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CHRONOLOGIC VARIATIONS ALONG THE CONTACT BETWEEN THE ECHOOKA FORMATION AND THE LISBURNE GROUP IN THE NORTHEASTERN BROOKS RANGE, ALASKA

by

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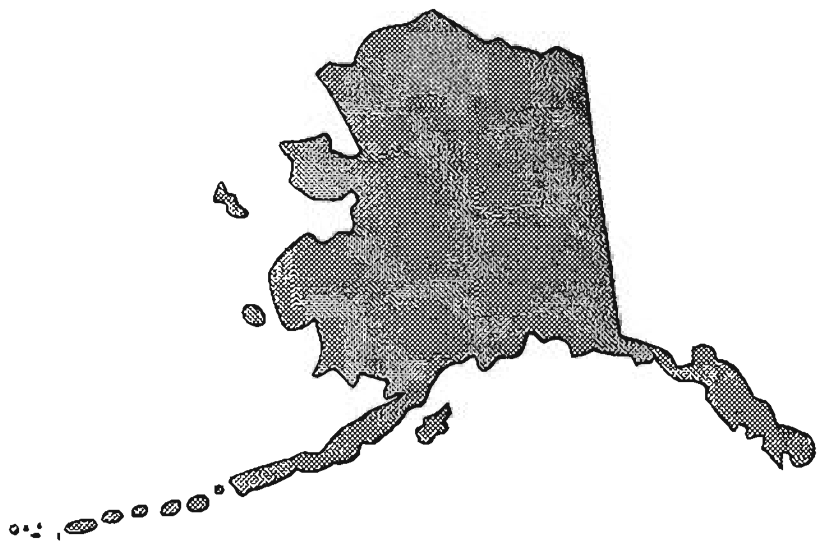

Alaska Department of Natural Resources
Division of Geological and Geophysical Surveys

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SYSTEMATICS OF GEOCHRONOLOGIC VARIATIONS ALONG THE PRE-ECHOOKA UNCONFORMITY IN NORTHEASTERN ALASKA

Mark S. Robinson[1], James G. Clough[1], John Roe[2], and John Decker[3]

The purpose of this study was to determine chronologic variations along an unconformity in northeastern Alaska by collecting conventional microfossil samples from rocks immediately above and below an unconformity surface. The unconformity that we selected for this study is the systemic boundary that separates the Carboniferous Lisburne carbonates from the overlying siliciclastic assemblage of the Sadlerochit Group. This unconformity is the Pennsylvanian - Permian boundary locally and is here named the pre-Echooka unconformity for the rock unit that immediately overlies the unconformity surface in the study area. The Echooka Formation rocks in the study area contain glauconite concentrations locally, therefore as a pilot study, we collected glauconite-bearing samples to test the applicability of radiometric dating of glauconite minerals in an effort to aid in the determine the systematics of chronologic variations above and below the unconformity surface.

Many unconformities are present in the stratigraphic record of northeastern Alaska. Orogenic events prior to the deposition of the Mississippian Kekiktuk Conglomerate produced an interregional erosional surface informally known as the pre-Mississippian unconformity. This unconformity separates the Precambrian Neruokpuk Formation and Proterozoic(?) Katakturuk Dolomite of the Franklinian sequence from carbonates and siliciclastic rocks of the Ellesmerian sequence. The fundamental control on the development of unconformities and the preservation of sedimentary sequences is base level, an equilibrium surface separating erosional and depositional environments. The stratigraphic record in northeastern Alaska records many unconformity surfaces. Figure 8 Appendix B, illustrates several of the major unconformities that have been recognized. The Ellesmerian sequence, contains many unconformities

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that were produced by changes in sea level and tectonic events that resulted in widespread unconformity surfaces marked by missing strata and mild discordances. One well developed regionally significant unconformity is present at the contact between carbonates of the Lisburne Group and siliciclastic rocks of the Sadlerochit Group. This contact is the Pennsylvanian - Permian boundary locally, and it marks the death of the Lisburne carbonate platform in northeastern Alaska and the onset of transgression and deposition of the clastic rocks of the Ellesmerian sequence.

The Lisburne Group in the northeastern Brooks Range is overlain unconformably by quartzarenite, siltstone, shale, and minor conglomerate of the Sadlerochit Group. Rocks of the Sadlerochit Group contain the main reservoir at Prudhoe Bay, North America's largest oil field (figure. 1).

The Sadlerochit Group is comprised of the Joe Creek and Ikiakpaurak Members of the Permian Echooka Formation, the Kavik Shale, Ledge Sandstone, and Fire Creek Siltstone Members of the Triassic Ivishak Formation. The Sadlerochit Group is overlain by phosphate-rich bioclastic rocks of the Shublik Formation. The Shublik is in turn overlain by quartzarenite of the Triassic Karen Creek Sandstone (Detterman, 1970, 1974, 1976, 1984; Detterman and others, 1975, Reiser and others, 1971).

Appendix B of this report contains an extended summary of the stratigraphic framework of the Sadlerochit and Shublik Mountains and the northeastern Brooks Range mountain front.

The distribution of rock units and the mechanisms of regional sediment dispersal and detailed environments of deposition that buried the Lisburne carbonate platform during the

Permian and Triassic are the subject of ongoing investigations that are part of the DGGS / University of Alaska - North Slope basin analysis program.

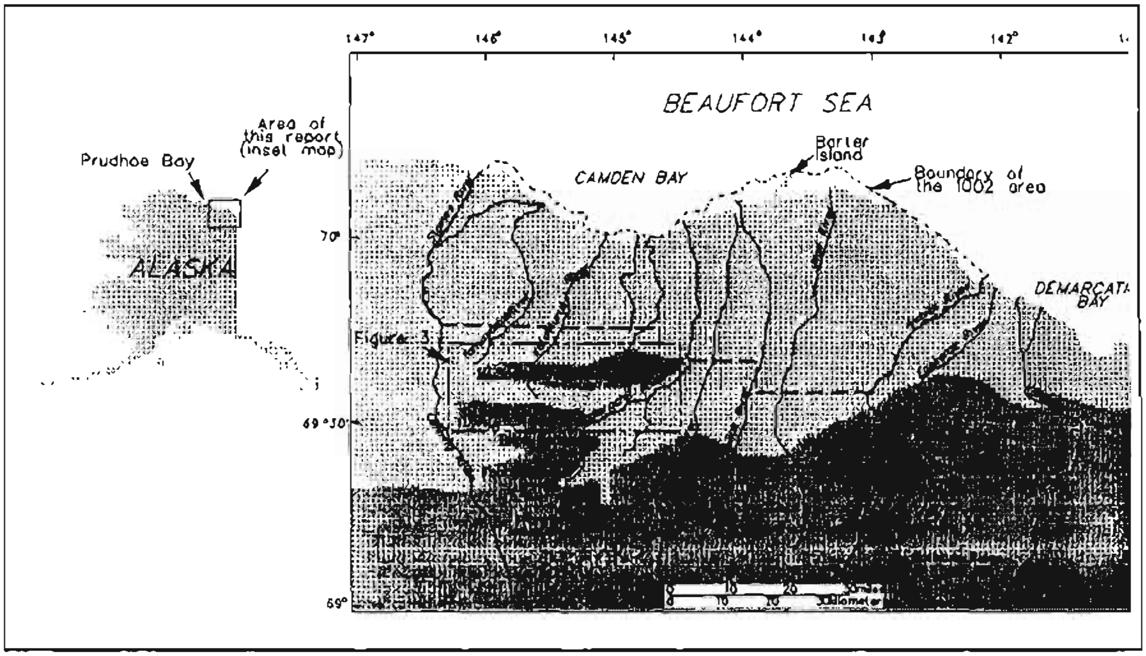

Figure. 1 Location map of northeastern Alaska

The systemic boundary separating Pennsylvanian and Permian rocks in northeastern Alaska forms a conspicuous contact between the Wahoo Limestone and mixed carbonates and terrigenous clastics of the Echooka Formation in the Sadlerochit and Shublik Mountains and along the Brooks Range Mountain front. The Echooka Formation is a recessive-weathering unit throughout the region, but its distinct orange-brown coloration, typical of marine Permian rocks of the circum-Arctic, contrasts markedly with carbonates of the Lisburne Group and is easily mapped.

The amount of erosional relief developed along the Pennsylvanian-Permian unconformity is highly variable. The most common contact between the Lisburne and Sadlerochit Group is a sharp planar surface with only minor relief. At scattered localities in the Sadlerochit Mountains and throughout the north flank of the central Shublik Mountains the contact is a deeply dissected surface with as much as 30m of local erosional relief. Regionally, there is more physical evidence for substantial erosional relief along the unconformity in the Sadlerochit and Shublik Mountains than in adjacent areas. There is less evidence of erosional truncation south and west of the Sadlerochit and Shublik Mountains where the contact is a disconformity.

Lithologic variation within the lower Echooka Formation was strongly influenced by subaerial dissection of the Lisburne platform surface. Subaerial environments of the weathering and erosion, laterally-restricted nonmarine depositional settings, and nearshore to offshore marine environments are recorded in the Echooka Formation. A consistent fining trend, expressed both vertically and laterally, records a gradual retrogradation and a persistent deepening of depositional environments through time.

Even though the contact between the Echooka Formation and the carbonates of the Lisburne Group is distinct and well exposed in the Sadlerochit and Shublik Mountains, little is known about the systematics of the age relationships between the rocks above and below the unconformity surface.

Conventional methods used to examine the systematics of age relationships at unconformity bounded surfaces involve intensive biostratigraphic sampling. During the current study we have sampled the intervals directly above and below the pre-Echooka unconformity for conodont and foraminifera analysis. In addition to the biostatigraphic sampling, we also sampled the basal units of the Echooka Formation for radiometric dating of glauconite.

The Echooka Formation and the upper part of the Lisburne Group in the study area contained conodonts and foraminifera and locally abundant glauconite. Figure 1. is a map of the location of the Sadlerochit and Shublik Mountains in ANWR. Figure 2 is a detailed map of the Sadlerochit and Shublik Mountains and contains the sample sites for this study in both

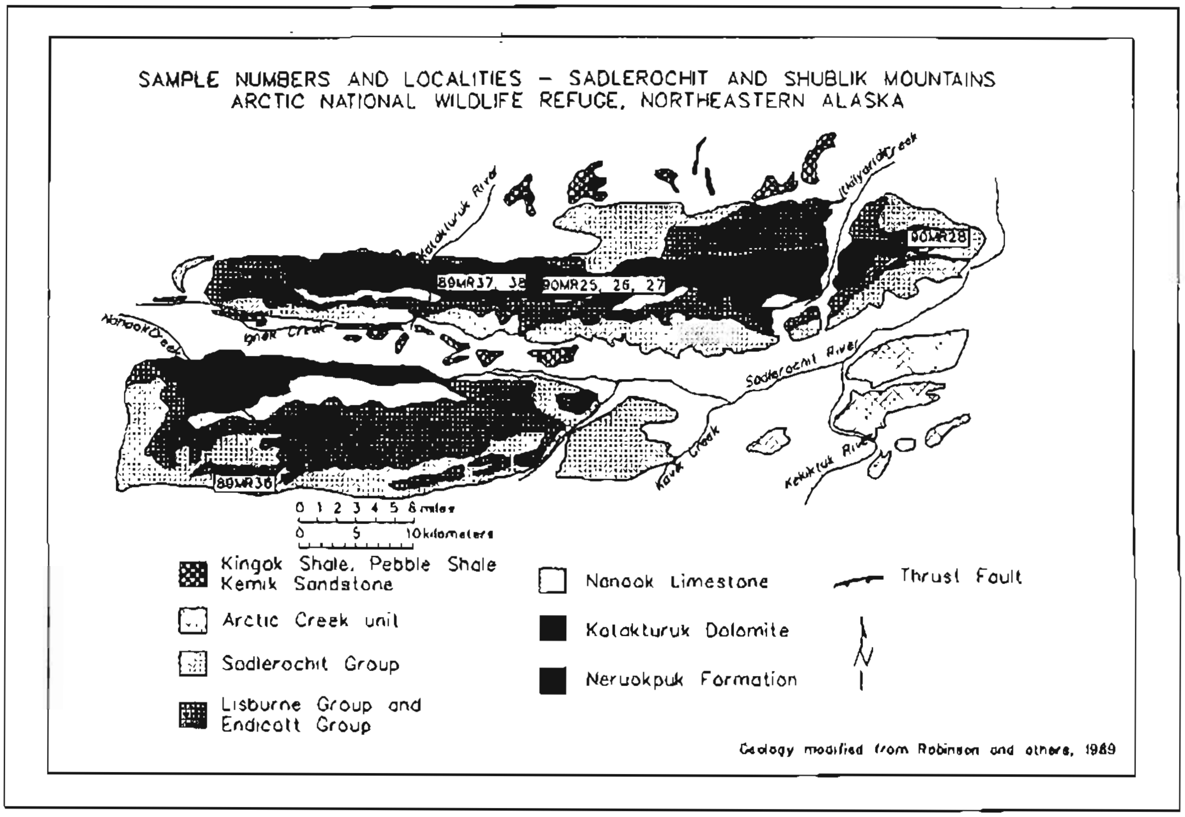

Figure 2. Sample localities in the Sadlerochit and Shublik Mountains, northeastern Brooks Range, Alaska

ranges. Figure 3. is a location map of the region near the Echooka and Ivishak Rivers in west-central ANWR. Figure 4 contains the location of sample sites in the Echooka - Ivishak Rivers region. The facies encountered in the carbonates of the upper Lisburne Group and within the basal Echooka strata are highly variable. The dominant control of the presence or absence of datable microfossils in the strata of both units is the environment of deposition.

Table 1. contains a summary of the glauconite, foraminifera, and conodont contents of the samples collected in the Sadlerochit and Shublik Mountains and to the west along the Brooks Range Mountain front. Table 1 shows the highly variable nature of the microfossil and glauconite contents of sample sites. There were sites however that did contain glauconite, foraminifera and conodonts that returned datable material.

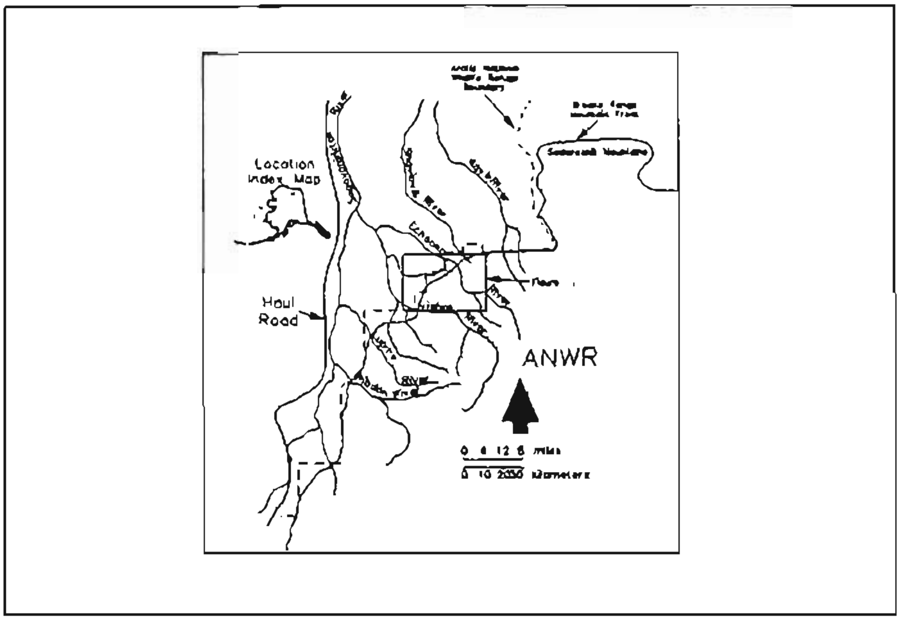

***Figure 3.** Location of the Echooka / Ivishak Rivers area, northeastern Brooks Range, Alaska*

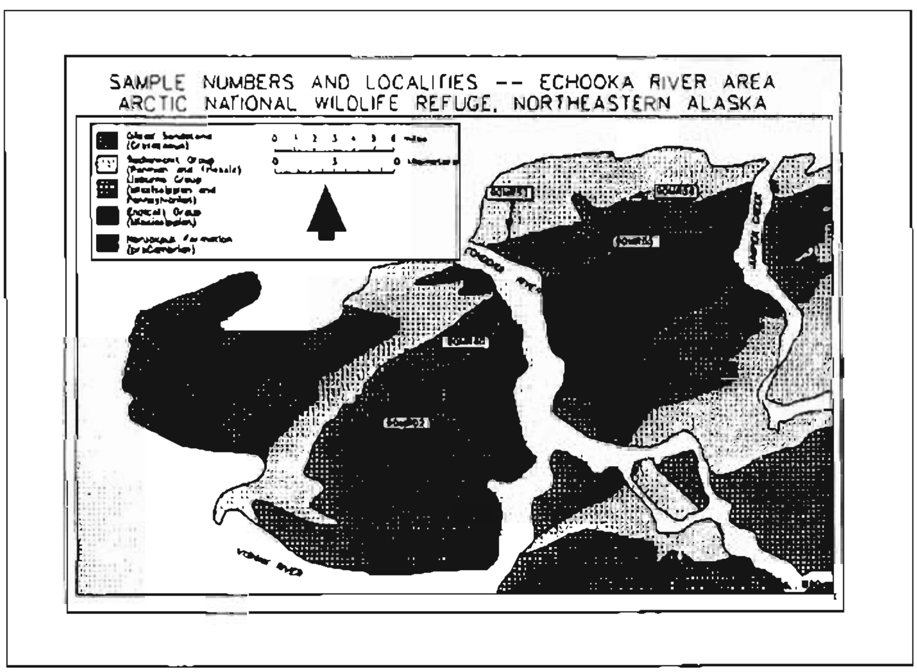

***Figure 4.** Sample localities in the Echooka / Ivishak Rivers area*

Table 2 contains results from samples that contained datable conodonts. Analyses of the conodont-bearing samples were conducted by Anita Harris of the U.S. Geological Survey. Examination of table 2 shows that the rocks at the top of the Wahoo Limestone section in the Sadlerochit and Shublik Mountains contain conodonts of early Late Morrowan to early Atokan age (330 - 310 Ma). Samples from the top of the Lisburne section (Wahoo Limestone) southwest of the Sadlerochit and Shublik Mountains near the Echooka and Ivishak River also contained conodonts that range from early Late Morrowan to early Atokan. One sample (89MR38A) from the Sadlerochit and Shublik Mountains yielded conodonts as young as earliest Permian age (See Appendix A for detailed conodont identifications and conodont alteration indices [CAI]).

Figure 5 is a geologic time scale that illustrates the magnitude of the pre-Echooka unconformity. The apparent discontinuity between the upper-most beds of the Lisburne Group and the lowest beds of the Echooka Formation (Sadlerochit Group) in the Sadlerochit and Shublik Mountains is shown by the shaded area in figure 5.

Table 2 also contains details of the conodont-bearing samples collected from the Echooka Formation in the Sadlerochit and Shublik Mountains and in the Echooka - Ivishak Rivers area. These samples, from the base of the Echooka Formation, yielded conodonts that range in age from earliest Permian to Guadalupian (280 - 270 Ma).

These data are the first indication of the significance of the erosional event that produced the pre-Echooka unconformity. Based on these conodont age data, there is apparently more than 30 and possibly as much as 60 million years of section missing between strata at the top of the Lisburne Group and strata at the base of the Sadlerochit Group.

Table 3 contains foraminifera age determinations for samples in the Sadlerochit and Shublik Mountains. Samples from the top of the Lisburne Group yielded foraminifera of late Chesterian to early Atokan age, while the basal units of the Echooka Formation yielded foraminifera of late Sakmarian or younger age. The foraminifera data indicate a stratigraphic gap ranging from 30 - 50 million years. The stratigraphic gap is of the same magnitude as indicted by the conodont data.

Table 1. *Summary of glauconite, foraminifera, and conodont contents of samples from this study.*

Sample Number	Rock Unit	Glauconite content	Foraminifera content	Conodont content
89MR36A	Top of Wahoo	Barren	Abundant	Abundant
89MR 36B	Bottom of Echooka	Low (<2%)	Abundant	Abundant
89MR37A	Top of Wahoo	Abundant	Barren	Barren
89MR37B	Bottom of Echooka	Low (<2%)	Barren	Barren
89MR38A	Top of Wahoo	Barren	Abundant	Abundant
89MR38B	Bottom of Echooka	Low (<2%)	Abundant	Abundant
89MR38D	Bottom of Echooka	Abundant	Barren	Barren
90MR2A	Bottom of Echooka	Low (<2%)	Barren	Barren
90MR25A	Top of Wahoo	Barren	Barren	Abundant
90MR27A	Bottom of Echooka	Abundant	Barren	Barren
90MR27B	Top of Wahoo	Barren	Barren	Barren
90MR26D	Top of Wahoo	Barren	Barren	Barren
90MR28A	Top of Wahoo	Barren	Barren	Abundant
90MR28B	Bottom of Echooka	Low (<2%)	Barren	Barren
90MR28F	Bottom of Echooka	Low (<2%)	Barren	Barren
90MR40A	Top of Wahoo	Barren	Barren	Abundant
90MR40E	Bottom of Echooka	Low (<2%)	Barren	Barren
90MR52C	Top of Wahoo	Barren	Barren	Barren
90MR52G	Bottom of Echooka	Low (<2%)	Barren	Barren
90MR55A	Top of Wahoo	Barren	Barren	Abundant
90MR56C	Top of Wahoo	Barren	Barren	Abundant
90MR 56G	Bottom of Echooka	Low (<2%)	Barren	Barren

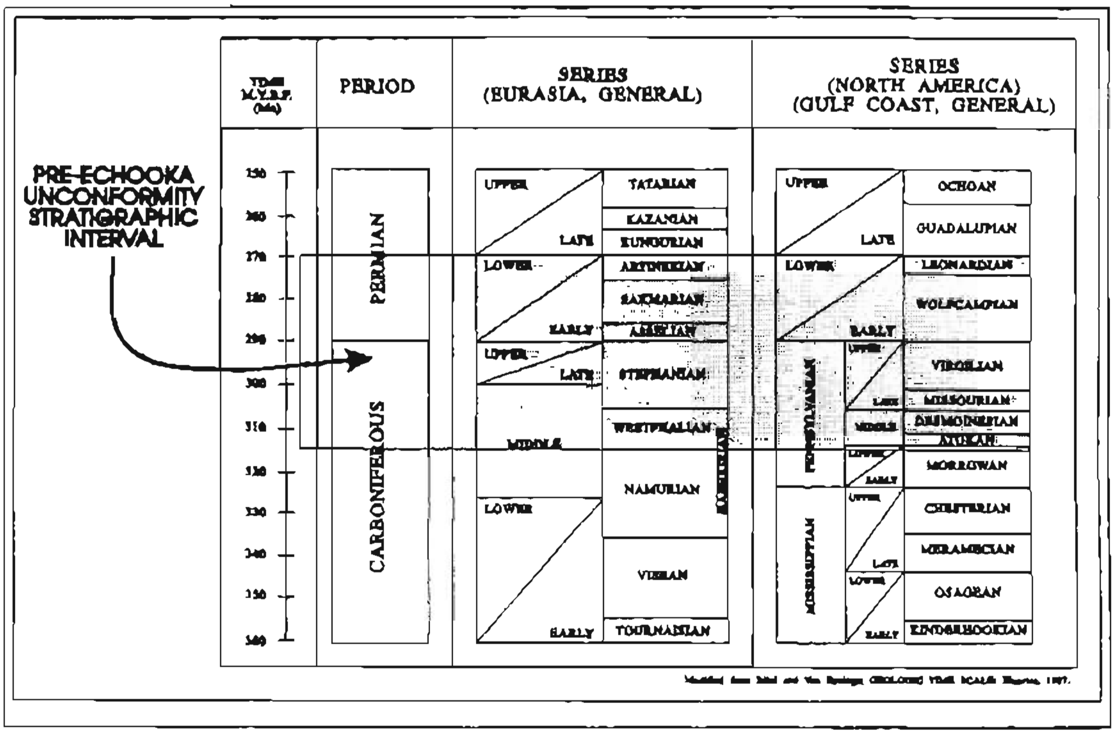

Figure 5. Stratigraphic interval represented by the pre-Echooka unconformity in the Sadlerochit and Shublik Mountains.

