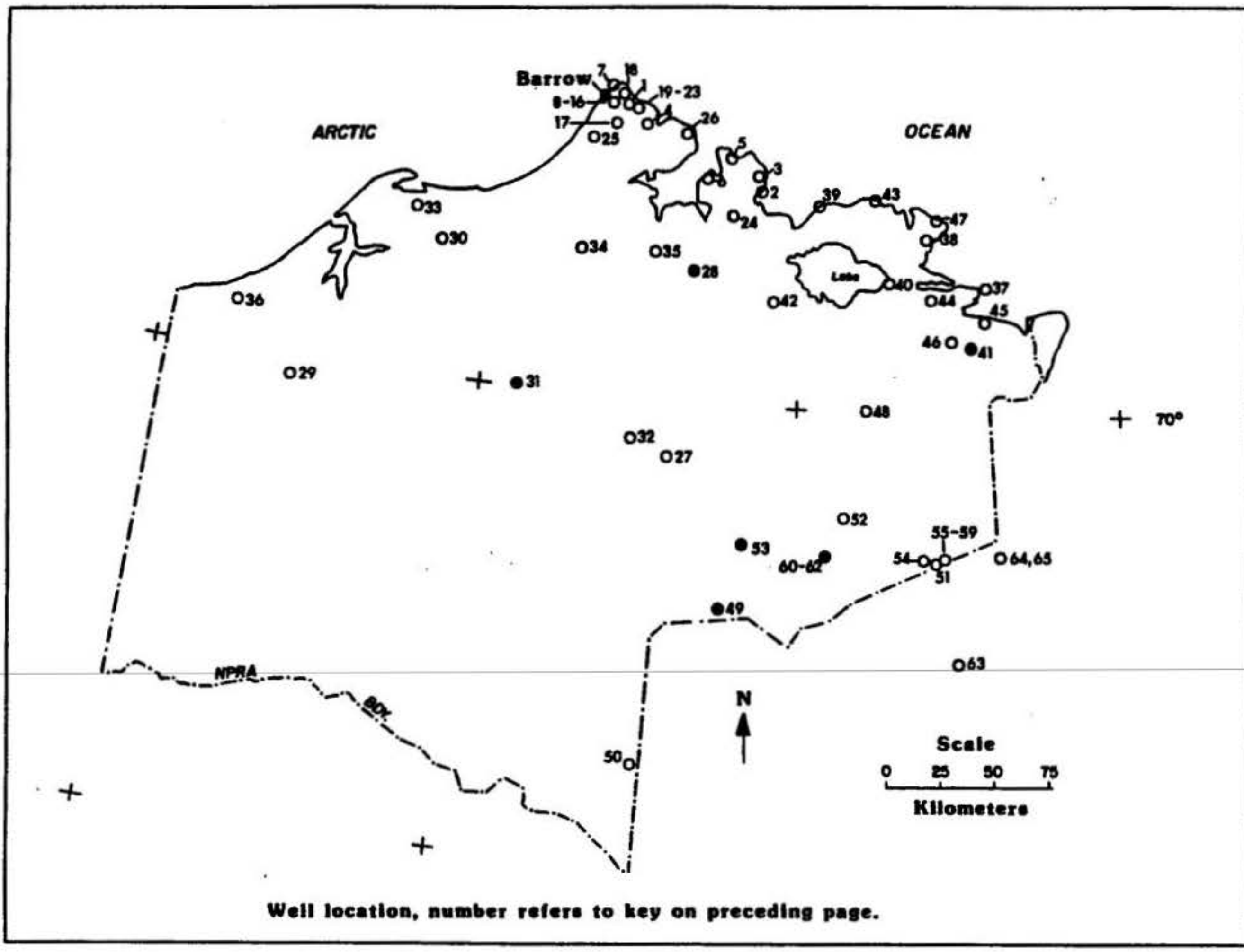

Figure 2.
Locations of wells, NPRA

2. Study Area and Summary of Previous Work

General Background

The history of geological studies and petroleum exploration in northern Alaska, and NPRA in particular, has been discussed by Carter et al. (1975, 1977), Collins and Robinson (1967), Reed (1958, 1969), Bird (1981b), and Gryc (1985), etc. Investigations of various aspects of the geology of the area, surface and subsurface, include a series of U.S. Geological Survey Professional Papers (cf. especially numbers 20, 301, 302, 303, 304, 305), as well as numerous other publications. Recent contributions of particular relevance to the present study, in that they synthesize the regional relationships, as well as many of the more detailed concerns, include Ahlbrandt (1979), Ahlbrandt et al. (1979), Bird (1981a, b), Bird and Andrews (1979), Molenaar (1981), Molenaar et al. (1981), Fox (1979), Fox et al. (1979), Blean (1976), Bartsch-Winkler (1979), Bartsch-Winkler and Huffman (1981, 1982), and Mull (1979).

Some of the principal points of concern to the present paper have been summarized previously by Mowatt (1983, 1984a, b). Reports featuring more complete descriptions of petrographic relationships and complementary information are in preparation by the present authors.

The wells sampled for the present work represent a broad regional coverage of NPRA. They were drilled during the period 1949-1952, when the present NPRA was managed by the U.S. Navy as Naval Petroleum Reserve Number 4 ("PET-4"). They are relatively shallow wells, the deepest (Fish Creek Test Well Number 1) reaching a total depth of 7020 feet.

In general, the stratigraphic units of concern here include several recognized intervals of Cretaceous age (cf. Figure 3, from Carter et al., 1977), which collectively have been included within the Brookian Sequence. Of particular interest, in descending stratigraphic order, are the Colville Group, the Nanushuk Group, and the Torok Formation (Shale). Each of these units has been determined to occur in thicknesses on the order of at least 1000 meters or more in the subsurface of NPRA. Further subdivision (cf. figure 4, from Ahlbrandt, et al., 1979) has been made within each of these units (cf. Detterman, 1973). Figure 5 (after Bird, 1981b) is a generalized cross section across northern Alaska, illustrating time-stratigraphic relationships. These units include materials representative of a variety of initial sedimentary depositional environments, encompassing continental, deltaic, shoreline, and marine settings. The resulting rock types presently preserved include a spectrum ranging from fine-grained claystones and shales, through

