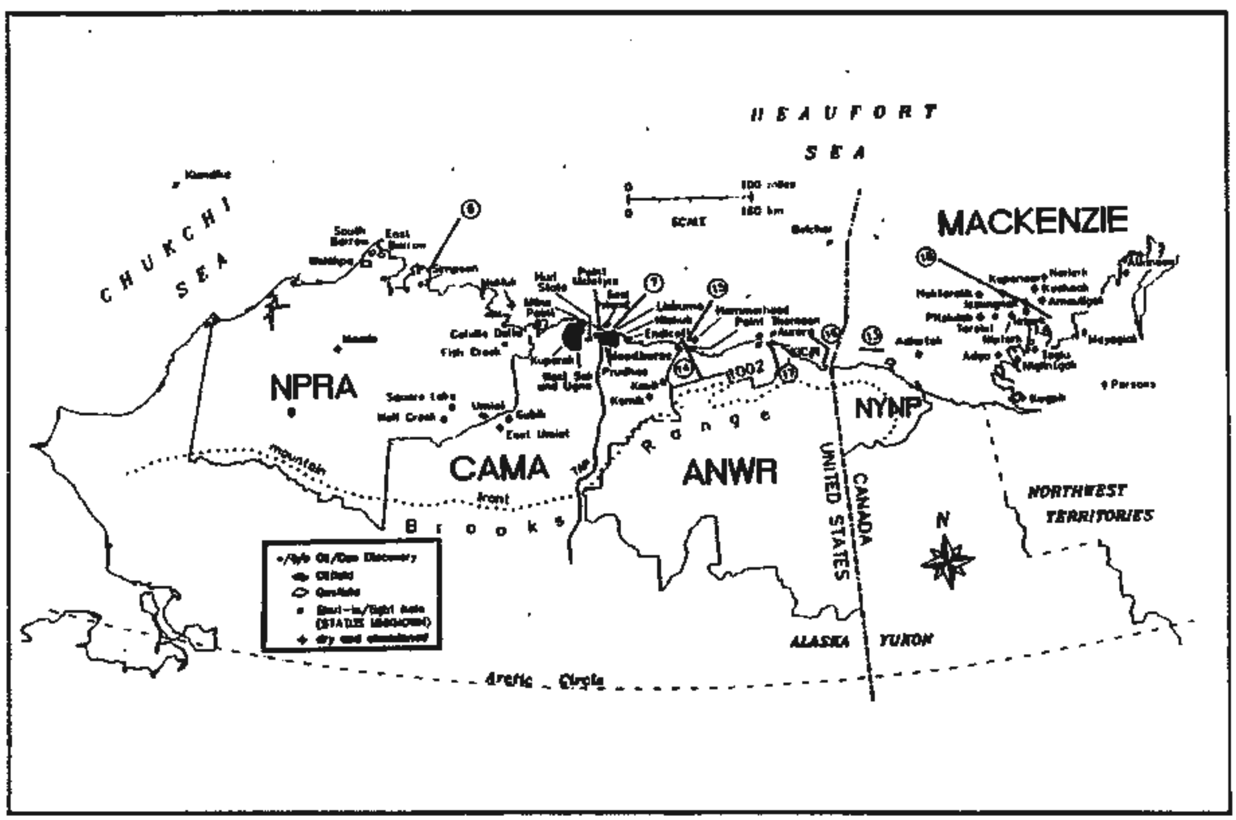
U.S. Department of the Interior
Bureau of Land Management

Alaska State Office
Division of Mineral Resources
222 West 7th Avenue, #13
Anchorage, Alaska 99513

BLM-Alaska Technical Report 13
BLM-AK-PT-90-038-3045-985
September 1990

Bedrock Geology of the Northernmost Bulge of the Rocky Mountain Cordillera

Arthur C. Banet, Jr.



Author

Arthur Banet, Jr. is a geologist in the Bureau of Land Management's Alaska State Office, Division of Mineral Resources, Branch of Mineral Assessment, Anchorage, Alaska.

Technical Reports

Technical reports issued by the Bureau of Land Management-Alaska present the results of research, studies, investigations, literature searches, testing or similar endeavors on a variety of scientific and technical subjects. The results presented are final, or are a summation and analysis of data at an intermediate point in a long-term research project, and have received objective review by peers in the author's field.

The reports are available while supplies last at BLM offices in Alaska. Copies are also availalbe for inspection at the USDI Resources Library in Anchorage, various libraries of the University of Alaska, libraries in other selected Alaska locations, the USDI Natural Resources Library in Washington, D.C. and at the BLM Service Center Library in Denver. Copies may be purchased through the National Technical Information Service, 5285 Port Royale Road, Springfield, Virginia 22161.

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No.

4. Title and Subtitle	5. Report Date
Bedrock Geology of the Northernmost "Bulge" of the Rocky Mountain Cordillera	September 1990
	6.
7. Author(s) Arthur C. Banet, Jr.	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Bureau of Land Management Alaska State Office 222 West 7th Ave., #13 Anchorage, AK 99513	10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) (G)
12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered BLM Alaska Technical Report 13
	14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Well logs, CDP seismic interpretations, field mapping and LANDSAT imagery, show that sediments ranging in age from Proterozoic to Recent exist in the subsurface and crop out around the northernmost bulge of the Rocky Mountains. These represent the Rapitanian, questionably the Franklinian, the Ellesmerian, the rift-assosicated Break Up, the Brookian and Tuktoyaktuk depositional megasequences. Each sequence records distinct and major changes in basin geometry.

North Slope hydrocarbon resources are distributed through out the megasequences. Currently, the Ellesmerian and Break Up megasequences are undergoing development. However current exploration indicates that the older sequences have an undetermined reserve base, and the Brookian units contain larger, but currently uneconomical oil and gas reserves and extensive coal deposits than either the Ellesmerian or Breakup sequences.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms

Alaska, Alaska North Slope, oil, geology, Arctic National Wildlife Refuge

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
while supplies last	nonsensitive	55
	20. Security Class (This Page)	22. Price nc

(See ANSI-Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

Bedrock Geology of the Northernmost Bulge of the Rocky Mountain Cordillera
(and its relationship to North Slope hydrocarbon resources)

Arthur C. Banet, Jr.

Bureau of Land Management
Alaska State Office
Anchorage, Alaska 99513

BLM-Alaska Technical Report 13
September 1990

Table of Contents

List of Tables

List of Plates

List of Figures

Bedrock Geology of the Northernmost Bulge of the Rocky Mountain Cordillera

(and its relationship to North Slope hydrocarbon resources)

1. Introduction

The northernmost part of the Rocky Mountain Cordillera rises above the Arctic Coastal Plain between the Sagavanirktok River in Alaska, and the Babbage River in the Yukon (figure 1). This part of the Cordillera is a distinct northward "bulge" forming the Franklin, the Romanzoff and British Mountains. It marks the transition from predominantly east-west geologic and topographic trends, common to the foreland fold and thrustbelt geometry of northern Alaska, to the predominantly north-south folding and faulting trends that are common to the rest of the chain through western Canada and the contiguous U.S. The east side of the bulge is flanked by Cretaceous sediments of the Blow River Trough and Rapid Fault Array. Pre-Brookian rocks dive beneath the Holocene cover in front of the Brooks Range allocthons on the west (figure 2).

This bend of the Cordillera also represents a dramatic change in the foreland. Only in Alaska and the northernmost Yukon does the Cordillera drain directly into an ocean basin that is actively receiving sedimentation from mostly straight flowing rivers whose lengths are measured in only tens of kilometers. In addition, the kinematics of compressional mountain building are more recent and better preserved in the bulge than in the rest of the Alaskan Brooks Range and the remainder of the cordillera through Canada and the U.S. Thus is juxtaposed an area of relatively recent uplift and a deep rift/flexural basin filling with the resulting depositional sequences of sediments recording the mountain building events.

Within this area, there are elements of several distinct and separate phases of deposition, provenance and orogeny. There are very thick and laterally extensive sedimentary sections below Cambrian units which suggests that a considerable amount of preserved Proterozoic section has still eluded significant analyses. Post-Proterozoic sediments include several depositional pulses from a northern (with respect to the present tectonic arrangement) source area, localized sediment sources, and finally a southern provenance which has dominated the sedimentation since the Mid-to-Upper Cretaceous.

Plate 1 shows a synthesis combining available onshore data. Even some of the more recent compilations miss, or ignore,

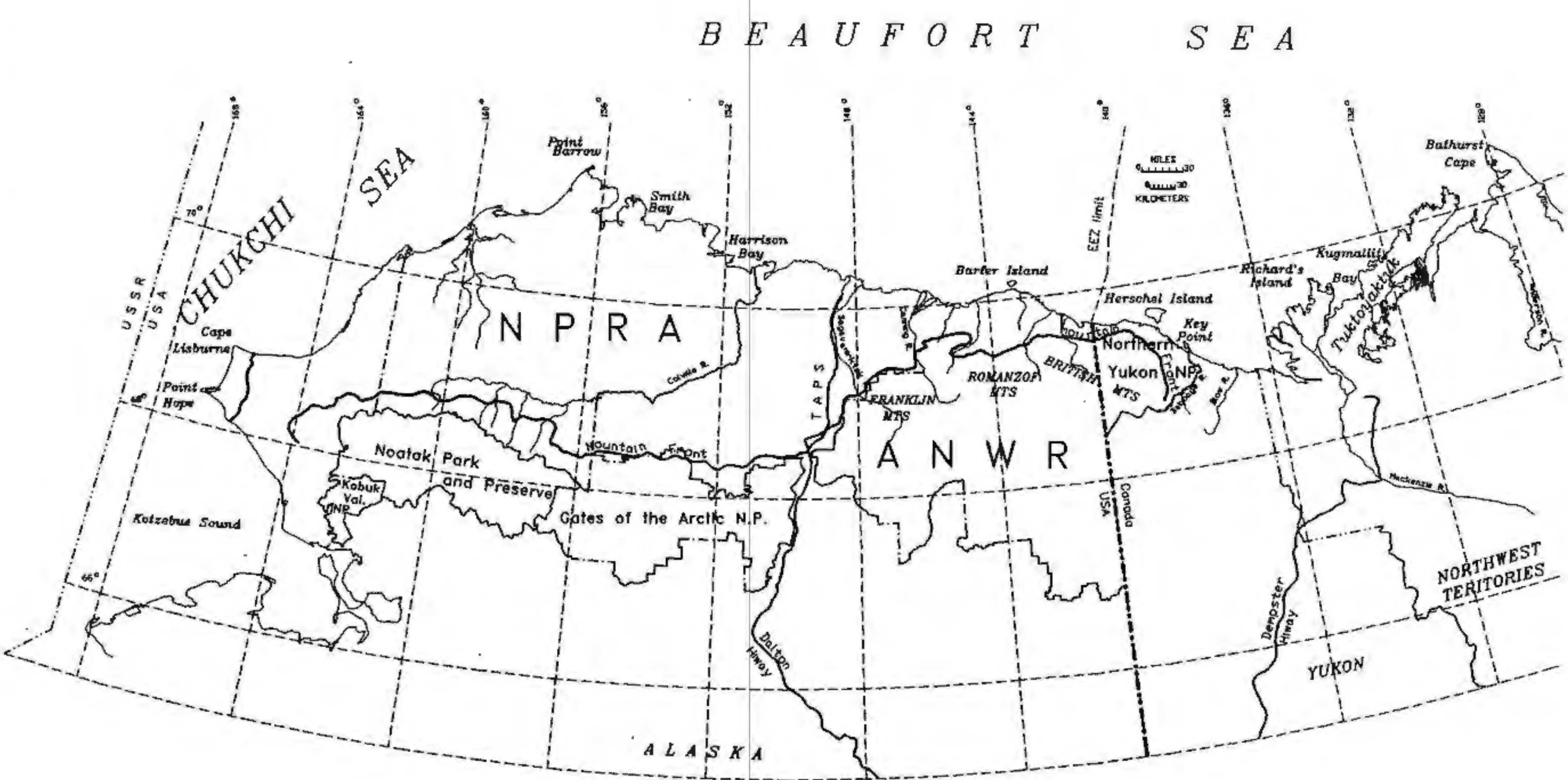


Figure 1. Index map of the arctic

showing major geographic features in Alaska, Yukon Territory and Northwest Territories

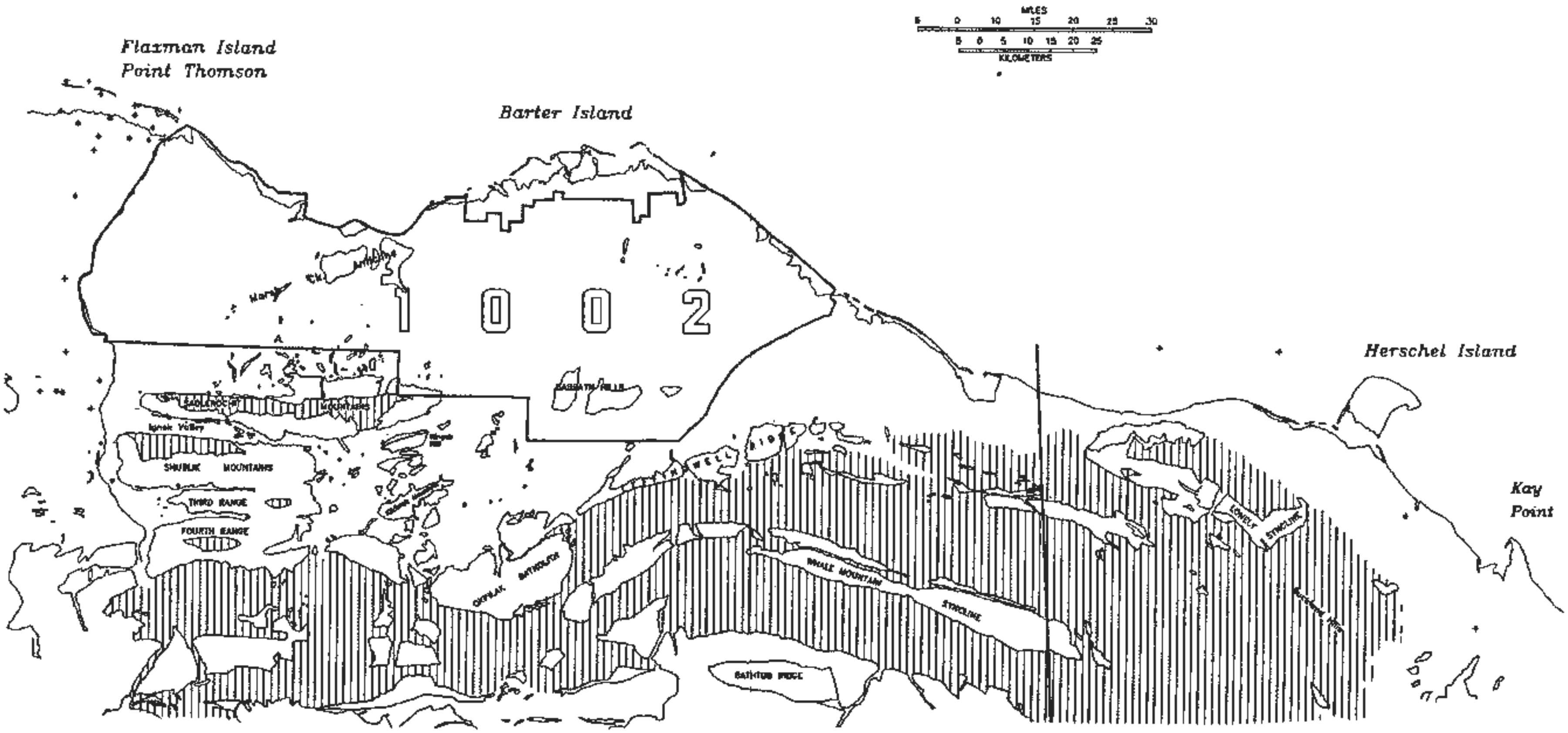


Figure 2. Major geographic features, outcrops and the arcuate trends of the "bulge"

(Key: pre-Ellesmerian rocks are shown as hatched) the extent of the older stratigraphy. This text reflects some of my fieldwork in the Arctic National Wildlife Refuge (ANWR; 1983, 1984 & 1985), near the International border along the Yukon River (1985 & 1986), and some of my conclusions pertaining to the Brookian and Ellesmerian sections. In addition, it is a combination of mapping based on outcrop trends, in Canada and the U.S. with emphasis on preserving established stratigraphic geometry and harmony. Diagnostic rock types and lithologies were employed with caveats because one man's phyllite often grades into another's argillite, and rock coloration can typically be perceived uniquely. Also, I attempt to shed some insight as to the diversity that exists amongst the variously assigned and perhaps prematurely defined or assigned basement rocks. As always, there is room for improvement, but this level of description fits well, and is usable, with my data base developed at 1:250,000 for the ANWR 1002 area Coastal Plain analysis of oil and gas resources. Consequently, mention of oil and gas resources is made with the descriptions of the stratigraphic units.