Table 2. Summary of Conodont ages and alteration data.

Sample Number	Rock Unit	Age[1]	Conodont Alteration Index[1]
89MR36A	Top of Wahoo	Early Atokan	3.5
89MR36B	Base of Echooka	Pennsylvanian to early Permian	3 - 4
89MR38A	Top of Wahoo	Pennsylvanian to early Permain	4
89MR38B	Base of Echooka	Leonardian to early Guadalupian	4
89MR25A	Top of Wahoo	Early Morrowan	
90MR28A	Top of Wahoo	Early late Morrowan	
90MR40A	Top of Wahoo	Early late Morrowan	
90MR55A	Top of Wahoo	Early Morrowan	
90MR56C	Top of Wahoo	Late Morrowan to early Atokan	

[1] Identifications by Anita G. Harris, U.S. Geological Survey, Reston, Virginia.

Table 3. Summary of foraminifera ages.

Sample Number	Rock Unit	Age[1]	Age[2]
89MR36A	Top of Wahoo	Late Chesterian to Early Atokan	Early Baskkirian (Early Atokan)
89MR36B	Base of Echooka	Late Sakmarian or younger	Artinskian or younger
89MR38A	Top of Wahoo	Early Atokan	Early Bashkirian (Early Atokan)
89MR38B	Base of Echooka	Late Sakmarian or younger	Artinskian or younger

[1] Identifications by P.L. Brenckle, Amoco Production Company, Tulsa Ok.

[2] Identifications by Silvie Pinard, Calgary, Alberta Canada.

Glauconite Occurrence And Significance

Glauconites have attracted the attention of many geoscientists because of their widespread and problematic occurrences in sedimentary rocks, unusual chemical characteristics, and interesting origins. From the lack of analytical instruments before 1940, glauconite came to denote all types of greenish-colored grains or pellets and almost all greenish-colored pigments in sediments (Odom 1984). Prior to 1978, compositional (Burst 1958), mineralogical (Hower 1961) and morphological (Burst 1958) limits were attached to definitions of the glauconite.

In 1978 the AIPEA Nomenclature Committee (Bailey 1980) made the following recommendation on the nomenclature of "glauconite" :

"Glauconite is defined as an Fe-rich dioctahedral mica with tetrahedral Al (or Fe^{3+}) usually greater than 0.2 atoms per formula unit and octahedral R^{3+} correspondingly greater than 1.2 atoms. A generalized formula is $K(R^{3+}{}_{1.33}R^{2+}{}_{0.67})(Si_{3.67}AlSi_{0.33})O_{10}(OH)_2$ with $Fe^{3+} >> Al$ and $Mg > Fe^{2+}$ (unless altered). Further characteristics of glauconite are d(060) > 1.510 Å and usually broader IR spectra than celadonite. The species glauconite is single-phase and ideally is non-interstratified. Mixtures containing an iron rich mica as a major component can be called glauconitic. Specimens with expandable layers can be described as randomly interstratified glauconite-smectite."

Glauconitic peloids occur throughout the geologic record. They have been recognized in rocks as old as Precambrain. Two major episodes of glauconite development occurred during

Phanerozoic time, first in the early Paleozoic and a second episode in middle-late Mesozoic time. Both of these episodes were characterized by climates dominated by temperate to warm conditions, widespread sea-level rise and transgression of cratons, dispersed cratonic blocks and open ocean gateways, and frequent decreased influx of terrigenous sediment. After the breakup of the Precambian super continent about 600 million years ago, the Cambrian transgression on large Laurasian cratonic blocks controlled the distribution of widespread glauconite deposits. Glauconite deposition reached a maximum at 250 million years ago, especially along continental margins of the opening Atlantic ocean basin. Abundant glauconitic greensand development continued until the middle Cenozoic (Chamley 1989). There is general agreement that most glaucony granules were deposited in rather shallow-water seas, with low terrigenous clastic sediment input, and under fairly warm humid climates. Most glaucony greensands deposits developed in open ocean areas along stable platform margins or on high oceanic platforms, and in shallow to deeper offshore depositional environments. In general ancient glaucony granules accumulated in more varied environments than modern ones (Chamley 1989). Ancient depositional facies range from intertidal and subtidal inner shelf environments to deep water offshore environs.

The microenviroment present during glaucony genesis is confined and chemically concentrated. Open-marine conditions generally do not chemically modify terrigenous materials, therefore a restricted microenviroment of some type is necessary to accommodate the cations necessary for the glauconization process; and for the fractional and volume increase of green granules and the chemical exchanges that take place during the growth of green layer silicates.

Appendix C of this report contains a compilation of the literature on glauconite formation, chemistry, and utility as a isotopic dating media.

Dating of glauconite by Rb-Sr and K-Ar methods has yielded sporadic results. Age determinations in general tend to be discordnant usually younger than statigraphic ages. These differences have been explained by a variety of mechanisms including; thermal and chemical alteration of the glauconite. Some glauconites have yielded radiometric ages older than their stratigraphic ages. These differences have been attributed to inherited radiogenic Sr and Ar. Glauconite granules may initiate their growth on an older mineral phase, ie. mica and thereby incorporating the older radiogenic phases. Unless complete replacement of the original detrital grain takes place, the isotopic ages of the glauconite grain will reflect the isotopic composition of the older phase and yield an older than stratigraphic age.

Most isotopic studies have been conducted on the granular type of glauconite either because it occurs in a geologically significant local or they are easy to identify. It is important to understand that even these granular types (fecal pellets, infillings, and detrital minerals) will inherit some amount of the radiogenic isotopes if they are not completely replaced. As the radiogenic isotopes of the substrate become incorporated in the growing glauconite minerals, these new mineral phases require sufficient time for complete equilibrium with the environment in which they develop. Glauconization occurs at the sea-sediment interface, where the temperature is low, 5-15°C, reactions are rather slow and equilibrium will only be attained gradually. If the initial substrate is itself neutral or in equilibrium with the seawater with respect to the isotope used, theoretically no inheritance occurs (Odin 1982).

Table 4 contains rubidium-strontium isotopic data for samples collected in the Sadlerochit and Shublik Mountains. These data yield discordant (younger) ages then expected based on microfossil data and recognized stratigraphic position. One possible explanation for the divergence in age might be that the age represents a diagenetic event or timing of isotopic homogenization. It is interesting that the indicated Rb-Sr age ranging from 124-137 (table 4) is a dominant metamorphic age throughout the north-central Brooks Range (Turner and others, 1978). Figure 6 is a Rb/Sr isochron diagram for samples collected in the Sadlerochit and Shublik Mountains.

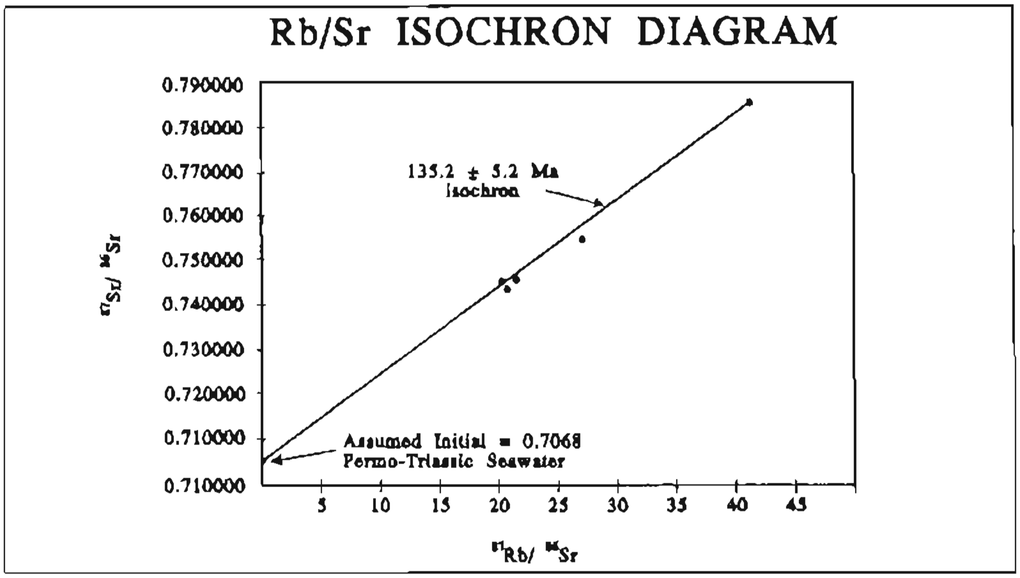

Figure 6. Rb/Sr isochron diagram for glauconite-bearing samples in the Sadlerochit and Shublik Mountains.

Glauconite from one sample collected in the Sadlerochit and Shublik Mountains was subjected to conventional K-Ar analysis to determine the apparent age of the contained glauconite. Table 5 contains the analytical data for the analyzed sample. The apparent age of the sample is 78.4±1.0 Ma. This apparent K-Ar age is much younger than the stratigraphic age and the age indicated by the conodont and foraminifera data.

Glauconites exhibit a rejuvenation (younging) of their K-Ar ages when subjected to conditions of burial and or leakage of Argon due to their immature structural development. Although the geochemical process is not exactly contemporaneous for all glauconite-bearing environments, the quantities of radiogenic argon measured does not reflect the precise moment at which glauconization of each sample begins, but rather according to the data given by

Odin and Dodson (1982) it reflects the timing of ***closure*** of the glauconite crystallization for a glaucony.

Table 4. *Rubidium - Strontium isotope data for glauconite samples collected during this study. Analyses conducted by K.A. Foland and F.A. Hubacher, Radiogenic Isotope Laboratory, Ohio State University, Columbus, Ohio.*

Sample Number[1]	Rb[2] (ppm)	Sr[2] (ppm)	$^{87}Rb/^{86}Sr$[3]	$^{87}Sr/^{86}Sr$[4]	Model Age[5]
90MR27A (R)	326.1	47.07	20.12	0.745902(11)	**136**
90MR27A (R)	322.6	45.43	20.62	0.744089(8)	**127**
90MR27A	317.S	42.76	21.54	0.746292(13)	**128**
89MR38D	245.6	17.48	40.92	0.786428(15)	**137**
89MR37A	201.1	21.86	26.75	0.753955(11)	**124**

[1] Each sample is a separate dissolution. all samples washed in the following manner: acetone wash, water wash, leach with 0.1 N HCl for 10-15 minutes followed by water wash. The splits noted by (R) are replicates for which sample was analyzed "as received" with no washing of any nature.

[2] The uncertainties are assigned at ± 0.1% for Sr and 0.4% for Rb for the given split. These uncertainties do not take into account sample heterogeneity or possible losses of small amounts of sample during washing prior to analysis.

[3] Atomic ratio. One-sigma analytical uncertainties assigned at ± 0.5%.

[4] Measured values normalized assuming normal Sr with $^{86}Sr/^{88}Sr$ = 0.119400. Uncertainties refer to the last digit(s) and are two standard deviations of the mean in-run uncertainties.

[5] Model Rb-Sr age in Ma. assuming initial $^{87}Sr/^{86}Sr$ = 0.7070. The decay constant for ^{87}Rb is $1.42 \times 10^{-11} y^{-1}$

This closure occurs when potassium content is equal to or greater than 7% K_2O. Few indisputable examples are available however concerning the rejuvenation or resetting of glauconite K-Ar dates as a result of burial alone. Accordingly most investigators call upon several factors including burial and diagenetic changes in the substrait to explain the differences in apparent isotopic ages and stratigraphic ages as indicated by contained fossils. Therefore a cautious approach must be applied to the interpretation of radiometric ages derived from glauconites.

Table 5 indicates that the glauconite pellets from the best sample collected in the Sadlerochit Mountains contains an average of 5.835% K_2O. This K_2O content indicates that the glauconite apparently is not closed chemically (immature), and therefore may have lost Argon, resulting in an apparent "young" K-Ar age.

Table 5. *Potassium-Argon isotopic data. Analyses conducted by K.A. Foland and F.A. Hubacher, Radiogenic Isotope Laboratory, Ohio State University, Columbus, Ohio.*

Sample Number	**K (wt %)**	**^{40}Ar rad (10^{-10} mol/g)**	**^{40}Ar rad/^{40}Ar total**	**Calculated Age (millions of years)**
90MR27A	5.84	8.07	0.913	
	5.83	8.132	0.899	
AVERAGE	**5.835**	**8.103**		**78.4±1.0**

APPENDIX A -- DETAILED MICROFOSSIL DESCRIPTIONS

Table 6 Conodont data

Sample Number (USGS Col. #)	**Rock Unit**	**Description** Conodont identifications and interpretations by Anita G. Harris, U.S. Geological Survey, Reston, Virginia
89MR36A	Top of Wahoo	4 Pa elements of *Adetognathus* sp.
(30895-PC)		1 Pa element of *Hindeodus minutus* (Ellison)
		11 Pa elements of *Rhachistognathus minutus* (Higgins & Boukaert)
		1 juvenile Pa element of either *Streptognathodus* sp. indet. or *Idiognathodus* sp. indet.
		2 ichthyoliths
		Phosphatized steinkerns and bioclasts of endothyroids, gastropods and pelmatozoans
		BIOFACIES: normal marine, moderate energy, shallow to moderate water depth
		AGE: *minutus-sinuatus* Zone into early Atokan
		CAI = 3.5 indicating host rock reached at least 170° C
89MR36B	Base of Echooka	1 small posterior fragment of a Pa element of *Neogondolella* sp. indet
(30896-PC)		1 indet. bar fragment
		AGE: Pennsylvanian - Permian
		CAI = 3 or 4; precise determinations not possible.
89MR38A	Top of Wahoo	1 juvenile Pa element of *Adetognathus* sp. indet
(30897-PC)		1 unassigned M element
		17 indet. bar, blade and platform fragments; some platform fragments are of post -Mississippian morphotype
		AGE: Pennsylvanian - early Early Permian
		CAI: 4 indicating host rock reached at least 200°C
89MR38B (30898-PC)	Base of Echooka	1 posterior Pa element fragment of *Neogondolella* sp. indet.. of Leonardian - early Guadalupian morphotype
		8 phosphatized steinkerns of endothyroids
		AGE: Leonardian - early Guadalupian (late Early to earliest Late Permian)
		CAI: 4 indicating host rock reached at least 200°C
90MR2A	Base of Echooka	Barren
90MR25A	Top of Wahoo	3 Pa element fragments of *Adetognathus* sp. indet.
(31265-PC)		8 Pa elements *Rhachistognathus minutus declinatus* (Baesemann & Lane)
		3 indet. bar, blade, and platform fragments
		BIOFACIES: Rhachistognathid, high energy, shallow water, normal marine depositional environment.
		AGE: *sinuatus-minutus* Zone, early but not earliest Morrowan into early Atokan (foram-equivalent to Mamet Zone 16 into early Atokan)
		CAI: 4 and 6 indicating host rock reached at least 200°C and some accompanying hydrothermal activity.
90MR26D	Top of Wahoo	Barren
90MR27B	Base of Echooka	Barren

APPENDIX A -- DETAILED MICROFOSSIL DESCRIPTIONS

Table 6 Continued

Sample Number (USGS Col. #)	**Rock Unit**	**Description** **Conodont identifications and interpretations by Anita G. Harris, U.S. Geological Survey, Reston, Virginia**
90MR28A	Top Of Wahoo	1 Pa element *Adetognathus* sp. indet.
(31266-PC)		2 Pa elements *Declinognathodus noduliferus japonicus* (Igo & Kotke)
		1 Pa element fragment sof *Idiognathodus* sp. indet.
		3 Pa element fragment of *Idiognathodus?* sp. indet.
		3 *Idioprioniodus* sp. indet. element fragments
		2 Pa elements *Rhachistognathus minutus declinatus* (Baesemann & lane)
		3 juvenile Pa elements *Rhachistognathus minutus* (Higgins & Bouckaert)
		1 Pa element fragment of *Idiognathodus* sp. indet.
		5 juvenile Pa elements *Rhachistognathus* sp. indet.
		14 Pa element fragments (generally posterior part of platform) of cavusgnathids and rhachistognathids
		26 indet. bar, blade, and platform fragments ; common phosphatized steinkerns of endothyrid foraminifers, gastropods and bryozoans
		BIOFACIES: Indeterminate, postmortem hydraulic mixing; relatively shallow water, high energy, normal marine depositional environment.
		AGE: *sinuosus* Zone to top of Morrowan (=late Morrowan) Upper half of Morrowan; (foram-equivalent to Mamet Zones 19-22)
		CAI: 4 indicating host rock reached at least 200°C
90MR28F	Base of Echooka	Barren
90MR40A	Top of Wahoo	19 Pa elements of *Declinognthodus noduliferus japonicus* (Igo & Koike)
(31269-PC)		16 Pa elements *Idiognathodus* sp.
		Idioprioniodus sp. indet. elements
		27 Pa elements *Rhachistognathodus minutus declinatus* (Baesemann & Lane)
		1 unassigned Pb element
		59 indet. bar, blade, and platform fragments
		BIOFACIES: Rhachistognathid-declinognathodid-idiognathodid biofacies: relatively shallow water, high energy, normal marine (probably apron of barrier or shoal facies)
		AGE: *sinuosus* Zone to to of Morrowan (=late Morrowan). Upper half of Morrowan; (foram-equivalent to Mamet Zones 19-22)
		CAI: 4.5 with surficial gray petina indicating host rock reached at least 250°C with possible higher temperature short term heating.
90MR40E	Base of Echooka	Barren
90MR52C	Top of Wahoo	Barren
90MR55A	Top of Wahoo	1 Pa element fragment *Adetognathus* aff. *A. spathus* (Dunn)
(31270-PC)		1 juvenile Pa element *Adetognathus* sp. indet.
		2 juvenile Pa elements *Idiognathodus?* sp. indet.
		1 Pa element *Rhachistognathus minutus havlenai* (Baesemann & Lane)
		1 Pa eleiment *Rhachistognathus minutus* (Higgins & Bouckaert)

APPENDIX A -- DETAILED MICROFOSSIL DESCRIPTIONS

Table 6 Continued

Sample Number (USGS Col. #)	Rock Unit	Description Conodont identifications and interpretations by Anita G. Harris, U.S. Geological Survey, Reston, Virginia
90MR55A cont'		**BIOFACIES:** indeterminate; postmortem hydraulic mixing. Probably relatively shallow water, normal marine depositional environment.
		AGE: *sinuatus-minutus* zone early but not earliest Morrowan into early Atokan. (foram-equivalent to Zone 16 into Early Atokan)
		CAI: 4.5 indicating host rock reached at least 250°C
90MR56C	Top of Wahoo	6 Pa elements *Adetognathus spathus* (Dunn)
(31271-PC)		1 Pa element *Declinognathodus noduliferus* (Ellison & Graves) subsp. indet.
		19 Pa elements *Idiognathodus* sp.
		1 Pa element *Neognathodus?* sp. indet.
		26 Pa elements *Rhachistognathus minutus declinatus* (Baesemann & Lane)
		11 Pa elements *Rhachistognathus minutus havlenai* (Baesemann & Lane)
		37 robust Pa element fragments (chiefly *Idiognathodus*)
		1 unassigned Pb element
		25 indet. bar, blade, and platform fragments; common phosphatized steinkerns of gastropods, bryozoans and tubules
		BIOFACIES: rhachistognathid biofacies with postmortem hydraulic addition of idiognathodids (the idiognathodids are hydraulically abraded whereas the rhachistognathids are not). High energy, shallow water, normal marine depositional environment -- probably barrier or shoal-water depositional setting.
		AGE: *sinuosus* Zone into early Atokan (=late Morowan-early Atokan). Upper half of Morrowian into early Atokan. (foram-equivalent to Mamet Zone 19 into early Atokan). "extremely hydraulically abraded"
		CAI: 4-4.5 indicating host rock reached at least 200° - 250°C
90MR56G	Base of Echooka	Barren

APPENDIX A -- DETAILED MICROFOSSIL DESCRIPTIONS

Table 7 Calcareous Microfossil Data

Sample Number	Rock Unit	Identifications
89MR36A[1]	Top of Wahoo	**Forams:** *Globivalvulina* of the *G. bulloides* gp.with some *Pseudoendohthyra* and *Eostaffella* sp.
		AGE: early Bashkirian
89MR36B[1]	Base of Echooka	**Forams:** geinitzinids, pachyphloids?, Permian "frondicularids"
		AGE: post-Sakmarian, (Artinskian or younger)
89MR38A[1]	Top of Wahoo	**Forams:** *Pseudoendothyra* (*P. britishensis, P. ornata, P.*spp.) with *Pseudostaffella*, *Globivalvulina* of the *G. bulloides* gp., *Eostaffella* spp., *Eostaffellina?* sp., palaeotextulariids, *Millerella?* sp.
		AGE: early Bashkirian (early Atokan) (Mamet foram Zone 21)
89MR38B[1]	Base of Echooka	**Forams:** geinitzinids, pachyphloids?, Permian "frondicularids"
		AGE: post-Sakmarian, (Artinskian or younger)
89MR36A[2]	Top of Wahoo	**Forams:** *Globivalvulina bulloides*, *Eostaffella* sp., Indet., encrusting forams
		AGE: late Chesterian or younger
89MR36B[2]	Base of Echooka	**Forams:** geinitzinids / frondicularids, nodosariids,
		AGE: late Sakmarian or younger
89MR38A[2]	Top of Wahoo	**Forams:** *Pseudoendothyra* sp., *Globivalvulina bulloides*, indet. encrusting forams., *Eostaffella* sp., *Biseriella parva*, *Palaeonubecularia rustica*
		Algae: *Donezella lutgini*, *Archaeolithophyllum* sp., *Berestovia?* sp., *Parastacheia?* sp.
		AGE: early Atokan
89MR38B[2]	Base of Echooka	geinitzinids, nodosariids, *Eostaffella* sp.
		AGE: late Sakmarian or younger

[1] Microfossil identifications by Sylvie Pinard, Calgary, Alberta Canada

[2] Microfossil identifications by Paul L. Brenckle, Amoco Production Co. Houston, Texas

APPENDIX B

STRATIGRAPHIC FRAMEWORK OF THE NORTHEASTERN BROOKS RANGE, ALASKA

Mark S. Robinson[4], James G. Clough[4], Keith Crowder[5], Keith Watts[5], John Roe[5] and Charles G. Mull[4], and John Decker[6]

Introduction

There are many unconformities in the stratigraphic record of northern Alaska. This study has focused on the interregional truncation surface at the base of the Echooka Formation, here named the pre-Echooka unconformity. The pre-Echooka unconformity represents a significant event in the geologic history of northern Alaska; the truncation of the Lisburne carbonate platform, and the initiation of clastic sediment deposition that resulted in the accumulation of the Sadlerochit Group, which forms the main producing reservoir at Prudhoe Bay, North America's largest oil field (Figure 7).

Regional and interregional unconformities define discrete lithostratigraphic packages in northeastern Alaska. The unconformities are the result of orogenic events that occurred throughout the Arctic and are from oldest to youngest; the Rapitanian (Proterozoic), Franklinian (early Cambrian to mid Devonian), Ellesmerian (early Mississippian to early Cretaceous) and the Columbian and Laramide (Brookain) orogenies.

The Rapitanian Sequence (Norris, 1985) in the Sadlerochit and Shublik Mountains consists of a heterogeneous assemblage of pre-Mississippian rocks including; slate, argillite, dark dolomitie and greenstone of the Neruokpuk Formation (Reiser and others, 1971, and 1978; and Robinson and others, 1989) and the thick platform dolomite succession of the Katakturuk Dolomite (Dutro, 1970; Clough, 1986, 1989). Lane (1991)suggests that the rocks identified as Neruorpuk Formation in the Sadlerochit and Shublik Mountains may actually

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represent an older succession (possibly Tindir Group) not differentiated in northeastern Alaska but exposed in the Ogilvie and Warnecke Mountains to the southeast.