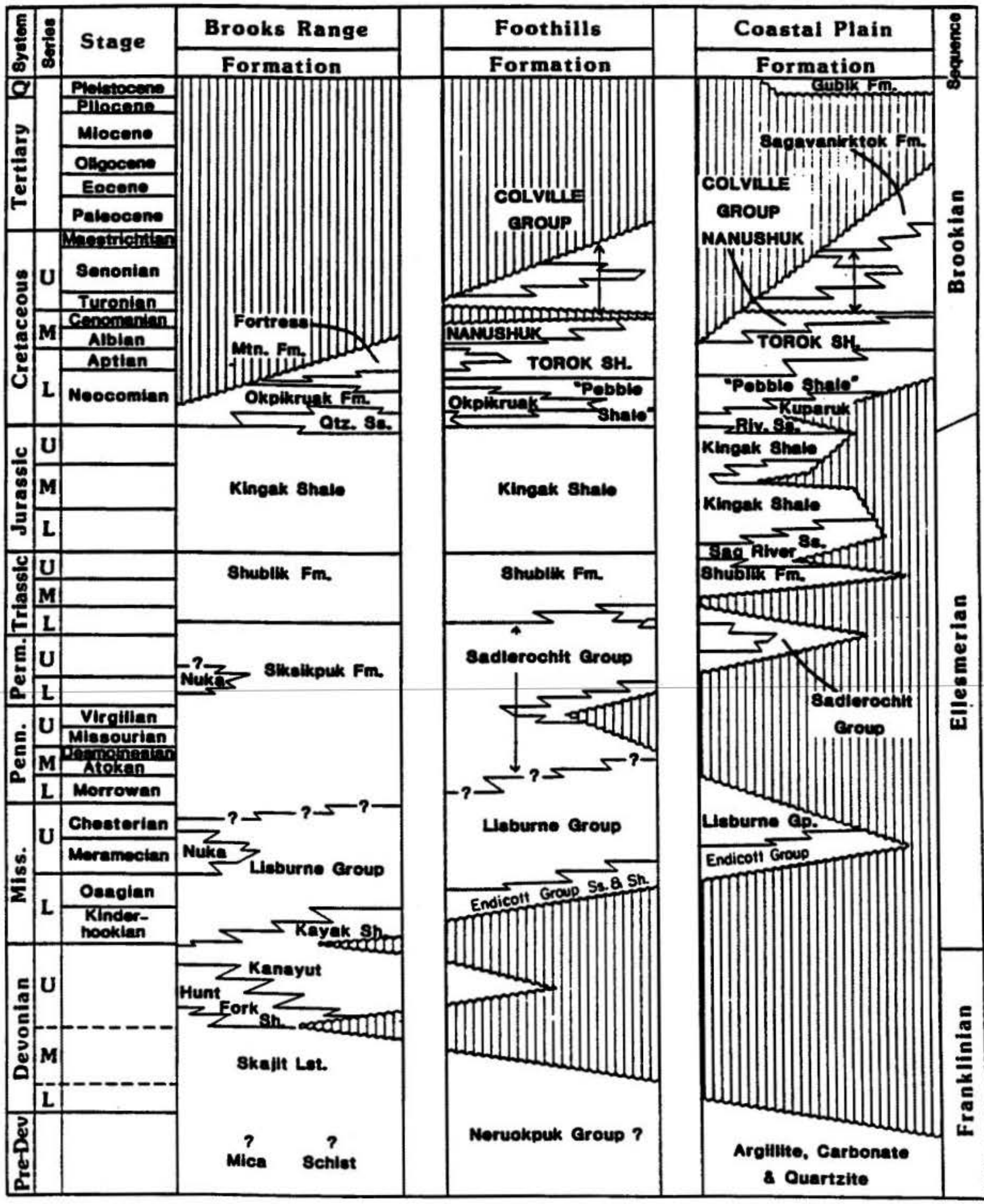

Figure 3.
General stratigraphic sections, NPRA (from Carter et al., 1977).

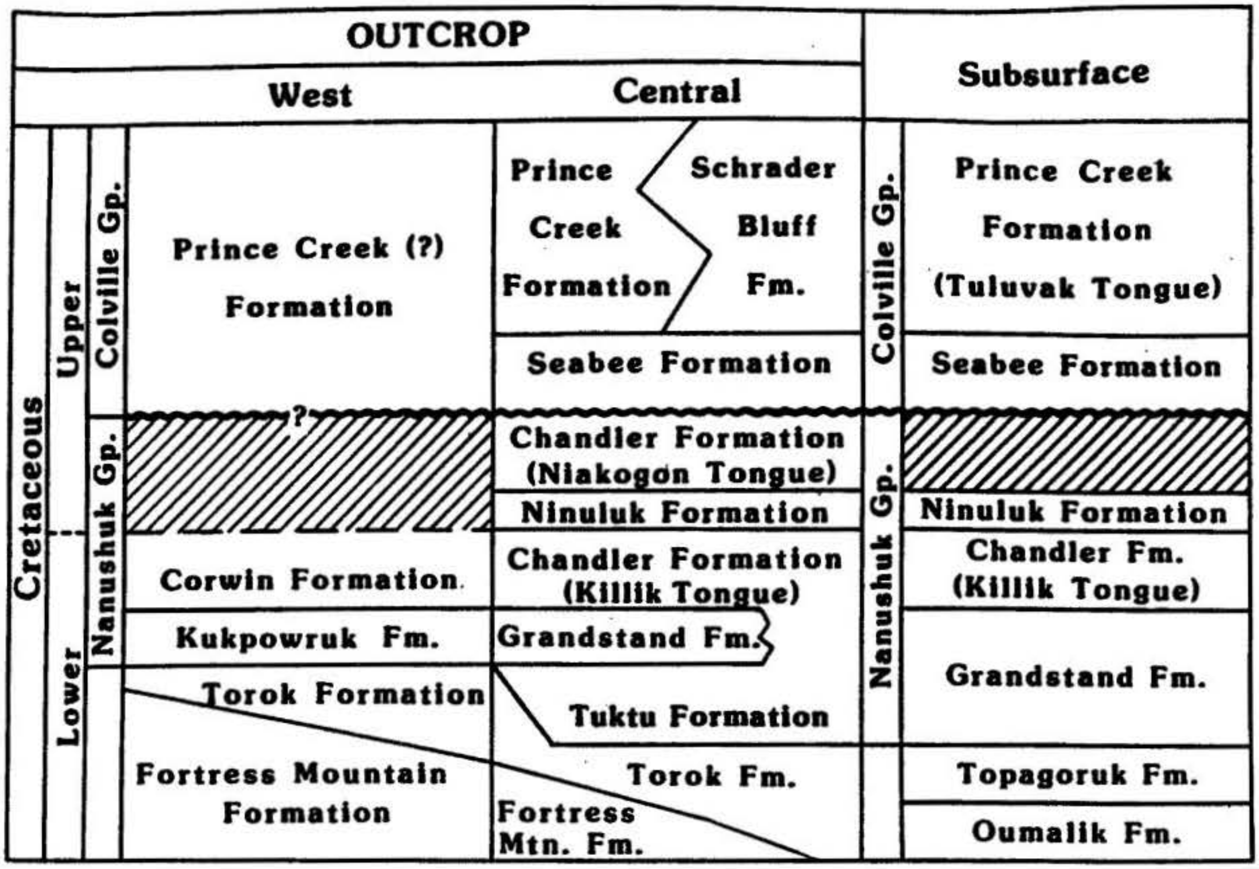

Figure 4.
Stratigraphic nomenclature for the Nanushuk Group and adjacent rock units from the North Slope of Alaska (from Ahlbrandt et al., 1979).