2. Previous Work

Leffingwell (1919) made the initial systematic geologic observations of the area and described the overall framework regional geomorphology, stratigraphy and structural style. He managed to touch upon most of the area's unique features by wintering over six complete, but not consecutive, years. This method allowed him access across the tundra in addition to reconnaissance up the rivers. Later workers have yet to match the scope and breadth of this initial endeavor. Although perhaps less dramatic, intermittent reconnaissance work continued from the late 1940's through the 1960's (Gryc and Mangus, 1947; Keller, Morris and Detterman, 1961; Brosge, and others, 1962; Reiser, 1970; Dutro and others, 1972). More complete, regional, mapping and detailed stratigraphic and structural descriptions followed (Lerand, 1973; Detterman, Reiser, Brosge and Dutro, 1975; Sable, 1977; Lyle and others, 1980; Reiser, others, 1980; Molenaar, 1983; Norris, 1984, 1985 a&b; McWhae, 1986).

The legislation concerning the oil and gas potential of the Arctic National Wildlife Refuge 1002 area spurred an ongoing burst of government, academic and industry interest. This includes the U.S. Department of Interior 1002 Area Coastal Plain Assessment, USGS Bulletin 1778, Pacific Section SEPM publication #50, MMS geologic report for the Beaufort Sea Planning area, course notes by the Canadian Society of Petroleum Geology, 1985; and Alaska DGGS Public Datas File 86-86, 87-27 a-l). While many arbitrarily stop at the international border, or are constrained by stratigraphy, structure, geochemistry, or are desk interpretations, they contribute considerably towards the understanding of this complex region.

3. Stratigraphy and Resources

The stratigraphy of the bulge is quite extensive, both in areal distribution and the amount of time that it encompasses. At the base there is a great volume of clastic, carbonate and volcanic rocks. These rocks are of pre-Cambrian age, and are relatively well exposed, but not yet thoroughly studied. They have certain similarities but also have some important dramatic dissimilarities. There area two Proterozoic sequences in this area. The Neruopkuk Formation is the more areally extensive and thicker of the two sequences. Consequently I choose to describe and discuss the geology of the Neruopkuk and its overyling sediments first because they appear to be more closely related to one another and also appear to have undergone similar tectonic histories.

The Katakturuk Dolomite is most prohably coeval to the Neruopkuk. It is less areally extensive, thinner than, and tectonically distinct from the Neruopkuk. The Katakturuk and the overlying Nanook Limestone are considered to be marginally related, but separate sequences. They are discussed separately from the Neruopkuk for similar reasons.

Leffingwell (1919) described the Neruokpuk Formation as the pre-Carboniferous, non-fossiliferous, quartzite, schist and semi-schist cropping out between the Hula Hula and Canning Rivers. "There is a marked angular unconformity at the top of the formation, and it is much more metamorphosed than the overlying sediments." His notes describe a marked east-west strike and a well developed south dip. These features are diagnostic to this unique section. Later workers, particularly those working the Naval Petroleum Reserve #4 National Petroleum Reserve—Alaska (NPRA) expanded the terminology to include essentially all pre-Carboniferous rocks on the North Slope. This included metamorphic and many sedimentary units of various age, origin and history, and thus "Neruokpuk" became basement rock for most assessment purposes. Norris (1985a) assigns the Neruokpuk to the Rapitanian Sequence, deposited from the Racklan Orogeny.

Satellite imagery (LANDSAT) of this part of the North Slope shows a distinct, curvilinear pattern of valley and ridge forming rocks. This trend is mostly continuous throughout the 300 km between the Canning River and the Babbage River. Although restricted to approximately 10 km in width south of the Okpilak Batholith, the curvilinear pattern of rocks is as much as 60 km wide in the Romanzof Mountains (plate 1). The exposure of these rocks in the "bulge" is a structural culmination, as the Neruokpuk rocks plunge off both ends beneath younger rocks. Thus, these rocks represent a discrete stratigraphic unit that is not related to pre-Ellesmerian rocks exposed on allocthons in the Central Arctic and NPRA. This is in agreement with Norris (1985b), and so the Neruokpuk sediments are treated as a separate entity or entities. Coincidentally the "bulge" is also the area of the highest peaks in the Brooks Range.

The Sadlerochit, Shublik Mountains and the Third Range are at the northwest extent of the "bulge." These mountain ranges are of note because they are conspicuously east-west trending rather than being curvilinear. They also appear to be projected up and out of the coastal plain sediments, rather than belonging to the more common arcuate leading edge of the Brooks Range.

At the cores of the east-west trending ranges are thick sequences of carbonate rocks. The Katakturuk Dolomite forms the core of the Sadlerochit Mountains, and both the Katakturuk and Nanook Limestone form the core of the Shublik mountains. The exposed core of the Fourth Range consists of interbedded limestone and shale which may be a distal equivalent of either the Katakturuk, the Nanook, or possibly one of the facies of the Neruopkuk. Field relationships suggest that the Katakturuk and Nanook are more closely related to each other than they are to coeval Neruopkuk facies and overyling lithologies.

Mapping scale varies on the North Slope and this area is no exception with both regional and small scale publications (Sable, 1965; Kososki and others, 1980; Reiser and others, 1980; and Norris, 1981). At 1:250,000 and smaller scales the degree of precision shown on the maps by Norris (1981) and the geology map in Kososki and others (1978) illustrates best, the areal extents and trends of the Neruokpuk and the coeval platform carbonate section.

Plate 1 is scaled to 1:250,000 and combines and enlarges Norris' seven subdivisions with units described and mapped by Reiser, others, (1980), in Kososki and others (1980) and Bird and Bader (1986). It also extends the correlations across the U.S.-Canada border. Although this synthesis may leave several stratigraphic and biostratigraphic questions unanswered, these units match quite well with the trends identified from LANDSAT satellite imagery.

A. Neruokpuk Formation

Norris (1985b) identified seven units (PN0 - PN6) within the Neruokpuk in the Yukon and tentatively correlated them to some 12 units identified by Dutro and others (1972), and Reiser and others (1980). Norris (1985b) estimates that there is at least 13,400 m of slightly metamorphosed (less than greenschist facies) section, but no schist or semi-schist. Also, it is likely all of pre-Cambrian age. The arcuate grain of the Neruokpuk shows that the entire section dips to the southwest in Canada and to the south in the U.S. This exposes at least parts of all units. No major unconformities have been identified within the Neruokpuk of Canada although Norris (1985b) notes that there are abrupt internal facies changes and possible unconformities bounding the units. At present, correlations are confusing because current mapping shows units that do not correlate across the border and some thrust faults that meet at the border but have opposite dip directions. In addition there are also bedding plane-parallel thrusts, and thrusts which cut upsection that translate or structurally superpose strata, contributing to the correlation confusion created by sedimentological changes.

Four Neruokpuk units span the border and four are identified only in Canada (plate 1). Thus, I am considering and describing eight units to comprise the Neruokpuk Group; N1 through N8. To facilitate comparasions, I show both my divisions N (1 - 8) and Norris's (1985b) PN(0 - 6) units where pertinent (figure 3).

The basal unit, N1/PN0, is a narrow linear band (~3km X 25 km). Exposures extend from southeast of the Lonely Syn-

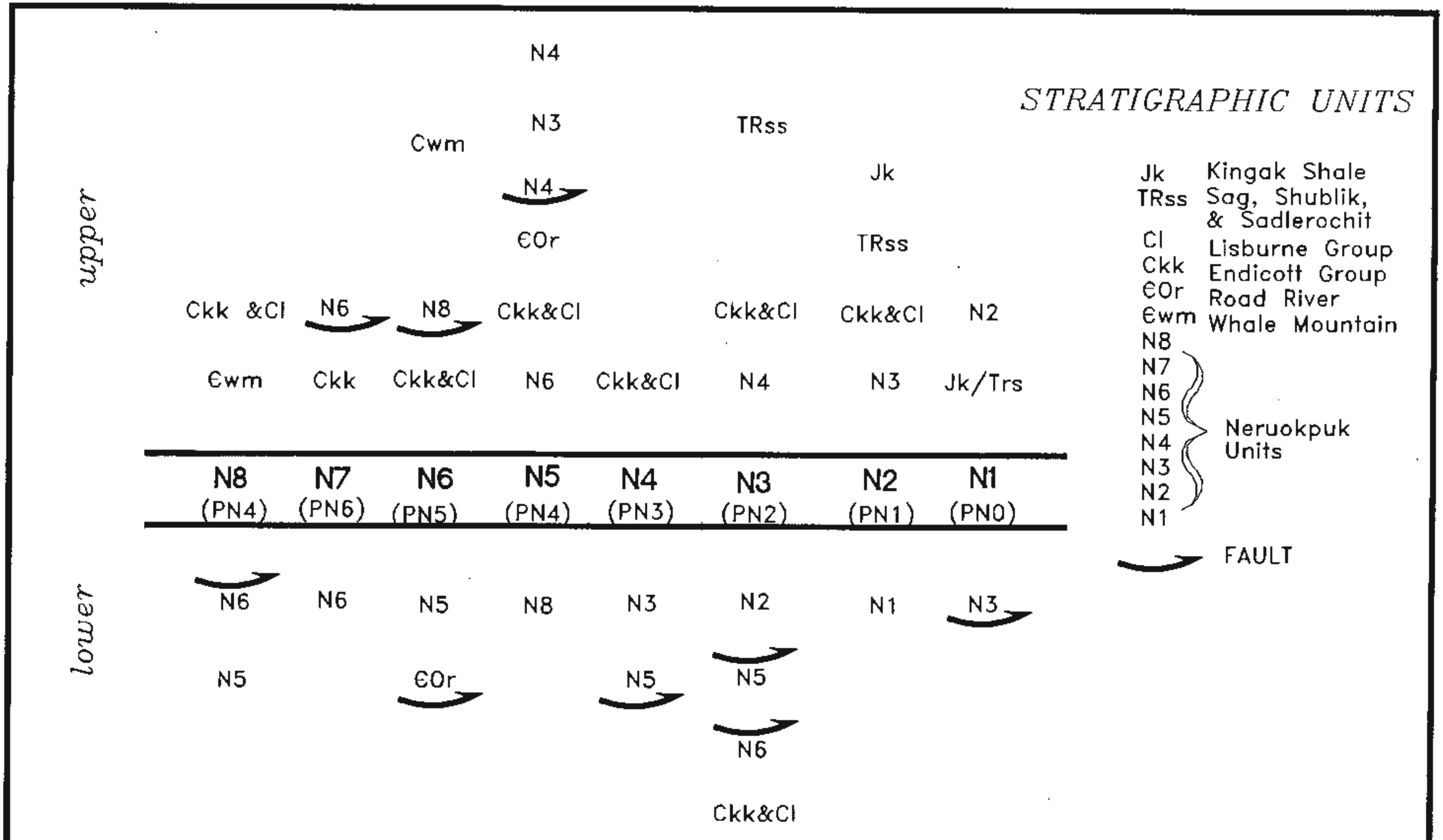


Figure 3. Major stratigraphic and fault contacts with the Neruokpuk formation

cline to between the Buckland Hills and British Mountains. N1 is composed of dark gray, or rusty weathering argillite and fine-grained sandstone. Norris (1985b) shows that these are mostly thin, interbedded lithologies and that tight folds are common. The base is obscured, even where N1 is thrust faulted over a younger unit (plate 1).

Unit N2/PN1 is also restricted to the Canadian side of the border (plate 1). It crops out in a longer, thinner southeast-trending band (~2.5km X 40km) that apparently, conformably overlies N1 (figure 3). This lithological unit is less than 1000 m thick and it consists of partially slaty argillite, limestone and sandstone. Unit N3/PN2 is one of the more areally extensive and thicker units on plate 1. It comprises an estimated 40 percent of the bedrock in this part of Canada, eh. It is two arcuate bands, mostly 10 - 20km wide in Canada and is only a few km wide X 20 km long in the U.S. (plate 1). It is interbedded, slaty, gray argillite, fine-grained to crystalline and argillaceous limestones, and fine-to coarse grained quartzose sandstone. On the U.S. side this unit includes a partly pelletoidal and pisolitic limestone with floating quartz grains (Reiser and others, 1980). In addition some of the unassigned slate, quartzite, and argillite units belong in this unit. Figure 3 shows the stratigraphic relationships of N3 with the other units.

A thrust fault-bounded syncline with steeply-dipping to overturned limbs, in the southcentral part of the N3 exposure, preserves all that is left of unit N4/PN3. Unit N4 conformably overlies unit N3 and has a thrust fault contact with unit N5 (plate 1). This is a mostly thin to medium bedded unit consisting of slaty, gray to olive colored argillite with lesser percentages of dark gray, crystalline limestone and minor pods or beds of calcareous siltstone. Norris (1985b) shows some of the bedding distorted by the severity of folding in the region.

Some correlation problems exist along the international border between Norris's PN2, PN4, and PN5 units and the stratigraphy mapped in Alaska. Plate 1 shows a regional compromise, based largely on preserving trends apparent on LANDSAT photos and matching up lithologies as closely as possible. Thus, unit N3/PN2 consists of interbedded argillite, sandstone and limestone in the Yukon. It spans the border south of the coastal plain where it is mapped and described (Reiser and others 1980) as red phyllite, green phyllite, and dark gray limestone which grades into sandstone. Combined thickness, including less areally extensive lithologies of slate, quartzite and chert, is probably less than 500 m in Alaska, which may reflect thinning of the of the distal portion of the unit or erosion.

Norris' widespread PN4 unit as mapped in the Yukon (Norris, 1981) is some 5100 m of interbedded, fine-to medium-grained sandstone and slaty, gray- to red argillite, with subordinate amounts of chert (Norris 1981, 1985b). I suggest that revision is needed within PN4 to reconcile previous interpretations of mapped units, which on LANDSAT imagery appear to be continuous. Thus plate 1 shows two distinct units N5 and N8.

In the Yukon, the PN4 unit is very widespread and appears on maps as three bands separated by younger and stratigraphically higher units. The two northern bands are elongate, northwest-trending exposures, some 50 km long by some 3 to 12 km wide (N5, plate 1). The southern band is over 100 km in length, up to 25 km wide, and is only in fault contact with younger units. Overall, the PN4 unit correlates, at least in part, with the descriptions of the quartzite schist and semischist member of Leffingwell's Neruokpuk unit where exposed around the Okpilak Batholith (Norris, 1985b).

Mapping in Alaska by Reiser and others (1972) and Dutro and others (1980) identified several pre-Cambrian interbedded, thin- to thick-bedded, quartz wacke, semi- schist, argillite, limestone and sandstone units along the border which correlate with Norris' two northern bands (N5). These units are continuous across the border as elongate northwest trending bands less than 5 km wide.

This lithology is Leffingwell's Neruokpuk and it also crops out in wide, east-west trending bands. One band extends from the vicinity of the Okpilak batholith, west to the Canning River. The other band is between the Bathtub and Whale Mountain synclines (plate 1). Maximum thickness may exceed 1700 m.

These units of Leffingwell's Neruokpuk are substantially thinner than Norris' estimated 5100 m of PN4 in the Yukon, but they do not correlate with the southernmost band of Norris's PN4 unit. Instead, the southern PN4 exposure correlates with a predominantly calcareous siltstone and sandstone unit which has yielded rare to few Cambrian-age fossil parts (Reiser and others, 1971 and 1980). Unit N8 replaces the southern part of Norris (1981) PN4. It is described as mostly very thin bedded and partly calcareous phyllitic siltstone, micaceous sandstone and graywacke and is estimated to range in thickness from approximately 700 to 1300 m.

To better fit the correlation, N8 also includes an overlying and extensive, thick, black, dark gray and greenish phyllite unit with lenses of sandstone and limestone (plate 1). Thus, N8 is a major stratigraphic component and it extends west from the Yukon, continuously to the Okpilak batholith and discontinuously into ridges of the Franklin Mountains (plate 1).

I suggest these divisions of PN4 because the LANDSAT photographs indicate that the elongate northwest trending bands of N5/PN4 are continuous across the international border. These elongate units are pre-Cambrian age which correlates with Leffingwell's Neruokpuk and Norris' PN4. And there is a stratigraphically higher, but still pre- Cambrian limestone and quartzite unit (N6/PN5) conformable above N5.

In addition the N8/PN4 unit is relatively contiguous on LANDSAT photos. It is a discernible, distinct, unit separate from the N5/PN4 unit north of Bathtub Ridge where both units are exposed. And N8/PN4 is only in fault contact with the older N6/PN5 unit where both are monoclinally southward dipping, in the Yukon Territory. With the current state of mapping and analyses, this separation best reconciles the stratigraphy to the outcrop trends and the ages of the units determined from the fossils.

Unit N6/PN5 extends westward in a broad arcuate trend that is mostly more than 10 km wide. It crops out from the British Mountains to south of Leffingwell Ridge, to the vicinity of the Okpilak Batholilth and possibly into the core of the

Fourth Range (plate 1). Stratigraphically, N6/PN5 fits above N5/PN4, Leffingwell's Neruokpuk, and below unit N7/PN6, where both are exposed, in the Yukon. This unit consists of some 1300 m of interbedded, black, crystalline limestone and yellow-weathering argillite (Norris, 1985b).