The Nanook Limestone (Dutro, 1970; Blodgett and others, 1986) and Mt. Coplestone

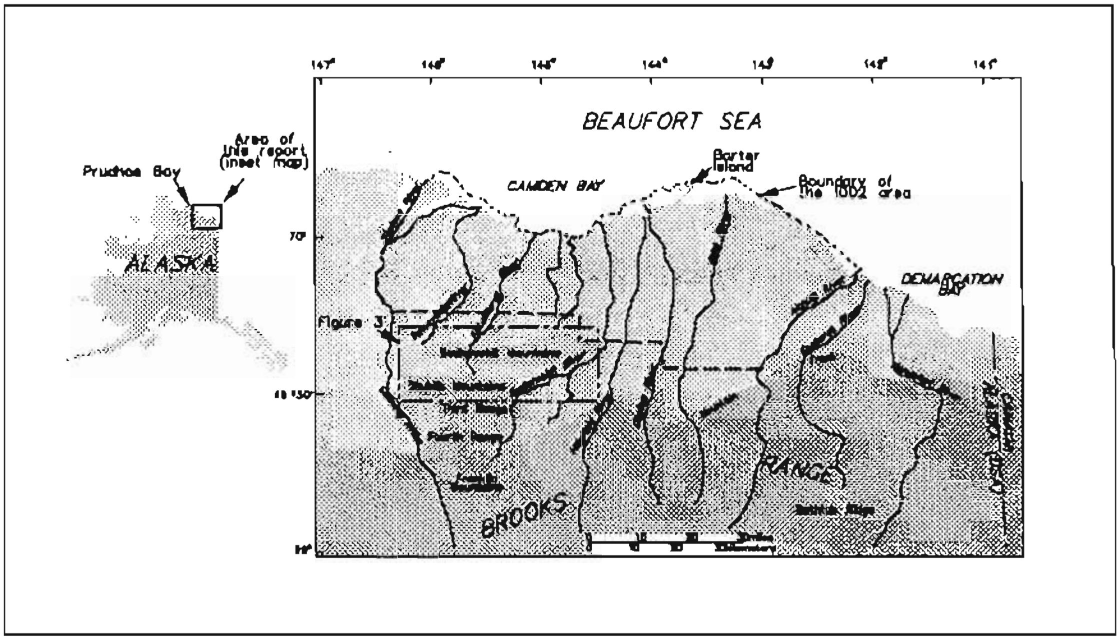

Figure 7. Location map of northeastern Alaska.

Limestone (Blodgett and others, 1992) is a 1300 meter thick succession of shallow water limestone and dolomite and minor shale turbidite and is the Franklinian assemblage in the Sadlerochit and Shublik Mountains.

The Ellesmerian sequence, originally named by Lerand (1973) in arctic Canada, is a dominantly marine assemblage of clastics and carbonates derived from a northerly source area. The carbonates of the Lisburne Group (Mississippian and Pennsylvanian) formed on a south facing (present day orientation) carbonate platform and the clastic succession of the Sadlerochit Group is separated from the underlying carbonates by a systemic boundary that represents the Pennsylvanian-Permian boundary (Crowder, 1990). The Ellesmerian sequence in the Sadlerochit and Shublik Mountains and along the Brooks Range Mountain front to the southwest, includes rocks of the Kekiktuk Conglomerate, Itkilliariak Formation, and Kayak

Shale (Endicott Group), the Alapah Limestone and Wahoo Limestone (Lisburne Group), the Echooka and Ivishak Formations (Sadlerochit Group), the Shublik Formation and Karen Creek Sandstone, Kingak Shale, the Kemik Sandstone and pebble shale unit.

The Brookian sequence (Lerand, 1973) is composed of a thick marine and nonmarine clastic succession derived from sediments shed northward as a result of the uplift of the Brooks Range (Columbian and Laramide orogenies). Molenaar and others (1987) subdivided the Brookian sequence in the Canning River region into three units; the Canning Formation (Campanian or Maastrichtian to Pliocene), the Hue Shale (Aptian(?) to Campanian or Maastrichtian), and the Arctic Creek facies (Jurassic to Campanian or Maastrichtian). We have followed this subdivision and have further subdivided the Arctic Creek facies into two informal lithostratigraphic units (Robinson and others, 1989).

The stratigraphic framework of the Prudhoe Bay area and that of mountainous area to the south is quite similar (figure 8). The major difference between the two areas is the presence of a thick platformal carbonate succession (the Katakturuk Dolomite and Nanook Limestone) in the Sadlerochit and Shublik Mountains. The Katakturuk Dolomite and Nanook Limestone unconformably(?) overly argillite of the metamorphic complex (Neruokpuk Formation?), which is usually considered basement at Prudhoe Bay.

The stratigraphic occurrence of hydrocarbons at Prudhoe Bay is well established by drilling (Jones and Speers, 1976); however the known occurrences of hydrocarbons in ANWR are restricted to oil seeps and to the occurrence of residual hydrocarbons "dead oil" in surface exposures. The stratigraphic distribution of known hydrocarbons at Prudhoe Bay and in ANWR .

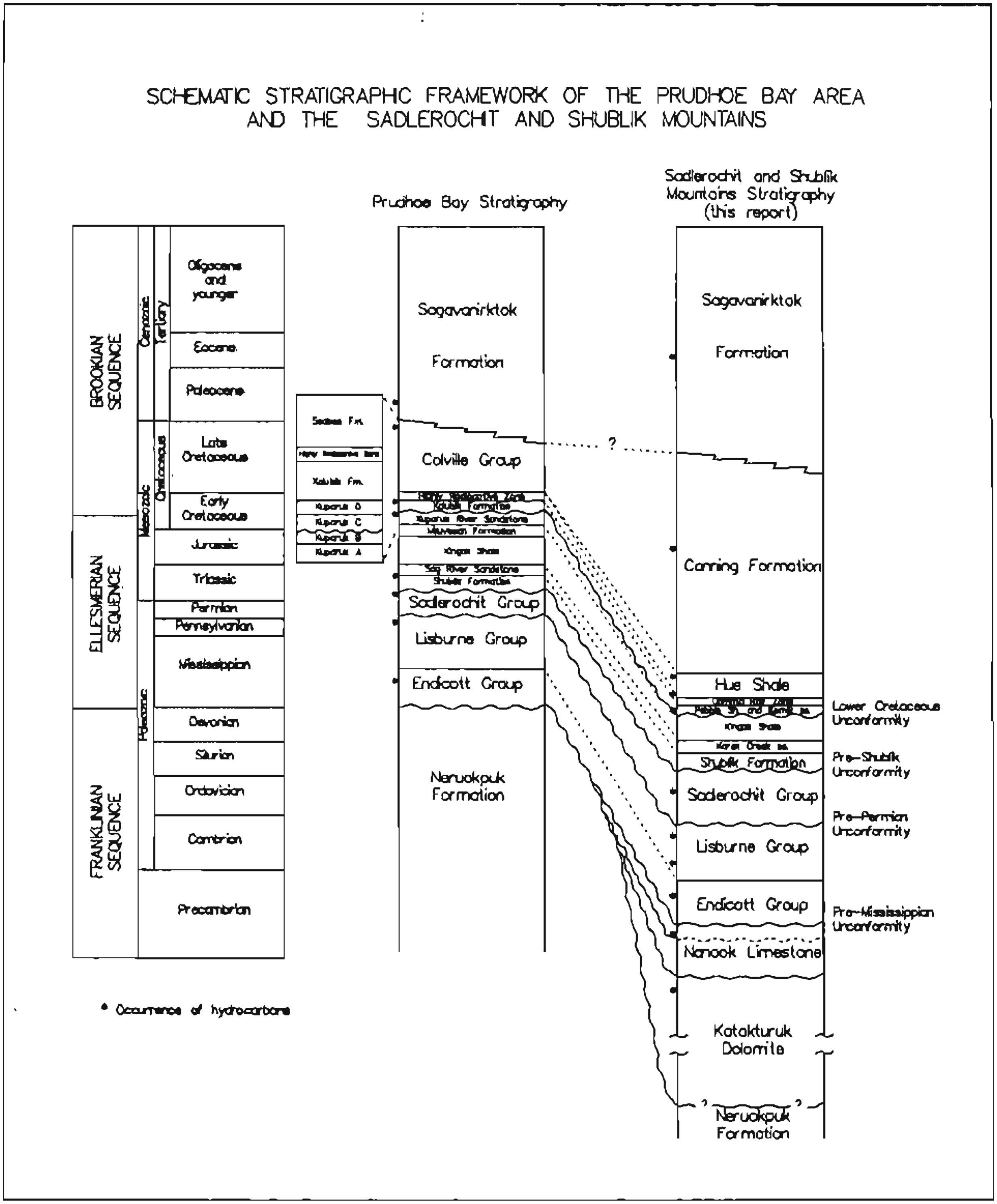

Figure 8. Stratigraphic framework of Prudhoe Bay and of the Sadlerochit and Shublik Mountains.

REGIONAL STRATIGRAPHIC RELATIONSHIPS

RAPITANIAN SEQUENCE

Neruokpuk Formation

Rocks of the Rapitanian sequence exposed in the Sadlerochit Mountains include: argillite, slate, quartzite, and mafic volcanic rocks assigned to the Neruokpuk Formation (Reiser and others, 1978 and Robinson and others, 1989).

Leffingwell (1919) named the Neruokpuk Schist for interlayered quartzite, siliceous phyllite, argillite, limestone, and shale that crop out in the Romanzof Mountains. Reiser and others (1978) described the Neruokpuk Schist as interlayered limestone, calcareous and dolomitic sandstone, shale, phyllite, mafic volcanic rocks, and quartzite and suggested a Proterozoic age for the unit because of their textural maturity and the apparent lack of fossils. In the and eastern Sadlerochit Mountains, Quartzite, dolomite, and slate of the Neruokpuk Formation are intruded by a mafic sill or dike. Isotopic data on pyroxene and feldspar concentrates and whole rock samples yield a Rb-Sr isochron age of 801± 20 Ma and a Nd-Sm isochron age of 704±38 Ma. These data are the first direct evidence that rocks of the Neruokpuk Formation in the Sadlerochit Mountains are Late Proterozoic or older. Lane (1991) cites this isochron data as evidence that these rocks are too old to be correlated with less argillaceous Early Paleozoic rocks recently mapped as Neruokpuk Formation along the northern Yukon Territory - Alaska Border. The Neruokpuk Formation in the Sadlerochit and Shublik Mountains has not been studied in detail and the stratigraphy, age, and relationship to the Neruokpuk elsewhere is poorly understood.

Isoclinal folding and well-defined axial plane cleavage is the dominant fabric within these rocks. The overlying units of the Katakturuk dolomite do not contain axial plane cleavage or isoclinal folding.

Rocks of the Neruokpuk Formation are overlain by or are in fault contact with platform carbonates of the overlying Katakturuk Dolomite. The exact nature of the contact between the Neruokpuk and the Katakturuk is not known at this time.

Proterozoic (?) volcanic unit

Proterozoic volcanic rocks are present in the western Shublik Mountains where they occur as a well developed flow sequence beneath and within the lower Katakturuk Dolomite. They are over 100 m thick where best exposed at the western end of the Shublik Mountains along Nanook Creek. There, they consist of diabase and basaltic flows that include 25 m of pillowed and poorly vesiculated metabasalt at the base; overlain by 10 m of folded and ripple-marked very fine-grained quartzitic sandstone; and 80 m of pillowed to massive metabasalt flows at the top of the unit with local pahoehoe texture and red-weathering zones at flow tops (Moore, 1987). The contact with the overlying Katakturuk Dolomite (unnamed dolomite of Dutro, 1970) is conformable, however the dolomitic rocks adjacent to the contact are extensively sheared (Clough, 1989). Similar pillowed metabasalts exposed in a fault sliver in the northeastern Sadlerochit Mountains are nearly identical mineralogically and compositionally to the Shublik Mountain volcanics. Recent preliminary isotopic data for the Mt. Coplestone volcanics in the Shubliik Mountains suggests that the basalts may be Proterozoic in age (S. Bergman pers. comm. 1991).

Katakturuk Dolomite

The Katakturuk Dolomite (Dutro, 1970) forms the anticlinal cores of the Sadlerochit and Shublik Mountains (figure 9). It is also exposed in the Old Man Creek-Hula Hula River region (figure. 7). The Katakturuk Dolomite was informally named the Mount Weller Dolomite by Leffingwell (1919) and was later given its present formal name by Dutro (1970) for its exposure in the Katakturuk River canyon in the central Sadlerochit Mountains. Dutro informally subdivided the unit into nine members based on a composite type section in the Shublik Mountains. Dutro's subdivision did not include two units immediately below his nine

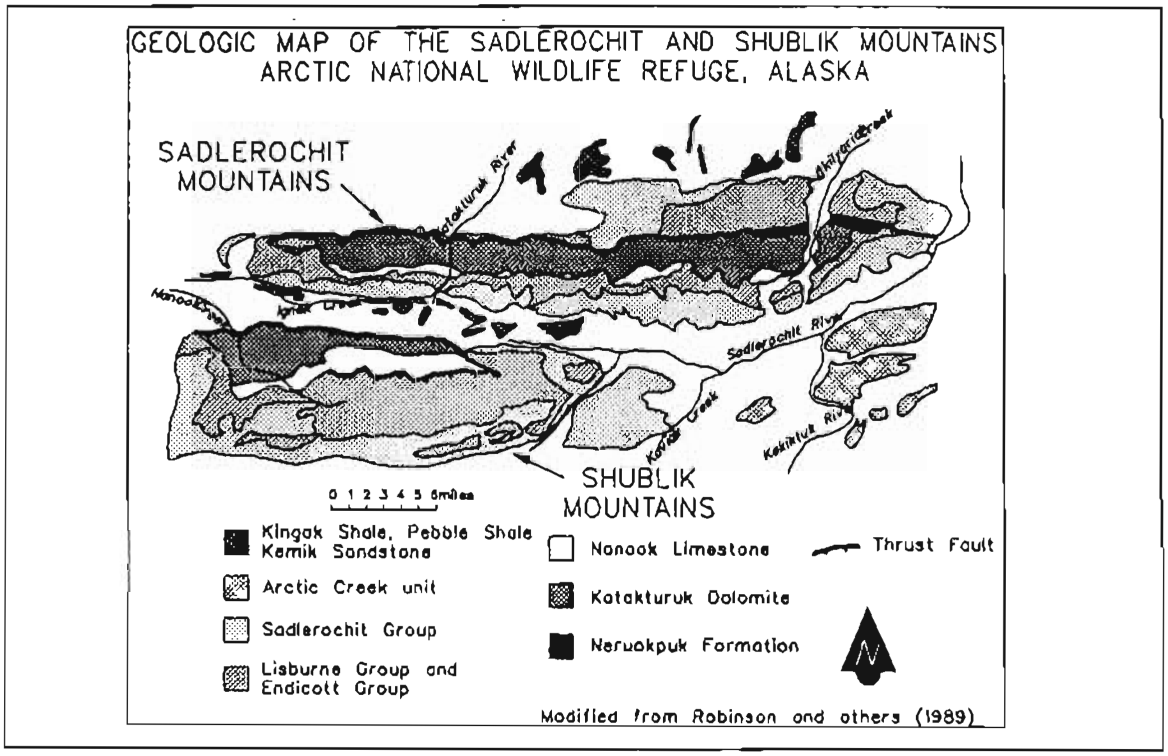

Figure 9. *Generalized geologic map of the Sadlerochit and Shublik* Mountains.

members or the Mount Copleston mafic volcanic flows in the western Shublik Mountains. During geological mapping (Robinson and others 1986, 1989) the Katakturuk Dolomite was subdivided into sixteen informal lithostratigraphic units, which include the unnamed dolomite of Dutro (1970) and four units which are stratigraphically above the uppermost Katakturuk exposed in the Shublik Mountains. These units are presented as informal members in Clough (1989) and herein.

New age revisions of the Katakturuk Dolomite and the overlying Nanook Limestone (Blodgett and others, 1986) and detailed stratigraphic studies (Clough, 1986, 1989; Clough and others, 1987) suggest that the Katakturuk Dolomite is older than mid Upper Cambrian and is probably Proterozoic in age.

In the Sadlerochit and Shublik Mountains, the Katakturuk Dolomite is predominantly dolomitic and comprises 25 million-year duration second-order supersequences (Clough and Goldhammer, 1992) containing subtidal to peritidal high-frequency cyclical carbonates deposited on a Late Proterozoic passive margin ramp. Lithologies include shale, dolomitic mudstone and lime mudstone turbidites and dolomitic breccias (deep water basin plain to slope apron settings); crossbedded oolitic grainstone, algal and cryptalgal-laminated mudstone, with abundant stromatolites (subtidal to intertidal settings); and pisolite, dolomitic mudstone with mudcracks, karst collapse breccia, microtepee and microspeleothem structures (supratidal settings) (Clough, 1986 and 1989) Clough and others, 1988). The carbonate facies are laterally continuous and can be correlated between the Sadlerochit and Shublik Mountains.

The Proterozoic passive margin in the northeastern Brooks Range, was paleogeographically situated with an east-west (present day orientation) shelf margin trend and basin located to the south (Clough 1986, 1989). The carbonate platform may have once been contiguous with some of the Canadian arctic Proterozoic carbonate platforms (ie. Dahl Group in northern Yukon) however, the present level of understanding of Brooks Range and Canada Basin tectonics makes Precambrian palinspastic restorations difficult.

The Katakturuk Dolomite uncomformably underlies rocks of the Nanook Limestone, Mt. Coplestone Limestone, Endicott Group, and Lisburne Group, in the Sadlerochit and Shublik Mountains, and structurally overlies rocks of the Neruokpuk Formation, Lisburne Group, and Sadlerochit Group, in the same ranges (Robinson and others, 1989). The Katakturuk Dolomite is almost 2400 m thick in the Sadlerochit Mountains and thins to about 1800 m thick in the Shublik Mountains where the upper 600 m has been removed beneath a pre-Nanook unconformity.

FRANKLINIAN SEQUENCE

Nanook Limestone

The Nanook Limestone (Dutro, 1970) is a thick sequence of limestone, dolomite and minor shale (figure 9) that unconformably overlies rocks of the Katakturuk Dolomite. The most complete section of Nanook Limestone is exposed in the Shublik Mountains (figure 9). In

1985, Late Cambrian and Early Ordovician trilobites and Late Ordovician gastropods were discovered in the upper 500 m of the Nanook Limestone (Blodgett and others, 1986). This discovery suggests that the lower part of the Nanook is older than Late Cambrian (and perhaps Proterozoic) in age and that the underlying Katakturuk Dolomite is probably Proterozoic in age (Blodgett and others, 1986). Exposures of Nanook in the Sadlerochit Mountains have yielded Upper Cambrian trilobites (James G. Clough pers. comm. 1989).

The Nanook Limestone is over 1,200 m thick and has been subdivided into six distinct lithostratigraphic units (Robinson and others, 1989). It consists of limestone, dolomite and minor shale and probably does not represent a continuous sedimentary succession. A major disconformity occurs at the top. Lower Devonian (Emsian) rocks of the Mt. Coplestone Limestone (Blodgett and others, 1992) rest with angular discordance on Upper Ordovician rocks (Blodgett et al., 1986). In the Sadlerochit Mountains only the uppermost unit of the Nanook Limestone (containing Ordovician and probably Cambrian rocks but lacking Devonian strata) has been recognized.

The basal Nanook Limestone consists of moderately deep water, interbedded, burrowed dolomite and calcareous shale turbidites deposited in a slope to near slope environment. Unfossiliferous limestone and vuggy dolomite in the middle part of the Nanook Limestone represents mostly shallow water deposition. Environments in the upper Nanook Limestone are shallow subtidal to intertidal and consist of peloidal and oolitic fossiliferous limestone and minor dolomite.

The Upper Limestone member is dominated by thick-bedded and massive, peloidal packstone to wackestone, oolitic wackestone to grainstone and bioclastic wackestone, and cryptalgal laminated mudstone. Grain types consist of peloids, ooids, and disaggregated coral and shell debris. The depositional setting is largely shallow subtidal to intertidal with locally restricted environments. Prominent oolitic horizons within the Upper Ordovician rocks suggest periodic shoaling conditions.

The Upper Limestone member (unit 8 of Dutro, 1970) contains the only age-diagnostic fossils discovered to date in rocks of the Franklinian sequence in the Sadlerochit and Shublik Mountains. The oldest fossils identified from this member consists of the trilobite *Plethometopus armatus*. This Late Cambrian species is known elsewhere only in North America. The Upper Limestone member also contains rocks of Upper Cambrian, Lower Ordovician, and Middle and Upper Ordovician and Lower Devonian (Emsian) age. Of significance is the absence of Silurian age strata due to a major regional unconformity (Blodgett and others, 1988).

Exposures of undifferentiated black dolomite and shale in the Third and Fourth Ranges (figure 7) situated to the south of the Sadlerochit and Shublik Mountains, contain poorly preserved brachipods (James G. Clough, pers. comm , 1991) and may represent coeval basin margin and plain sedimentation.

Mt. Coplestone Limestone

The recently named Mount Coplestone Limestone (Blodgett and others, 1992) disconformably overlies the Nanook Limestone in two outcrop belts in the Shublik Mountains. This new stratigraphic unit heretofore comprised the Devonian portion of the uppermost member of the Nanook Limestone defined by Dutro (1970). The age of the Mount Coplestone Limestone is late Early Devonian (Emsian) (Blodgett and others, 1992) and it rests on Upper Ordovician strata in the eastern 12 km-long outcrop belt and Middle Ordovician rocks in the 2 km-long western outcrop belt. The formation, over 71 meters thick, consists of thin- to medium-bedded, dark gray lime mudstone and bioclastic limestone formed in a shallow-water, partially restricted, inner-platform environment (Clough and others, 1988) overlain by the Kekiktuk Conglomerate of the Endicott Group.

ENDICOTT GROUP

The Endicott Group in northeastern Alaska rests on a major interregional unconformity (pre-Mississippian unconformity). The Group is a transgressive sequence and includes rocks of the Kekiktuk Conglomerate, Kayak Shale, and Itkillariak Formation. It ranges up to 100 m thick, and grades upward from a conglomeratic base to finer grained paralic sediments near the top (Armstrong and Mamet, 1975).

Kekiktuk Conglomerate

Brosge and others (1962) named the Kekiktuk Conglomerate for a thin unit of quartzitic sandstone and chert-pebble conglomerate that gradationally underlies the Kayak Shale (Bowsher and Dutro, 1957) and unconformably overlies the Neruokpuk Formation. Clasts in conglomeratic facies consist of subangular to rounded granules, pebbles and cobbles of black, gray, and white chert, quartz, quartzite and sandstone and siltstone. The Kekiktuk is interpreted to be a fluvial to near-shore marine succession (LePain and Crowder, 1990) that varies from 0 to 50 m thick in the Sadlerochit and Shublik Mountains. The variations in thickness probably represent erosional topography on the pre-Endicott unconformity (LePain and Crowder, 1990).

Kayak Shale

The Kayak Shale is predominantly dark-gray to black, fissile, calcareous shale with minor siltstone and thin-bedded ferruginous sandstone that was deposited in a marine environment. In the Shublik Mountains the Kayak Shale ranges up to 100 m thick, due to structural thickening. In the Sadlerochit Mountains, the Kayak Shale is thin and rarely exceeds a few meters thick. The northward pinch out and irregularity of the depositional thickness of the Kayak Shale is probably the result of deposition superimposed on topography developed on the interregional pre-Mississippian unconformity.

Siliciclastic rocks of the Endicott Group grade upward into platform carbonates of the Carboniferous Lisburne Group. The Itkilyariak Formation (Mull and Mangus, 1972), a lateral equivalent of the Kayak Shale, ranges from a few meters thick in the Sadlerochit Mountains to more than 150 meters thick west of the Canning River in the subsurface (Mull and Mangus, 1972). Bird and Jordan (1977) believe that the Itkilyariak Formation represents marginal marine and nonmarine depositional environment.

LISBURNE GROUP

The Carboniferous Lisburne Group in northern Alaska formed on an extensive carbonate platform which was later deformed as part of the Brooks Range fold and thrust belt. In northern ANWR, the Lisburne Group is parautochthonous and less deformed than rocks of the allochthonous Lisburne Group that characterize most of the northern Brooks Range (Armstrong and Mamet, 1977, 1978; Wood and Armstrong, 1975). The stratigraphy of the Lisburne Group is illustrated in figure 10 (Armstrong and Mamet, 1974; Watts et al., 1987). At Prudhoe Bay, it forms a significant hydrocarbon reservoir, and it represents a widespread potential hydrocarbon objective in the North Slope region (Bird and Jordan, 1977; Okland et al., 1987).