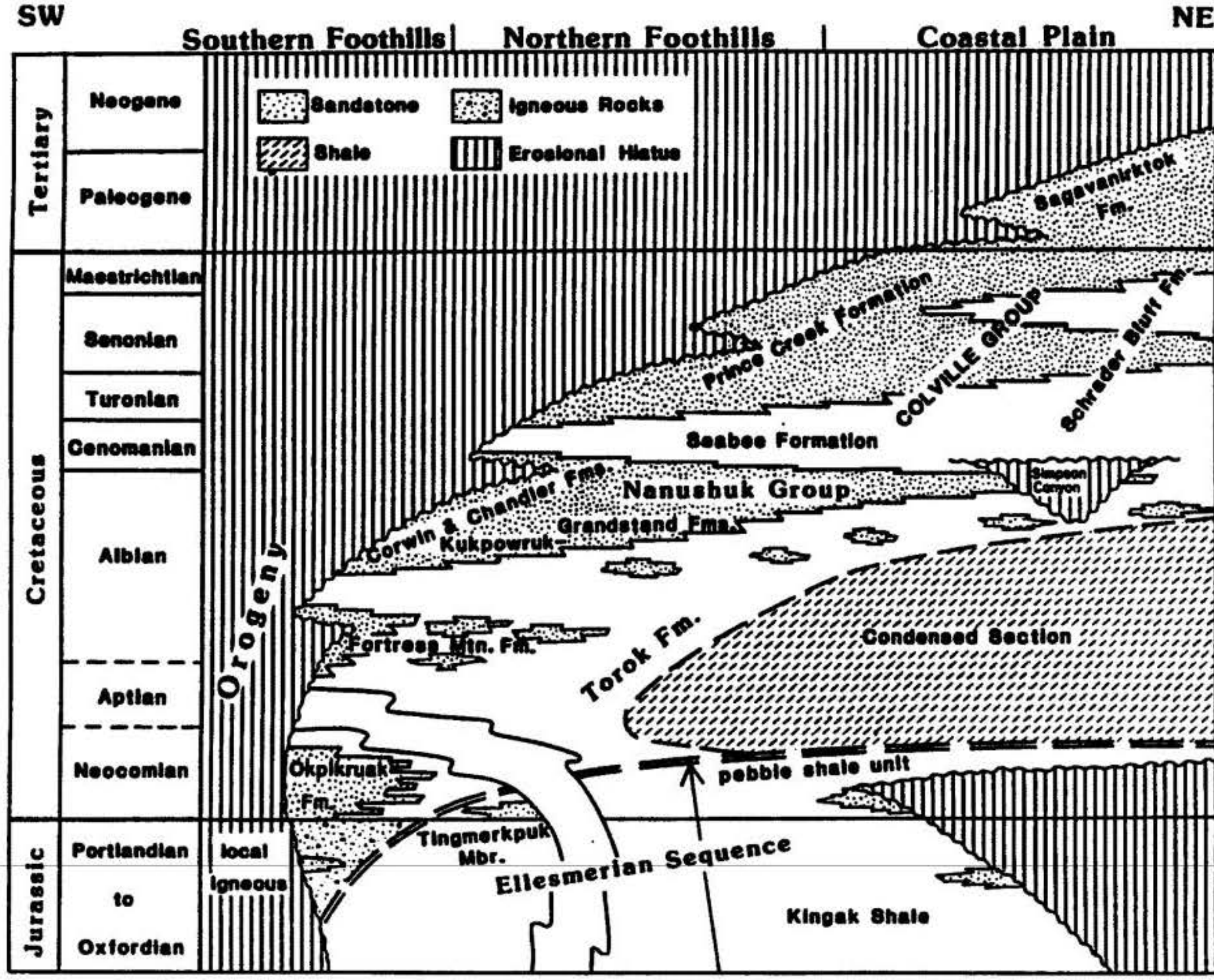

Figure 5.
Generalized schematic cross-section across northern Alaska, illustrating time-stratigraphic relationships (after Bird, 1981).

siltstones and sandstones, to occasional conglomeratic materials, as well as coal. The rock types of principal concern to the original NPRA land use planning/resource appraisal work and, hence, to the present discussion, were the coarser-grained, potential host-reservoir-conduit rocks. Thus, the sandstones were emphasized in the sampling and analysis, together with coarser siltstones, although finer-grained rocks were considered to some extent as well.

Considerations Regarding Diagenesis

Because of the nature of the original NPRA program, attempts to synthesize regional geological and geophysical information, as well as consideration of detailed petrologic/petrographic, mineralogic, and geochemical relationships, in the context of the current concepts of secondary porosity development can only be made in a preliminary fashion at the present time.

Published reservoir quality studies to date have dealt principally with the primary porosity aspects of these northern Alaska sequences in terms of depositional environments, source lithologies, etc. Little public mention has been made of the potential for secondary porosity development. Some commentary on secondary porosity has been offered, in regard to "leaching of feldspars" (Bartsch-Winkler, 1979) "in the eastern province," but without further discussion or implication. Bartsch-Winkler and Huffman (1981, 1988) also discuss some aspects of secondary porosity development vis-a-vis feldspars and clay minerals in a subsequent report, but the labile constituents, in particular the carbonate minerals, as potential candidates for appreciable secondary dissolution porosity development, regionally, have yet to be considered. Diagenesis has generally been considered negatively in most previous published work, relative to implications for reservoir rock quality.

Previous considerations of reservoir rock properties in NPRA have dealt principally with stratigraphic and sedimentologic factors, and less with perhaps more overriding geochemical and geophysical considerations. Predominant diagenetic trends in various sedimentary rock types worldwide have been demonstrated to be largely determined by chemical, thermal, and other physical factors, transecting and overprinting stratigraphic and lithologic boundaries to a considerable extent, on a large scale. Such diagenetic trends have been well documented with regard to organic maturation and to clay mineral diagenesis; apparently dissolution porosity development and its ultimate destruction must be considered similarly, in terms of large-scale geochemical processes in sedimentary materials (Schmidt and McDonald, 1979b).

Results of the present limited studies of Brookian sequences in the subsurface from NPRA indicate that significant proportions of carbonate minerals, as well as other potentially labile constituents, are present in these rock units. Various workers, including Hayes (1979), Pittman (1979), and Schmidt and McDonald (1979b), agree that many processes which might result in or aid in secondary porosity development may be factors to various extents in particular instances. These processes include fracturing of rocks, grains, and intergranular constituents, and shrinkage of various constituents.

However, the "vast majority" of secondary sandstone porosity results from dissolution of various solid constituents. Schmidt and McDonald stress the dominant role of carbonate minerals as secondary dissolution candidates, while relegating other labile constituents, such as feldspars and rock fragments, to somewhat lesser status in this respect. Pittman, as well as Hayes, while conceding the importance of the carbonates, indicate that authigenic and detrital silicates, especially feldspars and labile rock fragments, are also of at least equal importance, in general, and may be of predominant significance in many instances. The studies of Loucks et al. (1977), Lindquist (1976), and Land and Milliken (1981), among others, seem to support this contention.

It should be pointed out that geochemical relationships indicate that dissolution of carbonates, in particular, is favored by lowering the pH of a geochemical environment; several proposals have been advanced regarding the means by which such conditions may occur (cf. McDonald and Surdam, 1984; Surdam et al. 1989).

Schmidt and McDonald (1979b) emphasize the carbonate minerals as being particularly susceptible to diagenetic dissolution, and consider various means by which this can come about geologically. Generation of carbon dioxide (CO_2), by one or a combination of several geochemical mechanisms, is considered a principal factor potentially leading to carbonate dissolution in associated sedimentary materials, due to increased solubilities of carbonate minerals under increased concentrations of carbon dioxide in aqueous media. The geochemical mechanisms which could result in evolution of carbon dioxide include decarboxylation of organic matter undergoing thermal maturation, diagenesis of clay minerals, and heating of carbonates at elevated temperatures; other processes (igneous activity, hydrogen sulfide evolution, etc.) have been suggested as well, but in general they are considered as less likely to be effective, .