Reiser and others (1980) describe approximately 1000 m of multicolored and interbedded phyllite, argillite and platy- to massive dark gray limestone with floating quartz grains, local phyllite laminations, with additional units of thin- to medium-bedded pelletoidal limestone, that also have floating quartz grains. This N6 unit also includes relatively thin (mostly less than 100 m), and distinct local units of sandstone, dolomite, phyllite and limestone. These units are locally intensely folded to such an extent that suggests a very complicated and poorly constrained depositional and structural history (such as soft sediment deformation, pultiphasic deformation or decoupling of internal thrust plates).

In fact, map-expressions (plate 1) of N6 and N5 appear almost intertwined in the area north of Whale Mountain Syncline. Several thin (~1 to 3km scale) and alternating bands of units N5 and N6 form the valley and ridgetops, respectively. Whether these relationships are due to dramatic thickness changes, or folding or faulting or depositional contacts such as intertonguing lithologies, is as yet speculative.

A further complication is from Reiser and others', (1980) placement of the argillite, phyllite and limestone of N6, older than the N5 Neruokpuk, whereas their map in Kososki and others (1980) places the argillite, phyllite and limestone younger than N5, as is shown on plate 1, and which more closely resembles the Yukon stratigraphy. Clearly the stratigraphy is complicated and requires more analyses.

Unit N7/PN6 is the youngest of Norris' Neruokpuk divisions. It is restricted to a northwest trending band some 5 km by 20 km along the east side of the British Mountains. It is apparently conformable upon N6 and unconformably overlain by the middle Ellesmerian Endicott Group Kekiktuk Conglomerate. N7 consists of interbedded, dark gray sandstone and red argillite. Although there are similar lithologies in Alaska, no attempt has yet been made to stretch a correlation to N7.

As previously mentioned, unit N8 consists of the southernmost and widest band of Norris' PN4. It crops out continuously from the British Mountains to the Okpilak batholith and in isolated outcrops reaching to the Canning River. Thickness may be as much as 3000 m allowing for the subtraction of approximately 2000 m allotted to N5 from the original 5100 m. The combined thickness of Cambrian age, gray- to olive brown phyllitic siltstone and micaceous sandstone and black to greenish-gray phyllite in Alaska (Reiser and others, 1980), may be some 2500 m. Depositional thinning or erosion probably accounts for the remainder of thickness differential.

Although N8 is determined to be of Cambrian age, analysis of LANDSAT images reveals no distinct differences between its outcrop patterns and the other underlying Neruokpuk units. Thus, to whatever regional depositional sequence that unit N8 belongs, the order of magnitude of differences between it and the rest of the Neruokpuk is small compared to the extent of differences between it (N8) and the younger stratigraphic units in this area.

At present, there are at least two major hypotheses concerning the correlation and origin of the Neruokpuk units. Moore and others (1984) identify these units as fault bounded stratigraphic entities and consider them to be discreet tectono-stratigraphic terranes accreted to North America prior to the Devonian. Although this interpretation has considerable merit, as yet there is no detailed stratigraphy to demonstrate that there are significant differences between the ubiquitous argillites and subsidiary clastic and carbonate components of the Neruokpuk units.

Also the pervasive dip of the Neruokpuk units suggests that they all have similar depositional origin and have responded uniformly to similar tectonic influences. Likely they are one areally extensive accreted terrane rather than an amalgamation of lesser ones. Norris (1985b) suggests that the Neruokpuk sediments are deep water slope sequences representing turbidity current deposition from parts of the craton.

The nearshore facies comprise parts of the Tindir Group. The Tindir Group is a Proterozoic to Cambrian (?) sequence, identified several hundred kilometers to the south in the Yukon-Porcupine drainages of east-central Alaska and western Yukon. The Tindir sediments consist of an estimated 3000 m to 5000 m of thin to medium bedded black carbonates, thick shales and phyllites, quartzose sandstones, red bed conglomerates, and terrigenous volcanics, overlain by dolo-arenites, conglomerates, shales and more carbonates (Brabb and Churkin, 1969).

Norris (1985a) also assigns the Tindir Group to the Rapitanian sequence. Correlation problems are obvious in that the Neruokpuk sediments are very far away from the Tindir Group. They are also very thick (>13,000 m), which typically requires a very deep foredeep in which to be deposited; deeper than most modern analogs. Long-term subsidence can also collect large volumes of sediments, but again, this is a somewhat rare phenomenom. Also lithologic descriptions indicate that the Tindir Group has a large percentage of (my observation: is predominantly ?) carbonate units, and has considerable volcanic constituents which are lacking in the Neruokpuk lithologies. In addition, the Tindir Group apparently lacks the metamorphic rocks which are obvious in the coarser clasitcs of the Neruokpuk.

B. Post-Neruokpuk Sediments

Franklinian Rocks

Lerand's (1973) Franklinian Sequence is the regional succession of predominantly northerly derived (in present geography) sediments spanning the ages from base of the Cambrian to the top of the Devonian. In Canada, these sediments are typically shallow water clastics, volcanics and both reefal and platform carbonates. Much of the outcrop information on these rocks comes from the Canadian Arctic Islands, several hundred kilometers northeast of the Mackenzie Delta area. Both fold and depositional trends of the Franklinian Sequence at the Canadian Arctic Islands tend to run at approximately 90 degrees to post Neruopkuk clastics and post Katakturuk/Nanook carbonates of the bulge. Only a few wells, such as Mayogiak, which produces from Devonian carbonates, have apparently penetrated the Franklinian section in the Mackenzie Delta.

Cambro-Ordovician Equivalents

The sedimentary units which constrain the age of the Neruokpuk vary across the area. The oldest unit is the Whale Mountain Volcanics which consists of some 700 m to 1300 m of mafic volcanics, vesicular flows, agglomerates/breccias (likely lahars) that are locally silicified or welded, coarse and angular grained volcanic wackes, tuffs and widely isolated, elongate pods of limestone. The limestone, contains Late Cambrian brachiopods and intertongues with the volcanic flows and clastics.

The majority of the unit is preserved in the 80km X 10km east-southeast-trending Whale Mountain syncline. Here, it rests unconformably upon a previously folded and faulted unit of N8/PN4 (Norris, 1985b), and the phyllite component of its enigmatic Cambrian counterpart on the U.S. side (plate 1). The volcanics of the syncline are also in thrust fault contact with Mississippian carbonates along much of the north limb.

Smaller exposures of volcanic rocks exist around and atop parts of the Kikiktak mountain (figure 2, plate 1), and at the area where the upper Hula Hula river flows westward owing to structural influences. At the present stage of mapping though, data are lacking as to both the origin of these volcanics, and many of the depositional features.

Sediments of Cambro-Ordovician age are very important to the reconstruction of this area, and there appears to be at least two suites that overlie the Neruokpuk . The first consists of interbedded, varicolored chert beds and red and green phyllite which crop out along the southern part of the area and in the core of the Third Range (plate 1). Subsidiary lithologies include local, thin-bedded limestone and mafic intrusives. Altogether, it is an estimated 300 m to 1000 m thick and it represents mostly quiescent, deep water deposition.

This chert and phyllite unit overlies the mafic volcanics, and particularly the limestone facies, of equivalents to the Whale Mountain Volcanics (Reiser and others, 1980). It is unconformably overlain by the only Devonian age rock in the area (a sandstone, not shown at this scale) and Ellesmerian units. At present, data are insufficient to determine whether the chert and phyllite unit has a demonstrable affinity to the northerly derived Franklinian sequence.

The second Cambro-Ordovician-age unit is found as mostly linear bands and scattered pods of essentially coeval, deep-water sediments and volcanics that crop out along the mountain front, where the Kongakut River flows northwest to the border, and in Canada, sandwiched between N3/PN2 and the Ellesmerian rocks (plate 1). The lithologies are described as black slaty shale, locally phyllitic slate, gray phyllite, chert and argillite, with minor amounts of micaceous mudstone, siltstone and quartzite, and some limestone.

A Late Ordovician graptolite was recovered from the black shale, which may correlate to the Road River Group. This correlation would provide an important link between the thin distal sediments in this area and the thick wedge of sediments originating from the Selwyn basin to the south (Fritz, 1985) where the Road River Group exceeds 1000 m and includes thick massive carbonates. However, this too would preclude its inclusion into the Franklinian sequence. Carter and Laufield (1975) report that Silurian and Ordovician fossils (chitinozoans and a graptolite) have been recovered from cores of moderately- to steeply-dipping (20° to 70°N) basement rocks along the Barrow Arch at Barrow gas field and at Prudhoe Bay oil field. These correlations also would extend the amount of southerly dominated deposition from the North American plate/craton at the expense of Franklinian deposition.

Fortunately(?) for correlations, this area is several hundred kilometers from coeval possible Proterozic and Lower Paleozoic sediment source areas. Thus for speculative correlations it is quite possible to ignore or erode away the troublesome parts of the stratigraphy that do not fit. One example is the volcanic facies of the Tindir Group, that are apparently absent from the Neruokpuk. Another example is the absence from the bulge, of any of the nearly complete section (excepting, perhaps, the thin

Road River sediments of various Lower Paleozoic carbonates and clastics that overlie the Tindir Group in the Yukon-Porcupine drainage.

C. Pre-Cambrian to Devonian Carbonates

Katakturuk Dolomite

The Katakturuk Dolomite is one of two enigmatic carbonates that forms the core of the Sadlerochit and Shublik Mountains. At present, the Katakuruk and unconformably overlying Nanook Limestone are known to be in contact only in these two mountain ranges. The Katakturuk is also exposed at the core of Kikiktak Mountain, east of the Shubliks (plate 1). There is an unconformity between the Katakuruk and the Nanook, and a marked angular unconformity between them and the overlying Ellesmerian sediments (plate 2). This is similar to the relationship between the Neruopkuk sediments and the overlying Ellesmerian rocks. Typically these carbonate units are considered as basement for most assessment purposes (Hubbard and others, 1985; Bird and Magoon, 1987).

There is as yet, no congress as to the origin, emplacement and corellation of these Proterozoic and Lower Paleozoic carbonates to the Neruopkuk and related coveal sediments. The Katakturuk and Nanook are areally limited to only the northwest portion of the bulge. Both the Katakturuk and Nanook are mostly massive platform carbonates, rather than thin basinal and interbedded lithologies. They crop out in linear east-west trends, rather than being part of the regional curvilinear expression of the Neruopkuk outcrops. These outcrops are fault bounded where the basal portions are exposed along the front of the Sadlerochits and Shubliks.

From these mountain front trends, it is quite possible that the same platform carbonate lithologies and fault emplacement style are present in the cores of the Third and Fourth ranges. The Katakturuk, a dolostone, (Dutro, 1970) is the very thick, mostly massive, south-dipping (approximately 30 degrees), east-west trending core of the Sadlerochit and Shublik Mountains. It is typically very dense and is commonly gray, or white. The lithology represents predominantly shallow water-deposited algal mats,lime muds and grains with minor black-and-white, banded stromatolites.

I have observed that the dolostone is locally silicified, locally has quartz veins, is highly fractured and has elongate, normal-to-bedding, vugs that are especially well developed in both the lowest mappable and the uppermost members (Canning R. A-1 well penetrated some 190 m and cored some of the upper member). Robinson and others (1989) identified and mapped some 16 members comprising more than 2500 m of section.

There are two mafic volcanic units associated with the Katakturuk. At the west end of the Shublik mountains, there are dark brown or gray pillows or scorias of metabasalt and diabase. These underlie the carbonate facies of the Katakturuk, and are overlain or intebedded with thin-bedded and finegrained quartzose sandstones. On the northeast side of the Sadlerochit Mountains, there are mafic flows, pillows and breccias exposed within the lower facies of the Katakturuk carbonates. Moore (1987) describes field relationships, geochemistry, petrology and subsequent tectonic implications of their deposition/emplacement.

Recent workers (Blodget and others, 1986; Clough,1989) have revised the age of the Katakturuk from Devonian (Dutro, 1970) to Proterozoic or lowermost Cambrian. This revised age based on stratigraphic relationships with the unconformably, overlying and sparsely fossiliferous Nanook Formation, and equivalents to the Whale Mountain Volcanics, near Kikiktak Mountain. Mapping by Clough (1989) indicates that some 500 m of the Katakturuk may have been removed by pre-Nanook erosion.

Nanook Limestone

Units of the Nanook Limestone unconformably overlie the Katakturuk Dolomite. They are present in the central part of the Sadlerochit mountains and form the core of the Shublik mountains (plate 1). The Nanook represents at approximately 1300 m (Clough 1990) of light gray limestone, with minor amounts of gray shale and some siltstone. Lateral facies are mappable east-west, but are not as extensive as in the underlying Katakturuk formation. Fossils recovered from some of the lower part, but not the lowest part, of the formation are as old as Upper Cambrian and along with regional considerations, suggest an early Cambrian or uppermost Proterozoic age for the base of the Nanook (Blodget and others, 1988).

There is at least one major and angular unconformity within the Nanook. The upper members below the unconformity have yielded fossils of Cambrian through Ordovician age. Blodget and others (1988) report approximately 107 m of fossiliferous Devonian strata (Emsian stage and younger) that are preserved only in the eastern end of the Shublik Mountains. Paleoenvironmental reconstructions of these carbonates show that they are both east-west trending platform carbonates, with persistent to extensive, mostly shallowing upwards facies (Blodget and others, 1988, and Clough, 1989).

The Katakturuk thins to some 1800 m in the Shublik mountains. Further south, in the Third and Fourth Ranges there are black dolomite and shale lithologies. These black dolomite and shale units are currently mapped as N6 of the Neruokpuk Group (plate 1), but they may, in fact, represent coeval basin-margin and basin-plain equivalents of a south-facing Katakturuk carbonate platform. (Clough, 1989).

It is not immediately clear exactly how these thick and apparently coeval carbonates are related to the Neruokpuk and Franklinian depositional sequence rocks, respectively. They have distinct lithologies which differ significantly, one from the other. The carbonates of the Katakturuk are typically dolomitized, and silicified, yet the Nanook has certain similarites to the Franklinian Devonian carbonates from the Canadian Arctic Islands. Neruopkuk-type pulses of sedimentation are absent.

Both the Katakturuk and Nanook carbonates and Neruopkuk clastics dip predominantly to the south at outcrop. Consequently, both suites may represent the south-dipping southern domain reflectors identified on the 1002 area seismic lines (plate 3). Lower units of both lack fossils and upper units of both have been eroded at a pre- Ellesmerian unconformity. Both are suggested to have affinities to coeval Tindir Group strata to the south in the Yukon and Porcupine drainages, but in mutually exclusive manners: the Neruokpuk represents turbidity current deposited equivalents of the Tindir Group; and the Tindir Group with its overlying succession of lower Paleozoics are basinward equivalents of the Katakturuk and Nanook platform carbonates. Thus there is ample justification for postulating that these separate and coeval suites of rocks represent two or more well defined litho-tectonic terranes.

In addition, there is a major unconformity between the Katakturuk and Nanook. Even though these carbonates represent similar depositional environments (south-facing carbonate platforms), they represent distinct and separate periods of carbonate deposition. The angular unconformity separating the upper, Devonian age part of the Nanook also suggests another discreet period of carbonate sedimentation.

Consequently, rocks exposed in the Third and Fourth Ranges, identified as Neruokpuk may be assigned to the part of either the Katakturuk or Nanook depositional sequences. This is particularly valid for the carbonate sequence of the Fourth Range which has affinites to both N6 of the Neruokpuk and to a possible basinal facies of the Katakturuk. The Fourth Range carbonates are geographically closer to the Katakturuk rocks in the Shublik mountains than to the Neruokpuk. Also, the style of its emplacement is similar to the east-west trends displayed in the Sadlerochit and Shublik mountains.

D. Pre-Ellesmerian Seismic Reflectors

Plate 2 shows two thick and separate sequences present in the stratigraphy of the bulge. Their compositions suggest that they may be coeval, but probably preserve different episodes of sedimentation. Hypotheses treating them as discreet tectono-stratigraphic terranes or postulates that they are depositionally linked to coeval Tindir Group rocks require additional basic sedimentological data. In addition relationships between the Neruopkuk and Katakturuk/Nanook carbonates are also unclear.

Subsurface CDP seismic data from the ANWR 1002 Coastal Plain analysis shows that there is up to or greater than, 4 seconds (two-way travel time) of reflectors beneath the mapped Ellesmerian Sequence (plate 3). These reflectors may correlate either to the Katakturuk and Nanook carbonates or to the Neruokpuk. Most reflectors are not areally extensive, but they tend to be rather strong despite interference from fault diffractions and ice burst effects commonly seen in the lines published for the 1002 area of ANWR. These reflectors commonly have an angular contact with respect to the 'top of the pre- Mississippian' (TPM) reflector, which was the regionally mapped unit (plates 2 and 3).

Fisher and Bruns (1987) identify two major domains based on the geometry of these pre-Mississippian reflectors, and two important horizons present beneath the western half of the 1002 area, where data were favorable for interpretation.

The southern domain reflectors dip to the south much like both Leffingwell's Neruokpuk and the Katakturuk and Nanook carbonates, and are cut by north verging thrusts (see plates 3, 4, and 5 USGS Bulletin 1778).