Schrader (1902) described and named the Lisburne Formation for a thick sequence of light-gray limestone in the Anaktuvak River area of the central Brooks Range. Later, Leffingwell (1919) referred to similar rocks in northeastern Alaska as the Lisburne Limestone. Detailed work by Bowsher and Dutro (1957) in the Shainin Lake area, subsequently raised the Lisburne Formation (Limestone) to Group status and subdivided the rocks into two formations, the Wachsmuth Limestone of Early and Late Mississippian age, and the Alapah Limestone of Late Mississippian age. The Wachsmuth Limestone apparently thins to the northeast and is absent in the Sadlerochit and Shublik Mountains.

The Lisburne Group in ANWR is composed of two formations. The oldest, the Alapah Limestone of Late Mississippian age, was subdivided informally during geologic mapping into a lower cliff-forming unit and an overlying unit that forms distinctive talus-covered slopes. The overlying Wahoo Limestone has also been informally subdivided into a lower cliff-forming member of Late Mississippian age, and an upper thin-bedded, recessive weathering member of Early and Middle Pennsylvanian age.

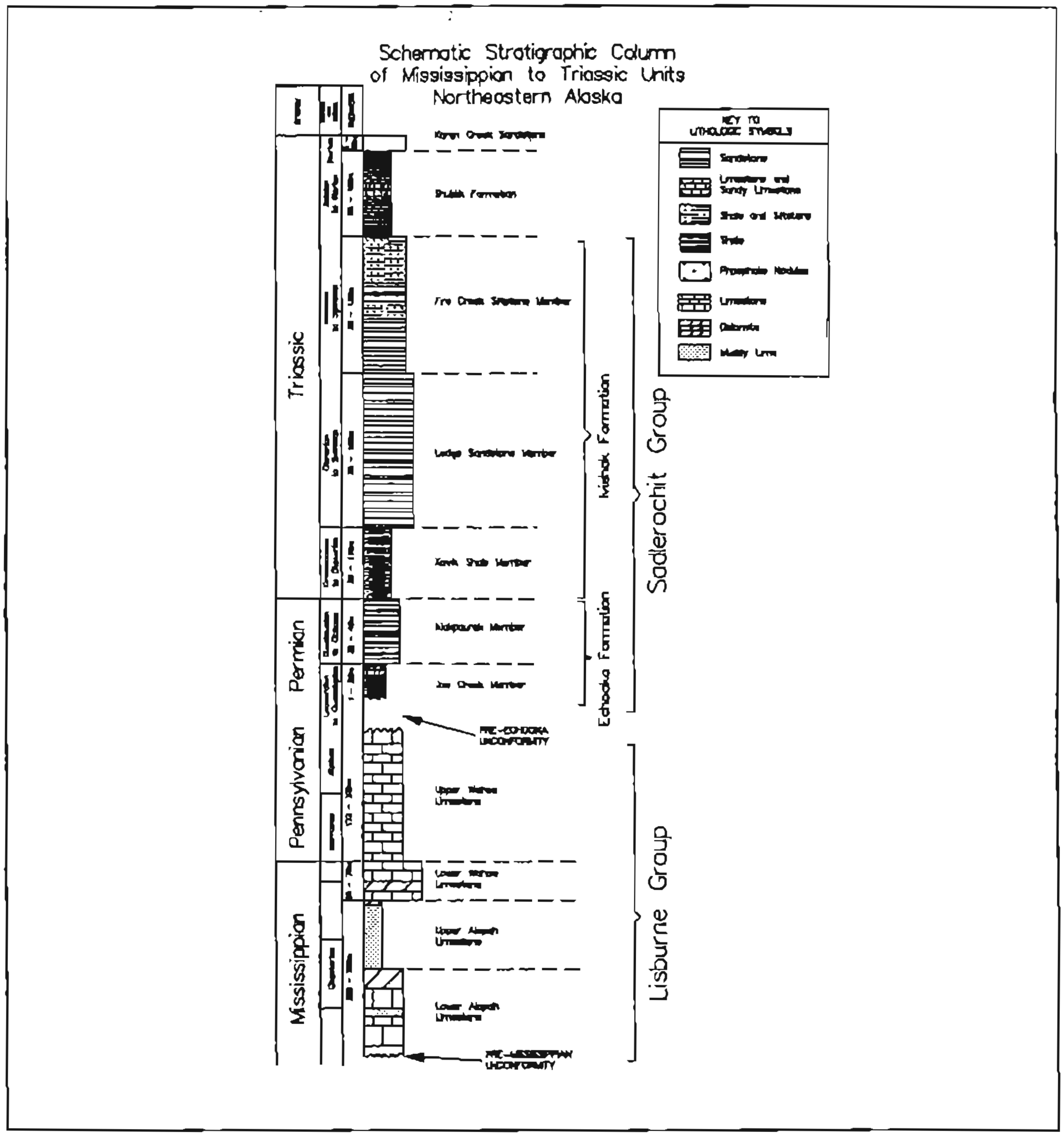

Figure 10. *Stratigrtaphy of the Lisburne and Sadlerochit Groups, northeastern Alaska.*

Rocks of the basal Alapah Limestone represent the top of a major transgressive sequence which is overlain by lagoonal to intertidal and possibly supratidal carbonates of the upper Alapah unit. The age of the basal Lisburne Group shows a rapid northward younging, demonstrating its northward transgression (Armstrong and Mamet, 1978). In the eastern Sadlerochit Mountains, the lower member of the Alapah Limestone was deposited either on

Itkilliariak Formation, Katakturuk Dolomite, or on the Neruokpuk Formation. In the western Sadlerochit Mountains where the Endicott Group (Kayak Shale and Kekiktuk Conglomerate) is thin and discontinuous, due to the depositional pinch out from south to north and west to east, the Alapah was either deposited on Endicott Group, on Nanook Limestone, or on Katakturuk Dolomite (Imm, 1989, in press).

The pre-Mississippian unconformity, a major break in the stratigraphic record in northeastern Alaska truncates all of the pre-Mississippian units in the Sadlerochit and Shublik Mountains and results in the deposition of Alapah Limestone on contrasting pre-Mississippian lithologic units. The lower Alapah contains cyclical repetitions of limestone and terrigenous sediments including shale and sandstone that occur at the top of each cycle. Medium- to coarse-grained peloidal and skeletal grainstones contain large-scale cross-stratification, which suggests a relatively high energy depositional environment.

In the Shublik Mountains the contact between the lower unit of the Alapah Limestone and the Kayak Shale (Endicott Group) is gradational. Terrigenous muds of the Kayak Shale pass gradationally upward into argillaceous limestones; suggesting either that offshore and/or lagoonal muds passed transgressively upward into carbonate banks; or that there was a significant decrease in the amount of terrigenous sediment. Farther south in the Fourth Range a similar gradational transition is present. The upper part of the Endicott Group south of the Shublik contains significant limestones; often containing colonial and rugose corals (Gruzlovic, 1988).

Once established, the Lisburne carbonate platform produced large quantities of carbonate sediment that resulted in progradation of carbonate facies of the upper Alapah unit. The upper Alapah unit consists of a thick sequence of poorly exposed, dark-colored, lime mudstone and dolomite, containing evaporite molds and collapse breccias. Dark-colored lime mudstone, dolomite, and lesser evaporite formed in either a restricted lagoonal to intertidal and possibly supratidal environment. Nodular calcite after gypsum and disseminated laths and molds of anhydrite indicate hypersaline conditions under arid climatic conditions.

Dolomite and cryptalgal laminite in the unit also suggest an intertidal to sabkha environment. Collapse breccias formed due to the dissolution of evaporite or carbonate, possibly during subaerial exposure of the unit. Recrystallized limestones at the top of the unit may have formed by fresh water diagenesis during subaerial exposure toward the end of the progradational event (Imm, 1989, in press). A small-scale unconformity marks the contact between the cliff-forming, fossiliferous, open-marine limestones of the lower Wahoo Limestone and the upper Alapah unit.

The lower Wahoo unit is a cliff-forming sequence composed of limestones containing abundant bryozoans and echinoderms (crinoids and other pelmatozoans) which formed in open marine conditions. The unit is similar to the Wahoo Limestone of the type locality (Watts, Harris, and others, in prep.). Petrographic analyses reveal that ooids locally occur at the top of three horizons in the unit, perhaps marking the top of shallowing-upward cycles (Imm, 1989, in press). The unit consists predominantly of skeletal packstones and grainstone with lesser wackestone. Variations in the amount of compaction in grainstones in the unit are evident and may be due to differences in the early diagenetic history. Disseminated quartz sand and silt becomes more abundant toward the top of the unit (Carlson, 1987).

The lower Wahoo unit is Late Mississippian in age; zones 18 & 19 of Armstrong and Mamet (1977) and corals (Armstrong, 1974). Abundant echinoderms (including crinoids) and bryozoans indicate normal marine salinities and suggest an open-marine paleoenvironment.

In the western Shublik Mountains, oolitic grainstones mark the top of shallowing-upward cycles. The grainstones represent local shoals that may have developed during relative low-stands of sea level or may represent shoals that built to sea level (Imm, 1989 in press). Variations in amount of compaction of grainstones in the unit can be correlated with shallowing-upward cycles (Imm, 1989, in press). Regressive grainstone deposits at the top of the cycles were affected by early fresh-water diagenesis and this cementation apparently prevented later compaction. Transgressive grainstone deposits were not affected by early cementation, and were highly compacted during burial diagenesis. An increase in quartz content toward the top of the lower Wahoo unit may be due to regression and the influx of terrigenous clastics from the north. The development of channels in the top of the lower Wahoo unit may have resulted from subaerial exposure or possibly due to localized submarine erosion (Carlson, 1987; and Imm, 1989, in press). However, elsewhere no unconformity is apparent and the Pennsylvanian-Mississippian boundary may lie below the lithostratigraphic contact between the upper and lower Wahoo formations. The top of the unit is marked by a distinct change in lithology and bedding character.

The upper Wahoo unit is Pennsylvanian in age (Morrowan and Atokan, Mamet Zones 20 and 21 respectively) and is composed of numerous shallowing-upward cycles. The upper Wahoo unit is most complete in the eastern Sadlerochit Mountains where erosion beneath the pre-Permian unconformity was least. The amount of section preserved as part of the upper Wahoo unit in the Sadlerochit and Shublik Mountains is controlled by the depth of erosion of the pre-Permian unconformity (Armstrong, 1974; Watts and others, 1987). The upper Wahoo unit thins to the west and south and the unit is entirely missing in the western Shublik Mountains, apparently the result of a deep level of erosion on the pre-Permian unconformity (Imm, 1989, in press).

Several paraconformities within the upper Wahoo unit were first recognized by Mamet (pers. comm., 1987) and confirmed through studies of microfacies and diagenesis (Carlson, 1987 and pers. comm., 1988). Near the base of the upper Wahoo unit, lithologic cycles culminate with the occurrence of cryptalgal laminite. Oolitic grainstone becomes increasingly common up section, and characterizes most of the lithologic cycles in the middle part of the upper Wahoo unit. Above the paraconformity that marks the Morrowan / Atokan boundary, Donezella algae occurs and marks the top of a number of lithologic cycles (Carlson, 1987). Above another paraconformity the uppermost part of the upper Wahoo unit contains small oncolites (Osagia?) that typify cycles which pass upward into peloidal limestones. The lithologic cycles reflect abrupt facies changes from an open-marine environment of deposition of the lower Wahoo unit to intertidal environments that dominate the upper Wahoo unit.

The cycles may have formed due to repeated migrations of ooid shoals and associated changes in sea-level (cf. James, 1984) that apparently developed on a gently dipping carbonate ramp and repeatedly migrated across the region. Repeated progradations of the shoals, each followed by a rapid transgression, led to the development of numerous shallowing-upward lithologic cycles that comprise the unit. The paraconformities and evidence of subaerial diagenesis indicate emergence of the platform during significant relatively low-stands of sea level. However, most of the shallowing-upward cycles in the upper Wahoo unit are not marked by emergence but rather indicate southward migration of lagoons behind the shoals followed by rapid transgressions.

The pre-Permian unconformity is a major break in the stratigraphic record. Erosion into the Lisburne platform resulted in the development of significant erosional topography on the unconformity in response to either differential uplift or the development of bypass channels on the emergent Lisburne platform. The greatest amount of erosional relief occurs in the western Shublik Mountains.

The Lisburne Group carbonates apparently formed in relatively temperate to semi-arid climate (not tropical) as indicated by a limited fauna and flora and the presence of evaporites.

The composition of basal units of the Alapah Limestone in the central and eastern Sadlerochit Mountains is dependent on the composition of the underlying bedrock. This indicates that the basal units were derived from the erosion of underlying pre-Mississippian bedrock. The presence of distinctive lag deposits including dolomitic conglomerates and breccias, indicates that there is no major dislocation between the lower Alapah and the underlying pre-Mississippian rocks and therefore the contact between the pre-Mississippian units and the Alapah Limestone in the Sadlerochit Mountains is not a major detachment surface. However, in the Shublik Mountains, where the Kayak Shale is present, a major detachment is present (Imm, and Watts, 1987; Wallace, 1987; Robinson and others, 1989).

PERMIAN AND TRIASSIC SEDIMENTATION

The Lisburne Group in northeastern Alaska is overlain unconformably by quartzarenite, siltstone, shale, and minor conglomerate of the Sadlerochit Group. In ascending order, the Sadlerochit Group is composed of the Permian Joe Creek and Ikiakpaurak Members of the Echooka Formation, the Kavik Shale, Ledge Sandstone, and Fire Creek Members of the Triassic Ivishak Formation. The Sadlerochit Group is overlain by phosphate-rich bioclastic rocks of the Shublik Formation. The Shublik is in turn overlain by quartzarenite of the Triassic Karen Creek Sandstone (Detterman, 1970, 1974, 1976, 1984; Detterman and others, 1975, Reiser and others, 1971). The Upper boundary of the Ellesmerian sequence is the Lower Cretaceous Unconformity (LCU), another interregional angular discordance that progressively truncates older rocks northward. Because of the this northward truncation, Upper Ellesmerian siliciclastics may not extend very far into the subsurface of the coastal plain north of the Sadlerochit Mountains.

The systemic boundary separating Pennsylvanian and Permian rocks forms a conspicuous contact between the Wahoo Limestone and mixed carbonates and terrigenous clastics of the Echooka Formation. The Echooka is a recessive weathering unit throughout the Sadlerochit and Shublik Mountains. It becomes thicker and finer grained to the southeast and southwest where it is more resistant and forms distinctive hogback exposures.

The amount of erosional relief developed along the pre-Permian unconformity is highly variable. The most common contact between the Lisburne and Sadlerochit Groups is a sharp planar surface with only minor relief. At scattered localities in the Sadlerochit Mountains and throughout the north flank of the central Shublik Mountains the contact is a deeply dissected surface with as much as 30 m of local erosional relief (Imm, 1989 in press). Regionally, there is more physical evidence for substantial erosional relief along the unconformity in the Sadlerochit and Shublik Mountains than in adjacent areas. There is little evidence of erosional truncation toward the south and west where the contact is a disconformity. Bedding characteristics and lithology of both Lisburne and Sadlerochit rocks vary systematically with the amount of erosional relief along the unconformity. Where the contact is sharp and planar, the upper beds of the Wahoo Limestone immediately beneath the unconformity are not deeply weathered and retain original depositional fabrics. Above the unconformity, the basal rocks of the Echooka Formation are rhythmically-bedded, well-organized calcarenite with stratification concordant to the unconformity. In contrast, where substantial erosional relief is developed along the unconformity the upper beds of the Wahoo Limestone are often deeply weathered and the basal rocks of the Echooka Formation are a poorly-organized assemblage of pebble, cobble, and boulder conglomerate.

Good exposures of the Echooka Formation in the Sadlerochit and Shublik Mountains are limited to stream cuts and hogback outcrops flanking the mountains. The formation is particularly well-exposed in the Sadlerochit Mountains adjacent to the Katakturuk River canyon and along the north and south flanks of the central Shublik Mountains. The Echooka is thinnest in northernmost exposures and averages 20 m in thickness along the south flank of the Sadlerochit Mountains. The formation gradually thickens toward the south and reaches a maximum of 200 m thick near the Ivishak River.

Echooka Formation

The Echooka Formation in the Sadlerochit and Shublik Mountains is subdivided into the conglomerate member (informal) and the overlying Joe Creek and Ikiakpaurak Members (Detterman, 1975). The conglomerate member is a laterally-restricted, crudely channelized chert pebble and cobble conglomerate unit ranging from less than 2 to more than 15 m thick. The conglomerate succession differs significantly in organization, composition and depositional setting from the "typical" Joe Creek Member and records a distinct depositional/erosional episode. It is therefore useful to consider the conglomerate unit separately and restrict the Joe Creek Member to include the fossiliferous, variegated, well-organized succession of sandy calcarenite and calcareous sandstone that overly either the Wahoo Limestone or, where present, the conglomerate member. The Joe Creek Member in this usage ranges from 1 to 20 m thick and is overlain by 15 to 20 m of very fine-grained quartzarenite, siliceous siltstone, and green or black shale of the Ikiakpaurak Member.

The basal conglomerate member of the Echooka Formation is not persistent laterally and is confined entirely within erosional valleys dissected into the surface of the Lisburne Limestone. The orientation of valleys we have studied trend generally northeast to southwest. The conglomerate member varies in thickness from less than 1 m to as much as 24 m thick over a lateral distance of 100 m. The base of the member consists of an irregular, deeply-weathered succession of limestone boulders and cobbles, essentially rip ups derived from the Lisburne limestones. Individual sedimentation units are multiple, mutually-erosive channel-fill successions. Each channel-fill becomes crudely sorted and stratified up section. The conglomerate fines irregularly up section and is abruptly overlain by rocks of the Joe Creek Member. The conglomerate member is developed at scattered locations through the Sadlerochit Mountains and throughout the north flank of the central Shublik Mountains. The conglomerate is absent along the south flank of the Shublik Mountains and the Wahoo Limestone is directly overlain by calcarenite of the Joe Creek Member.

Throughout the Sadlerochit Mountains and Shublik Mountains, a recurring organization is developed in the Joe Creek Member at two scales. At a large scale, the Joe Creek is characterized by an overall upward-fining expressed in both maximum and average grain sizes. However, the internal organization of the Joe Creek is more complicated. The basic building blocks are multiple upward-fining cycles, each separated by an erosional surface and composed of three internal components: (1) a basal layer of fossiliferous, chert pebble conglomerate, (2) an interval of plane-parallel laminated sandy calcarenite, and (3) intensely bioturbated calcareous siltstone or sandy calcilutite. These components form distinct depositional units ranging from 20 cm to 1 m thick.

The upward-fining depositional cycles gradually lose their identity as the Joe Creek Member gradually becomes finer-grained up section. Conglomerate layers, which dominate the cycles near the base of the member, become thinner and contain fewer internal erosional surfaces up section. The conglomerate is increasingly replaced by plane-parallel laminated calcarenite up section. This gradual change in organization is accompanied by a marked increase in the extent of bioturbation.

The Ikiakpaurak Member in the Sadlerochit Mountains, consists of an upward thinning and fining succession of intensely bioturbated, glauconitic and calcareous quartzarenite with minor siltstone interbeds. Quartzarenite beds are separated by intervals of thinly-laminated, glauconitic, red, green, and black shale. At outcrop scale, individual quartzarenite beds are laterally persistent and vary from medium- to thick-bedded and contain disseminated organic matter and concentrations of glauconite and pyrite at various horizons. All of the quartzarenite beds are thoroughly bioturbated and contain no internal primary stratification. Rocks of the Ikiakpaurak Member grade upward into marine shale and siltstone of the Kavik Shale unit.

The Ikiakpaurak Member is thicker along the southern flank of the Shublik Mountains and consists of a thick, monotonous sequence of dark gray to black siliceous siltstone and very fine-grained sandstone. Intense bioturbation has apparently destroyed all internal primary sedimentary structures and, with the exception of a few rare fossil hash layers, individual depositional units cannot be distinguished. In vertical section, the Ikiakpaurak lithology varies from well-bedded dark gray quartzarenite in the lower part to thick, massive siliceous siltstone units comprising the upper part.

Echooka Formation in the Gilead Creek area, near the Ivishak River, contains two distinctive facies that have been differentiated as lithostratigraphic units during geological mapping of the area (Reifenstuhl and others, 1990 and Pessel and others, 1991 in press). The lower(?) member consists of a succession of bioturbated, fossiliferous, glauconitic and calcareous quartzarenite, sandy limestones, and minor calcareous siltstone. Quartzarenite beds range between 2 cm and 10 cm thick and are separated by intervals of thinly-laminated, glauconitic, red, green, and black shale. At outcrop scale, individual quartzarenite beds are laterally persistent and vary from medium- to thick-bedded and contain disseminated organic matter and concentrations of glauconite and pyrite. All of the quartzarenite beds are thoroughly bioturbated and contain no internal primary stratification. Sedimentation rates were apparently fairly low during deposition of this unit and *Zoophycus* and other grazing forms were successful at thoroughly reworking sediment and destroying primary sedimentary structures. The contact between the calcareous facies of the Echooka and the underlying limestones of the Lisburne Group appears to be either a gradational or an unconformity.

An upper(?) unit of the Echooka recognized in the Gilead Creek area consists of medium dark-gray, fine- to very fine-grained, siliceous, cherty, sandstone and siltstone. This silica-rich succession contrasts sharply with the calcareous facies and bedding within sandstone intervals is irregular. Individual beds have convolute tops and bottoms, and the are heavily burrowed. The vertical burrows range up to 8 cm in length and up to 1 cm in diameter and contain a dark-gray finer grained, silty material. The sand layers also contain abundant spiriferid braciopods and a few gastropods. Pyrite is abundant and the unit weathers to a distinctive red-brown color.

The relationship between the calcareous facies of the Echooka and the siliceous facies of the Echooka is not known at this time, however it is possible that there is an unconformity between the two units. Subaerial environments of weathering and erosion, laterally-restricted nonmarine depositional settings, and nearshore to offshore marine environments are recorded in the Echooka Formation. The consistent fining trend, expressed both vertically and laterally, throughout the unit, records a gradual retrogradation and a persistent deepening of sedimentary environments through time.

Lithologic variation within the lower Echooka was strongly influenced by subaerial dissection of the Lisburne platform surface. The basal conglomerate member where present, records a mixed erosional-depositional episode prior to drowning the exhumed carbonate platform. Deposition initially may have occurred by collapse of valley and gully walls. Coarse sediment was subsequently transported episodically within the confines of erosional topography, producing crudely channelized and stratified successions. The organization is reminiscent of fluvial sedimentation, but the lack of lateral-accretion migration patterns and overbank sediment suggest that no stabilized fluvial system existed. Rather, deposition occurred sporadically, most likely during flash floods, producing small and irregular depositional environments within a broad region otherwise subject to extensive mechanical weathering and erosion.

The initial retrogradation of shallow marine environments in response to transgression is recorded in fossiliferous strata of the Joe Creek Member. The early Joe Creek environments were as often erosional as depositional, and perhaps more so. Numerous erosional surfaces separating upward-fining cycles indicate a high degree of stratigraphic incompleteness. The characteristic fining-upward cycles formed during episodic, single-event depositional episodes. The events were likely large, episodic storms affecting nearshore and inner shelf environments. Through time, retrograding environments and gradually deepening waters lessened the erosional impact of storm events. The corresponding up section change in the Joe Creek Member is striking: individual cycles contain fewer amalgamated beds and conglomeratic layers, fewer erosional surfaces, thicker depositional units, and more intensely bioturbated horizons. These "complete" upward-fining cycles through most of the Joe Creek are likely the response to gradient or "relaxation" currents which transported shoreface-derived sediment seaward.

The gradual transition from well-stratified Joe Creek Member to intensely bioturbated siliceous siltstone and sandstone of the Ikiakpaurak Member records continuously increasing water depth, increasing distance from detrital sources, and waning influence of storm-driven sedimentation. Rare fossil-rich layers and graded beds in the Ikiakpaurak record the rare storms of unusual intensity or duration. By Late Permian time, erosional influence of storms was negligible and the region was primarily a depositional environment. Sedimentation rates continued to be low and *Zoophycus* and other grazing forms became increasingly successful at thoroughly reworking sediment and destroying primary sedimentary structures.

Gradationally overlying rocks of the Echooka Formation are shale and siltstone of the Kavik Shale member of the Ivishak Formation.