Organic acids, formed during alteration/maturation of organic materials, have been invoked as well to serve as agents of dissolution (cf. Surdam, et al., 1989, etc.). Present knowledge, as represented in recent literature, together with personal communications with a number of workers currently active in this field, does not permit definitive evaluation of the relative significance of these, as well as other possible diagenetic mechanisms/ processes which might be involved in the formation of secondary dissolution porosity.

The occurrence of conditions (temperature-pressure-geochemical environment) appropriate for the dissolution of carbonate minerals (plus or minus other labile constituents) might be considered not unlikely, geologically, in rocks as old as these (Cretaceous) somewhere within an extensive sedimentary basin with the tectonic-provenance-sediment types- depositional environments-burial history characteristics of the northern Alaska region. Hayes (1979), Pittman (1979), and Schmidt and McDonald (1979b) discuss these factors quite lucidly, and it would seem worthwhile to consider the NPRA samples in the context of these ideas. It is fully appreciated that any diagenetic dissolution which indeed does occur within a given horizon in any particular area may well result in essentially concurrent deposition of another phase(s), with no net gain in either porosity or permeability. There may even be decreases in porosities and/or permeabilities as the net result of diagenetic processes, depending upon the resultant of an array of interrelated physical and chemical factors in any particular situation.

There is no question that the deleterious effects of diagenetic processes on reservoir rock qualities may indeed be very significant in many instances. In particular, reactions involving feldspars and/or other labile silicates, resulting in the ultimate (local, proximal, distal) formation of other solid reaction products (i.e., clay minerals, quartz, plus or minus zeolites, other feldspars, especially) may well be quite influential in this type of resultant state of affairs, within the immediate neighborhood of dissolution and/or elsewhere within the subsurface. There is considerable evidence, however, that such diagenetic products (cements, rims, coats) are, together with other earlier formed materials, themselves susceptible to modification during the course of more advanced diagenetic events, under changing conditions of temperature, pressure, or geochemical environment.

In addition, it is apparent that significant amounts of dissolution porosity can be developed from rocks of extremely low porosity ("irreducible minimum," i.e., 0.5-2.5 volume percent) and permeability, under not uncommon geological circumstances. The cited authors state that this type of secondary dissolution porosity can develop in very "tight" rocks. They attribute this to the irreducible lamellar porosity, often aided and abetted by fractures (micro and larger), in providing access for the leaching fluids which initiate the dissolution. Interestingly, the relative proportion of irreducible porosity increases with decreasing grain size of the rock, so that fine to medium sandstones, as well as coarse siltstones, remain very much of interest in regard to being potential reservoir rocks from the point of view of secondary dissolution porosity development.

At the current state of knowledge, prediction is often uncertain, at best, but there seems little doubt that, overall, the relationships discussed by Schmidt and McDonald (1979b), as well as by others, are at least qualitatively correct. They certainly represent enough geologic situations, with sufficient combinations and variations of depositional sedimentary environments, lithologies, geochemical factors, burial histories, tectonic effects, geothermal gradients, pressure conditions, associated stratigraphies, etc., to suggest that the underlying cause and effect relationships concerning diagenetic changes associated with dissolution porosity development are at least reasonably well appreciated, although not thoroughly understood.

The discussion in the present report is predicated upon acceptance of the generalizations advanced by Schmidt and McDonald and the other cited authors, as a reasonable general working hypothesis. The present discussion is intended to focus on this particular aspect of the rocks studied, i.e., the potential for rocks with similar characteristics to undergo development of appreciable secondary dissolution porosity elsewhere within the Cretaceous sedimentary sequences of northern Alaska. It has been observed that such secondary dissolution porosity has, in fact, developed, to various degrees, within some of the wells studied and discussed here.

3. Analytical Work

Sampling

For the present study, wells were selected for sampling on the basis of availability of core material, geographic location, and lithology. Samples were obtained from cores from the only wells available to the authors at the time, i.e., those drilled under the auspices of the U.S. Navy during the Naval Petroleum Reserve Number Four program, through 1952. The wells sampled were Meade Test Well 1, Fish Creek Test Well 1, East Topagoruk Test Well 1, Titaluk Test Well 1, Knifeblade Test Wells 1 and 2A, and Wolf Creek Test Wells 1, 2, and 3.

Small samples were taken from the cored intervals of each well, selected on the basis of described lithologies and visual examination.

Analyses

Petrographic studies have been carried out on selected samples from each well, in conjunction with limited chemical, scanning electron microscopy, and X-ray diffraction analyses. Of particular interest is the development of discernible secondary dissolution porosity, as well as the presence of appreciable carbonate mineral and other potentially labile constituents.

In addition, scrutiny of lithologic descriptions based on other work reported in the literature was carried out, in order to determine the extent of recognized "calcareous" and other material potentially of interest with respect to development of dissolution porosity. These other descriptions include relatively little petrographic work on subsurface samples. The contributions of Krynine (1947, 1948), Krynine and Ferm (1952), Fox (1979), Fox et al. (1979), Bartsch-Winkler and Huffman (1981, 1988) are exceptions, but the concept of secondary porosity was touched upon only briefly, in the latter three papers.

Results

Tables 1 through 9 summarize the cored intervals examined in the present study. The cored horizons consist at least in large part of sandstone-siltstone, with varying proportions of finer-grained (mudstone-shale) clastic materials. In all the NPRA wells, appreciable to predominant thicknesses of mudstone-shale also occur within the stratigraphic sequences. The volume of these fine-grained materials, together with their contents of organic material, suggest their potential as hydrocarbon source rocks under appropriate geochemical conditions. The juxtaposition of thick potential source rocks with appreciable thicknesses of potential reservoir rocks (i.e., the sandstones-siltstones, with potential for development of dissolution porosity) seems noteworthy.

Diagenesis of clay minerals within these fine-grained rocks also needs to be considered, in terms of the present discussion (cf. Curtis, 1978, 1981, etc.).

Examination of previously published lithologic descriptions indicated significant amounts of calcareous material to be present throughout the sedimentary horizons of interest.

During the course of the present petrographic studies, it was recognized that there are considerable amounts of carbonate minerals, both as apparent primary detrital sedimentary particles of various sizes as well as in other modes of occurrence, present in many of the rocks of sandstone-siltstone aspect which were examined, particularly within the Nanushuk Group and Topagoruk/Torok Formation.

The amounts of these carbonate minerals range from nil to occasional samples with more than 50 percent by volume; the majority of samples studied petrographically showed ranges on the order of five to 30 percent, based on visual estimates.

The detrital constituents include apparently monomineralic carbonate grains, as well as grains composed only in part of carbonate minerals. Petrographic examination shows that at least a considerable proportion of the carbonate minerals in many of the rocks studied is of sedimentary clastic detrital origin, based on observed textural and grain size relationships.

The other recognized modes of occurrence of the carbonate minerals include intergranular cement (often as poikilotopic patches), fossil fragments, micritic mud and/or clasts, and apparent replacements of other materials. X-ray diffraction analyses were made on some selected samples. Based on these data and on petrographic study, an appreciable portion of the sedimentary clastic detrital carbonate material most likely is dolomite (plus or minus ankerite, ferroan dolomite?), with lesser siderite as well, whereas the intergranular cement consists at least in large part of calcite, for the samples analyzed.