The northern domain reflectors are more continuous, dip more steeply, and generally dip to the north, except at the coast where dips are steep and varied. Horizon A is the base of the north domain reflectors. These reflectors show possible onlap geometry with respect to Horizon A (plate 3). Basement-controlled, rift-associated normal faulting drops these reflectors very deep in the adjacent offshore (north). Horizon B is the base of southern domain reflectors (USGS Bulletin 1778, figures 18-1 & 2). Fisher and Bruns (1987) also suggest that part of the sequence thickness, and two-part geometry be attributed to triangle-zone-style deformation.

This style is similar to the compressional deformation in which multiple repitions, usually referred to as duplexes, uplifted the sediments forming Marsh Creek anticline feature which is a prominent feature in the west part of the ANWR 1002 area. This style of deformation can dramatically increase seismic interval thicknesses.

Seismic definition and character deteriorate substantially across the 1002 area and trends in the eastern portion are less clear. The publicly released seismic data (from the U.S. Interior Department 1002 Area Coastal Plain Assessment and USGS Bulletin 1778) show that north verging thrust faulting is more extensive eastward, at the expense of the north domain reflectors. The south domain rocks are considerably shallower in the east. An eastward continuation of this trend (suggested by the Bouguer gravity anomaly map on USGS Bulletin 1778, plate 2) could explain the lack of Ellesmerian rocks exposed at the mountain front along the international border (plate 1).

Finally, there is the consideration of the oil potential of these rocks. Field descriptions suggest that these rocks have been locally metamorphosed to the greenschist facies and even intruded by the Okpilak batholith and consanguineous igneous rocks. Lithologic descriptions commonly include argillite, phyllite, assorted wackes and universally lack terms pertaining to petroleum (such as porous, permeable, stained, etc.).

However, basement-penetrating (more correctly, pre-Carboniferous) wells in the Pt. Thomson areaencountered up to 130 m of, as yet unassinged, dolostone, argillite, phyllite, sandstone, shale and limestone lithologies with shows and tests of hydrocarbons (plate 1, table 1). These unassigned lithologies are similar to Neruokpuk N6. Considering the similar descriptions, and subsurface seismic coverage, it appears likely that hydrocarbons can at least migrate through these Proterozoic to Cambrian(?) Neruokpuk, or Katakturak/ Nanook rocks. Oil migration is important as the prospects identified in the 1002 coastal plain analysis may be, in part, comprised of Neruokpuk sediments.

The hydrocarbon producing potentials of the coeval Katakturuk and Nanook carbonates and the various facies of the Franklinian sequence rocks are as yet largely unrealized. Devonian-age Franklinian Sequence carbonates at Mayogiak on the Aklavik arch, produce oil in the Mackenzie delta area (figure 4). Drill stem tests of the upper member of the Katakturuk at Canning River. A-1 produced more than 320 m3/day fresh water from vugs and fractures (table 1). Outcrop descriptions of Katakturuk lithologies frequently note common-to-abundant fractures and vugs. Nanook limestone lithologies are mostly fine grained-to crystalline. However the presence of one or more intraformational unconformities supports postulates of enhanced secondary porosities and permeabilities developing upon the unconformity surfaces. These various carbonate units also share a possibility, with the Neruopkuk, of being the basement rock of the Point Thomson area (table 1).

Of more importance though, is the similar possibility as with the Neruokpuk rocks, that it is these carbonates forming the 1002 area prospects.

E. Granitic Rocks

Plate 1 shows exposures of granitic rocks in the bulge. The larger body is the Okpilak batholith which covers approximately 370 km2. It is also in the area of the highest peaks. The smaller body, to the south is the Jago stock which covers less than 35 km2. The Mt. Sedgewick, Ammerman granites are additional small igneous bodies located some 50 km. to the south and east, in Canada (Norris and Yorath, 1981). The 1700 km2 Old Crow batolith is approximately 150 km to the south.

All these granitoid bodies are acidic igneous intrusive typically described as very-fine-grained to very-coarse-grained, quartz monzonites to syenodiorites, having mostly gradational textural contacts. Sable (1977) reports that the granites in the bulge have common biotite, and muscovite accessory minerals, common galena, pyrite, chalcopyrite, and purple fluorite. Precious metals and pegmatites are lacking. All these grainitoids are also severely weathered and commonly hydrothermally altered which results in abundant grus. Sable (1977), Norris and Yorath (1981), and Dillon and others (1987) report on radiometric age-date determinations for these plutons.

Maximum ages are determined (lead-alpha and potassium-argon from biotites and horneblendes, and lead-lead from zircons) to be approximately 430 ma which is roughly the Silurian-Devonian boundary. Further analyses (lead losses) suggest overprinting at approximately 60 ma dates associated with tectonically driven orogenesis.

Table 1. Oil and gas tests from wells in Point Thomson Unit

WELL	INTERVAL (meters)	GAS Mm^3/day	OIL MT/day	GOR m^3/MT	API degrees
		BASEMENT COMPLEX			
Sohio AK Is 1	4571-4579	62.3	24.5	2542	>40
Exxon AK St F1	4249-4365	70.1	21.3	3291	35
Exxon AK St A1	3961-4018	salt	water		
		POINT THOMSON SANDS			
Exxon AK St C1	4092-4133	96.3	122	789	37
Exxon AK St F1	4204-4232	120	39.8	3015	35
Ex. Pt.Thom.U1	3912-3924	109	28.9	3772	45
	3951-3978	377	320	1178	18
Ex. Pt.Thom.U3	4228-4232	180	66.6	2703	38
		COLVILLE TURBIDITES			
Exxon AK St A1	3830-3851	62.3	350	178	23
Exxon AK St F1	3669-3682	3.3	19.2	172	22
Ex. Pt.Thom.#1	3472-3481	63.7	18.5	3440	44
Ex. Pt.Thom.#2	3530-3559	3.5	34.7	101	21
Mobil W.Staines	3551-3570	flowed	2.4		

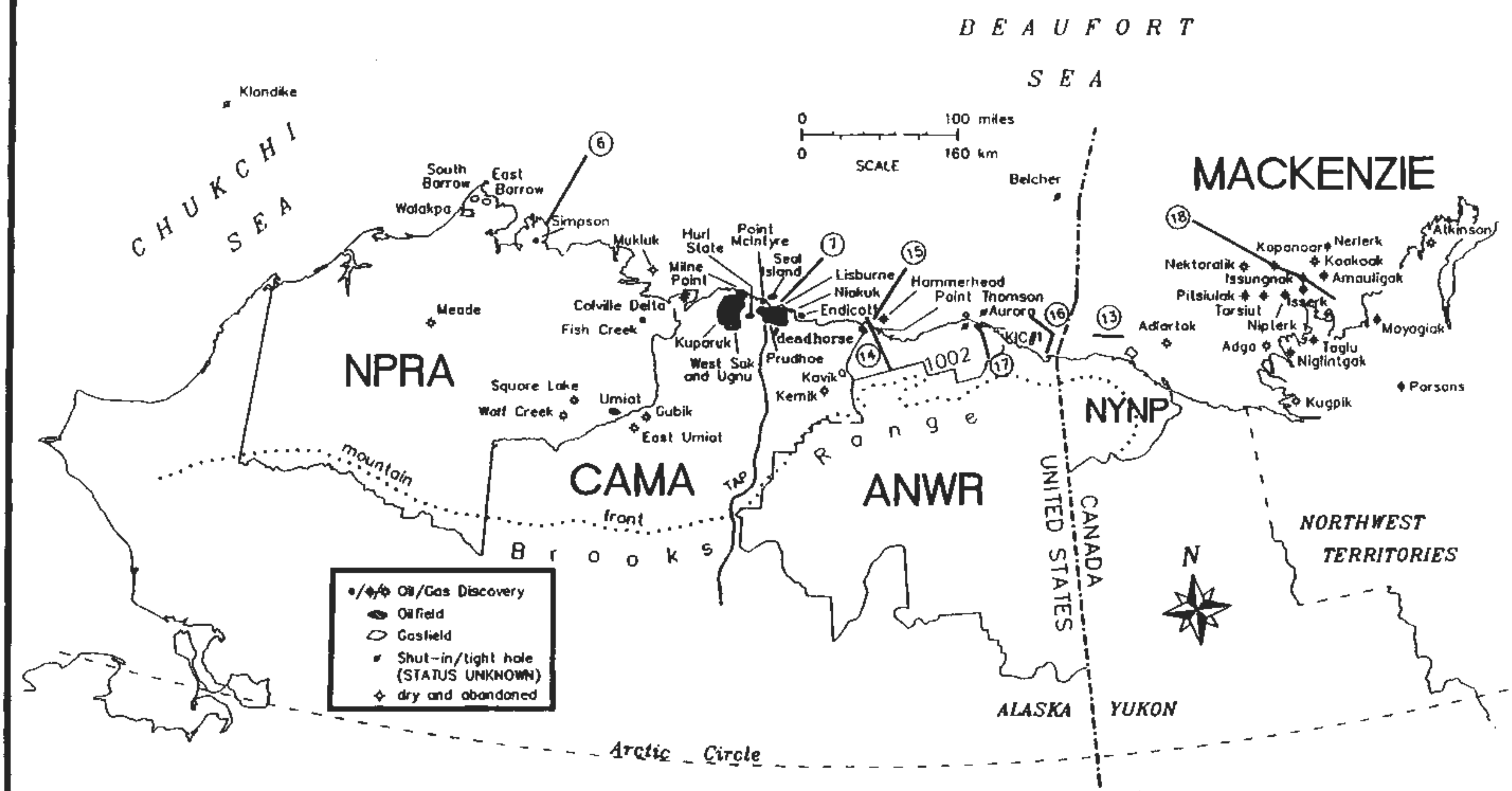


Figure 4. Some of the major oil and gas activities in the Arctic

including the National Petroleum Reserve—Alaska (NPRA), Central Arctic Management Area (CAMA), Arctic National Wildlife Refuge (ANWR), and Northern Yukon National Park (NYNP)

(Key: numbered circles show seismic line location and figure reference)

This interpretation supports field data (Leffingwell, 1919; Mertie, 1923; Reed, 1968; Sable, 1977) which describes the Neruokpuk as being altered by the granite, but not the unconformably overlying lower Mississippian and younger Ellesmerian rocks. Leffingwell (1919) noted the absence of any channel lag deposits of Okpilak granite in the basal Ellesmerian Kekiktuk conglomerate, and Reed (1968) suggested that pre-Kekiktuk erosion removed more than 10 km of section. Bouguer gravity data (Kososki and others, 1978) shows a -130 mgal anomaly coincident to the location of the Okpilak batholith. This is the largest negative Bouguer gravity anomaly on the North Slope (Barnes, 1977).

Published density data shows that the Okpilak batholith is 2.64 g/cc vs. 2.68 g/cc for the surrounding lithologies. Geophysical modelling based on density differences does not comfortably accomodate a rooted granite having -130 mgal anomaly. And, mapping (Decker, 1987) of sheared zones at the basal granitoid contacts supports interpretation of a fault emplacement for the batholith.

Bird (1977) reports another granitoid body that has similarities to the granites of the bulge. Drilling operations at the E. Teshepuk #1 well NPRA along the Barrow Arch hit "conglomeratic sandstone" at a 3237 m. Closer analyses determined that the quartz and feldspars in the samples had an interlocking texture. A wash or lag deposit was ruled out because the grains had had no weathering rims on grains, no adhering matrix clays, no sand matrix, and no rounded or smooth edges.

Bird and others (1978) report that the E. Teshepuk granitiod yields discordant radiometric age-dates (332 ma from K-feldspar and 243 ma from biotite). These are considered minimal ages from slightly altered feldspar which suggests that the actual age is closer to the age of the granites of the bulge. X-ray fluoresence analyses of these cuttings are comparable to the Okpilak batholith composition chemistry (Bird and others, 1978). In addition, the E. Teshepuk granite is assosciated with a Bouguer gravity negative anomaly. However, it is not as significant as the Okpilak anomaly, which may be due to differences in surrounding bedrock types, mode of emplacement or geometry of the subsurface body(bodies). Barnes (1976) shows an irregularly shaped, northwest trending -20 mgal anomaly on the east side of Teshepuk Lake. Bird and others (1978) report that the well is on the flank (as defined by the -20 mgal contour) of this inferred feature.

F. Ellesmerian Sequences

Lerand's Ellesmerian Sequence (1973) detailed northerly-derived sedimentation from the Upper Devonian to the Jurassic. Typically, these units are treated as a single entity. However, Hubbard and others (1987) further divide the northerly derived, petrologically mature provenance sediments into depositional megasequences owing to the much more extensive data base that is available for the post Upper Mississippian stratigraphic section. Each megasequence boundary is coincidental to regional unconformities as a result of basin response to adjacent tectonic processes (Hubbard and others, 1985). Devonian-age regional uplift and the post-orogenic emplacement of the Okpilak Batholith and associated plutons marked the initial stages of clastic deposition.

Lower Ellesmerian Megasequence

Hunt Fork Shale and Kanayut Conglomerate

This basal megasequence of Ellesmerian rocks is not known in the area of the bulge owing to both erosion and non deposition. But elsewhere, for some 1000 km across the length of the Brooks Range, it is only known from structurally allocthnous blocks. Yet, the Hunt Fork Shale and the overlying Kanayut Conglomerate (Lower Devonian) represent some 2600 m of a major northeasterly derived synorogenic clastic wedge (Nielsen, 1981, Moore and Nielsen, 1984). Depositional facies range, upsection, from deep water basinal, black, sparsely fossiliferous shale with some turbidity current deposits through massive-bedded, nonmarine, braided-stream, cobble conglomerates.

Middle Ellesmerian Megasequence

Endicott Group

A marked, angular unconformity separates Hubbard and others' (1987) first and second Ellesmerian megasequences in this part of Alaska. They show this to be a major regional erosional and tectonic event marked by regional folding and faulting patterns. This is also the top of the pre-Mississippian (TPM), reflector that was mapped for the ANWR 1002 oil and gas analysis report. Seismic time-maps of the TPM show the extent of large, seismically identifiable prospects. Plate 1 shows the exposures of the Ellesmerian rocks.

These are essentially juxtaposed to the outcrops of the older rocks on the Alaska side of the border roughly forming a Romanzof Mountains anticlinorium. Whereas on the Yukon side of the border, the Ellesmerian rocks are largely removed by erosion. Middle Ellesmerian megasequence deposition began with a Lower Mississippian transgressive sequence that is known the length of the Brooks Range. The Kekiktuk Conglomerate is the basal unit of the clastic Endicott Group. The Kekiktuk usually consists of up to 120 m of siltstone, fine-to medium-grained sandstone and conglomerate, deposited predominantly in braided and meandering stream environments. Thin (generally <1 m thickness) coal beds of anthracite rank are present in deltaic lithologies.

Overall, the outcrops of coarse-grained conglomerates are discontinuous along the mountain front in the bulge, but are better developed, exposed, and preserved to the south. The sandstones and siltstones are quartzose, gray or tan, with carbonized wood and leaf imprints. The chert pebble conglomerates typically have silty, gray to brown matrix material, with moderately sorted and rounded black and white chert pebbles.

At outcrop these rocks are indurated and very hard. But secondary porosities and permeabilites (averages 20 percent and 1150 md respectively) developed along unconformity surfaces and diagenetic pathways, have enabled the migration and accumulation of approximately 52 MM MT oil and 20 MMM cubic meters associated gas, in place (Berhman and others, 1985) at the Endicott Field immediately offshore, northeast of Prudhoe Bay (table 2). The Kayak and Itkilyariak shales overlie the Kekiktuk or are present in its place. The Kayak described from fresh drill cuttings is up to 400 m of gray to black fissile shale, and it is generally phyllitic at outcrops in the Arctic National Wildlife Refuge. The Itkilyariak is also phyllitic, but it is maroon or reddish at the Prudhoe Bay Field and at crops along the mountain front in ANWR (Mull and Mangus, 1972).

Lisburne Group

The Endicott Group shales grade into the platform limestones of the Lisburne Group (U. Mississippian - Pennsylvanian). These carbonates are the among the most areally extensive and resistant lithologies of the Brooks Range. They also extend into Canada, where drilling in the Mackenzie delta area has penetrated the carbonates in some 18 tests (Dixon and others, 1988). Thickness in this area is approximately 600 m.

The lower, somewhat less resistant unit is the Alapah Formation, and it is separated by a thin shale unit from the upper and more resistant, ledge forming Wahoo Formation. These limestones are predominantly hard, dense, gray, massive and micritic. Microfossils, vugs and fractures, some calcite-filled, are common throughout the section. Across the North Slope there are also zones with distinctive lithologies and fabrics like dolomites, oil shales, layers of black and white chert nodules, macrofossils and ooids.

Well and outcrop porosities and permeabilities are typically low. But, fractures and secondary porosity, mostly developed at an unconformity surface, facilitate oil production at the Lisburne Field near Prudhoe, with reserves estimated to be approximately 20 - 30 MM MT (table 2). Kumar (1989) showed some of the relationships between fracture distribution, orientation and permeabilities versus oil production from the Lisburne Field as determined from 3D seismic analyses. Nonproduceable oil column was found in the W.T. Foran well in NPRA. Residual oil was also encountered offshore at the Mukluk well.