IVISHAK FORMATION

Kavik Shale Member

The Kavik Shale Member of the Ivishak Formation is poorly exposed along the flanks of the Sadlerochit and Shublik Mountains, where the interval is typically covered by talus derived from the overlying Ledge Sandstone Member. Where exposures are developed along actively-eroding streams, quartzarenite of the upper Echooka Formation fines rapidly up section into dark gray silty shale with minor sandy siltstone or very fine-grained quartzarenite characteristic of the Kavik Shale Member. The Kavik Member thickens from less than 30 m in the northeast Sadlerochit Mountains to a maximum of 115 m along the south flank of the Shublik Mountains.

Although the grain size difference is small, the contact between the Kavik Shale and underlying Echooka Formations is abrupt. In exposures along the southwestern flank of the Shublik Mountains, the Kavik rests with slight angular discordance on the Echooka and may record a surface of depositional onlap. The internal stratification of the Kavik Member is well-organized and lacks evidence of slumping or soft-sediment deformation at any scale.

Very fine-grained quartzarenite beds within the Kavik form a symmetric pattern in vertical sequence, expressed as an upward thinning and fining cycle followed by a coarsening and thickening trend. The lower 5 to 10 m of the member is characterized by an upward thinning and fining succession of very fine-grained quartzarenite and sandy siltstone with silty shale interbeds. The sandstone beds thin rapidly upsection and lose identity entirely within the middle 10 to 30 m of the member. The pattern is repeated in reverse in the upper beds of the Kavik where an upward thickening and coarsening sequence within the upper 10 m of the Kavik marks a rapid transition into the basal beds of the Ledge Sandstone Member.

Ledge Sandstone Member

The Ledge Sandstone Member is well exposed along the north and south flanks of the Sadlerochit and Shublik Mountains. The succession is equivalent to the chief hydrocarbon-producing unit at the Prudhoe Bay field. In ANWR, the Ledge has been studied in varying detail by Keller and others (1961), Detterman and others (1975), Molenaar (1983), McMillen and Colvin (1983) and Crowder and Harun (in press). The Ledge Member in the Sadlerochit and Shublik Mountains region consists of 35 to 190 m of fine-grained quartzarenite with minor chert pebble conglomerate intervals. The Ledge Sandstone is internally composed of highly-variable lithofacies which record a range of shallow marine environments, described in detail in a subsequent paper. Our comments here describe predictable organizational patterns that recur across the Sadlerochit and Shublik Mountains that constrain the range of sediment dispersal environments.

The Ledge Sandstone rests abruptly on interbedded siltstone and quartzarenite beds of the Kavik Member and is the culmination of the general upsection coarsening and thickening of sandstone beds in the upper 50 percent of the Kavik Shale. The base of the member ranges from abrupt and erosional to gradational, and the unit thickens and fines toward the south and southwest.

With the exception of small scour-and-fill structures and minor channel-fill successions, the bulk of the Ledge Member in the Sadlerochit Mountains region is uniformly bedded. Relatively minor intervals of quartz and chert pebble conglomerate occur near the top of the succession at many localities. At various locations, the Ledge contains intervals characterized by tabular sets and cosets of trough and planar cross-stratification. Most of the member, however, is dominated by parallel laminae and low-angle inclined stratification. Bounding surfaces of individual beds are difficult to distinguish except where they are accentuated by thin clay or siltstone drapes or burrowed horizons less than 2 cm thick. Where these horizons are lacking, there is apparently little relation between bedding and original depositional events: many apparent "bedding planes" are parallel fracture surfaces unrelated to changes in depositional style or rate.

The only systematic change in internal organization is a persistent pattern of multiple upward thickening and coarsening, then thinning sequences developed within the Ledge Member across the Sadlerochit Mountains and along the eastern flank of the Shublik Mountains. These sequences become progressively thicker upsection and culminate in crudely-channelized conglomeratic sandstone in the upper 5 to 10 m of the Ledge Member.

Along the south flank of the Shublik Mountains the internal organization of the Ledge Sandstone is distinctly different from equivalent rocks to the north. Sandstone units within this region are separated by distinct shale or siltstone partings and bedding planes record distinct breaks in sedimentation. The beds contain a broader suite of sedimentary structures, including isolated deformed beds with ball and pillow and other soft-sediment load structures. The upper beds of the Ledge Member are more intensely bioturbated and some horizons contain distinct *Diplocraterian* sp. and *Arenicolites* sp.

Through most of the Sadlerochit and Shublik Mountains region, the Ledge Member is overlain with slight angular discordance by shale, siltstone, and quartzarenite of the Fire Creek Member. North of the Sadlerochit Mountains, the top of the Ledge Member is truncated by the Lower Cretaceous unconformity, which places the Lower Cretaceous Kemik Sandstone and Pebble Shale unit unconformably on Ledge Sandstone. Erosion along the unconformity surface has apparently removed the Kingak Shale, Karen Creek Sandstone, Shublik Formation, and Fire Members north of the Sadlerochit Mountain front.

Fire Creek Siltstone Member

The Fire Creek Member is not well-exposed in the Sadlerochit and Shublik Mountains, although its cuesta-forming topographic expression is readily mapped throughout the region

(Robinson and others, 1989). The unit is continuously exposed at its type locality along Fire Creek in the eastern Shublik Mountains. At this location, the Fire Creek member consists of interbedded very fine grained, light brown siltstone and silty shale and dark gray quartzarenite. The Fire Creek Member is 33 m thick at the type locality and ranges between 0 and 135 m thick elsewhere (Detterman and others, 1975).

Although clearly a component of the Ledge dispersal system, the internal organization of the Fire Creek Member differs significantly from the underlying siliciclastic succession. The lower 75 percent of the Fire Creek Member is composed of alternating beds of fine- to medium-grained quartzarenite and sandy siltstone, with rare shale interbeds. The quartzarenite beds characteristically contain soft-sediment deformational structures including ball and pillow, overturned and contorted stratification, flame structures, and dish and related dewatering features. Large-scale intraformational truncation surfaces and translational slumps are developed throughout the lower part of the Fire Creek Member.

The stratification style and internal organization of the Fire Creek changes abruptly in the upper 25 percent of the succession. Bedding is regular and lacks dewatering and slumping features. Trough cross-stratification and ripple laminae are abundant. Organic partings, consisting primarily of plant debris, increases upsection, accompanied by a marked increase in bioturbation in the upper 5 m of the member. The contact between the Fire Creek Member and the overlying Shublik Formation is abrupt and erosional, and is marked by a quartz and chert-pebble conglomerate bed ranging from less than 10 to 70 cm in thickness.

The major influx of terrigenous clastic sediment of the Kavik, Ledge, and Fire Creek Members of the Ivishak Formation are components of an extensive coastal plain dominated by deltaic and interdeltaic environments. In the Sadlerochit and Shublik Mountains region, the Ivishak Formation records primarily marine processes that dominated sediment dispersal in a largely interdeltaic system. The degree to which the terrigenous influx occurred was in response to tectonic uplift, erosional dissection into the Lisburne platform, and regional changes in strand-line position.

The contact between the Echooka Formation and Kavik Shale in the Sadlerochit and Shublik region is likely a depositional onlap surface recording continued rapid drowning of coastal environments. The symmetric pattern of upward thinning of quartzarenite beds in the lower Kavik and upward thickening in the upper Kavik record a reversal in environmental migration pattern. The lower cycle is a continuation of retrogradational patterns begun during Echooka time. The upper cycle records progradational terrigenous influx and construction of a depositional platform over which the Ledge Sandstone was dispersed.

The environments of Ledge Sandstone dispersal were dominated by marine processes throughout the Sadlerochit and Shublik Mountains. The dominance of plane-parallel laminae and low-angle inclined bedding suggest conditions of near continuous agitation and sediment reworking. Despite the large amount of sand recorded in the Ledge, the organization is largely aggradational. It is likely the Ledge preserves little record of its original dispersal environments and is largely the sedimentary overprint of a broad suite of shallow marine environments of sediment reworking. The Ledge in this region may thus record a balance between continued sea-level rise and a major influx of terrigenous sand.

The bulk of the Fire Creek Member is a record of retrograding environments in deepening waters, increasing distance from terrigenous sources, and a change toward an episodic, single-event depositional style. Abundant soft-sediment deformational features, translational slumps and numerous low-angle intraformational truncation surfaces indicate sediment dispersal occurred along a significant depositional slope. The upsection retrogradational pattern reverses itself near the top of the Fire Creek Member, where the succession records a rapid shallowing, culminating in subaerial erosion at the Fire Creek-Shublik boundary. The Fire Creek Siltstone is unconformably overlain by the Shublik Formation in northeastern Alaska.

Shublik Formation

The Shublik Formation is a distinctive unit composed of phosphatic and organic-rich bioclastic limestone and calcareous shale with minor quartzarenite and siltstone intervals of Middle to Late Triassic age. The Shublik rests with apparent angular discordance on the Sadlerochit Group throughout the northeast Brooks Range. The heterogeneous assemblage of rocks assigned to the Shublik Formation range from 80 to 150 m thick and have a consistent internal organization. The formation is of considerable economic interest because of its high phosphate content and organic-rich horizons, which are a possible source beds of Prudhoe Bay oil (Magoon and Bird, 1985). The composition and organization of the Shublik is significantly unlike sand-rich units of the Sadlerochit Group and records a major change in depositional style. The Shublik has been the subject of a number of stratigraphic and geochemical studies, particularly those of Tourtelot and Tailleur (1971), Detterman and others (1975), Seifert and others (1979), Magoon and Bird (1985), and Parrish (1987). Our studies have concentrated on the stratification style and organization of the formation.

The basal contact between the Shublik Formation and the Fire Creek Member of the Ivishak Formation is variable. At most locations, the contact is marked by quartz- and chert-pebble conglomerate, which is in turn overlain by thinly interbedded siltstone and silty sandstone. Minor relief is developed along the unconformity surface, ranging from 10 cm to 2 m. More rarely, the contact is a planar surface with thinly-bedded siltstone resting abruptly on irregularly-bedded quartzarenite of the Fire Creek Member. Significantly, the Shublik rests with pronounced angular discordance on metamorphic rocks of the Franklinian sequence at several localities in the Yukon Territory (Crowder and others, in preparation). These regional relations suggest the unconformity at the base of the Shublik Formation may have major tectonic significance and the potential to truncate the entire Ellesmerian sequence in some areas of the ANWR subsurface.

Four internal lithologic units have been recognized within the Shublik Formation. The lower unit is composed of organic-rich siltstone with thin (<2 cm) fine-grained quartzarenite beds. The sandstone layers are laterally continuous at outcrop scale and are often graded and internally plane-parallel to ripple laminated. The lower siltstone unit is abruptly overlain by bioclastic limestone containing minor glauconite and conspicuous phosphate nodules ranging from 1 to 3 cm in diameter. The phosphate mineralogy is described in detail by Tourtelot and Tailleur (1971) and Parrish (1987). The limestone contains extremely abundant shells of Halobia and Monotis. The bioclastic limestone beds are thinly stratified and laterally continuous, and are arranged in an upward-coarsening and thickening sequence. Bioclastic limestone units are abruptly overlain by organic-rich marl and black mudstone, which grades upsection into calcareous siltstone and very fine-grained sandstone at the top of the formation. The Shublik is abruptly overlain by highly bioturbated quartzarenite of the Karen Creek Sandstone.

Karen Creek Sandstone

The Karen Creek Sandstone rests abruptly with an irregular contact on the upper siltstone of the Shublik Formation. The Karen Creek is a highly bioturbated and poorly stratified succession of very fine-grained quartzarenite. Disseminated brachiopod fragments and phosphatized whole shells are common at many localities. The formation ranges from about 3 m thick along the Kavik River to 38 m near the Jago and Aichilik Rivers (Detterman and others, 1975). The geometry of the unit is apparently undulatory, with rapid, non-directional thickness changes.

The Shublik Formation and Karen Creek Sandstone apparently record an abrupt change from shallow marine depositional environments of the Ivishak Formation to shelf-dominated deposition. The shelf environments were apparently beneath the reworking depth of nearshore processes.

We believe the unconformity at the base of the Shublik Formation records a rapid downdropping of the basin floor that allowed deep marine sedimentation directly on the shallow marine or nonmarine deposits of the Sadlerochit Group. This would also explain the apparent lack of transitional facies between the Fire Creek Siltstone and Shublik Formation.

These relations suggest the basal Shublik unconformity may have tectonic significance and may be related to early stages in the rifting history of northeastern Alaska. The initial Shublik environment exhibits hemipelagic shelf sedimentation that was occasionally interrupted by minor density or turbidite flows.

Parrish (1987) argues that the regional geochemical environments required for deposition of Shublik sediment associations ranged from an oxygenated nearshore to anoxic offshore environments, and concludes that an upwelling zone marked by high biologic productivity existed in Mid- to Late Triassic time. We suggest that in the Sadlerochit and Shublik Mountains region this zone existed within a middle shelf environment influenced by geostrophic or storm relaxation flows, which transported sediment seaward to build the distinctive upward-coarsening organization of carbonate units of the Shublik Formation. The abrupt transition from Shublik to the Karen Creek Sandstone records both an influx of siliciclastic sediment, probably derived from local sources and a regional shallowing to inner shelf conditions. It also records a of high degree of bioturbation and sediment accumulation and reworking by geostrophic and related shelf current system.

Kingak Shale

The Kingak Shale, of Jurassic to Neocomian age, conformably overlies the Shublik Formation and the Karen Creek Sandstone in the southern Sadlerochit Mountains and throughout the Shublik Mountains. It has been removed by erosion beneath the Lower Cretaceous Unconformity (LCU) north of the Sadlerochit Mountains. Detterman and others (1975) estimate that the Kingak in Ignek Valley ranges between 45 and 365 m thick.

The Kingak consists of black and orange-brown-weathering, noncalcareous, soft clay-shale. Clay ironstone concretions to 15 cm in diameter are abundant throughout the unit. Iron-stained, very-fine-grained sandstone interbeds are also present. Open-space fractures contain quartz crystals to 1.5 cm long, abundant slickensides, and local brecciation are common.

Kemik Sandstone

In the Sadlerochit and Shublik Mountains area of northern ANWR, Detterman and others (1975) recognized only the Kemik and pebble shale members of the Kongakut Formation; the siltstone member of the Kongakut is not present and the clay shale member is not differentiated from the Kingak Shale.

The Kemik Sandstone of Early Cretaceous (Hauterivian) age crops out extensively in the Sadlerochit and Shublik Mountains. At its maximum thickness, the Kemik consists of about 30 meters of clean quartzose, very fine to fine-grained sandstone.

In ANWR the Kemik overlies a regional mid-Neocomian unconformity (LCU) that truncates progressively older beds to the north. On the north side of the eastern Sadlerochit Mountains, the LCU truncates the Lower Triassic Ivishak Formation. To the south the unconformity dies out, and the Kemik is apparently gradational with the Lower Cretaceous part of the Kingak Shale. Three contrasting Kemik facies have been recognized (Mull, 1987) The most significant facies is a laminated, cross-bedded sandstone facies that is widespread on the south side of the Sadlerochit Mountains and is interpreted as a barrier island complex (Mull, 1987 and Knock, 1987). Mull named this the Ignek Valley Member and it is a potential hydrocarbon reservoir in the subsurface north of the Sadlerochit Mountains. Development of the Ignek Valley Member barrier-island complex appears to have been primarily by a process of vertical accretion with no major lateral migration of the facies trends either landward or seaward. Decreasing size and abundance of distinctive white tripolitic-chert clasts in the sandstone suggest longshore drift from northeast to southwest along the barrier island complex. The chert clasts were probably derived from truncated Mississippian to Pennsylvanian Lisburne Group northeast of the Sadlerochit Mountains. A burrowed pebbly siltstone facies on the north side of the eastern Sadlerochit Mountains has been interpreted as a back barrier lagoonal deposit (Mull, 1987). This facies was named the Marsh Creek Member by Mull (1986). South of the barrier island deposits of the Ignek Valley Member, a silty and muddy facies represents offshore marine deposition. Mapping suggests that the barrier island sediments were deposited in a relatively narrow belt that trends about S 80° W through the Sadlerochit and Shublik Mountains area (Knock, 1987 and Mull, 1987). However, at Marsh Creek on the north side of the eastern Sadlerochit Mountains, the burrowed pebbly siltstone facies of the Marsh Creek Member is structurally overlain by imbricated sections of the Kingak Shale and the cross-bedded sandstone facies of the Ignek Valley Member. These beds were apparently displaced northwestward on a thrust fault (detachment?) within the Kingak Shale.

The Kemik Sandstone is correlated with several discontinuous sandstone bodies in northern Alaska, including the Put River Sandstone in the Prudhoe Bay oil field, the upper part of the Kuparuk River Formation in the Kuparuk oil field, the Cape Halkett sandstone (informal name) in the National Petroleum Reserve in Alaska, and a reported hydrocarbon productive sandstone and conglomerate interval in the subsurface of the Point Thompson area west of ANWR (Mull, 1987).

The Kemik Sandstone is conformably overlain by the pebble shale unit. The contact between the pebble shale unit and the three Kemik facies is sharp and it apparently does not interfinger. This contact appears to indicate a rapid marine transgression of the pebble shale over the Kemik.

The pebble shale unit consists of laminated black shale with a high organic content, and contains zones with scattered matrix-supported pebbles and cobbles that are composed dominantly of chert and quartzite. Many samples of the pebble shale unit also yield abundant well-rounded, frosted quartz grains. Originally described by Collins and Robinson (1967) in the subsurface near Barrow, 300 kilometers northwest of ANWR. The pebble shale unit is widely recognized both in the subsurface and in surface exposures of the northern Arctic Slope. It is not well exposed on the surface, but in most places in the subsurface its thickness is remarkably uniform, ranging from 70 to 100 meters thick (Molenaar, 1983; Mull, 1987).

Originally considered to be entirely Jurassic the top is now considered to be Early Cretaceous (Molenaar, 1983). The Kemik Sandstone, the overlying pebble shale unit, and underlying Kingak Shale are the uppermost rocks of the Ellesmerian sequence and were deposited at a significant point in the stratigraphic evolution of northern Alaska. During this time a previously relatively stable platform area to the north ceased to influence deposition and was abruptly truncated and transgressed by marine deposits. This abrupt change in sedimentation patterns was related to rifting of the Arctic Alaska plate (Mull, 1987).

The clean quartzose very fine-grained sandstone facies of the Kemik may have reservoir potential in the subsurface north of the Sadlerochit Mountains. It is both overlain and underlain by black shale with a high content of organic material. Because of its possible reservoir potential and close association with hydrocarbon source beds, it is considered a major objective for hydrocarbon exploration in the subsurface of ANWR.

BROOKIAN SEQUENCE

The Brookian Sequence was named by Lerand (1973) for Cretaceous and younger sedimentary rocks in Arctic Canada and northern Alaska that were derived from a southerly source. Molenaar and others (1987) subdivided the Brookian sequence in the Canning River region into three units: the Arctic Creek facies (Lower Jurassic to Albian), the Hue Shale (Albian to Campanian), and the Canning Formation (Campanian to Maastrictian). We have followed this subdivision and have further subdivided the Arctic Creek facies, here named the Arctic Creek Unit, into two informal lithostratigraphic units: Arctic Creek unit sandstone turbidites and Arctic Creek unit shale.

Detterman and others (1975) formally named the Kongakut Formation for an isolated section of Brookian and pre-Brookian strata in the Bathtub Ridge area located approximately 70 km southeast of the Shublik Mountains. We have not found this nomenclature suitable in the Sadlerochit and Shublik Mountains area, instead we have used the informal nomenclature of Camber and Mull (1987) developed for the Bathtub Ridge section.

Throughout most of northeastern Alaska rocks recognized as part of the Brookian depositional system can be organized into two groups, each corresponding to sedimentation into one of two contemporaneous, roughly east-west trending basins. Sediments deposited in the northern basin consist of non-marine and shallow marine clastic deposits, shelf turbidites and shale. These deposits formed by generally west to east progradation over the relatively stable portion of the old Ellesmerian platform and are generally less than 5000 m thick. The provenance area for these deposits is not well understood but is thought to be somewhere to the west, possibly near the present day Chukchi Sea; not the Brooks Range immediately to the south. The Brooks Range had little or no influence on sediment supply or sediment dispersal patterns within the northern basin until latest Cretaceous or earliest Tertiary time.

Sediments in the southern basin consist predominantly of deep marine turbidites and shale which locally interfinger with very proximal conglomeratic deposits and debris flows. The sedimentary sequence within the southern basin is greater than 5000 m thick and locally attains a thickness of over 12,000 m. Rocks of the southern basin were most likely derived from very local sources directly from the Brooks Range orogen.

A deep trough-like depression developed north of uplifting Brooks Range and provided an effective barrier to sediment transport and dispersal into the northern basin until latest Cretaceous time, when southern-sourced sediments overtopped the foredeep and overlapped onto northern-basin deposits. Despite non-communication between the northern and southern basins during their early development, sediments within these basins collectively form a mountainward-thickening sedimentary prism typical of foreland basins developed in front of fold and thrust belts worldwide.

Three important relationships exist that distinguish Brookian strata in ANWR from Brookian strata in the Prudhoe Bay region and farther west in NPRA. 1) in ANWR, rocks of the southern basin have been thrust northward into juxtaposition with rocks of the northern basin, 2) Upper Cretaceous and Tertiary deposits of the northern basin are significantly involved in the thrusting, and 3) in ANWR the Lower Cretaceous deposits of the northern basin are depositionally thinner, while Upper Cretaceous and Tertiary deposits are much thicker.

ROCKS OF THE NORTHERN BASIN

Hue Shale

The Hue Shale (Molenaar and others, 1987 [formerly the Shale Wall member of the Sea Bee Formation of the Colville Group]) conformably overlies the pebble shale unit (figure 10). The basal contact of the Hue Shale is placed at the lowest stratigraphic occurrence of bentonite. It is conformably overlain by turbidites of the Canning Formation. The Hue Shale is Aptian(?) to Campanian in age at the type section on Hue Creek in the north-central Shublik Mountains, where it is 222 meters thick. The unit consists of black, organic-rich, non-calcareous shale, clay shale and siltstone. Interbedded tuff and bentonite are common and weather to form brightly colored (orange and maroon), bare, low-relief hills. The unit is generally less than 300 meters thick at most outcrops in the region.

Canning Formation

The Canning Formation (Molenaar and others, 1987) in ANWR is a marine sequence consisting of dark-gray and black shale, dark bentonitic shale, siltstone, and gray to brown sandstones interpreted as deep(?) water, slope or basin plain turbidites (Vandergon and Crowder, 1987) of middle or outer fan facies association (Mutti and Ricci Lucchi, 1972). The Canning Formation may be as old as Santonian and as young Eocene based on palynomorphs (Vandergon and Crowder, 1986). Bouma intervals are variable, and show evidence of shallowing-upward depositional cycles. Sandstones of the Canning Formation are petrographically similar to the sandstone turbidite facies of the Arctic Creek Unit (Decker and others, 1987). The lower contact with the Hue Shale is located whenever possible at the lowest occurrence of sandstone or siltstone turbidites. Unit varies between 1200 and 1800 m thick west of the Canning River (Bird and Molenaar, 1987).

ROCKS OF THE SOUTHERN BASIN

Arctic Creek Unit

The Arctic Creek unit is poorly exposed in low relief hills between the Shublik Mountains and the Aichilik River and consists of a Jurassic to Albian age sedimentary succession of black shale (Jurassic and Early Cretaceous), manganiferous shale (Early Cretaceous) and deformed sandstone, siltstone, and shale turbidites interbedded with shale (Albian). Bentonite occurs locally but its volume and stratigraphic position are poorly known due to poor exposures. Bedding within the unit east and southeast of the Kekiktuk River (eastern Shublik Mountains) generally dips to the south and the section has been repeated along north-vergent faults (Robinson and others, 1989).

The Arctic Creek unit is similar to the sedimentary succession exposed at Bathtub Ridge, about 80 km southeast of the Sadlerochit and Shublik Mountains. It may represent a detached and northward-transported extension of the of the Bathtub depositional system that has been thrust northward into juxtaposition with the typical Ignek Valley strata (Decker and others, 1987).

The Arctic Creek unit is dissimilar to the typical Cretaceous section exposed in Ignek Valley however. The typical Ignek Valley sequence consists of Kingak Shale (Berriasian to Valanginian), Kemik Sandstone (Hauterivian), Pebble Shale unit (Neocomian), Hue Shale (Albian? to Campanian), and turbidites of the Canning Formation (Campanian to Pliocene). The two main differences which distinguish the Arctic Creek unit from the typical Ignek Valley sequence are: 1) the lack of the regionally persistent Kemik Sandstone in the Arctic Creek section, and 2) the lack of Albian turbidites in the typical Ignek Valley section.