X-ray diffraction analysis of most of the samples studied petrographically remains to be done, together with staining work and scanning electron microscope studies, in order to define the mineralogic and textural relationships with greater certainty. In light of current concepts of diagenesis, it would seem that rocks such as these, with their appreciable contents of carbonate minerals, ought to be considered as candidates for development of secondary porosity, potentially in considerable amounts, under appropriate diagenetic conditions.

These rocks also contain appreciable amounts of other materials, including potassium feldspars and plagioclase feldspars, as well as lithic fragments encompassing a spectrum of igneous, metamorphic, and sedimentary lithologic types, which should also (Hayes, 1979; Pittman, 1979) be considered as potential candidates (i.e., "labile") for dissolution, under appropriate geochemical conditions.

The carbonate mineral components of these rocks consist principally of detrital, replacement, fossil fragment, and authigenic cement material. An ill-defined, fine-grained, "micritic" material also occurs quite frequently, apparently at least in large part as clasts of sedimentary material, as well as a more pervasive intergranular matrix. In either case, in the latter instance, the material does seem to represent primary sedimentary material, which appears in some samples to be undergoing incipient recrystallization to a microspar.

Although compelling evidence for a recrystallization sequence of micrite-microspar-more coarsely crystalline carbonate was not recognized, the suspicion lingers that such may well be occurring as one of numerous readjustments which the original sedimentary materials are making while striving to achieve a closer approach to physicochemical equilibrium under the diagenetic regimen imposed subsequent to burial.

Rocks such as those studied, in large part, thus essentially can be considered as having an appreciable portion of their "diagenetic lives" yet ahead of them, given the more or less common course of geologic events. They would be prime candidates for further modification, perhaps including secondary porosity development, during the subsequent course of such events, in all likelihood. Presumably the calcareous material described in the previously published reports would also represent such material in other portions of NPRA. This was verified for the wells examined petrographically, in comparison with their respective lithologic descriptions as reported previously.

In Wolf Creek Test Well 3, examples of the development of secondary dissolution porosity are clearly discernible. Porosity is developed in a sequence including intervals enriched in organic matter, and varying degrees of dissolution of carbonate and other minerals can be seen, apparently related to stratigraphic distance from the organic-rich zones, in interlayered sandstones and siltstones. In this case, presumably the generation of carbon dioxide accompanying thermal maturation of the organic materials was sufficient, perhaps in concert with other geochemical-physical factors (e.g., organic acids), for the development of an environment conducive to dissolution, on a relatively local scale. Under regionally dominant similar conditions, presumably such secondary porosity development, in precursorial rocks of appropriate character, would be developed on a more extensive basis, pervading appreciable volumes of the sediments involved.

Somewhat similar features were also noted, to various extents, in petrographic examination of materials for each of the other wells studied.

Of the limited number of wells reported on here, those in which this type of porosity has been most well developed are located in the southeastern part of NPRA. This indicates that geologic factors have combined to provide environments particularly conducive to the development of secondary dissolution porosity in this particular area, at the depths sampled, at least on a small scale.

4. Discussion

General Comments

The present work is intended to present some preliminary observations, and to point out possible implications for hydrocarbon generation, migration, and accumulation in the Cretaceous sedimentary rocks of northern Alaska. More detailed studies–some presently in progress–of the petrology/petrography, mineralogy, and geochemistry of these rocks, together with associated finer-grained rocks, are required in order to clarify matters.

Investigations of the clay mineral relationships, particularly diagenetic trends, in the claystones and shales interbedded with the coarser-grained clastics are of interest, together with determinations of thermal maturation states of associated organic material. Such information should be useful, in the context of basin-wide geological and geophysical relationships, in permitting a somewhat more definitive assessment of the potential for development of secondary porosity in equivalent strata elsewhere within the sedimentary basin, under favorable temperature, pressure, and geochemical conditions.

Should this potential seem reasonably high, decisions as to hydrocarbon exploration within these Cretaceous horizons would need to take this into account. To date, the prevailing general concept has been that these rocks are relatively unprospective in terms of hydrocarbon reservoirs, due to low primary permeabilities and porosities, where they have been studied, and that these conditions would persist or worsen at greater depths within the basin.

As stressed by Schmidt and McDonald (1979b) and Hayes (1979), however, this is not necessarily the case, but rather quite the contrary. Secondary porosity has been documented by these (and other) authors as being responsible, worldwide, for significant levels of porosity at depths well beyond that hitherto considered reasonable, based solely on persistence of primary porosity.

As the above authors point out, secondary dissolution porosity has been recognized in sandstones of essentially every primary textural type and mineralogical composition, in any state of diagenetic alteration, and apparently is not limited unduly by paleogeography or geological setting. In fact, it is stated that this type of porosity "occurs in every sizeable sedimentary basin in which sandstones have been examined using the appropriate criteria" (Schmidt and McDonald, 1979b).

According to the latter authors, "the volume of secondary porosity equals or exceeds that of primary porosity in the sandstones of many sedimentary basins worldwide, and a significant percentage of the world's reserves of natural gas and crude oil are contained in secondary porosity." They also point out that "primary migration of hydrocarbons commonly follows closely after the secondary porosity has been formed, because in the maturation of organic matter, the main phase of hydrocarbon generation follows after the culmination of decarboxylation. This close association of source and reservoir in time and space favors the accumulation of hydrocarbons in secondary porosity."

They conclude that "the main geological and economic significance of secondary sandstone porosity is that it extends the depth range for effective sandstone porosity far below the generally accepted depth limit for effective primary porosity. Generation and primary migration of hydrocarbons occurs mainly below the range of effective primary porosity."

The northern Alaska Cretaceous sedimentary sequences are known to contain tantalizing shows of oil and gas, as well as a large volume of potential source and reservoir rocks in a geologic context not at all inhospitable for hydrocarbon genesis, migration, accumulation, and preservation. It would seem appropriate to examine further the possibilities of appreciable development of secondary porosity in potential reservoir rocks within this sedimentary basin, based on inferences to be drawn from the known relationships.

As discussed by Schmidt and McDonald (1979b), thermal maturation of hydrocarbon source rocks "appears to be directly responsible for the generation of most secondary sandstone porosity. The majority of conventional crude oil and natural gas in clastic sequences has been generated in the source rocks after the intercalated sandstones had lost their primary porosity and after they had gained their secondary porosity. For this reason, secondary sandstone porosity is a favorable habitat for crude oil and natural gas in clastic sequences."

More extensive discussion of NPRA Cretaceous sedimentary rocks in this context must await more complete development, compilation, and synthesis of information regarding petrologic characteristics, geological framework, geochemical and geophysical relationships. Tentatively, however, it seems as though the details, as elucidated by the various cited authors, taken point by point, seem to be relevant to the Cretaceous sequences of northern Alaska, based on the information currently available. These observations would seem to represent a reasonable point of departure for the further work required to investigate more thoroughly this aspect of the hydrocarbon resource potential of these rocks, over this large region, within this thick sequence of sedimentary materials.

Geologic Controls

The potentially more important factors to be considered in an overview of regional diagenetic relationships include the following:

1. Original sediment composition and texture.
2. Sedimentation history.
3. Subsidence history.
4. Geothermal gradients, general and in detail.
5. Geopressures.
6. Regional and local geochemical conditions.
7. Regional and local hydrodynamics.
8. Structural/tectonic events, with consequent effects on pressure-temperature relationships in particular.
9. Local temperature and/or pressure effects, as related, for example, to igneous activity.
10. Heat buildup from diagenetic reactions.