Further west and to the south of the bulge, the Lisburne Group platform carbonates are more varied in lithology. Bird and Jordan (1977) list subdivisions used around the Prudhoe Field. From mapping further south, Mull and others (1982) reported an oil shale lithology, referred to as "blubber rock" lithology, in the Lisburne on allocthons in the central arctic area. This unique lithology may be indicative of a coeval, but completely separate Lisburne. At Tunalik well (NPRA), the westernmost subsurface penetration, more than 425 m of Lisburne was found, including 22 m of volcanic rocks (Banet, 1983). Campbell (1967) described 1250+ m of both predominantly carbonate and clastic Lisburne rocks at the its westernmost crops along the Chukchi coast.

Upper Ellesmerian Megasequence

Sadlerochit Group

A compound and regressive third Ellesmerian megasequence followed uplift, tilt and erosion of the Lisburne Group carbonates. This is the Sadlerochit Group, and it records a third phase of Ellesmerian mountain building. The basal Echooka Formation is a marine sandstone. It rests unconformably on an eroded Lisburne surface that has measurable relief in northeast Alaska. The sandstones are sorted, mostly fine grained, quartzose, white to light-gray and thin-to medium-bedded with planar cross beds.

At outcrop they are silicified with minor amounts of limonitic and glauconitic cement. These sands are hard except were oil stained. They characteristically weather to brown to rust-colored flagstones less than 0.5 m across. Thickness varies from approximately 2 m at the west end of the Sadlerochit Mountains to approximately 5 m north of the Okpilak Batholith.

Ivishak Formation

Well and outcrop data from this area record the next transgression. This is known as the Kavik Shale Member and it is some 60 to 120 m of thick, black, fissile shale, interbedded with thin, widespread units of coarsening upwards pro-delta siltstones and fine grained sandstones. Although vitrinite thermal maturities are as high as the metagenetic stages in measured samples from the ANWR 1002 area, total organic carbon analyses indicate that these lithologies may have hydrocarbon source potential in areas where correlatable facies are less severely altered (table 3).

The overlying Ledge Member sandstones (commonly referred to as Ivishak sands) represent the culmination of a major marine regression. These are thick to massive-bedded, fine-grained to coarse-grained sandstones and black and white, chert-pebble conglomerate. They are quartzose, mostly well-sorted, amalgamated channel sands representing meandering, braided streams and alluvial fan deposition. Exploration drilling finds these sands across most of the North Slope Coastal Plain. Thicknesses are variable, and up to 200 m at Prudhoe Bay. Although fossils are scarce, palynomorphs from interbedded shales yield late Permian - early Triassic age. Allochthon-resident, time-equivalent, distal facies exposed in the Brooks Range consist of banded cherty shales, interbedded siltstone and siliceous shale of the Siksikpuk Formation (plate 2).

Exposures of the Sadlerochit extend across this area and thicknesses average more than 130 m along the south flank of the Sadlerochit Mountains. These rocks are very hard and dense. They are usually completely silicified, with minor amounts of limonite cement. Typically they weather into large brown to rust-colored blocks (>1.0 m) that fracture across grains; even across the large clasts.

The Ledge is the main reservoir unit of the Prudhoe Bay Field. There, lithologies that are similar to those exposed in the Sadlerochits, have porosities up to 35 percent and permeabilities in excess of 4000 MD (Jamieson and others, 1980) owing largely to secondary porosity from unstable grain dissolution along unconformity surfaces and diagenesis of the cements. In fact, the entire column at Prudhoe tends to be heavily oil-saturated to the extent that production is limited mostly by permeability barriers. Original in-place reserves were estimated to be ~4.144 MMM MT oil and ~850 MMM cubic meters of gas (table 3). Approximately 1100 MM MT has been produced since 1976, and improved recoveries may approach 50 percent of the original in place reserves.

The Ledge sandstone is overlain by the thin and interbedded gray to dark-gray and black siltstones and shales of the Fire Creek Siltstone Member. This is a regionally discontinuous unit due to erosion.

Most individual silststone beds are less than 0.1 m thick and the entire unit ranges in thickness from approximately 30 m to 60 m where it crops out on the south side of the Sadlerochit Mountains.

Shublik Formation

Restricted marine conditions persisted with the deposition of limestone, calcareous sandstone and black phosphatic shale. These lithologies comprise the regionally extensive Shublik Formation. The limestone and shale are black, with phosphatic concretions, and typically bear Monotis and Halobia fossils. The calcareous sandstones are mostly gray with lesser amounts of concretions and fossils. These lithologies are widespread across the north side of the Brooks Range. They are also usually associated with high concentrations (mass percent) of organic carbon and phosphate. Specifically, these are oil prone indigenous kerogens and are thus considered to be rich source rocks. Geophysical logs usually show this interval to be high ("hot") in natural gamma radiation and readily identified. Facies become more mud rich and less calcareous or phosphatic to the south (plate 2). Coeval units in the Brooks Range are the Otuk Formation and Blakenship member.

The critical timing of the uplift, erosion and porosity enhancement followed by the subsequent burial of the thermally maturing Shublik source rock, in migrational proximity to the Sadlerochit reservoir sandstones, created the North Slope hydrocarbon habitat that bears the Prudhoe Bay and lesser fields (table 2). At Prudhoe, the Shublik is also an oil-bearing reservoir rock. At the Kemik and Kavik anticlines it tested dry for oil, but has presently subeconomic amounts of gas.

Karen Creek/Sag River Formations

Stratigraphically equivalent units, the Sag River and Karen Creek (U. Triassic) sandstones, overlie the Shublik. These sand bodies are widespread across the North Slope and are typically found in wells in NPRA to outcrops in the mountains south and east of the 1002 area of ANWR. They have characteristics of shallow marine depositional environments. This regional regression marks the end of Hubbard and others' (1987) third megasequence and final pulse of Ellesmerian sedimentation. These sands are mostly siltstone to very-fine-grained sandstone, white to light gray, generally quartzose with common-to-abundant glauconite, and they are typically bioturbated. Thicknesses range up to 16 m and the unit is a minor reservoir at Prudhoe due to secondary porosities. At the Kavik anticline it tested gas from fractures. At outcrops in this area, it is silicified and hard, commonly fractured, with some quartz veinfill, and it weathers tan to brown.

G. Breakup Sequences

The breakup megasequence rocks record the series of tectonic events that terminated regional sedimentation from the northern orogenic influences and effected the opening of the Arctic Ocean-Canada basin. This was a discontinuous and multistage process which involved multiple prerift, failed-rift and rift uplifts. Accompanying suhsidences formed by predominantly high angle normal faulting and filled during alternating energetic erosional and quiescent periods. Depositional centers were along a predominantly east-west trending, basement-linked feature now referred to as the Barrow Arch (figure

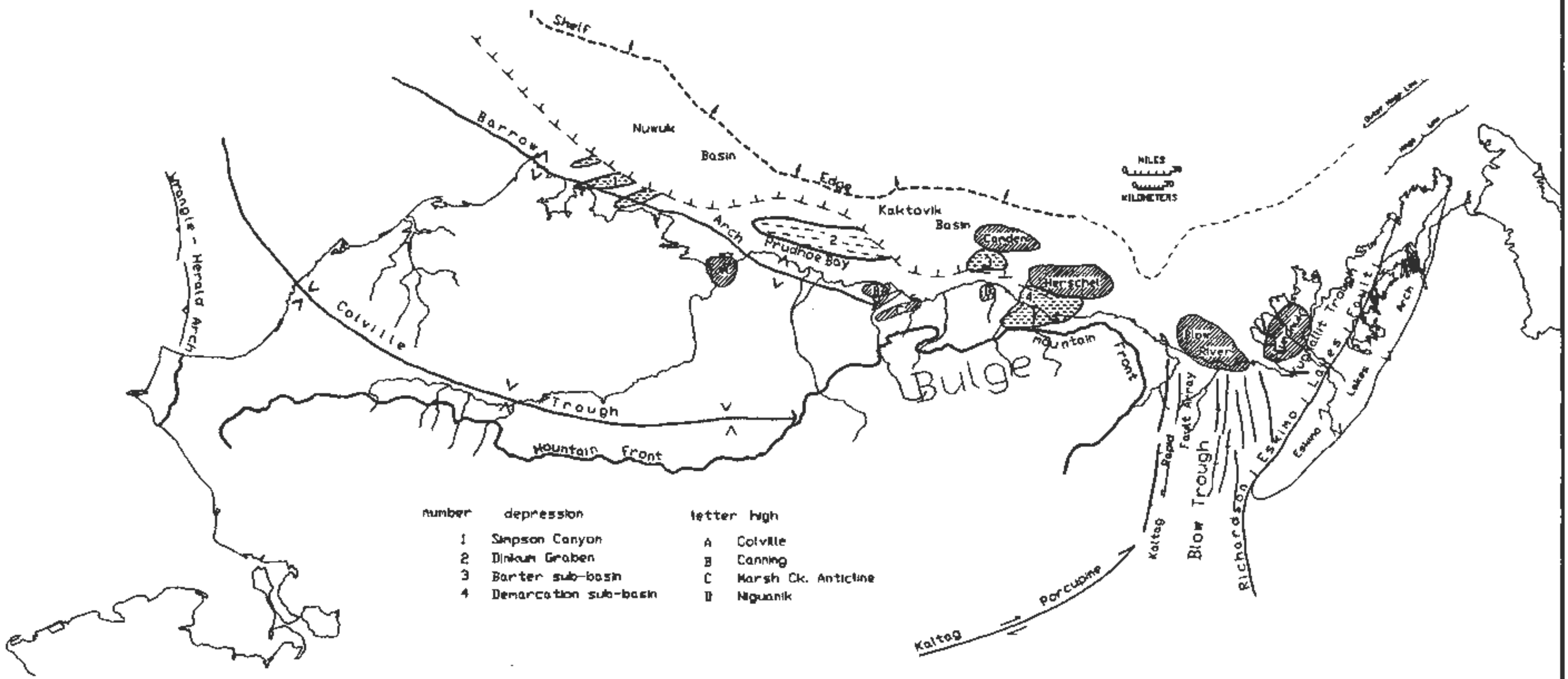


Figure 5. Major North Slope-related tectonic features

(Key: sub-basins listed by number; highs named or have letter designations)

5). The major down to basin normal faulting is controlled by the spreading that opened up the Canada basin. This is the Hinge Line, and it is mostly immediately north of the Barrow Arch proper (figure 5) which is the structural culmination of the Breakup uplift. Thus there are limited areas of pre- Breakup rocks preserved north of the Arch and south of the Hinge Line.

Kingak Shale Formation

The Kingak Shale (Jurassic - L. Cretaceous) is disconformable upon the Ellesmerian Sequence Sag/Karen Creek sandstones. It represents two North Slope transgression/regression couplets, the lower Breakup megasequence (Lower Beaufortian) and the major change in basin polarity (Hubbard and others, 1987). It is found in wells of western NPRA and almost continuously at mountain-front outcrops across Alaska, into the Yukon Coastal Plain (usually swales or covered by float since it is not a ridge-forming unit), and there is a lithologically similar unit in wells in, and outcrops around, the Blow River Trough (plate 1, figure 5).

Consequently, this unit represents quite different interpretations to different investigators working outcrops as opposed to working the Barrow Arch area. Workers after Lerand (1973) or Bird and Molenaar (1987) who work in the Brooks Range typically include the Kingak with the Ellesmerian Sequence. Coeval lithologies preserved only on allocthons are also believed to record some of the earliest subduction-related precursors of the Brookian events. Hubbard and others (1987) and Carman and Hardwick (1983) modify sequence nomenclature to accommodate a discrete separate and regionally extensive northerly derived depositional event between Ellesmerian and Brookian rocks.

Across northern Alaska, the Kingak thickens southward from the Barrow Arch area into the Colville Trough where it is at least 1000m of section. Drill hole and seismic data show mostly thin, typically interbedded, mostly discontinuous sandstone and siltstone units within the Kingak Shale immediately on both sides of the Barrow Arch. Drill hole data from the Colville trough and outcrop data from the mountain front show that it is mostly dark gray-to-black shale with some bentonitic beds, quite silty, and locally fissile. The Colville trough data show the Kingak to represent undisturbed, deep-water, trailing-margin sedimentation.

The Kingak shale crops out both in the mountains and on the Coastal Plain in ANWR where it is gray-to-black, very silty shale with some mega-fossils including crinoids and ammonites. Farther south and particularly west, it and older formations, (the Sag River/Karen Creek, Shublik and Ivishak) grade into the rhythmically interbedded chert, siliceous shale and silicified limestone lithologies of the Otuk Formation (Bodnar, 1985) which are only exposed on allochthons in the Brooks Range (plates 2 and 3).

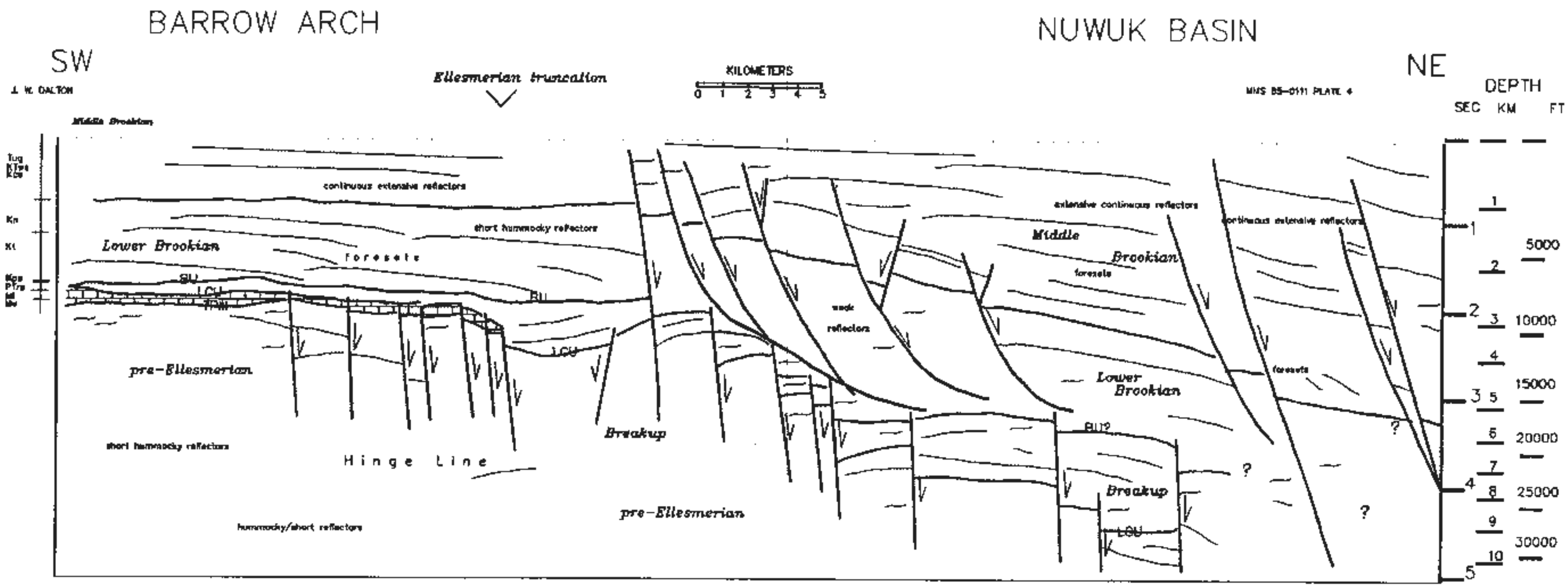
Both the shelf and slope facies, however, have units with significant amounts of indigenous organic carbon and can be considered potential hydrocarbon source beds. Bentonite beds in the upper part of the section are attributed to the onset of subduction related volcanism and precursor to Brookian uplift and sedimentation which may have started as early as the Bajocian stage. The northern suite of interbedded and coarser- grained clastics marks several tentative beginnings of rifting/pre-rifting that opened the Arctic Ocean. The easterly-plunging Barrow Arch is a remnant of that uplift. In northeast Alaska at the Point Thomson/Flaxman area, the Arch complex is comprised of mildly metamorphosed (probable unit N6) Neruokpuk sediments that are some 2000 m deeper than the more metamorphosed rocks that form the basement at the Arch's apex near Barrow. Sporadic and episodic pulses of mostly fine-grained, quartzose but argillitic and glauconitic clastics were shed from these early rift associated uplifts and incorporated into the Kingak.

Despite some petrologically poor reservoir potential, wells in the Barrow area tap these sands for gas reserves (arguably commercial) and similar-age sands (L. Jurassic) at Walakpa have been tested for gas reserves (table 2). Both sands have oil shows. The more widespread sandstone units such as the Simpson sandstone from NPRA mark the mostly regional mid-Jurassic (Bajocian) disconformity while rift/ pre-rift influences were negligible. It also divides the Kingak into a widely recognized lower and an upper unit.