Sandstone turbidites of the Arctic Creek unit are generally gray to brown, very fine- to medium-grained, thin- to very thick-bedded quartzose lithic sandstone and siltstone, interbedded with black shale. Bouma intervals are variable but generally contain well developed Tc intervals in turbidites thinner than 30 cm; thicker beds are dominated by Ta and Tab intervals. Amalgamated Tbcbc turbidites are common along the Hulahula River east of the Sadlerochit Mountains. Sandstone beds at the base of the turbidite section are up to 3 m thick and although poorly exposed, can be traced along strike for several kilometers. These beds coarsen and thicken upward from underlying siltstone turbidites and were probably deposited in a non-channelized outer-fan environment. Outer-fan facies deposits are overlain by laterally discontinuous thin- to medium-bedded turbidites interpreted as channelized middle-fan facies turbidites which contain weakly developed thinning and fining upward cycles. These middle-fan facies deposits are well exposed along the Hulahula River and less so along the Kekiktuk River, east of the Shublik Mountains. Sandstones of the middle-fan facies, contain varying proportions of quartz, white mica, and carbonate, with few rock fragments. Carbonate grains typically are prisms derived from Inoceramus or composite hexagonal plates that are echinoid fragments. Locally, carbonate grains constitute from 5 to 95 percent of the rock; they are commonly leached in the deeply weathered surface outcrops. Carbonate-rich beds tens of centimeters thick may have excellent secondary porosity potential in the subsurface. The stratigraphic thickness of the sandstone turbidite unit is uncertain because of several thrust faults and folds which repeat the section. A composite section generalized from several thrust sheets is about 2600 m thick.

Shale-dominated intervals within the Arctic Creek unit east of the Kekiktuk River includes the type locality of the Kingak Shale (Leffingwell, 1919). The lower part is black clay shale with red-weathering ironstone beds and nodules, and the upper part is blue-black shale with red-weathering ironstone beds that are more resistant than the underlying black shale. Thrust faults may be locallized within the shale-dominated horizons between the sandstone turbidite intervals. There may also be a fault between rocks of the Arctic Creek unit and the type Kingak Shale exposures at Kingak Bluffs. Shale beds with demonstrable stratigraphic continuity immediately below the sandstone turbidites are unfossiliferous and may be in part correlative with the pebble shale unit in Ignek Valley or the manganiferous shale at Bathtub Ridge. The stratigraphic thickness of the shale-dominated unit is uncertain.

SUMMARY AND INTERPRETATION OF THE BROOKIAN ROCKS IN THE SADLEROCHIT AND SHUBLIK MOUNTAINS

Two coeval but contrasting Brookian age stratigraphic sequences occur in the northern Arctic National Wildlife Refuge. These strata were probably deposited in separate basins that can be traced regionally to the west. Sediments in the Ignek Valley-Sadlerochit Mountains area were deposited within a northern basin while sediments in the Arctic Creek and Bathtub Ridge areas were deposited in a southern basin.

The three main differences which distinguish the Arctic Creek-Bathtub Ridge sequence from the Ignek Valley sequence are: 1) the lack of the regionally persistent Kemik Sandstone in the Arctic Creek-Bathtub Ridge sequence (although quartzose siltstone turbidites do occur at Bathtub Ridge at about the same chronostratigraphic level as the Kemik Sandstone), 2) the lack of manganiferous shale in the Ignek Valley sequence, and 3) the lack of Albian turbidites in the Ignek Valley sequence.

Our work suggests that the Arctic Creek and Bathtub Ridge sequences were once part of a continuous depositional basin, and that the Arctic Creek sequence has been thrust northward along a detachment surface within the Kingak Shale into juxtaposition with the Ignek Valley sequence. The contrasting lithofacies of the Arctic Creek-Bathtub Ridge sequence and the Ignek Valley sequence suggest that deposition took place in two separate basins or in distinct non-overlapping portions of the same basin.

In addition, it is likely that thrust faulting has displaced the Ignek Valley sequence northward into the Marsh Creek area on the north side of the eastern Sadlerochit Mountains. Thrust telescoping can account for the apparent absence of the Ignek Valley sequence along much of the Sadlerochit River valley south of the eastern Sadlerochit Mountains and for the juxtaposition of contrasting lithofacies of the Kemik in the Marsh Creek Area (Knock, 1987, Mull, 1987, and Robinson and others, 1989).

We also believe that the Paleocene fluvial and deltaic deposits of Sabbath Creek (Buckingham, 1987) are probably part of the Arctic Creek-Bathtub Ridge sequence, not the Ignek Valley sequence. The Sabbath Creek strata occur northeast of Arctic Creek and east of the Sadlerochit Mountains. Coeval deposits of the Ignek Valley sequence consist of Campanian to Paleocene turbidites of the Canning Formation. Paleocurrents from the Canning Formation suggest that the depositional basin deepened to the east and northeast in the direction of the non-marine and shallow marine deposits of Sabbath Creek. We speculate that the Sabbath Creek strata were thrust northward along with the Arctic Creek facies, probably during Eocene time.

Appendix C

Overview Of Glauconite: Its' Occurrence, Distribution, and Chemistry

Compiled by John Roe

This paper is a annotated compilation of references that deal with glauconite. Currently, the definitive work on glauconite has been done by Giles S. Odin and many if not all the current ideas on its genesis and geochemistry originate from him. Current researchers accept his work and present their results on that basis.

The paper consist of sections dealing with the origin and genesis of modern glauconite pellets, modern and historical occurrences, followed by important considerations of isotope studies and effects of heating and burial. I have included various examples that may be relevant to the study of North Slope glauconites.

Much of the following discussion in this paper is based on and/or has been freely excerpted from several key references. These are Numerical Dating in Stratigraphy (Odin ed., 1982), De Glauconiarum Origine (Odin and Matter, 1981), Green Marine Clays (Odin ed., 1988) and Clay Sedimentology (Chamley, 1989).

Introduction

Glauconites have attracted the attention of many geoscientist because of their widespread and problematic occurrences in sedimentary rocks, unusual chemical characteristics, and interesting origins. From the lack of analytical instruments before 1940, glauconite came to denote all types of greenish-colored grains or pellets and almost all greenish-colored pigments in sediments (Odom, 1984). Prior to 1978, compositional (Burst, 1958), mineralogical (Hower, 1961) and morphological (Burst, 1958) limits were attached to definitions of the glauconite.

In 1978 the AIPEA Nomenclature Committee (Bailey, 1980) made the following recommendation on the nomenclature of "glauconite" :

"Glauconite is defined as an Fe-rich dioctahedral mica with tetrahedral Al (or Fe^{3+}) usually greater than 0.2 atoms per formula unit and octahedral R^{3+} correspondingly greater than 1.2 atoms. A generalized formula is $K(R^{3+}_{1.33}R^{2+}_{0.67})(Si_{3.67}AlSi_{0.33})O_{10}(OH)_2$ with $Fe^{3+} >> Al$ and $Mg > Fe^{2+}$ (unless altered). Further characteristics of glauconite are d(060) > 1.510 Å and usually broader IR spectra than celadonite. The species glauconite is single-phase and ideally is non-interstratified. Mixtures containing an iron rich mica as a major component can be called glauconitic. Specimens with expandable layers can be described as randomly interstratified glauconite-smectite."

Note: mode of origin is not a criterion within the definition of glauconite.

Celadonite, a mica mineral formed during the alteration of volcanic basaltic rocks was thought to form a continuous isomorphous replacement series (Foster, 1969). But, on further investigation it was determined Celadonite is a separate mineral specie from glauconite (although the difference is somewhat minor). The primary difference between celadonite and glauconite is the chemical composition of celadonite's 2:1 layer.

There has always been confusion over use of the term glauconite; it has been used as a chemical, compositional, and morphological designation. To add to the confusion Odin and Matter (1981) proposed the term glauconite be abandoned and introduced the term "glaucony" (plural glauconies) as a facies name to designate all green pellets and glauconitic as a term to describe mineralogy. Supporting Odin and Matter, Clauer (1982) defined clay and glaucony in terms used by sedimentologist to describe facies. Most European researchers have followed the lead of Odin while most references by North American authors use glauconite in a more generic sense. Clauer (1982) reflects this when he states:

"The term *glauconite* is also ambiguous in the sense used by many English-speaking authors to describe *all* the iron rich micaceous clay mineral occurring as green pellets in sediments." (italics authors)

Add to this, the term "verdissement" introduced by G. S. Odin (1981) to describe the process of greening of substrates and the whole issue becomes very muddled. Unfortunately, many references used in the preparation of this paper do not state in what manner they use the term glauconite and they often omit critical chemical data as to the composition of that material, therefore we have maintained their usage in conveying their results and interpretations.

Identification

Illite is the most abundant sedimentary mineral of the mica group; it is also the most common clay mineral (Clauer, 1982). It has a basic recticular distance (001) of 10Å which has a characteristic thickness of the elementary unit composed by a primary Al octahedral layer surrounded by two Si-Al tetrahedral layers. These layers are held together, ordinarily, by K ions at interlayer site (figure 11). Illites show no evidence of interstratification but nevertheless contain less K and more H_2O^+ than true micas (Newman and Brown, 1987).

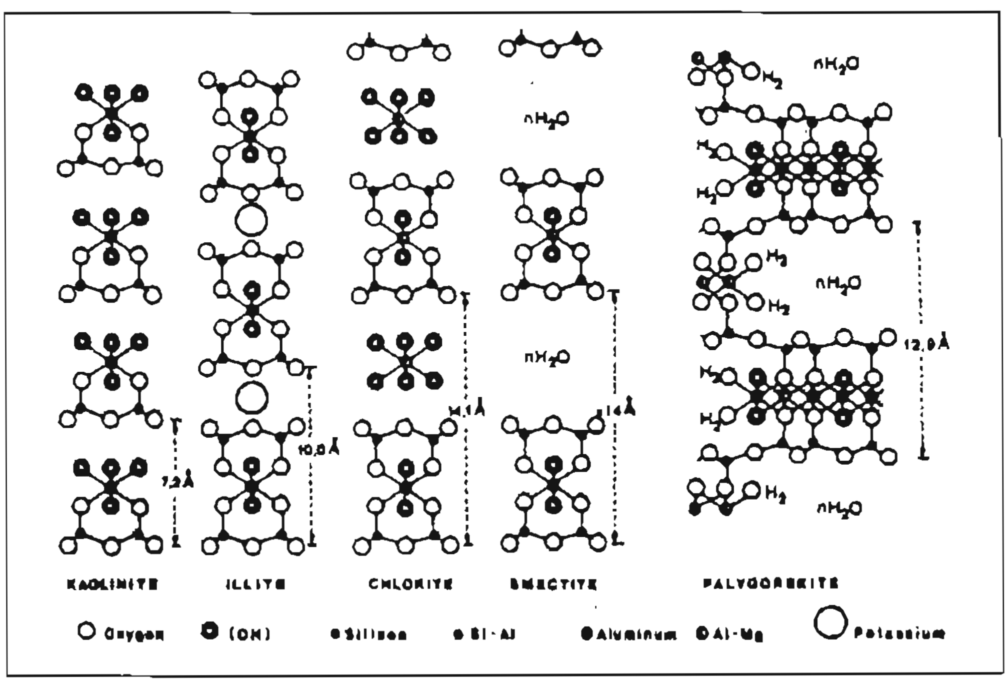

Figure 11. Schematic presentation of the structure of clay minerals, (Odin, 1982)

Thompson and Hower (1975) showed that glauconite is structurally similar to illite and likewise contains less K and more H_2O^+ than micas but glauconite differs from illite by containing more Fe. Clauer (1982) maintains that within the crystal lattice as Fe becomes more abundant than Al in the octahedral positions, the mineral is a glauconite 's.s.' or a glauconitic mica. According to Velde and Odin (1975) there is no mineralogical and/or chemical continuity between glauconite and illite. Chamley (1989) classifies glauconite or glauconitic mica as an iron- and potassium- rich 10 Å illite. Characteristics of evolved glaucony include; Fe_2O_3>20% and K_2O>4%.

Moore and Reynolds (1989) have shown that X-Ray Diffraction (XRD) are unique and easily distinguished from other clay minerals. XRD patterns of both illites and glauconite are unaffected by ethylene glycol solvation and heating to 550°C. Glauconite has a higher 001/003 intensity ratio than illite, but the main difference is the very weak or nonexistent glauconite 002 (5 Å) reflection (figure 12).

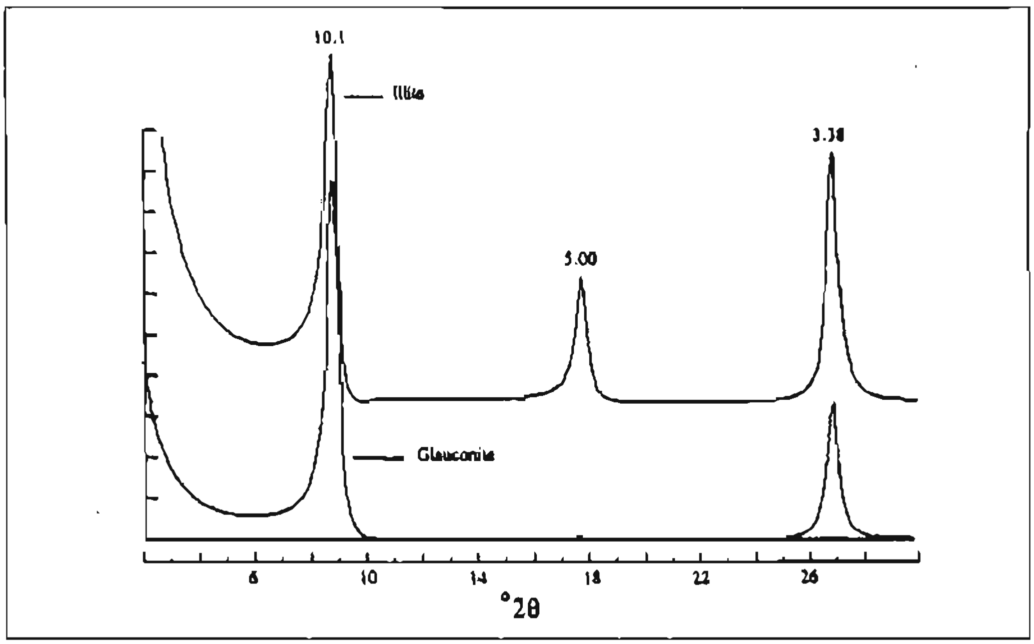

Figure 12. XRD patterns for illite and glauconite (Moore and Reynolds, 1989).

Occurrence

Glauconitic peloids occur throughout the geologic record. They have been recognized in rocks of Precambrain age. Two major episodes of glauconite development occurred during Phanerozoic time, first in the early Paleozoic and a second episode in middle-late Mesozoic time (figure 13). Both of these episodes were characterized by climates dominated by temperate to warm conditions, widespread sea-level rise and transgression of cratons, dispersed cratonic blocks and open ocean gateways, and frequent decreased influx of terrigenous sediment. After the breakup of the Precambian supercontinent about 600 million years ago, the Cambrian transgression on large Laurasian cratonic blocks controlled the distribution of widespread glauconite deposits. Glauconitic deposition reached a maximum at 250 million years ago, especially along continental margins of the opening Atlantic ocean basin. Abundant glauconitic greensand development continued until the middle Cenozoic (Chamley, 1989). There is general agreement that most glaucony granules were deposited in rather shallow-water seas, with low terrigenous clastic sediment input, and under fairly warm humid climates. Most glaucony green sand deposits developed in open ocean areas along stable platform margins or on high oceanic platforms, and in shallow to deeper offshore depositional environments. In general ancient glaucony granules accumulated in more varied environments than modern ones (Chamley, 1989). Ancient depositional facies range from intertidal and subtidal inner shelf environments to deep water offshore environ; including carbonate shelves (Van Houten and Puruker, 1984) and even in mixing zones between freshwater and saline water (Whiteside and Robinson, 1983).

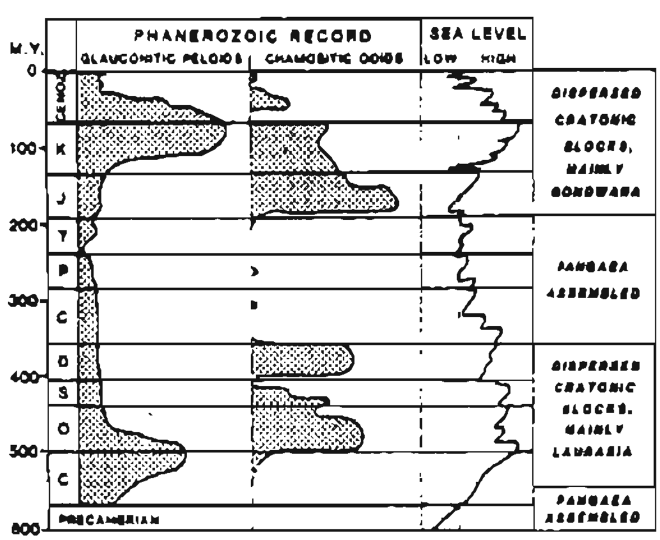

Figure 13. Phanerozoic history of glauconitic peloids and chamositic ooids (Van Houten and Purucker, 1984).

The majority of Recent glauconite formation seems to be limited to low latitudes (figure 14) although, there are scattered occurrences at higher latitudes (Odin and Fullagar, 1988). These occurrences at higher latitudes appear to be relicts from Quaternary or Holocene time indicating periods of climatic change. Recent glauconite deposits also seem to be concentrated where the reworking by currents and burrowing by organism are minor.

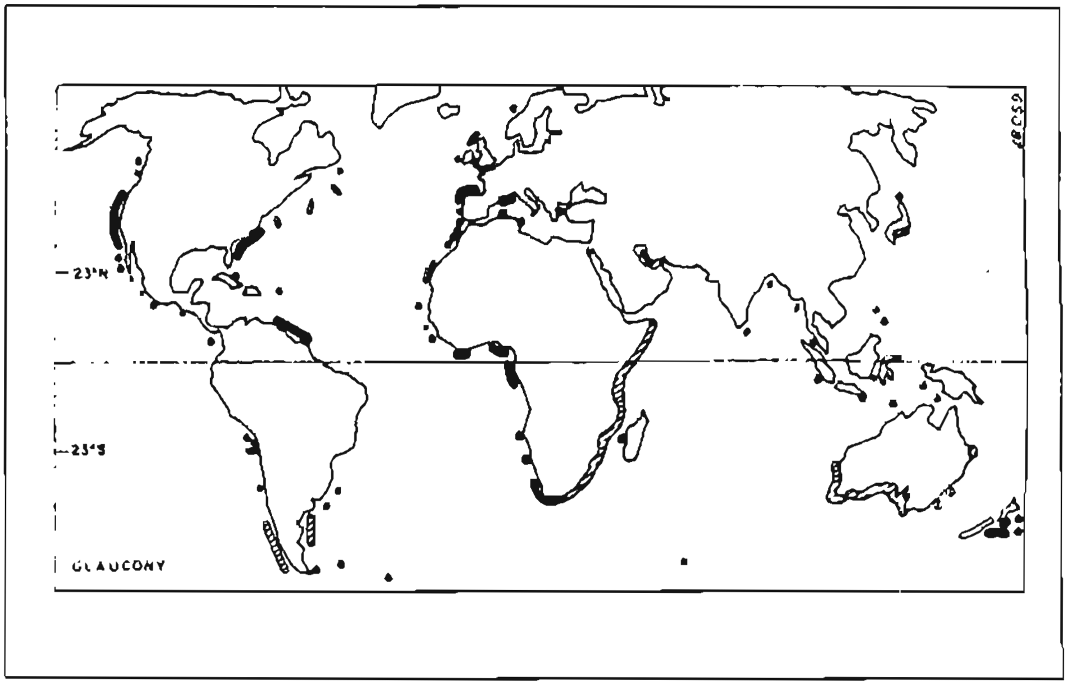

Figure 14. Distribution of glaucony in the surface sediments of the worlds ocean (Odin, 1988). Hatched areas are without detailed mineralogical data.

Origin

Historically, three mechanism have been invoked in explaining the genesis of glaucony grains. The layer lattice theory (Burst, 1958, and Hower, 1961), the epigenic substitution theory (Ehlmann and others, 1963), and the currently popular precipitation-dissolution-recrystalliation theory (Odin and Matter, 1981; and Ireland and others, 1983). The first two theories are not widely accepted in the current literature, they will not be discussed in detail but an brief overview will be presented.

The layer lattice theory was widely accepted in the sixties (see Millot, 1964, 1970) and was suggested for the evolution of many clay minerals. However, based on modern observations and techniques it is no longer considered viable. This model purposes that authigenic green clays results from the transformation of any degraded layered silicate, and that the authigenic mineral retains a memory of past structure. According to this model, a pre-condition for glauconitization is that a mineral with similar crystal structure to glauconitic minerals such as illite and smectite must be present (Hower, 1961).

Based on their own observations of glauconitization of Recent material, Odin and Matter (1981) dispute Hower's (1961) and Burst (1958) theory. They listed seven observations which are incompatible with that theory, five are listed here: (1) The greening of mica sheets takes place between mica sheets not in place of them, and therefore does not require the initial framework or ions of 10 Å layered minerals. (2) Greening often develops on calcareous substrates (shells) devoid of any clay minerals. (3) Similarly, most glauconized hardgrounds in ancient formations are on limestones or chalk. (4) A given type of substrate may give way to either glaucony or verdine as in the Gulf of Guinea, both types of green grains are characterized by very different authigenic clays. (5) Most glauconization processes clearly show a break in iron enrichment, which suggest a dissolution-recrystallization instead of a progressive transformation of a 2:1 clay.

The epigenic theory of origin has not been addressed extensively in the literature and is similar to the precipitation-dissolution-recrystallization of Odin and Matter (1981) in that it supposes neoformation processes similar to those implied by the precipitation-dissolution-recrystallization (Ehlmann and others, 1963).

The currently popular precipitation-dissolution-recrystallization theory of Odin and Matter (1981) explains the formation of authigenic clay minerals in stages and is directly influenced by the material providing a platform for mineral growth. All of these factors are directly affected by the local environment.

Glauconization of fecal pellets on the upper margin of the Gulf of Guinea provides a good example of the actual process of glauconitization, since different stages of evolution are recognized on grains that have not under gone burial (Odin, 1988).

The evolution of fecal pellets, in the Gulf of Guinea, through glauconitization is described by Odin (1988) as a three stage process (figure 15). (1) The initial fecal pellet consist of gray mud rich in detrital kaolinite, with minor amounts of other terrigenous clay minerals, biogenic carbonate shells and debris, and quartz grains. The mineral and chemical composition of the fecal pellet is identical to that of the sediment matrix. (2) Some pellets turn into ochre to light-green grains, and show dissolution of fine grained calcareous particles and the first appearance of Fe- rich smectite. Kaolinite and quartz are also present. The organic carbon within the fecal pellet tends to decrease relative to the surrounding sediment, which suggest intense microbial activity (Chamley, 1988). Porosity within the pellet is produced by the dissolution of carbonate grains. Silt- and clay-sized carbonates are replaced by authigenic Fe-clays (smectites), that constitute small globules, often arranged in caterpillar-like structures . Light-green granules contain much more iron and somewhat more potassium than gray pellets, and much less aluminum (Odin, 1988). A third stage of development is comprised of dark-green grains.