There likely are other influential factors to be contended with as well. The complexities are formidable indeed. For the present, discussion here is restricted to a review of selected factors from among the foregoing.

With regard to consideration of diagenetic processes in terms of geochemical relationships, namely chemical reactions, the dominant controls must be related principally to chemical composition, temperature, and pressure. The lithology/mineralogy of the precursorial sediments has been reviewed above.

Assuming the dominance of temperature over pressure the geothermal gradient factor represents a potentially very significant control. It is fully appreciated that a considerable degree of uncertainty must exist with respect to extrapolating geothermal gradient data to a depth and/or areally, to any extent, with any reasonable degree of certainty, particularly in detail (Gretener, 1979, 1981). Some regional data were available, however, so the following comments are offered.

Regional Factors

The Cretaceous rocks encountered in the wells drilled through 1952, as well as in the subsequent wells for which data were readily available, presently lie at shallow to intermediate depths, none deeper than approximately 2288 meters. The lone exception is in the Oumalik Test Well 1, in which the Oumalik Formation occurs at depths between 1428 and 3318 meters; in this well, the Topagoruk Formation (Torok Formation equivalent) is encountered between 862 and 1482 meter depths. These are minima, of course, with respect to possible maximum burial depths for these rocks. The presence of appreciable carbonate, and the textural relationships, where known, are indicative that these rocks have not ever been buried to depths (and/or subjected to physico-chemical conditions) that would have facilitated the development of extensive secondary porosity and/or destroyed such secondary porosity.

The vitrinite reflectance data reported by Magoon and Claypool (1979, 1980a-f) and Claypool and Magoon (1980a-d) for the rock units in a number of wells (South Simpson 1, South Harrison Bay 1, West Fish Creek 1, Drew Point 1, Kugrua 1, W. T. Foran 1, South Barrow 14, South Barrow 16, South Barrow 17, and South Barrow 19) are of interest in this context (unfortunately, lithologic information for these wells was not readily available to the present authors, so it is not considered in the present report).

Vitrinite reflectance values, expressed as "optical reflectance, in percent," range on the order of 0.2 to 0.4 (reaching 0.64 in one well, Cape Halkett 1) for Colville Group samples, 0.3 to 0.6 for Nanushuk

Group samples, and 0.4 to 0.79 for Torok Formation samples reported. Other vitrinite reflectance data reported include average values in the Kaolak 1 Well of 0.51 to 0.74 for the Nanushuk Group, and 0.86 to 1.15 for the Torok Formation; reported average values in the Topagoruk 1 Well were 0.41 to 0.49 for the Nanushuk Group, and 0.49 to 0.79 for the Torok Formation; reported average values in the Umiat Test Well 11 were 0.40 to 0.48 for the Colville Group, 0.46 for the Nanushuk Group, and 0.42 to 0.54 for the Torok Formation. These authors state that "on the basis of empirical use of vitrinite reflectance data, the Nanushuk Group is mature in the western and immature in the central part of the North Slope." They urge discretionary use of the data due to their empirical nature.

According to Schmidt and McDonald (1979b), vitrinite values must be on the order of 0.6 or greater to indicate appreciable thermal maturation having taken place in the organic matter whose reflectance is being measured. At this level, significant decarboxylation of organic matter can occur, with evolution of carbon dioxide, and consequent implications for dissolution of carbonate minerals in associated rocks. Values of the vitrinite reflectance less than 0.6 are below values associated with the onset of the major portions of the decarboxylation of organic matter, hence below the values associated with the major portion of carbonate/other labile materials dissolution as well.

Thus, most of the northern Alaska rocks for which data are available, with the exception of deeper portions of the Kaolak and Topagoruk Wells, have not as yet undergone a regimen of thermal maturation sufficiently intense for either of these processes to have taken place to appreciable extents, nor would generation of liquid hydrocarbons have reached significant levels as yet either. These statements of Schmidt and McDonald regarding the organic geochemical relationships agree with the comments of Magoon and Claypool, based on the vitrinite reflectance data as well as other geochemical evidence which the latter cite in their papers, and are in keeping with the interpretations given in other references as well (cf. Tissot and Welte, 1984; Jones and Edison, 1978; etc.).

It is noteworthy that the vitrinite reflectance values, in general, show progressive increases with depth. The trends and the higher values reported to date are consistent with and supportive of the presence of temperature, pressure, and geochemical environment conditions favorable for the development of secondary dissolution porosity in rocks of appropriate composition (i.e., carbonate- and/or other labile constituent-rich) at depth within the study area.

Of additional relevance here is the matter of geothermal gradients within the study area. Tailleur and Engwicht (1978) indicate thermal gradients, measured and estimated, on the order of 25.2 to 39.6 degrees Celsius per kilometer of depth over this region.

These values, when compared with other areas worldwide in which more thorough studies of thermal maturation of organic material and other diagenetic relationships have been carried out, suggest (Schmidt and McDonald, 1979b; Gretener, 1979, 1981; Galloway, 1979) that this is a not uncommon range of values, and that the scheme for diagenesis, secondary porosity development, organic maturation, etc., as summarized above is not unreasonable in terms of the known relationships, and with regard to potential application in northern Alaska.

Portions of these rock units which have been more deeply buried and/or subjected to relatively localized favorable temperature, pressure, and geochemical environment conditions are thus indicated as being of potential interest with regard to development of secondary porosity and, perhaps, associated hydrocarbon accumulations.

Published data indicate that portions of the rock units in question here (Colville Group, Nanushuk Group, Torok Formation/Topagoruk Formation) have indeed been buried to, and presently exist at, somewhat greater depths elsewhere in northern Alaska. Estimations based on Bird and Andrews (1979), as well as data in Molenaar (1981), suggest that values on the order of 3050 meters to the bottom of the Nanushuk Group, and in excess of 5185 meters to the bottom of the Torok Formation are perhaps not unreasonable.

These may well be underestimations, given the relatively sparse data base available to the present authors. An isopach map of the combined thicknesses of the Torok Formation and the Nanushuk Group (Bird and Andrews, 1979) indicates that considerably greater maximum depths of burial for these units may well have occurred. The Nanushuk Group, alone, is shown (Bird and Andrews, 1979) as having a progressively thickening isopach interval in a northeast to southwest direction across the region, with a maximum isopach contour of 4800 meters "based on selected well and outcrop sections."

Carter et al. (1977) indicate similar approximate ranges of burial depths for the Nanushuk Group and Torok Formation southward across the North Slope Basin, from the Arctic Ocean coastline towards the Brooks Range.

Brosge and Tailleur (1971), in their overview of northern Alaska, indicate thicknesses for the various Cretaceous intervals in keeping with these ranges as well. These same authors, in a previous contribution (1969), also comment, regarding the Nanushuk Group (specifically the Grandstand Formation), that "the greatest volumes and highest percentages of sandstone are nearest the probable source areas along the south and southwest edge of the outcrop." In this earlier publication, they also present isopach maps showing the aforementioned trends of thickening of the Cretaceous sedimentary horizons southward from the present coastline into the deep basin. The value given on their Figure 6A is 6100 plus meters as a minimum depth to the base of Cretaceous rocks, along the east-west trend of the deepest portions of the "Colville Geosyncline."