Coeval facies in Canada are mostly black, fissile to very silty shales. Poulton (1982) describes thin-bedded probable turbidite sandstones and shale on the Coastal Plain immediately east of the U.S. border. These crop out atop the N3 unit of the Neruokpuk sediments either unconformably with all Ellesmerian Sequence sediments eroded or as an allochthon at a fault contact (Norris, 1985b, 1986). East of the Rapid Fault array in the Blow River Trough, there are cyclic, coarsening-upwards (medium-to coarse-grained), glauconitic sandstone and shale sequences. These are easterly derived sediments that shale out entirely or are faulted away by the north-south strike-slip components of the Rapid Fault Array towards the bulge (figure 5). The organic thermal maturities of these facies tend to be high and typically into the metagenetic range; considerably higher than the thermal maturities seen in the U.S., except for some fault uplifted Kingak exposures within the mountains.

Upper Breakup Megasequence

The upper break up megasequence also consists of two early to mid-Cretaceous depositional sequences: these, recording the effects of successful rifting! Across most of the North Slope there is discernible angular unconformity between the two breakup sequences (figures 6 and 7). This is commonly known as the Lower Cretaceous Unconformity (LCU), at which the Kingak and older sediments are truncated along the Barrow Arch as observed in NPRA, the Prudhoe Bay area and in wells adjacent to-and at selected outcrops in the western part of the bulge. Carman and Hardwick (1983) first presented the concept of localized, non-Ellesmerian and non-Brookian sediments along the trend of the Barrow Arch. They limit their Barrovian breakup sequence to these rocks above the angular Lower Cretaceous Unconformity (LCU) in their detailed subsurface analysis of the clastic sediments of the Kuparuk Field area. Craig and others (1985) call these the Rift Sequence rocks in their Beaufort Sea analysis.



BU Breakup unconformity

LCU Lower Cretaceous unconformtiy

TPM Top of pre-Mississippian- truncates pre-Ellesmerian

Figure 6. Seismic profile across Barrow Arch to the Nuwuk Basin

showing the Lower and Middle Brookian megasequences overstepping the truncated Upper and Middle Ellesmerian megasequences (hatched). The Breakup megasequence develops with the down-to-basin rift faulting of the pre-Ellesmerian rocks along the Barrow Arch.

(Note: substantial vertical exaggeration; arrows show throw on faults, representative reflectors shown; unconformities weighted.)

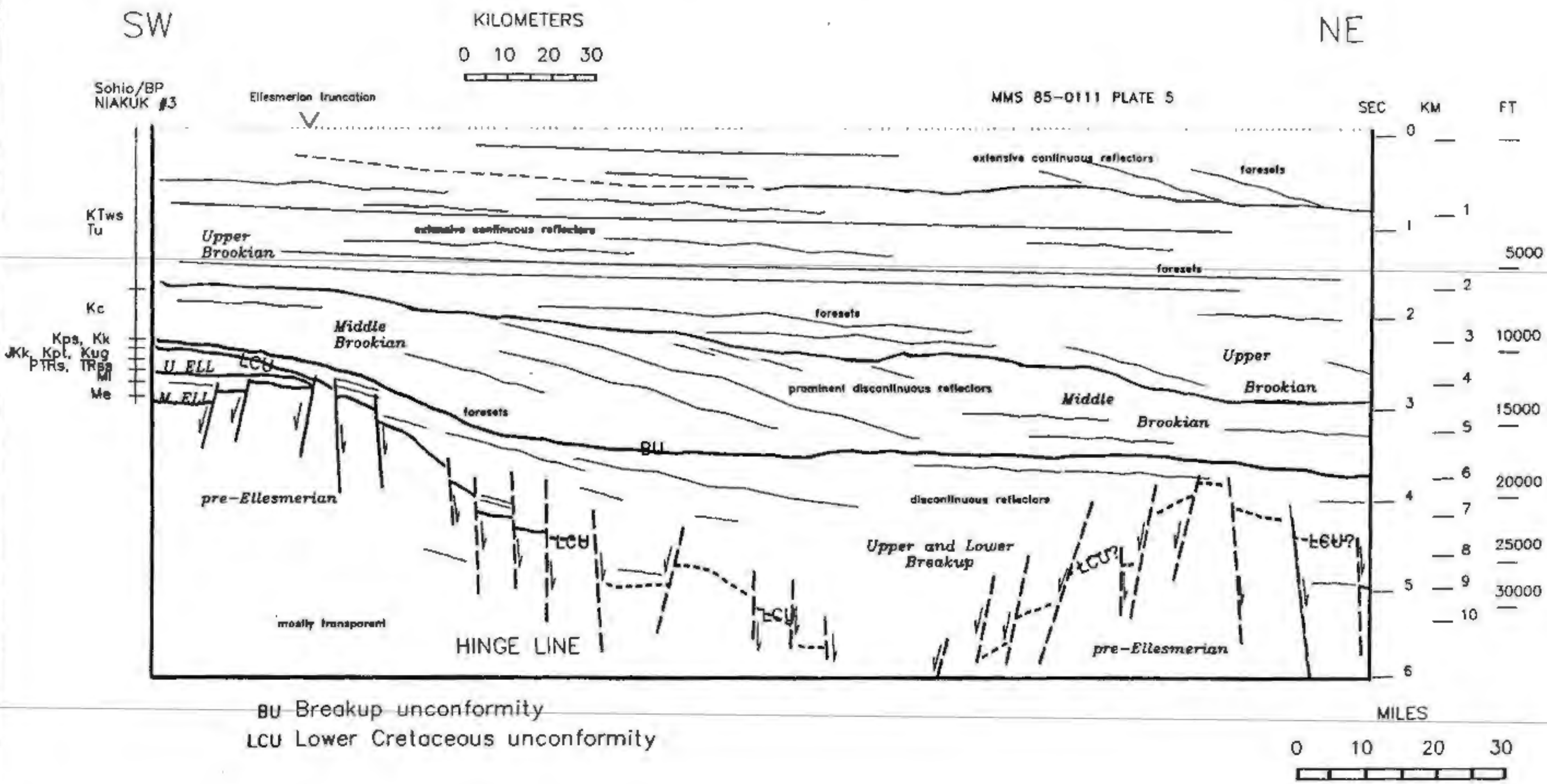


Figure 7. Seismic profile offshore from Prudhoe Bay

showing the elements of all major sedimentary megasequences.

Pre-Ellesmerian units are down-to-basin normal faulted by Breakup rifting. Ellesmerian megasequences are uplifted and truncated. Breakup units thicken markedly in the rift. Lower and Middle Brookian megasequences overstep older units and prograde seaward from Hinge Line faulting.

(Note: substantial vertical exaggeration; arrows show throw on faults, representative reflectors shown; unconformities weighted.)

Konagkut Formation

Pebble Shale

Lower Cretaceous rocks are above the LCU across the North Slope. Detterman and others (1975) describe a varied lithology that includes over 600 m of siltstone, shale, and sandstone which crops out along the Kongakut River, north of Bathtub syncline. Drill hole data and outcrops along the mountain front usually show only the shale and sandstone units.

The shales are typically black, fissile to blocky, locally pyritic, with several bentonitic beds, and they have characteristic and rounded, floating, frosted sand grains, pebbles and some cobbles. Sandstones and siltstones are thin-bedded, and not entirely uncommon. This is the Pebble Shale Unit (Hauterivian - Valanginian). It typically has one to three percent organic carbon Type II or Type III kerogens (table 3) indicating that it is capable of generating oil, gas or condensate upon reaching thermal maturity (Magoon and others, 1987).

Field scintillometer measurements and oil well gamma ray logs show a diagnostic, highly radioactive zone at the top of this unit which is a widely used marker in subsurface work on the North Slope. The Pebble Shale Unit is approximately 100 m to 150 m at outcrops and in well logs. Further west, the Pebble Shale unit extends through the subsurface of the Coastal Plain into the Central Arctic area and into NPRA. At outcrops along the mountain front, its stratigraphic relationships change and it is mapped as a member of a deep water sequence of rhythmically bedded, thin, flysch-like, fine-grained, sandstones, siltstones and shale (Gryc and others, 1951). These southernmost sediments are far removed from the Break Up geology along the Arch and tend to reflect the early stages of southerly-derived Brookian orogenic input.

Kemik Sandstone

The Kemik Sandstone (Hauterivian) is a stratigraphic unit consisting of isolated- to overlapping elongate northeast-trending sandstone bodies. Typically, these sands are some 40 km by 10 km and up to 50 m thick. Where present, the Kemik sand is the basal part of the Pebble Shale unit, lying above older units truncated by the LCU.

Kemik lithologies are mostly fine- to medium-grained, quartzose sandstones that are petrologically similar to the Ellesmerian sequence rocks. Ripple marks, large-scale trough cross beds, mud bands, and clam shell impressions are common throughout the Kemik, as are thin stringers of black and white, chert-pebble, clast-supported conglomerates. This geometry and description is characteristic of modern offshore barrier bar depositional environments. The Kemik sandstones crop out along the mountain front, are a seismically mapped unit in the Teshekpuk Lake area (Teseneer, 1985), and are known in the subsurface as far west as Tunalik well (Banet, 1983) in NPRA. Noncommercial amounts of dry gas (up to 28 MMM cubic meters at Kavik), and shows of oil and gas have been found and tested from this unit at several North Slope wells (table 2).

Point Thomson Sands

Additional Early Cretaceous breakup sands are thicker than the Kemik. But well data show that they are areally restricted to the Barrow Arch trend along the northern coast in the subsurface. These sandstones occupy grabens and/or the flanks of localized fault uplifted highs, and they are directly connected with the rifting events.

Lack of good well control away from the developed oil fields probably means that numerous localized unconformities amongst the sands and shales are undocumented, but probably important in determining hydrocarbon migration pathways and trapping mechanisms. The Point Thomson sands consist almost 100 m of fine-grained quartzose sands and conglomerates with abundant angular dolomitic lithic fragments and lesser amounts of argillite fragments. The nonmarine log character, drill cuttings lithology and petrology, and the geometry suggest that these sands are not far removed from their localized sediment source. These sands are directly adjacent to ANWR and have an estimated 49 MM MT of recoverable oil/condensate, and 141 MMM cubic meters gas.

Ugnuravik Group

Carman and Hardwick (1983) describe in detail the amalgamated, stacked, fluvial channel and shallow marine-derived sandstone units comprising the Kuparuk Formation of their proposed Ugnuravik Group. They describe these as poorly-sorted quartzose sandstones, varying from fine- to medium-grained and rarely coarse-grained or conglomeratic. Intergranular clay is ubiquitous. These sandstones were deposited as a result of localized and predominantly northwest-southeast trending normal faulting. Thicknesses vary widely across the area due to this syndepositional faulting.

Interest in these sands is excited by the estimated 630 MM MT of in-place reserves estimated to be in the Kuparuk River Field reservoirs. Subsequent onshore drilling reported in the weekly Petroleum Information news has revealed that these sands occur over an area from at least the NPRA eastern boundary, along the Colville River to Gwydyr Bay. These sandstones are typically oil bearing, having recently tested flow rates of approximately 150 MT/day from the most recent discoveries in the Colville Delta. Worldwide, syn-rift and post-rift sediments are receiving increased oil and gas activity in, for example, South America, the North Sea, Canadian Hibernia, and the west coast of Africa.

Simple extrapolation of these breakup sequence sands eastward across the Canning River, from the Point Thomson discoveries suggests an exciting, and perhaps underestimated 'play' for oil and gas exploration in the Arctic Coastal Plain and adjacent offshore of northeast Alaska, and perhaps, northwestern Yukon.

East of the Blow River Trough/Rapid Fault Array, most coeval, regressional, clastic-wedge sedimentation is linked with transtensional events (Dixon, 1982), with marine conditions predominating. Although a mostly shale-rich environment, some sands were deposited and have been the focus of some exploration for gas and oil in the Mackenzie delta.

H. Brookian Sequences

Lerand's (1973) Brookian rocks are the demonstrably diachronous and extremely thick, entirely southerly derived clastics that prograde north and east over all of the previously described North Slope tectonic and stratigraphic elements. The first of three megasequences began with deep-water, tuffaceous, turbidite-sand sedimentation several hundred kilometers to the south and west of the present mountain front. This may have been as early as the Bajocian stage, and likely no later than Tithonian of the Jurassic, in the central Brooks Range (Hubbard and others, 1987).

This initial pulse of deep water sediments comprising the basal portion of the lowest Brookian megasequence are mostly inferred as their field relationships tend to be obscured far back in the Brooks Range, or are far traveled on allochthons, or are deeply buried beyond seismic and drill hole resolution.

Lower Brookian Megasequence

Bathtub Graywacke

Lower Brookian megasequence sedimentation in northeast Alaska consists of some 800–1200 m of dark gray- green medium to coarse-grained graywacke, conglomerate, siltstone and shale which are restricted to the axis of Bathtub Syncline. Reiser and others (1980) describe these as mostly cyclic units consisting of shale interbedded with thin- to medium- or massive- bedded sandstones and chert or Ellesmerian-pebble conglomerates. Planar cross bedding, graded units, fluting, load casts, abundant carbonaceous material and plant material corroborate that these are turbidites and that they were deposited from the south. Although the Bathtub graywacke lacks fossils, Detterman and others (1975) assign the Bathtub Graywacke to younger than Pebble Shale (Hauterivian) with which it is conformable, and older than the locally unconformable Arctic Creek unit (Albian).

Fortress Mountain Formation

Elsewhere along the Brooks Range mountain front, as far west as the NPRA, there are conspicuous, isolated outcrops of similar, well indurated, often compositionally immature, nearly coeval, crudely bedded, poorly to well-sorted, lithic arenites and conglomerates. These are the Fortress Mountain Formation. Crowder (1987) summarizes these exposures as ridge-forming thumbprint synclines, and shows locations of outcrops restricted to the rolling foothills parallel to the entire mountain front (figure 8).

Overall, Crowder (1987) estimates these sandstones, conglomerates and shales may be as much as 3000 m thick, but limited exposure and section-repeating thrust faulting (as in the Awuna No.1 well, NPRA) are necessary caveats. Rather than representing a single basin filling episode, detailed field mapping (J.S. Kelley personal communication, 1989) suggests that, at least locally in the Chandler Lake quadrangle, these northward prograding clastics are separate units, and that they are possibly separated by unconformities. Consequently I suggest that all the Fortress Mountain sands of the thumbprint synclines and in the subsurface are diachronous both north-south and east-west. They represent multiple, slightly/areally limited, overlapping episodic and sporadic pulses of predominantly fault-controlled regional sedimentation from uplifts along the incipient Brooks Range mountain front.

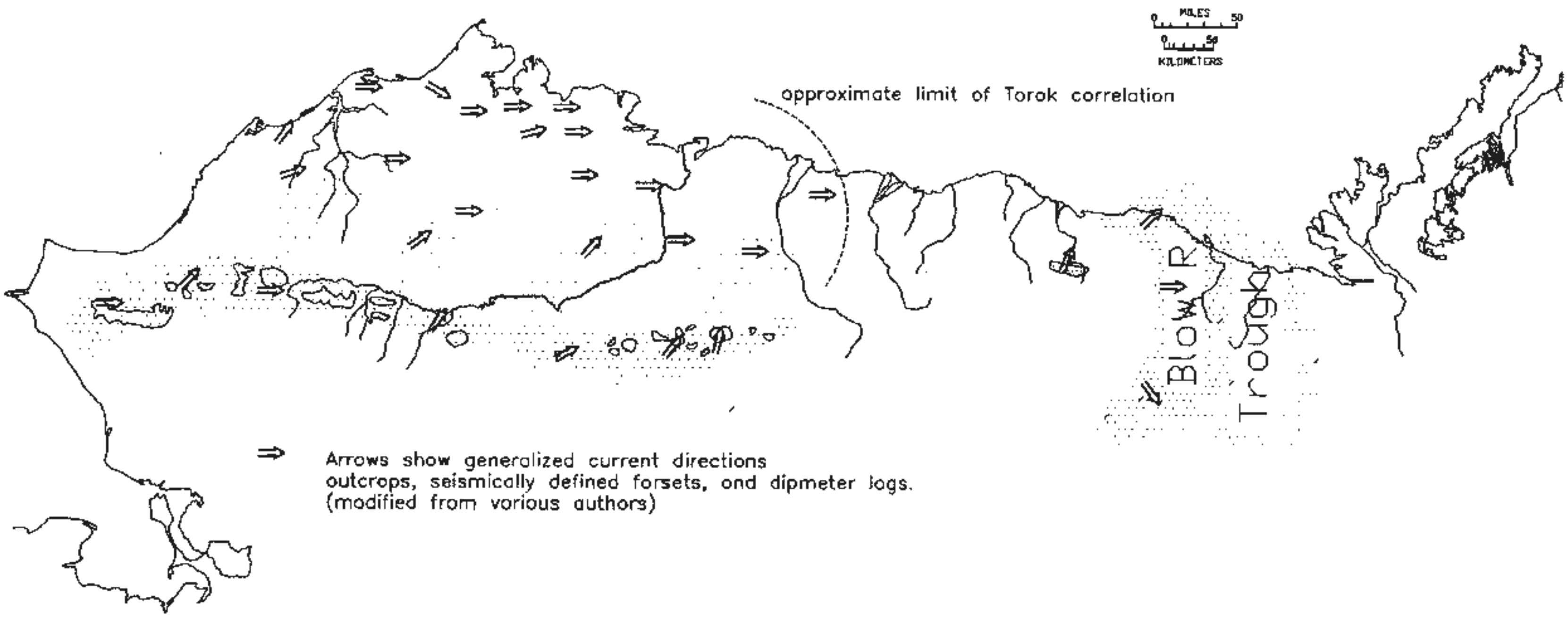


Figure 8. Lower Brookian megasequence

Fortress Mountain Formation, Torok Shale, Bathtub Graywacke, and Albian flysch

(Key: approximate extents of coarse-grained lithologies are hatched; "thumbprint" synclines are outlined)

Albian Flysch

Further east, the Blow River Trough began to receive Brooks Range sedimentation during the Albian (figure 8). Dixon and others (1985) describe a very thick flyschoid sequence of deep-water turbidites and cobble conglomerates that thins dramatically eastward. These Albian sandstones and shales overlie the Jurassic Kingak Shale in two Yukon coastal plain wells (plate 1). This is a depositional relationship somewhat similar to the break up sequence rocks along the Barrow Arch. That these sediments closely resemble coeval rocks that crop out between the Yukon and Porcupine rivers, i.e., the Biederman Argillite and Kathul Graywacke (Brabb and Churkin, 1969), lends support to portions of Smith's (1987) strike slip reconstruction of the Arctic. What is now south of the Brooks Range would have been in close proximity to the Blow River Trough and receiving input from the rising British Mountains. These Albian rocks evidently share a similar burial history also as they are pervasively well indurated with siliceous cements and thermally mature beyond the oil, gas or condensate levels (Dixon personal communication, 1988).