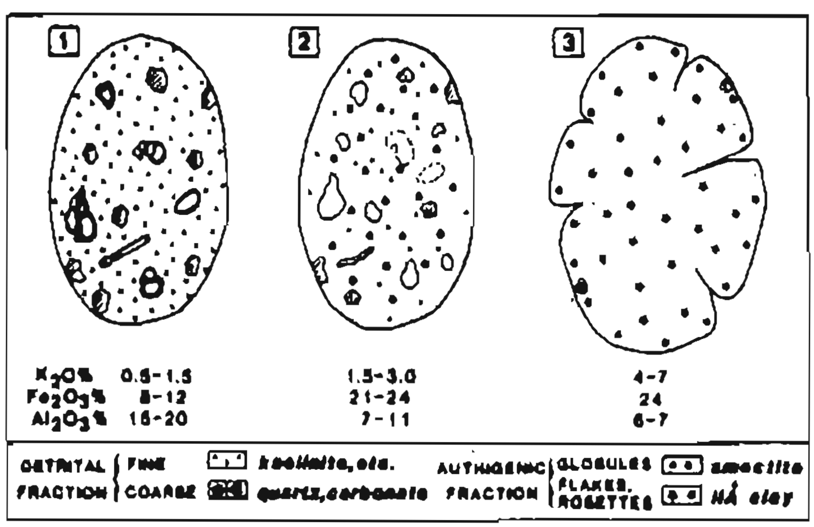

Figure 15. Evolution of fecal pellets in the Gulf of Guinea margin through glauconization. Chemical data through microanalyses (Odin, 1988).

The internal zone of each grain contains pellets consist of rosette-of flakes-like microcrystals made of 11 Å glauconitic minerals strongly enriched in potassium. Most terrigenous particles have been replaced by this stage of development, with the exception of some kaolinite sheets in the outermost zone and a few grains of quartz. With the development of glauconite minerals, there is a significant decrease in porosity within the developing grain.

These stages of evolution have been developed from detailed studies on various continental margins (Odin, 1988; Odin and Lamboy, 1988; Odin and Frohlich, 1988). In nearly all cases investigated, initial grains experience a dissolution of biogenic and terrigenous materials, a precipitation of Fe-smectitic clay, and a recrystallization of poorly ordered Fe- and K-glauconitic illite associated with increased volume. The degree to which glauconite has matured is in any given setting is reflected in a inverse relationship between weight percent potassium and the proportion of expandable clay layers (Hurley et al., 1960).

Length of Genesis - Time And The Glauconization Process

Based on detail studies evidence of a complete sedimentary succession in the Paris basin, Odin and Dodson (1982) estimated that the time represented by the formation of a nascent (immature) glaucony would require between 10^3-10^4 years of close contact (active ion exchange) between seawater and evolving glauconite grains, while a highly-evolved (mature) glaucony would require 10^5-10^6 years of seawater exchange for their evolution. Chamley (1988) lowered the estimates by an order of magnitude and emphasizes that very small micas scattered within fecal pellets may undergo potassium and iron enrichment within a few years.

Increases in maturity (glauconization) can also be recognized in Recent glauconites; K_2O content increases with depth of burial during the initial development stages. Highly evolved glauconies have spent more time near the seawater-sediment interface then there less mature counterparts. Odin and Dodson (1982) and Chamley (1988) agree that the process of glauconization of a substrate is not instantaneous, even on the scale of geological time.

Microenviorment

The microenviroment present during glaucony genesis is confined and chemically concentrated. Open-marine conditions generally do not chemically modify terrigenous materials, therefore a restricted microenviroment of some type is necessary to accommodate the cations necessary for the glauconization process; and for the fractional and volume increase of green granules and the chemical exchanges that take place during the growth of green layer silicates. Evidence that suggest a confined environment enhances the glauconization process include: 1) the development of greening inside microtests and not outside, 2) the absence of greening on too small unconfined grains, and 3) the darker greening increased maturity in the central zone of grains compared to their periphery.

Confined conditions necessary for chemical exchanges and glauconization must not be too confining, since greening does not develop in a too closed chemical system (e.g. buried substrates or central part of large substrates), because recharge and a renewal of ions is necessary for granule growth. The semi-permeable wall of tests (i.e. shell material) create a near perfect climate to provide a semi-confined condition (Odin and Matter, 1981).

A microenviroment developed near the interphase between reducing and oxidizing conditions and in close proximity to the sediment-sea water interface is also important to the glauconization process. Harder (1980) stresses the importance of silica availability in controlling the formation of either 7 Å or 10 Å green clays. Ions are mainly provided by exchange with sea water as demonstrated by the stopping of the glauconization process after the grains are buried. There is evidence that underlying sediments contributes ions during the greening process. Iron tends to be mobilized by reducing conditions at depth and migrates upwards and is re-precipitated as ferric oxides (Ireland and others, 1983). Grain movement by bioturbation and or bottom currents may provide a mechanism to explain how all faces of a grain that is being glauconized, are able to incorporate ions (Chamley, 1989).

Habits

Glauconite occurs throughout the geologic record in some granular fashion. Because the formation of glaucony or glauconite peloids occurs predominantly on a substrate is itself granular. Ancient glauconite occurs almost exclusively as pellets which are believed to be fecal in origin due to their resemblance to modern fecal pellets. In Recent glauconite grains it is often possible to identify their origin because their maintained their original morphology.

Odin and Matter (1982) have identified four different granular "platforms" in or on which glauconite can form.

Internal Molds

Internal molds are probably the most common habit for the occurrence of modern green clay material. The vast majority of internal molds are from calcareous microfossils (Odin, 1988). These substrates are predominant on the deepest part of the present continental shelves of Morocco, Norway, southeastern United States, and Makassar Strait, Borneo. In these sediments, (Odin, 1988) foraminifera are the most common fossils but ostracods, and small molluscs or bryozoans are also present (Odin and Fullagar, 1988). Conversely, internal molds of siliceous microfossils test seem to characterized high latitudes or submarine highs. The chambers of these test are comparatively large voids, and the question arises as to whether or not green authigenic clay directly fills these voids or replaces a clay-size material which previously filled chambers.

Fecal pellets

Fecal pellets form the predominant substrate for glauconitization in many Recent sediments (Odin, 1988). Mud grains of similar shape have also been noted and it is not clear if these mud grains formed by a strictly physical process, or the product of biogenic activity (Odin and Fullagar, 1988). Pryor (1975) reported that considerable amounts (4.5 mm per year) of fecal pellets can be produced by mud-eaters or filter feeding organisms. These organisms occupy a wide range of water depths in the shallowest part of the continental shelf and sometimes at more than 100 meters depth.

Fecal pellets change their color, form and size morphology with increasing water depth (Pryor, 1975). With increasing depth they change in color, form, and size. As depth increases so does their size and they lose their form due the development of cracks. Variations in grain size as a function of depth manifest themselves in many ways; shallow green grains are smooth and 250 μm to 400 μm in diameter, grains developed are cracked and dark green and may reach 1 mm in diameter. Also the internal structure of individual grains evolves from a heterogeneous and pore rich to a dense homogeneous pellet in the oldest and deepest sediments. The pores are present in the early stages of evolution due to the dissolving of remnant carbonate grains.

A modern example from the upper continental margin of the Gulf of French Guiana show the distribution of glauconized fecal pellets (figure 16) with respect to other substrates (Odin, 1988). The mineralogy may be restricted to bands parallel to the coast based on the settling velocity of grains of equal size (Pryor, 1975).

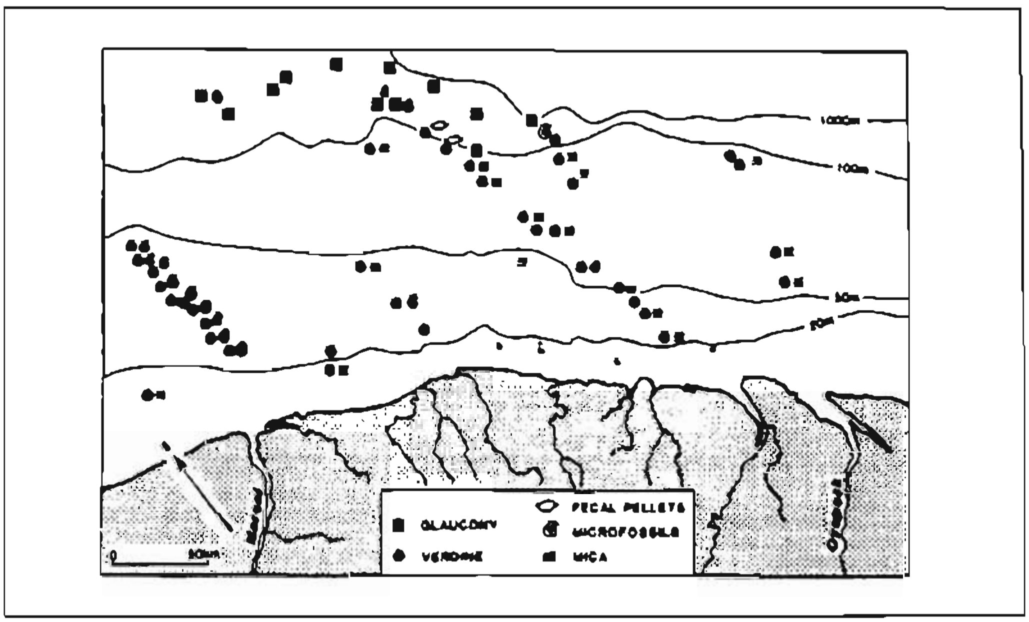

Figure 15 Bathymetric distribution and nature of green clay granules from the continental margin of French Guiana (Odin, 1988)

Stages of Glauconitization of Fecal Pellets

Odin and Matter (1981) and Odin (1982) consider the mechanism of glauconitization of pellets as consisting of four successive stages at the sediment-water interface. (Figure 17)

1. The <u>nascent</u> stage corresponds to the first development of iron rich glauconitic minerals (mostly Fe-smectite) at the expense of detrital material. The K_2O content ranges between 2 and 4%, while detrital clays usually contain no more than 1.5% K_2O. This first stage is strongly dependent on porosity (pores on the order of 5-10 μm) that allows ion migration and chemical reactions. These first crystals grow as blade forms on edge and

perpendicular to the surface of the substrate. They commonly develop a boxwork-like fabric by coalescing.

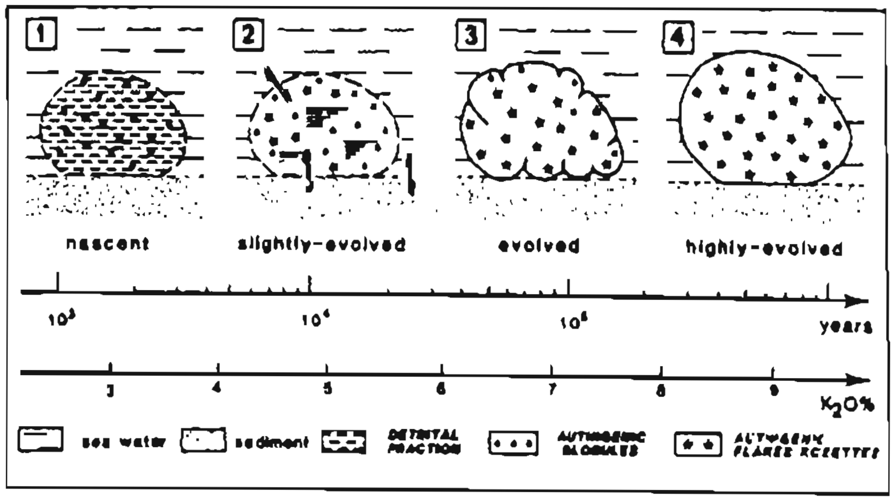

Figure 17. Successive glauconitization stages (Odin, 1988).

2. The slightly evolved stage is characterized by the near disappearance of detrital material and presence of inferred pores that are progressively filled with authigenic clays that contain between 4 and 6% K_2O. Iron is still abundant as in the nascent stage; it most likely results from the Fe^{2+} mobilized at depth within the reducing sediments, migrating upwards close to the more oxidizing sea-water interface (Ireland and others, 1983). Glauconitic clays usually consist of poorly crystallized 11-12 Å minerals arranged in globular, caterpillar-like or blade like particles. During this stage, Fe-smectite is altered and replaced by glauconitic minerals strongly enriched in potassium and iron. Electron-microscope and microchemical observations made by Parron and Amouric (1987) suggest that glauconite mica could result either from a siliceous gel incorporating Fe and K after destabilization of a Fe-montmorillonite, or from a ferriferous gel incorporating Si and K after destabilization of a nontronite.

3. The evolved stage results from a series of successive recrystallization events that obliterate the initial structure. The original shape of substrates progressively disappears.

Clay minerals present during this stage exhibit X-ray diffraction peaks close to 10 Å. The clay growth occurs preferentially and more rapidly in the central zone of the grains, which results in a volume increase in the core area of the individual grains. The increase core volume results in the formation of cracks in the outer zone (Chamley, 1989). K_2O content at this stage of development ranges between 6 and 8%.

4. The highly evolved stage corresponds to the filling of cracks within the individual grains with authigenic minerals. This infilling results in the development smooth grains. K_2O content exceeds 8% at this stage. Clays consist of poorly crystallized glauconitic minerals that do not evolve significantly if the green granules remain at the sediment-sea water interface. A crystal reorganization and ordering of glauconitic minerals may occur after burial and during early diagenesis (Odin, 1988). The development of well-ordered structures probably explains why there are differences between glauconite granules on the modern sea floor and those that formed during the Quaternary and those from many ancient glaucony deposits. The ancient glauconite pellets consist of almost pure, better-crystallized glauconite minerals. The environmental conditions of glaucony ordering after burying are still poorly understood (Chamley, 1988). If glaucony grains are not buried they may remain stable and constitute relict materials or the may evolve toward goethite or phosphatizied glaucony (Lamboy, 1976). Geothization of glaucony occurs in extremely oxidizing conditions, which are commonly associated with a sea level drop (regression). Phosphatization of glaucony occurs in a reducing environment, and often correlates with transgressive conditions (Chamley, 1989).

Carbonate and Silicate Bioclast Substratum

These substrates were long considered of little importance in the glauconitization process (Odin and Matter, 1981). Their significance was first demonstrated by Lamboy (1968) off northwestern Spain where glauconite development on this substrate predominates over all other substrates.

Carbonate or silicate bioclastic material appear to be glauconized by two different mechanisms. Green authigenic clays may fill voids: either natural pores or pores created by biogenic or chemical alteration (Odin, 1982). This filling process is generally similar to that observed in microfaunal chambers. Green clays may replace also the carbonate or silicate substrate often preserving the initial structure at the microcrystal scale. This process is similar to pseudomorphism.

Mineral Grains And Film Habits

Irrespective of their chemical composition, a wide range of mineral grains are susceptible to glauconitization. Glauconized quartz, silica, chert, feldspar, mica (white or black), calcite, dolomite, phosphate, volcanic glass, and diverse rock fragments have all been described (Odin and Fullagar, 1988).

Morton and Long (1984) analyzed two different glauconite habits on a single glauconite pellet. Their microprobe analysis clearly shows that there is a difference in the relative purity of the glauconite in the corona and the contrasting interior They think that the difference in chemistry of the corona can be explained by some type of accretionary process since glauconite is not likely evolved directly from apatite core rich material. Therefore they believe that the glauconization process is an evolutionary process with successive development of glauconite, whose chemistry is the product of diagenetic environment.

Two dominate varieties of glauconitic film habits have been observed in nature. A green film is often present on large carbonate bioclasts such as mollusk shells and occasionally on rock boulders or synsedimentary nodules. The second variety of glaucony facies occurs as extensive zones of glauconization, where the entire substrate has undergone glauconization (Odin, 1988).

Geologic Significance

Water depth plays a dominate role in controlling the suitability of different types of substrates for glauconitization. On the Western African margin, for example, planktonic foraminifera test that form dominant substrate preferentially evolve toward glaucony only on the upper continental slope and outer shelf in water depths ranging from 65 to 500 meters. During a eustatic transgression, successively landward substrates may be glauconized which provides a good indication of the modalities of sea-level change (Odin, 1988). Another indication that a transgression may have occurred may be evidenced in a given section by the landward occurrence of younger glaucony granules successively developed from planktonic test, benthic bioclasts, fecal pellets, mineral and rock grains and coastal shell bioclasts (Figure 18). The presence of glauconized coastal shell bioclasts indicates major transgression in the absence of subsequent reworking, while the dominant glauconized planktonic substrates suggest rather sea-level stability or even a regression. Glaucony deposits frequently correlate with transgressive sequences in the geologic record (Chamley, 1988). Transgressive conditions are not required to account for massive glauconization. However, they may explain extensive greening in the shallower substrates that are successively available as sea level rises.

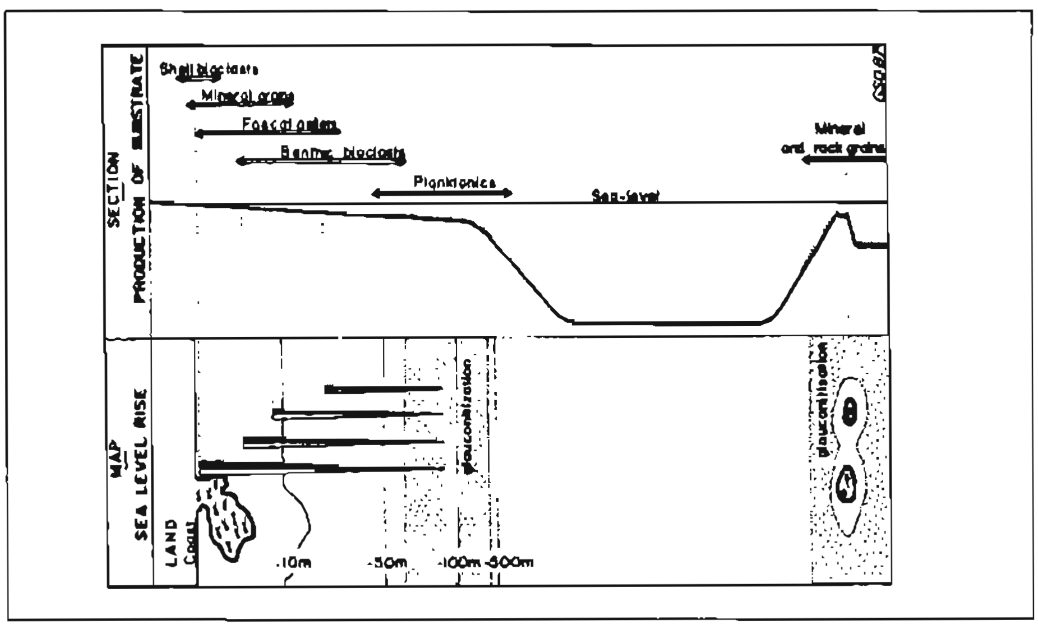

Figure 18. *Distance between the zone of production of substrates and zone of glauconization. The larger the distance the larger the transgression needed before glauconization is possible.*

Ancient vs. Modern Glauconitization

The mineralogy and geochemistry of Fe-granule clays differs notable in recent and ancient deposits. Late Cenozoic glaucony peloids contain poorly crystallized glauconitic minerals marked by broad X-ray refractions between 10 and 11 Å. By contrast, much pre-Cenozoic glaucony, characteristic of greensands and sandstones, contain true glauconite with a well defined 10 Å peak. Often not stressed in the literature, this difference implies specific geochemical conditions of depositions for both modern and ancient glaucony, or a crystal ordering after burial through diagenesis and aging. Chamley (1988) believes that diagenesis plays a dominant role because the crystalline arrangement does not usually correlate with appreciable chemical modifications but rather structural rearrangement. However, Louail (1984) noticed, that in Late Cretaceous-age sediments of Western France, the existence of a stage intermediate between terrigenous clays and authigenic glauconite, marked by the development of lathed Fe-smectite. This intermediate stage seems to indicate the possibility of chemical evolution. This question remains open, since lathed Fe and Al-Fe smectites occur in both glauconitic and non glauconitic marine environments during the late Phanerozoic times (Chamley, 1988). It is also important to note that some recrystallization of ancient glaucony granules may occur if greensand deposits are elevated above sea level and exposed to meteoric waters (Morton and Long, 1984). Such a recrystallization may induce a modification of isotopic compositions and may offer an opportunity to date sea-level changes.

Radiogenic Isotopes

Dating of glauconite by Rb-Sr and K-Ar methods has yielded sporadic results. Age determinations in general tend to be discordnant usually younger than statigraphic ages. These differences have been explained by a variety of mechanisms including; thermal and chemical alteration of the glauconite. Some glauconites have yielded radiometric ages older than their stratigraphic ages. These differences have been attributed to inherited radiogenic Sr and Ar.

Most isotopic studies have been conducted on the granular type of glauconite either because it occurs in a geologically significant local or they are easy to identify. It is important to understand that even these granular types (fecal pellets, infillings, and detrital minerals) will inherit some amount of the radiogenic isotopes if they are not completely replaced. As the radiogenic isotopes of the substrate become incorporated in the growing glauconite minerals, these new mineral phases require sufficient time for complete equilibrium with the environment in which they develop. Glauconization occurs at the sea-sediment interface, where the temperature is low, 5-15°C, reactions are rather slow and equilibrium will only be attained gradually. If the initial substrate is itself neutral or in equilibrium with the seawater with respect to the isotope used, theoretically no inheritance occurs (Odin, 1982).

Ar data as a function of K_2O content

Odin and Dodson (1982) demonstrated a relationship between argon and potassium content in modern glauconitic fecal pellets. Six glaucony fractions were chosen representing various steps of evolution from nascent to evolved. Based on their morphology, all samples apparently were fecal pellets. The grains were clearly glauconized; they are paramagnetic and green in color, their X-ray diffractograms are dominated by 10 Å glauconitic minerals.

Odin and Dodson (1982) feel they were probably formed by crystal growth from pore fluids. Genesis of the less evolved grains, found from at the shallowest depth, cannot have begun more than 18,000 years ago. This assumption is based on the correlation of popular relationship between depth of formation and maturity with sea level changes over the last 24,000 years (Odin and Dodson, 1982).

Despite their recent age, all green grains contain significant amounts of radiogenic argon (Table 8). This argon must have come from the substrates themselves because analyses reveal only quartz and traces of kaolinite within the green grain (Odin and Dodson, 1982). This example indicates a general trend in the chemistry of Recent glauconites; the more mature the grain and higher the potassium content the less amount of inherited argon present. This example also brings to light the question of when does initial closure take place and what is the initial isotopic argon ratio?

Odin and Dodson (1982) investigated the *potassium content/inherited argon* relationship in the Tertiary of west Texas. Middle Eocene glauconies from the Weches formation (Texas) were analyzed and found to contain radiogenic argon contents that decreased systematically with increasing K_2O (figure. 19). They concluded, that radiogenic argon is inherited from the initial substrate, and this inheritance decreases as the potassium content of the glaucony increases.

	Sample Number	K%	%^{40}Ar	^{40}Ar nl/g	Apparent Age
fine fraction	A593	1.70	82.3	29.6±0.37	473±26
	A593	1.55	87.6	29.93±0.47	517±28
	A594	1.58	53.9	30.4±0.6	516±28
Grains	G313	3.00	74	15.12±0.4	149±11
	G490	4.25	45.6	7.12±0.30	50.3±4.5
	G319	6 60	31.9	2.64±0.17	12.3±1.2

Table 8 *Results of isotopic analysis on fine fractions and recently glauconitized fecal pellets from the Gulf of Guinea. All clays are dominantly kaolinite. For the green paramagnetic grains the apparent age diminishes when the potassium content increases, but zero age is never reached. The genesis begin less than 10^6 years ago (Odin and Dodson, 1982).*

Another example of radiogenic argon inheritance linked to the early stage evolution of glaucony is found in Adams (1975). Table 8 above, contains the results of isotopic analysis of samples from Early Miocene nascent to slightly evolved glauconies. The inferred process is the glauconization of inherited chlorite. The chlorite may have been derived from a mid-Cretaceous biotite tuff or from the underlying schist which have yielded conventional K-Ar ages of 120-140 Ma. While a sample with 3.9% K (R3011) yielded the youngest age, it is the oldest stratigraphically, and although the sample is not deeply buried it seems to have lost argon. Another interesting observation is the stratigraphically younger samples yield the older ages. It is possible that this provenance of the younger sediments includes older stratigraphic units and that older isotopic ages reflect inheritances of Ar from older sources.

Sample Number	K%	Ar,nl/g% ^{40}Ar	Age Million years	Depth (meters)
2.04	6.11	61.1	73.8±1.0	11.75-12.5
R3007	1.52	6.45	70.31±1.4	39.5-40.5
R3008	2.97	3.40	22.13±0.4	84-85
R3009	4.29	3.42	28.22±0.3	100.5-101.5
R3010	4.61	3.56	38.72±0.3	175-176
R3011	3.86	1.866	51.11±0.2	186-186.5

Table 9. *Results of isotopic analysis on glauconite from a drill hole near Oamaru, New Zealand, showing the process of glauconization of a chlorite possibly derived from the underlying Mid-Cretacous schist or tuffs (Adams, 1975).*

Another example of the relationship of the potassium content and apparent K-Ar age is given in Kreuzer and others, (1973). Here, Late Eocene to Miocene glauconitic marls and limestones were analyzed. They showed, the isotopic ages that decrease with increasing potassium content. This may indicate that with increasing maturity the older substrates are more and more recrystallized and contain less and less radiogenic Ar.