There are considerable uncertainties attendant to drawing firm conclusions based on interpretation of sparse data here, but the inferences seem plain enough, i.e., portions of the rock units of interest may well have been buried to considerable depths within the northern Alaska region.

Presumably, these deeper intervals, if originally carbonate- (and/or other labiles-) bearing, represent likely candidates for development of secondary dissolution porosity. Such of these rocks as now contain appreciable amounts of carbonate (or other labile constituents) could well have undergone extensive dissolution porosity development had they resided elsewhere within the sedimentary basin, particularly at greater depths where the temperature, pressure, and geochemical environment conditions would be expected to favor dissolution.

A reasonable argument can be made for a continuing source of carbonate material as detritus originating in the Brooks Range to the south, where areally extensive, thick sequences of Paleozoic carbonate rocks were being exposed to weathering and erosion attendant upon regional uplift, and are so exposed at the present time. There seems to be no shortage of potential carbonate detrital source material nor lack of continuing conditions of mechanical weathering, rapid, relatively limited transportation, and deposition in the Cretaceous sedimentary prism which makes up the present study area.

These thickness relationships, increasing in a general south-southwest-west sense, combined with the apparent trend of increasing carbonate contents to the west-southwest (Fox et al., 1979; Molenaar, 1981; Bartsch-Winkler and Huffman, 1981, 1982) across the study area, suggest that particularly favorable conditions for development of secondary porosity at depth perhaps would also be in the western-southwestern-southern portions of the region.

Based on various petrographic and mineralogic criteria, Smosna (1987, 1989) indicates as well the relatively immature diagenetic character of the shallower Cretaceous rocks of present concern.

5. Conclusions

There is little question that, texturally and compositionally, the "subgreywacke-lithic arenite" aspect of many of the sandstones and siltstones examined and/or reported to date in the Cretaceous horizons of northern Alaska seems somewhat forbidding, in terms of reservoir rock characteristics, at least based upon initial impressions.

Admittedly, the observed petrographic relationships might be interpretable as making the diagenetic adjustments regarding dissolution and subsequent development of secondary porosity difficult, if not essentially impossible. The complexities are considerable, however, and experience has amply demonstrated the fallacy of prejudgment based on insufficient evidence in mineral resource geology.

The suggestions advanced in the present paper are just that, namely comments offered based on some observed relationships from a particular region, viewed in light of known relationships elsewhere, in a framework of geological theory which continues to appear to be increasingly well understood as more and more specific examples are documented. Perhaps the northern Alaska sedimentary horizons discussed herein will afford yet additional examples.

The general relationships in the Cretaceous sequences of northern Alaska, as well as the specifics of the samples and information available to date, suggest the desirability of consideration within the framework of diagenesis presented by Schmidt and McDonald (1979b).

Thus, rocks elsewhere within the northern Alaska sedimentary basin which are analogous to the labile-rich Cretaceous rocks encountered so far in the shallower wells might well have been exposed to temperature, pressure, and geochemical conditions more favorable for the development of the secondary dissolution porosity which might be expected to result in rocks of this nature, during a course of diagenetic events which might be considered more or less "normal" or "pre-programmed" (cf. Hayes, 1979; Galloway, 1979; Schmidt and McDonald, 1979a, b).

Perhaps a not unreasonable position might be, as these authors suggest, that sediments with compositional and textural characteristics such as those represented by many of the clastic sedimentary strata of northern Alaska are, essentially, predestined for such a fate, by their very compositional and textural makeup, given the appropriate and not at all unusual subsequent course of geological events in major sedimentary basins.

Thus, in addition to the various "plays" presented by Carter et al. (1977), perhaps an additional "deep Cretaceous" play is not geologically unrealistic within northern Alaska. Further, and even more speculatively, extending the diagenetic-secondary dissolution porosities theme to other, older clastic and/or carbonate rock horizons, perhaps other "deeper basin" plays are not beyond the realm of geologic reason either in this region.

These possibilities may at least offer some additional degree of support, although perhaps less substantive than would be desirable, for the eventual extensive deep drilling which will be required to thoroughly test and evaluate this region in terms of hydrocarbon resources. There is the distinct possibility of the existence of reservoir rocks of significantly better quality then heretofore appreciated, given the secondary dissolution porosity relationships recognized.

It has been suggested previously that the western North Slope region of Alaska, if indeed a significant hydrocarbon province, is likely to be predominantly "gas-prone" (Magoon and Claypool, 1979). This reasoning is based on the types of continental-shoreline-nearshore depositional environments presently recognized, and the resultant likelihood that the associated organic materials will be dominantly terrigenous in character.

It should be pointed out that recent insights (Snowdon, 1980; Powell and Snowdon, 1980; Langhus, 1980, for example) regarding precursorial organic materials and their resultant hydrocarbon maturation products indicate that such reasoning may be somewhat simplistic. In particular, work in the Mackenzie Delta region of northwest Canada shows that organic precursorial materials which normally would be characterized as "gas-prone" have, in fact, been the progenitors of appreciable amounts of liquid hydrocarbons.

Indeed, Magoon and Claypool (1979) indicate that "visual kerogen estimates of the Nanushuk Group indicate that at least 50 percent of the constituents are herbaceous and amorphous material or 'oil-prone' source rocks... These data appear to contradict the PHC/OC and H/C ratios, which suggest that these rocks are gas-prone... This apparent discrepancy warrants further investigation." Given present uncertainties regarding organic source materials, diagenesis, migration pathways, and reservoirs, the region must be considered as prospective for hydrocarbons, including liquids.

Application of the conceptual framework presented here may or may not prove to be appropriate, in detail, for these northern Alaska sequences, although the limited data presently available seem to be supportive. The additional information required to resolve the matter remains to be obtained, compiled, synthesized, and interpreted.

The relatively scanty amount of subsurface sample control and data available to date throughout NPRA is insufficient to permit sound evaluation with regard to potential petroleum resources. Various considerations (cf. cited references) indicate that the petroleum potential of the region remains to be assessed rigorously, and that the known geologic relationships support/suggest the desirability of such assessment.

Further studies of materials such as those described herein, particularly in the context of such other subsurface data as may be available, would seem to present opportunities for interested parties to pursue this.

According to Gryc (1985): "During the period 1945 through 1952, 45 shallow core tests and 36 wells were drilled in and adjacent to NPR-4... A total of 28 test wells were drilled in the period 1974 to 1982... " In addition, one well, Brontosaurus, has been drilled by the private sector within NPRA.

Thus, to date, some 110 exploratory wells have been drilled within or adjacent to NPRA (a geographic area on the order of 37,000 square miles—about the size of the state of Indiana). Many of these wells were drilled only to relatively shallow depths. Thus, this sizable sedimentary basin has been by no means thoroughly tested by drilling, with respect to substantively evaluating the potential for the occurrence of oil and gas resources.

Table 1.

Summary of salient features of cores studied

Meade-1 Well.

Depth (meters)	Formation	Lithology	Carbonates Estimated volume %
90-92	Chandelar	Sandstone	50
462-465	Grandstand	Sandstone-Siltstone	10
555-558	Grandstand	Sandstone-Siltstone	10-30
640-643	Grandstand	Sandstone-Siltstone	5-20
733-736	Grandstand	Sandstone-Siltstone	10-20
914-920	Grandstand	Sandstone-Siltstone	3-20
920	Grandstand	Sandstone	5-10

Table 2.