Torok Formation

The Torok Formation represents the distal and transgressive facies of this Albian portion of the lower Brookian clastic sequence. It is several thousand meters of black, gray or brown fissile shale, with minor bentonitic zones, thin-bedded siltstones or sandstones and multiple thin zones of high gamma ray readings. The gamma ray zones become more basal and more pronounced towards the northeast as the Torok thins. Northward progradation, as is demonstrated so clearly by the well developed foresets on NPRA seismic lines (Molenaar, 1981), onlaps upon the breakup sequence and overlaps the Barrow Arch in the subsurface west of Prudhoe. Whereas the Torok is several thousand meters thick in wells in NPRA, it thins eastward across the Central Arctic coastal plain (plate 2). Exploratory drilling shows that the Torok pinches out south and east of Prudhoe Bay. It has no identified equivalent in northeast Alaska.

Kerogens from the Torok are predominantly Type II and Type III (Banet, 1983; Magoon and Claypool, 1985; Banet, 1989) and are regionally considered to have equal potential to genetrate gas or oil upon reaching thermal maturity. Gas shows are common but minor in the sandstones of the Torok and Fortress Mountain. However, fracture-created porosity and permeability in well-indurated Fortress Mountain sandstones produced some 300 MT/day of water in Awuna No. 1 well drillstem tests (NPRA). Also with the proposition of multiple sediment provenances for these sandstones and possible different tectonic and burial histories along the range front, I suggest that it may be worthwhile to re-evaluate these sands for in-place hydrocarbon resources.

Arctic Creek Unit

The paraconformably, overlying, thick sequence of Nanushuk sandstones and shales are proximal equivalents of the Torok (plate 2). These mostly nonmarine sandstones represent the most extensive infill of the Colville trough. In northeast Alaska these are represented by the Arctic Creek unit (Bird and Molenaar, 1987) which crops out south and east of the Sadlerochit Mountains, and east of the

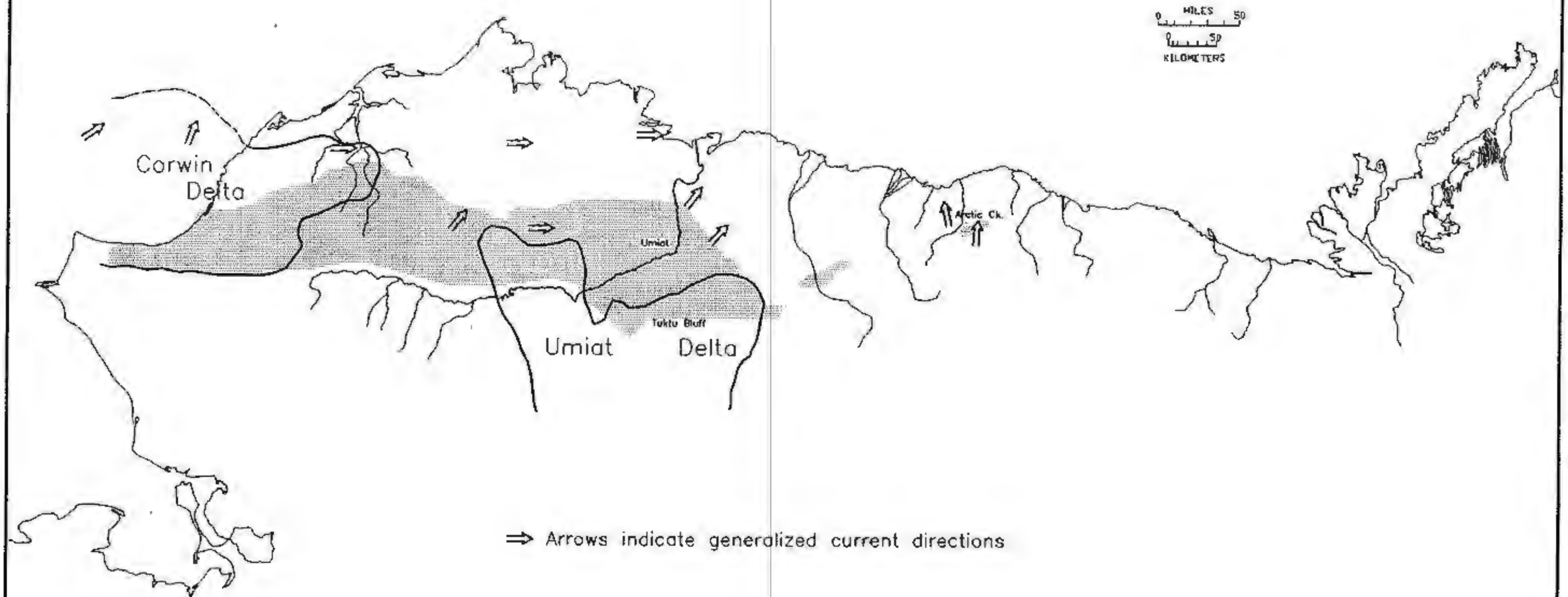


Figure 9. Lower Brookian megasequence, Nanushuk sands, and time-equivalent Arctic Creek facies

(Key: outcrop belt is shaded)

Third Range (figure 9). Detterman and others (1975) originally described these sediments and correlated them to the (Albian) Tuktu Formation from the Umiat area.

The Arctic Creek unit consists of interbedded, very fine-to fine-grained, tan-weathering, gray, flaggy, siliceous sandstone, siltstone and dark gray shale. Immediately south of the Sadlerochit Mountains (plate 1), these units are thick- to massive- bedded with flute casts, grooves and crossbeds which show current directions that indicate northwest transport. They thin dramatically eastward and the amount of plant debris and carbonaceous material on bedding surfaces increases. Dips are steep-to-perpendiular at the westernmost outcrops, decreasing to only several degrees southward, in the central part of the ANWR 1002 area.

Nanushuk Group

The Arctic Creek unit is a distal equivalent of the the Nanushuk Group. The Nanushuk Group which filled the west and central portions of the Colville trough is a regressive sequence of thin, shallow, marine sandstones and shales that become thicker and nonmarine upsection. Ahlbrandt and others (1979) identify two coalescing deltas in NPRA; the Corwin from the west and the Umiat from the south (figure 9). Sands from both fluvial-deltaic systems tend to be very fine- to fine, and rarely medium-grained, with abundant angular to subangular black and white chert fragments, in hand specimen. Bartsch-Winkler (1979) identified reactive clasts and authigenic cements which detract from inherent reservoir potential owing to loss of primary porosties and permeabilites.

The nonmarine Nanushuk crops out in anticlines and synclines of the rolling foothills from the western end of the Brooks Range on the Chukchi coast to the Sagavanirktok River. Seismic and well data show a predominantly east-northeast progradation from NPRA to approximately the vicinity of the Toolik No. 2 well in the Central Arctic area.

Nanushuk resources include vast quantities of subbituminous to bituminous rank coal. Hypothetical resources approach one MMM MT, within NPRA (Callahan, and Martin, 1984). In the three exploration phases of government sponsored phases of NPRA exploration, the Nanushuk frequently had shows and routinely produced oil and gas upon testing shallow Coastal Plain targets and foothills' structures. The greatest identified in-place reserves (table 2) are estimated to be 10 - 14 MM MT oil at Umiat field and 8.3 MM cubic meters of gas at Gubik field (Foland and others, 1988).

Middle Brookian Megasequence

Hubbbard and others' (1987) middle Brookian megasequence is a result of regional Laramide uplift. Deformation and erosion of the Nanushuk and older rocks that took place along the mountain front during episodes of predominantly northward verging thrusting and regional uplift.

After uplift these sediments were removed and the grains were tumbled, sorted and reworked. These 'rejuvenated' and compositionally more mature sediments were deposited as the thick clastic wedge of the Colville Group (U. Cretaceous - Eo-

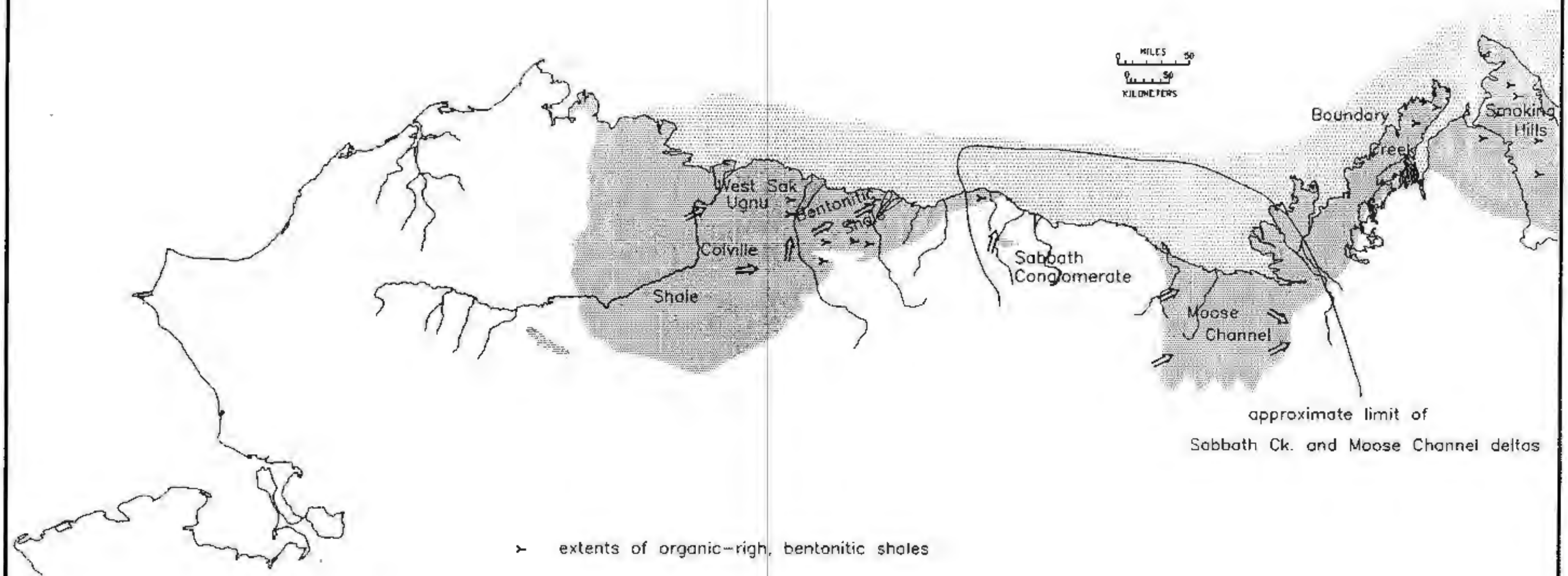


Figure 10. Middle Brookian megasequence and local formation nomenclature.

(Key: outcrop belt is heavily hatched; extents are lightly hatched) cene) sediments that prograded east-northeast across the present Coastal Plain area and filled the eastern third of the Colville Trough (figure 10). This episode of sedimentation spread offshore (present day) and filled the Nuwok and Kaktovik basins with upper Cretaceous and younger sediments (figure 5). This represents as much as 10000 m of a single transgressive-regressive couplet.

Seen in the seismic stratigraphy, the basal part conists of onlapping foresets and these are overlain by widespread mostly flat lying topsets (figures 6 and 7). Locally the Simpson Canyon and several deep subsea channels were cut into the Nanushuk and Torok Formations and filled with thick piles of Colville sediments (figure 5). Fieldwork and interpretation of industry exploration well logs around the periphery of ANWR records a fairly complete middle Brookian Megasequence history.

In addition to the data showing contiuuing trends of the major elements of east-northeast progradation, there are also elements of that are directly affected by the now (and finally), close proximity of the Canadian provenance rocks from east of the Blow River Trough/Rapid Fault Array (figure 5). Pronounced erosional unconformity, or local depositional hiatus separates the mid- from Late Cretaceous rocks from the central North Slope through the Yukon and the Mackenzie delta.

Colville Group

In and around ANWR, the Colville group is divided into two units. The basal part is marine shales. Upsection, there are interbedded depositional units of turbidites to nonmarine sandstones that are present in wells and coastal plain outcops,and in the subsurface, at least as far out as the Point Thomson area (plate 3).

Shale Wall Unit

The Shale Wall Unit (Detterman and others, 1975)/Bentonitic Shale is the basal Colville Group Member. This is the upper part of Molenaar's (1983) Hue Shale. It consists of up to 150 m of black, papery- to cardboard-texture shale with abundant white to cream colored bentonite bands. These bentonites range in thickness from several millimeters to approximately one meter, but are mostly five to 20 cm.

This bentonitic shale is found in wells immediately west of ANWR where it is typically overpressured. At outcrops around the Sadlerochit Mountains there is a thin, hard siliceous sinter layer that weathers to a charachteristic reddish-orange, for which Leffingwell (1919) named the unit the Ignek Formation (speculating that sinter was clinker from burned coals). These outcrops and those on the coastal plain are commonly very steeply dipping to perpendicular-bedded and faulted. Most importantly though is the source rock potential of this unit. Analyses show TOC's are as high as 14 percent and amorphous, algal or Type II kerogens are common (Banet, 1989; Magoon and others, 1987; Palmer and others, 1979), making this unit the North Slope's richest potential hydrocarbon source rock (table 3).