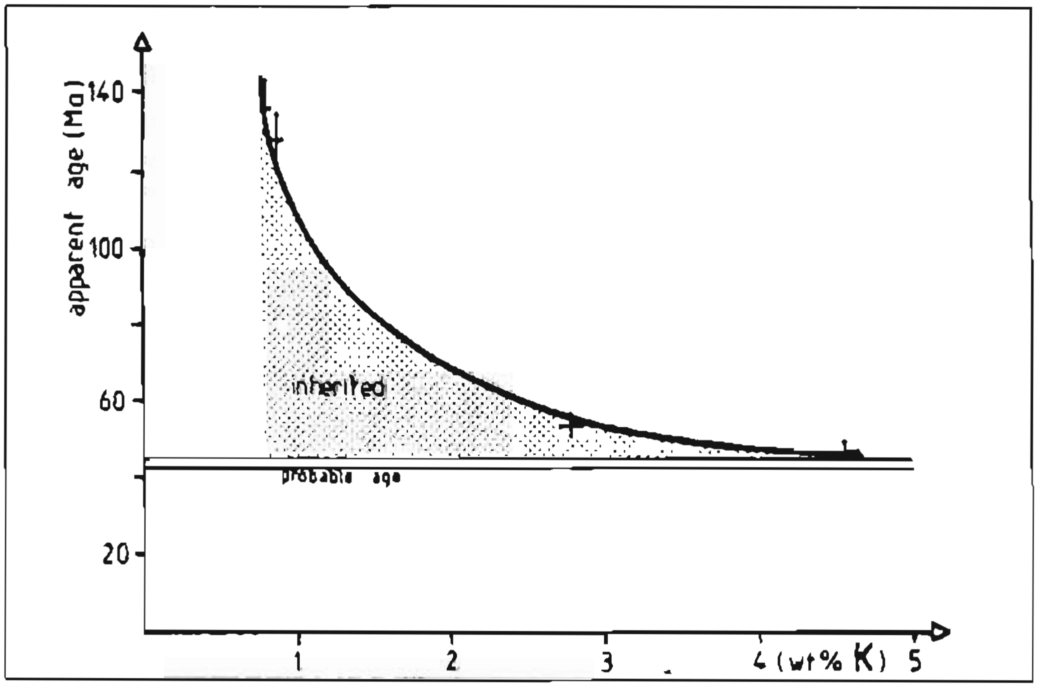

Figure 19. *The apparent ages of glauconies from the Weches formation (Middle Eocene of Texas) according to Ghosh (1972). The potassium enrichment (glauconization) leads to slow removal of the inherited radiogenic argon of the initial substrate (Odin and Dodson, 1982).*

The trend of younger ages with increasing maturity is also demonstrated by the glauconization of Recent material in the Gulf of Guinea (figure 20). Although the geochemical process is not exactly contemporaneous for all samples, the quantities of radiogenic argon measured do not reflect the precise moment at which glauconization of each sample begins, but rather according to the data given by Odin and Dodson (1982) it reflects the timing of closure of the glauconite crystallization for a glaucony developed from a ^{40}Ar-rich substrate. This closure occurs when potassium content is equal to or greater than 7% K_2O.

These examples indicate, that inherited radiogenic argon may be trapped in the growing lattice of glauconite minerals, and in the remnants of older mineral phases that are being glauconized.

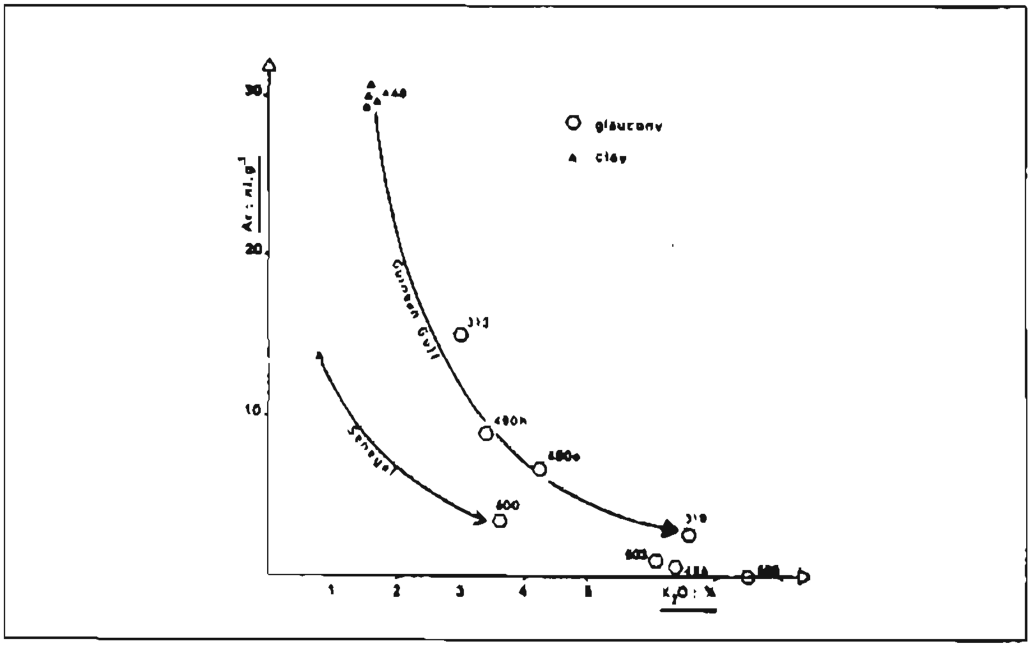

Figure 20. *The radiogenic argon content of glauconies lying on the present continental platform. The evolution of the parent material from the fine clay fraction used by mud-eaters to an evolved glaucony. The example from Sengal show a similar trend (Odin and Dodson, 1982).*

Leaching experiments conducted on various glauconies with concentrated saline solution removes less argon from a Recent glaucony than from ancient glauconies richer in potassium. This suggest that the radiogenic argon in Recent glaucony is not in a glauconitic-type structure but is contained in the more solid structure of an inherited grain. Heating various glauconies with 5.7-7% K_2O at 250°C leads to the loss of a few percent of the radiogenic argon by diffusion. However, when heating Recent glaucony from the Gulf of Guinea, no detectable effect was present. Odin and Dodson (1982) believe also this confirms that radiogenic argon within Recent glauconies with low potassium content is contained in remnants of older original minerals.

Weathering and Reworking of Glauconies

The direct effect of weathering on glauconite as well as the reworking of glauconite grains throughout a stratigraphic interval can have an important implications for regional geologic interpretations.

Recent Weathering

Odin and Hunziker (1974) collected numerous samples containing glauconite and representative of various degrees of weathering. Ten samples representative of various degrees and possibilities of weathering were selected for X-ray diffraction studies. Diffractograms show the non-weathered grains are composed of tightly closed glauconitic minerals (the interlayers are very thin, due to the abundance of potassium which collapses the successive layers). In the reworked (weathered) glauconies the alteration may be detected by slight opening in the interlayers of the clay structures and exhibited on the powder diffractograms.

Figure 21 demonstrates the change in appearance of the (001) diffraction peaks which indicate a mean initial thickness of the 'layer+interlayer' close to 10 Å, as for all micas. After weathering, the (001) peak shows a broadening of the 'layer+interlayer' thickness which increases to 11 Å or more.

The loosening of the structure is accompanied by the extraction (loss) of 10-15% of the potassium content and some radiogenic argon. This loss could lead to a slight rejuvenation of the apparent K/Ar age.

Behavior of Glauconitic Minerals During heating

The exact conditions of radiogenic argon retention and diffusion is crucial in determining the reliability of radiometric dating. Odin and Bonhomme (1982) cite over 9 different studies where the important loss of argon under a vacuum may occur at temperatures as low as 100°C or as high as 600°C. Evernden (1960) heated some glauconite under middle temperature range (300°-600°C) and mid-high pressure (70-700 bars) range and found a correlation between water mobilization from the crystal lattice and argon diffusion. If high enough pressure is applied to prevent the loss of water, argon diffusion is greatly reduced. Experiments at high pressures and low temperatures indicate the diffusion of argon out of the glauconite lattice is related to a recrystallization process which has a greater effect on less evolved glaucony than in the higher evolved (K-rich) samples.

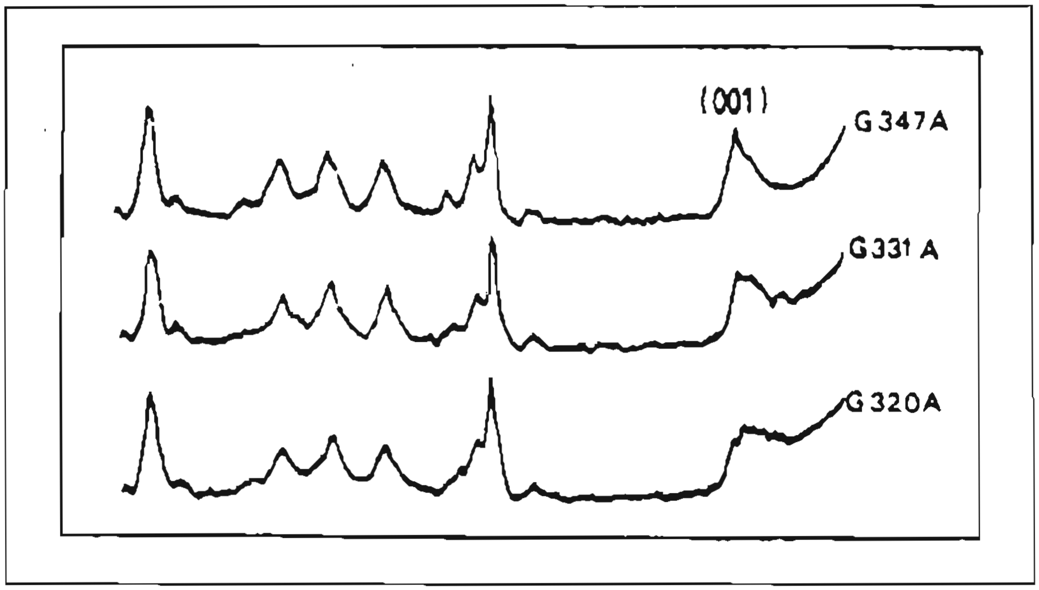

Figure 21. *X-ray diffractograms of weathered glauconites. The evolution of the (001) diffraction peak shows a progressive opening (swelling) of the interlayers related to potassium extraction (Odin and Rex, 1982).*

Other experiments have been conducted comparing illite and glauconite. Various clay size fractions were stepwise heated. After stepwise heating for 24 hours at, 250° C, 375° C, and 500° C, the illite patterns of argon mobilization were distinctly different from those of the glauconite, but there is little difference within the different size fractions. Glauconite released most of its radiogenic argon (72%) by the end of the 375° C heating step, and almost all argon had been released by the end of the 500° C step. Where as, illite released only a small fraction (10%) of its radiogenic argon at 375° C and only averaged 45% by the end of the 500° C step. It appears that composition (potassium and iron content and percentage of expandable layers) has a greater effect than particle size on argon retention (Hassanipak and Wampler, 1988).

Burial

Generally speaking, the effect of pressure and temperature histories on Glauconite may be hard to distinguish from diagenetic effects, due to the similar responses

Frey and others (1973) investigated K-Ar ages of glauconite bearing formations of Cretaceous and Tertiary age in the Glaris Alps (Switzerland). They found a systematic decrease in age when approaching a zone of incipient metamorphism, which was controlled by the overburden of a nappe pile. The K-Ar ages of the glauconites at the zone between unmetamorphosed and low grade metamorphism correlate with K-Ar ages from stilpnomelanes and riebeckites within the metamorphic zone. Folinsbee and others, (1960) similarly relate the apparently younging K-Ar ages of glauconites from drill holes on the Canadian platform to orogenic events. Cambrian glauconies containing 7.3-7.5% K and buried to 10,000 meters, yielded an apparent age characteristic of the Caledonian orogeny. Jurassic glauconies with 4.5-5.8% K showed an apparent age related to a regional mid-Cretaceous orogeny, while Albian glauconies with only 4% K showed an apparent age which might be related to the Laramide orogeny.

One of the best examples of ambiguity that may arise is demonstrated by the re-examination of samples from the Mid-Late Eocene Kreyenhagen formation of California by Evernden and others, (1960). His results show the apparent K-Ar ages become dramatically younger with increasing depth. In his dissertation, Obradovich (1964) reexamined Evernden's samples and arrived at a different conclusion. Obradovich (1964) cleaned Everden's samples ultrasonically, concentrating higher potassium samples and obtained new apparent ages. These new apparent ages are younger than the expected stratigraphic age but, do not show the steep decline in apparent that Evernden's interpretation presents (Figure. 21). Notice how the ages remain more or less unchanged down to 2500 meters depth.

Glauconites exhibit a rejuvenation (younging) of their K-Ar ages when subjected to conditions of burial. Few indisputable examples are available however concerning the rejuvenation or resetting of glauconite K-Ar dates as a result of burial alone. Therefore a cautious approach must be applied to radiometric dates from glauconites. On the other hand, if other age control are present, results from isotopic analysis of glauconites may be useful as an indicator of periods of elevated temperatures.

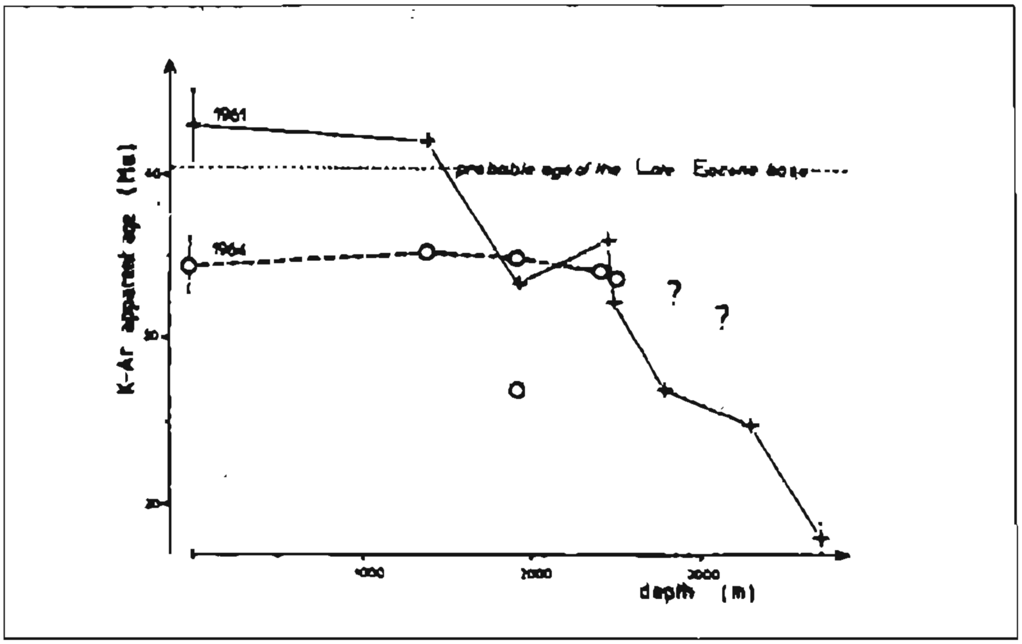

Figure 21 Apparent ages of glauconites from the Keyenhagen fm. according to Evaerden et al. (1961) (+) and to Obradovich (1964) (O).

Rb-Sr

Rb-Sr isotopic age determinations were first done by Cormier (1956) who began the study of authigenic minerals enriched in Rb and depleted in Sr. The results were encouraging as the isotopic ages seemed reasonable when compared to stratigraphic ages and complimentary K-Ar dates (Hurley and others, 1960). Similar to K-Ar age determinations, many Rb-Sr ages for glauconites are often 10-20% lower than Rb-Sr ages measured on micas from coeval igneous rocks (Hurley and others, 1960; Grant and others, 1984; Grant, 1982; Morton and Long, 1984). This discrepancy is usually attributed to a preferential leaching of radiogenic isotopes from minerals with various proportions of expandable layers with weak structural bonds. The authors appear to have assumed glauconitic fractions alter during post-depositional burial. The young ages were then related to late closure of the Rb-Sr systematics in response to diagenic events (e.g. cation exchange).

Rb-Sr isochron ages, measured by Grant (1982), for lower Silurian glauconites from Ohio and Indiana (370±11 m.y.) and upper Cambrian glauconites from the New and Old Lead Belts in Missouri (423±7 and 387±21 m.y.) are anomalously young. Because these glauconitic bearing rocks have been buried less than 1 km. Grant and others (1982) surmised the resetting of glauconites was due to cation exchange between diagenic and Mississippi Valley-type ore fluids.

Cation exchange

Cation exchange reactions are greatly affected by the physical size of the clay fractions. Three predominant size domains include: 1) the expandable and non-expandable layers, 2) individual microscopic crystallites (<2 microns), and 3) the entire glauconitic pellet. Individual layers cannot be physically separated, but cations firmly held in non-expandable layers, in principle, may be isolated by replacement of all exchangeable cations in the expandable layers using a cation-exchange reagent. Cation exchange in the expandable layers would take place easily by cation exchange or alteration of composition which would more likely take place during diagenic reorganization (Morton, 1984).

Morton (1984) experimented with glauconite pellets and a clay-size fraction to determine if Rb and Sr isotopes could be removed easily and he found ammonium acetate (NH_4OAc) removed only loosely bound, and exchangeable Rb and Sr. He feels this treatment eliminates the problem of removing exchangeable cations. When he dated his samples he determined that 1) the age of the ammonium acetate treated pellets was equal to untreated clay size fraction and 2) the age of treated pellets is significantly greater than the age of the (treated) corresponding clay-size fraction (Figure 22).

The results from the type 1 example indicates the whole-pellet and fine fraction would have to remained totally undisturbed since formation so as to record the time of deposition. In Morton's (1984) case this idea situation did not exist. He found that in all of his samples the ages were younger than the expected age of deposition, suggesting they had undergone a later diagenic homogenization.

Morton's (1984) research demonstrated the age of the pellets is considerably older than the age of the corresponding clay fraction. He concluded that the pellets remained in a closed system while the crystallites record a later diagenic event.

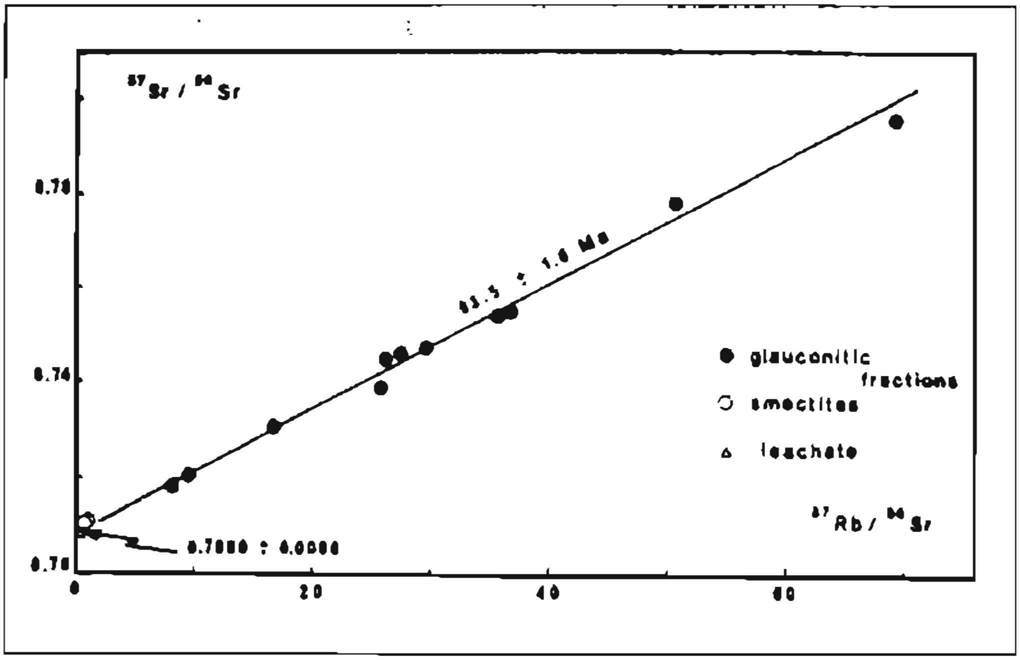

Figure 22 Isochron diagram of the glauconites, smectites and carbonate from the Cenomanian, France (Morton, 1984).

Perhaps important to a North Slope application, Grant and others (1984) conducted cation exchange experiments with dilute Sr bearing solution and an artificial oil field brine and found that glauconite absorbs large amounts of Sr. Some of the Sr attaches to the glauconite lattice strong enough to resist leaching by NH_4OAc (ammonium acetate).

Sr Isotopic Homogenization

It is clear the Rb-Sr systematics of clay minerals are greatly altered by cation exchange and that they must remain inclosed to obtain data with stratigraphic significance. Different events such as diagenesis, metamorphism or weathering may, nevertheless, later modify the isotopic balances of these minerals.

Research by Claure (1982) indicates clay minerals lose ^{87}Sr relative to ^{86}Sr and interstitial waters gain ^{87}Sr relative to ^{86}Sr in Recent sediments up. Recent smectites from the uppermost 2 cm of deep sea red clays in the Pacific Ocean have $^{87}Sr/^{86}Sr$ almost equivalent to that of sea water (Claure, 1982). This provides evidence for Sr equilibrium between seawater and sediments. Contrary to Claure; Dasch (1969) showed that sedimentary (clays and felspars) material of the Atlantic ocean after decarbonization, have heterogeneous $^{87}Sr/^{86}Sr$ ratios but these ratios are higher than the compiled ratio for modern seawater by Claure (1976).

Odin and Hunzikler (1982) use Claure's (1982) observation of sediment-seawater strontium isotope equivalence in their interpretation of Cenomanian glauconies from Normandy, France. Eleven glauconitic fractions were measured as well as two smectites and one leachate (calcite). The glauconies ratios lay along an isochron yielding an age of 95.5±1.6 million years and the initial $^{87}Sr/^{86}Sr$ ratio of .0708. The age is similar to the K-Ar isochron of 93 million years. The $^{87}Sr/^{86}Sr$ ratio of the leachate and the smectites are almost on the isochron of the glauconite fraction suggesting that all the minerals had the same ratio during their period of deposition. The ratios suggest that the glauconitic fractions have ratios identical to that of the environment, since those of the carbonates and contemporaneous water are almost equivalent.

$^{40}Ar/^{39}Ar$

Attempts to use glauconite in $^{40}Ar/^{39}Ar$ dating have not been successful (McDougall and Harrison, 1988). This is due particularly to variable loss of ^{39}Ar, during irradiation, by recoil which can be as much as 27% (Hess and Lippolt, 1986, Foland and others 1984). This, coupled with the instability of glauconite during heating, decreases the likelihood of yielding reliable $^{40}Ar/^{39}Ar$ dates. Although, Grant (1982) did use $^{40}Ar/^{39}Ar$ step heating techniques to identify when his glauconite samples lost ^{40}Ar and provided a effective tool for verifying other thermal events. experiments

Stable Isotopes

Oxygen isotope compositions of Recent glauconite pellets from the Congolese shelf show high ^{18}O values up to 24% higher than present sea water indicating a presence of detrital material within the pellet (Odin, 1988). Morton and Long (1984) determined the delta ^{18}O values for glauconite from the Llano (Texas) uplift. ^{18}O values from Late Cambrian and Early Pennsylvanian glauconites were lower than Recent glauconite which is considered to be forming in equilibrium with modern marine water. The low ^{18}O values infer the glauconite was at equilibrium with meteoric waters and they suggest this used the low delta ^{18}O in infer glauconite diagenesis did not occur in response to a thermal event but the low ^{18}O suggest the glauconite was in equilibrium with meteoric water at some other time. Thus, the oxygen data substantiated their Rb-Sr age data supporting the hypothesis that recrystallization occurred during regional emergence above sea level.

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