Summary of salient features of cores studied

East Topagoruk-1 Well.

Depth (meters)	Formation	Lithology	Carbonates Estimated volume %
375	Grandstand	Sandstone	10-20
381	Grandstand	Sandstone	10-20
537-542	Grandstand	Sandstone	10-20
630-636	Topagoruk	Sandstone-Siltstone	10-20
646-652	Topagoruk	Sandstone-Siltstone	20-50
662-663	Topagoruk	Siltstone	10-20
665-670	Topagoruk	Sandstone	20-50
671-677	Topagoruk	Sandstone-Siltstone-Shale	30
692-698	Topagoruk	Sandstone	30
770-772	Topagoruk	Siltstone	10-20
837	Topagoruk	Sandstone-Siltstone	10
930-933	Topagoruk	Siltstone	10
934-937	Topagoruk	Siltstone	5-10
947-954	Topagoruk	Sandstone	5
1106-1112	Topagoruk	Sandstone	10-50

Table 3.

Summary of salient features of cores studied

Fish Creek-1 Well.

Depth (meters)	Formation	Lithology	Carbonates Estimated volume %
132-134	Schrader Bluff	Siltstone	3-5
380-383	Schrader Bluff	Sandstone-Siltstone	5-10
504-507	Schrader Bluff	Sandstone	3-5
574-577	Seabee	Siltstone	20-30
639-642	Seabee	Sandstone-Siltstone	5-10
837-840	Seabee	Sandstone	5
918-920	Topagoruk	Sandstone-Siltstone	5
921-924	Topagoruk	Sandstone	5
942-946	Topagoruk	Sandstone-Siltstone	30
980-982	Topagoruk	Sandstone	50
983-986	Topagoruk	Sandstone-Siltstone	10
1043-1046	Topagoruk	Sandstone	10
1047-1049	Topagoruk	Sandstone	5-10
1699-1702	Topagoruk	Sandstone	10-20
1702-1705	Topagoruk	Sandstone	10
1705-1708	Topagoruk	Sandstone-Siltstone	10
1709-1711	Topagoruk	Sandstone-Siltstone	10
1712-1714	Topagoruk	Sandstone	50
1715-1717	Topagoruk	Sandstone	20-50
1721-1722	Topagoruk	Sandstone	10-50
1725-1728	Topagoruk	Sandstone	10-20
1729-1731	Topagoruk	Sandstone	10
1825-1828	Topagoruk	Sandstone	10-20
1860-1863	Topagoruk	Sandstone	20-50
1864-1865	Topagoruk	Sandstone	10
1866-1869	Topagoruk	Sandstone	10
1870-1872	Topagoruk	Sandstone	10-20
1873-1875	Topagoruk	Sandstone-Siltstone	10
1933-1935	Topagoruk	Sandstone-Siltstone	10-50(?)
1990-1922	Topagoruk	Sandstone-Siltstone	5-20
2043	Topagoruk	Sandstone-Siltstone	10
2144-2146	Topagoruk	Sandstone	10
2173-2176	Topagoruk	Sandstone	10

Table 4.

Summary of salient features of cores studied

Titaluk-1 Well.

Depth (meters)	Formation	Carbonates Lithology	Carbonates Estimated volume %
934-937	Grandstand	Sandstone	5-50
996-1001	Grandstand	Sandstone	10-40
1020-1026	Grandstand	Sandstone	10-30
1060-1064	Grandstand	Sandstone	5-50
1065-1069	Grandstand	Sandstone	5-20
1101-1103	Topagoruk	Sandstone-Siltstone	10-20
1134-1137	Topagoruk	Sandstone	10-30
1140-1145	Topagoruk	Sandstone	20-30
1166-1172	Topagoruk	Sandstone-Siltstone	30-50
1240-1246	Topagoruk	Sandstone-Siltstone	30-50

Table 5.

Summary of salient features of cores studied

Knifeblade-1 Well.

Depth (meters)	Formation	Lithology	Carbonates Estimated volume %
59-60	Chandler	Sandstone	5-20
83-84	Chandler	Sandstone	20-30
96-97	Chandler	Sandstone	10 plus
113	Chandler	Sandstone	5-10
176-177	Chandler	Sandstone-Siltstone	30
256-257	Grandstand	Sandstone	20-30
262	Grandstand	Sandstone	3-40
272-273	Grandstand	Sandstone	30-50
282-283	Grandstand	Sandstone-Siltstone	30-40
296-297	Grandstand	Sandstone-Siltstone	10-40
360-361	Grandstand	Sandstone	5
392-393	Grandstand	Sandstone	0-10
401	Grandstand	Sandstone	10-50
426-427	Grandstand	Sandstone-Siltstone	5-20
432-433	Grandstand	Sandstone	0-10
460-461	Grandstand	Sandstone	10
530	Grandstand	Sandstone	20-30

Table 6.

Summary of salient features of cores studied

Knifeblade-2A Well

Depth (meters)	Formation	Lithology	Carbonates Estimated volume %
53-54	Grandstand	Sandstone	3-5
113	Grandstand	Sandstone	0-10
234-235	Grandstand	Sandstone	10 plus
239	Grandstand	Sandstone	5-40
245	Grandstand	Sandstone	< 5
250	Grandstand	Sandstone	5
262	Grandstand	Sandstone	10-20
467	Grandstand	Sandstone	10
470-471	Grandstand	Sandstone	10
482-483	Grandstand	Sandstone	10
490-491	Grandstand	Sandstone	10
498-499	Grandstand	Sandstone	10-20
502	Grandstand	Sandstone-Siltstone	5-20
1661	Grandstand	Sandstone	5-10
1803-1806	Grandstand	Sandstone-Siltstone	5-10

Table 7.

Summary of salient features of cores studied

Wolf Creek-1 Well.

Depth (meters)	Formation	Lithology	Carbonates Estimated volume %
245-246	Chandler	Sandstone-Siltstone	0-20
267-268	Chandler	Sandstone	0-5 plus
335-336	Chandler	Sandstone	TR
395-396	Chandler	Sandstone-Siltstone	0-10(?)
400-401	Chandler	Sandstone	10

Table 8.

Summary of salient features of cores studied

Wolf Creek-2 Well.

Depth (meters)	Formation	Lithology	Carbonates Estimated volume %
292-293	Chandler	Sandstone	0-5
299-3001	Chandler	Sandstone	0-5
312-313	Chandler	Sandstone-Siltstone	0-5
373-375	Chandler	Sandstone-Siltstone	0-20
433-434	Chandler	Sandstone	0-10

Table 9.

Summary of salient features of cores studied,

Wolf Creek-3 Well.

Depth (meters)	Formation	Lithology	Carbonates Estimated volume %
457-463	Grandstand	Sandstone-Siltstone	0-50
463-467	Grandstand	Sandstone-Siltstone	0-50
467-472	Grandstand	Sandstone-Siltstone	0-10
472-473	Grandstand	Sandstone	< 5
473-479	Grandstand	Sandstone-Siltstone	0-50
479-485	Grandstand	Sandstone-Siltstone	0-10
485-491	Grandstand	Sandstone-Siltstone	0-20
510-516	Grandstand	Sandstone-Siltstone	5-40
588-593	Grandstand	Sandstone	5-10
593-596	Grandstand	Sandstone	5-10
676-681	Grandstand	Sandstone	10-20

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