Boundary Creek and Smoking Hills

Figure 11 illustrates the age relationships between three widely separated, but lithologically similar and organic rich,

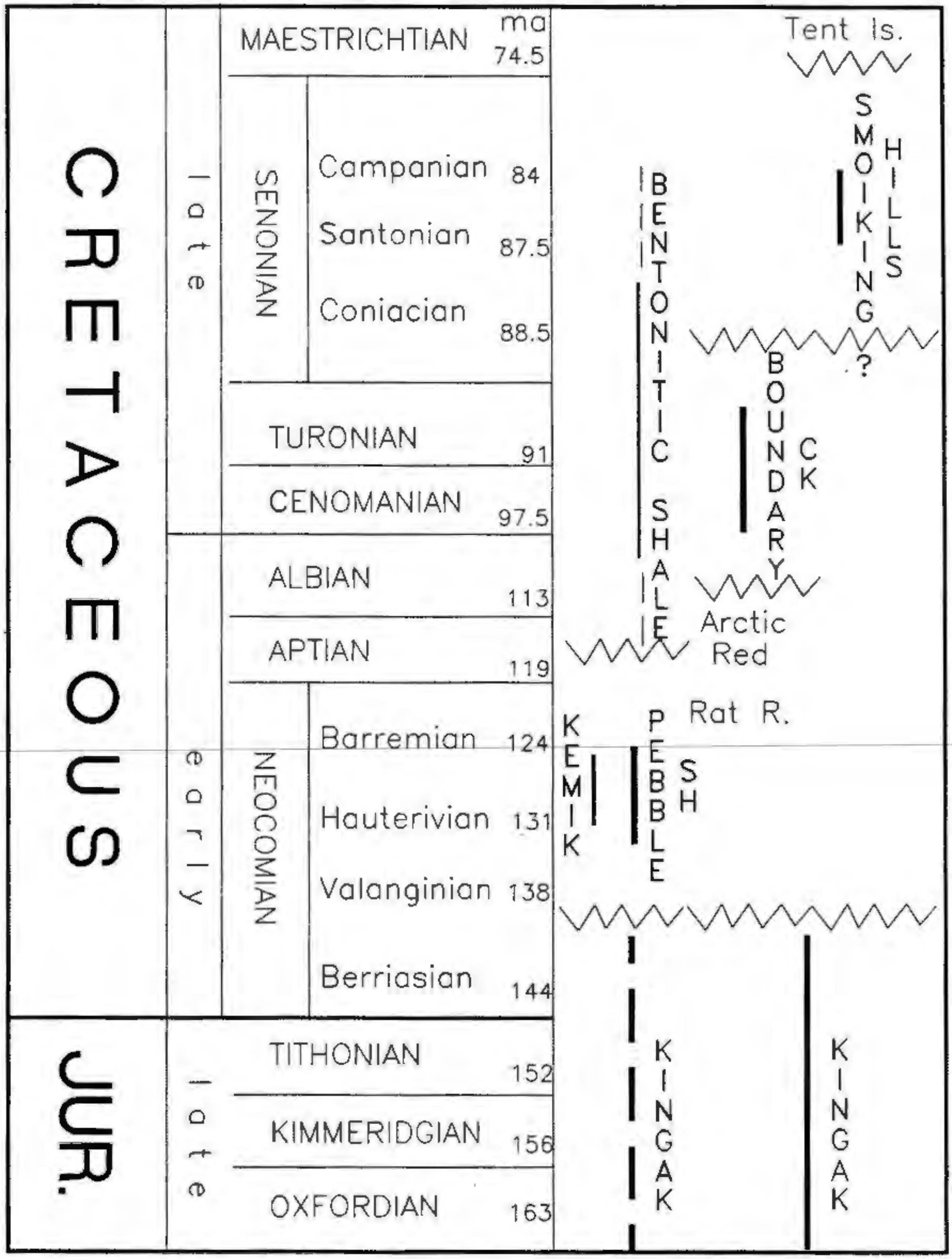


Figure 11. Diagram showing stratigraphic relationships of the various bentonitic shales, northeast Alaska and the Yukon

Upper Cretaceous shales that have significant hydrocarbon genterating potential in both Canada and in the U.S. The Boundary Creek Formation consists of some 1100 m, of very bentonitic, paper-shale that has up to 7 percent TOC. The Boundary Creek is the westernmost and older of the two similar Canadian shales (figure 10). Further east, restricted to the east part of the Mackenzie Delta, the Smoking Hills formation is some 130 m of very bentonitic, papery, organic rich shale with up to 12 percent TOC (Dixon and others, 1985)

Logs from the wells along the Canning River (plate 3) and outcrops west of Katakturuk River in ANWR indicate that there is a section of gray, silty to very silty, and soft, shale and turbidite sandstones overlying the basal bentonitic shale. The sandstones are gray, weathering to tan, mostly fine-grained with moderate sorting, and abundant subangular chert grains (chert litharenites). Flute casts and grooves are common and the units show some fining upwards trends. The sandstones range in thickness from from several centimeters to stacked channels that are tens of meters.

At outcrops in ANWR, the thinner bedded sandstones are commonly more laterally continuous than the thicker channel sands. These sandstones are interbedded with very silty shale and are mostly indurated except where oil stained. Along Niguanak Creek on the ANWR Coastal Plain, the easternmost exposure (U.S.) of Bentonitic Shale is overlain by a thick, light gray, smectitic shale containing large, rounded, rust-colored, calcereous spheroidal concretions, that are up to a meter in diameter. This is the most distal lithology overlying the Bentonitic Shale. The Bentonitic Shales in Canada are unconformably overlain by Tertiary deltaic sequences.

The nearshore and nonmarine facies of the middle Brookian megasequence are preserved further west. From the east part of NPRA through approximately Prudhoe Bay. These deltaic through fluvial environments of deposition consist mostly of fine-grained, coarsening upwards stacked channel and sheet sandstones (Werner, 1985, 1987). Coal, conglomerates and floating chert pebbles are minor lithologies. The West Sak (Maestrichtian) and the overlying Ugnu (Paleocene) sandstones are proximal, time-equivalent facies correlatable to the Colville Group shales (figure 10). Both units are found in the shallow subsurface (600 - 1400 m) west of Prudhoe. They contain an estimated 5600 MM MT in-place (only 13 production test wells have been drilled from a single gravel pad) of low reservoir temperature (~15 - 20°C), low API gravity (~10 -20°) oil (Werner, 1987). This is the largest North Slope hydrocarbon accumulation.

Sabbath Creek Conglomerate

In ANWR, some 25 km south of the coast, between the Jago and Siskutatuvik Rivers there is a second coeval (U. Cretaceous-Paleocene) pulse of nonmarine-nearshore sediments. This is some 3000 m of homoclinal, north dipping and east-west trending, conglomerates, sandstones and moderately carbonaceous, black, platy to fissile shale (plate 1, figure 10). Bentonite is completely lacking from any of these shales. There are no internal faults repeating this secton. Dips of only a few degrees to the north increase steadily downsection to approximately 40° at the south end of the exposure. There is a sequence-bounding thrust fault at the base of the section (plate 1). Plates 3 and 4, lines 84-20,-24,-30 and 85-50, in Bulletin 1778 (Bird and Magoon, eds. 1987) illustrate the extent of stacked compressional faulting that has emplaced this part of the section some unknown horizontal and vertical distance from its depositional origin.

Detterman and Spicer (1981) identified this as the Sabbath Creek Section. The conglomerate is mostly matrix supported, with angular to sub-angular, black and white chert pebbles and cobbles with lesser amounts of igneous and metamorphic rocks. The matrix consists of medium-to coarse-grained, poorly sorted sandstone and angular chert grains. There are some minor thin coals, but whole tree trunk casts and plant impressions are more common and suggest that conditions at depostion were mostly oxidizing.

The sharp and distinct nature of the depostional contacts indicate that two very different environments are preserved in these rocks. Cross cutting channels and the vertically-stacked, large scale cross beds indicate high energy, such as hraided stream depositonal events. The alternating, interbedded, fissile-to-platy black shales, suggest low energy, near marine and perhaps estuarine or fan delta conditions. Buckingham (1987) identified coarse-clastic depositional environments ranging from lower delta plain to meandering and braided stream regimes.

McClean (1987) noted superimposed pervasive post depositional mechanical deformation indicative of deep burial and diagenesis. The extent of diagenesis and amount of plastically deformed ductile grains have irreversibly destroyed much of the Sabbath Creek's reservoir potential.

Lyle and others (1980) correlated the Sabbath Creek with the widespread Moose Channel formation which is found in wells and outcrops in the Yukon Territory (figure 10). Buckingham (1987) and McClean (1987) note both compositonal and depositional direction differences between these two conglomerate units. Analysis of the Natsek N-56 well (plate 1), some 100km northeast of the Sabbath exposures, indicates that the Moose Channel Formation has considerahly more coal, occurring in thin widely separated beds.

Dietrich and others, (1985) suggest that these Natsek conglomerates may be younger and not correletable to the Moose Channel, but as with many offshore picks, corelations are tentative as the lithologies are so similar and sufficient well data are lacking. Like the Fortress Mountain, the Sabbath Creek and Moose Channel conglomerates are at least nearly coeval and represent closely related pulses of sporadic and episodic sedimentation. However, the Sabbath Creek and Moose Channel conglomerates differ in that flow directions (north and east-northeast, respectively) indicate that they probably do not overlap (figure 10). Also, their provenance includes different units of the Neruokpuk (figure 6, Buckingham, 1987).

Moose Channel Fomation

The Moose Channel Formation of the Fish River depositional sequence is the first major fluvial/deltaic system deposited in the Beaufort-Mackenzie basin. It is linked with the lower part of the overlying Lower Reindeer Sequence to the Brookian rocks deposited from Laramide tectonics (Dixon and others, 1985). The upper Reindeer and younger deltas are shown to build out from the approximate location of the present Mackenzie delta and Richards Island with clastic input from the Tuktoyaktuk Penninsula (figure 12), and not solely in direct response to Brooks Range uplifts (Dixon and others, 1985). Overall, these deltaic depostional sequences are commonly cut by syndepositional, down-to-basin, listric normal faults that sole out to the north as the sequences become shalier.

Reindeer Sequence

The Reindeer Sequence is more areally extensive than the underlying Fish River Sequence and has considerable input from the Tuktoyaktuk Penninsula, east of the present Mackenzie delta. The Reindeer consists of the Ministicoog (Paleocene) and Reindeer (early Eocene) formations that represent distal prodelta shales and interbedded mudstones, through delta plain (Aklak) and delta front (Taglu) siltstones, sandstones and coal-bearing sediments (Dietrich and others, 1985). Figure 13 shows the abrupt erosional change in thickness in the Reindeer Sequence near the international border owing to syndepositional and tectonic/diapiric folding and faulting. Elsewhere in the Mackenzie delta, Reindeer Formation rocks, particularly the prodelta and delta front sands are the major offshore oil and gas reservoirs in the Mackenzie Delta.

Upper Brookian Megasequence

Hubbard and others' (1987) third Brookian megasequence records the last and ongoing(?) phase of Brooks Range mountain building. Both the depositional sequences and the structural deformation comprising the framework for the Upper Brookian megasequence are best recorded in the seismic, magnetic and gravity geophysical data, well logs available from in and around ANWR and from offshore (Grantz and May, 1983; Craig and others, 1985; Dixon and others, 1985; Bird and Magoon eds.,1987). Craig and others (1985) relate the seismic stratigraphic sequences in the eastern U.S. Beaufort Sea to the most currently available well and seismic interpretations from the Mackenzie basin (Dixon and others, 1985).

Wells penetrating the Upper Brookian megasequence are more numerous in Canada, especially in the Mackenzie delta area. Data towards the International border, which is directly pertinent to the Brookian tectonics, is sparse, but some seismic, logs and cores are available to the public. In addition, the Unocal Hammerhead and Shell Corona wells, offshore of ANWR, have recently become available.

Available data show that the upper Brookian megasequence has Eocene to middle(?) Pliocene age sediments. It is as thin as ~500 m offshore of Prudhoe Bay, and thickens to ~2500 m in wells immediately northwest of ANWR (Plate 3). Offshore of ANWR this sequence may be some 6000 m thick (figure 14). Across this area the sediments represent a single eastward prograding transgressive regressive depositional couplet. This is the Sagavanirktok Formation of Lyle and others (1980) and Molenaar (1983, 1987). Gryc and others (1951) and Detterman and others (1975) originally described these sediments but corellated them to sedimentologically equivalent (i.e. depositional facies), but older, middle Brookian

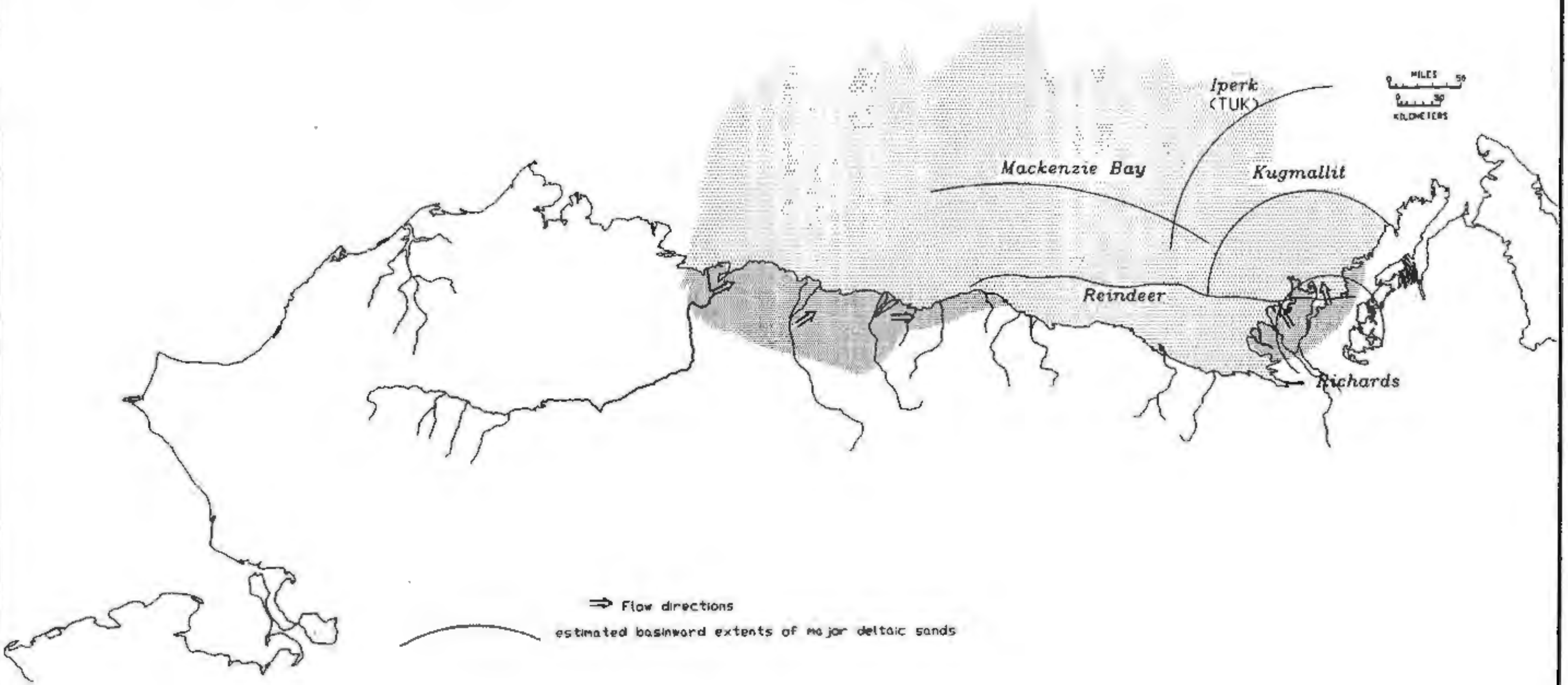


Figure 12. The Upper Brookian megasequence

showing the extents of the Sagavanirktok and major deltaic complexes in the Canadian Beaufort

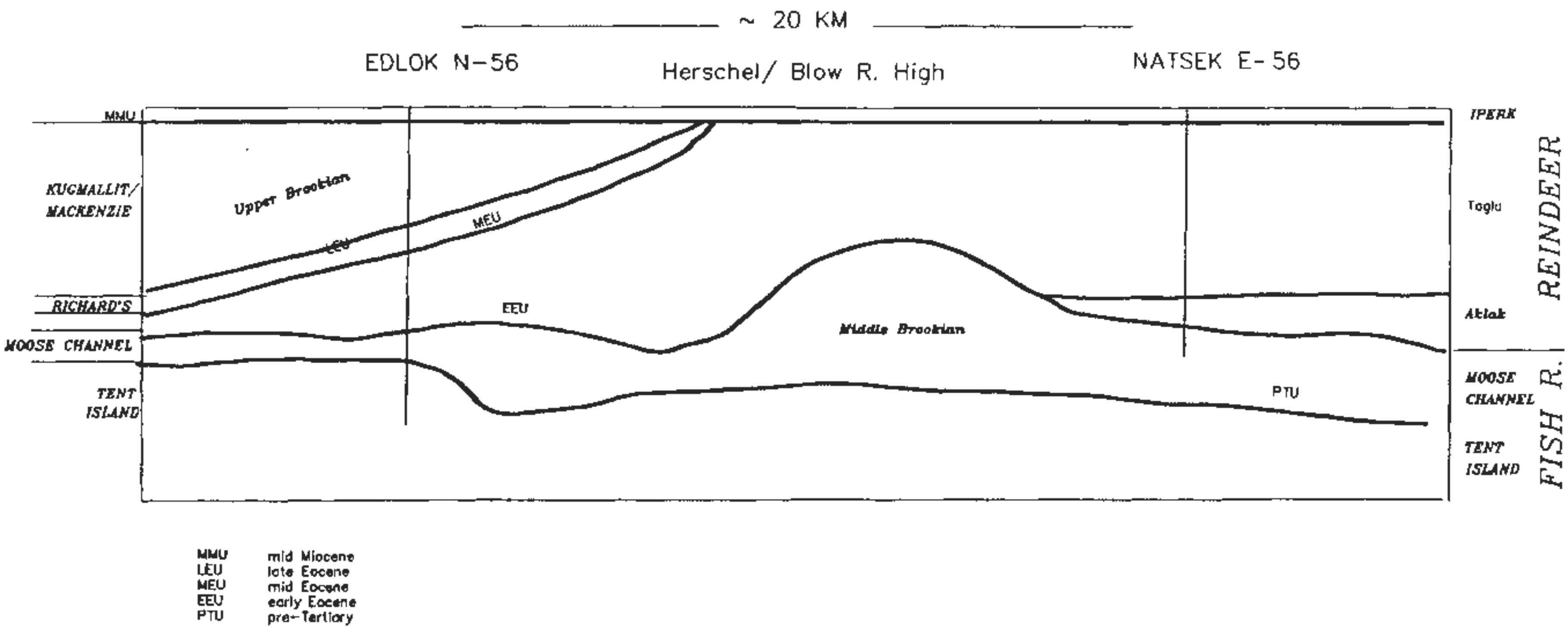
(Key: outcrops are heavily hatched; estimated extents are lightly hatched)

(modified from Dixon and others, 1985)

Figure 13. Schematic cross-section between Edlok N-56 and Natsek E-56 wells

showing major depositional sequences, erosional unconformities and the effects of accompanying uplift

(from Dietrich and Dixon, 1985)



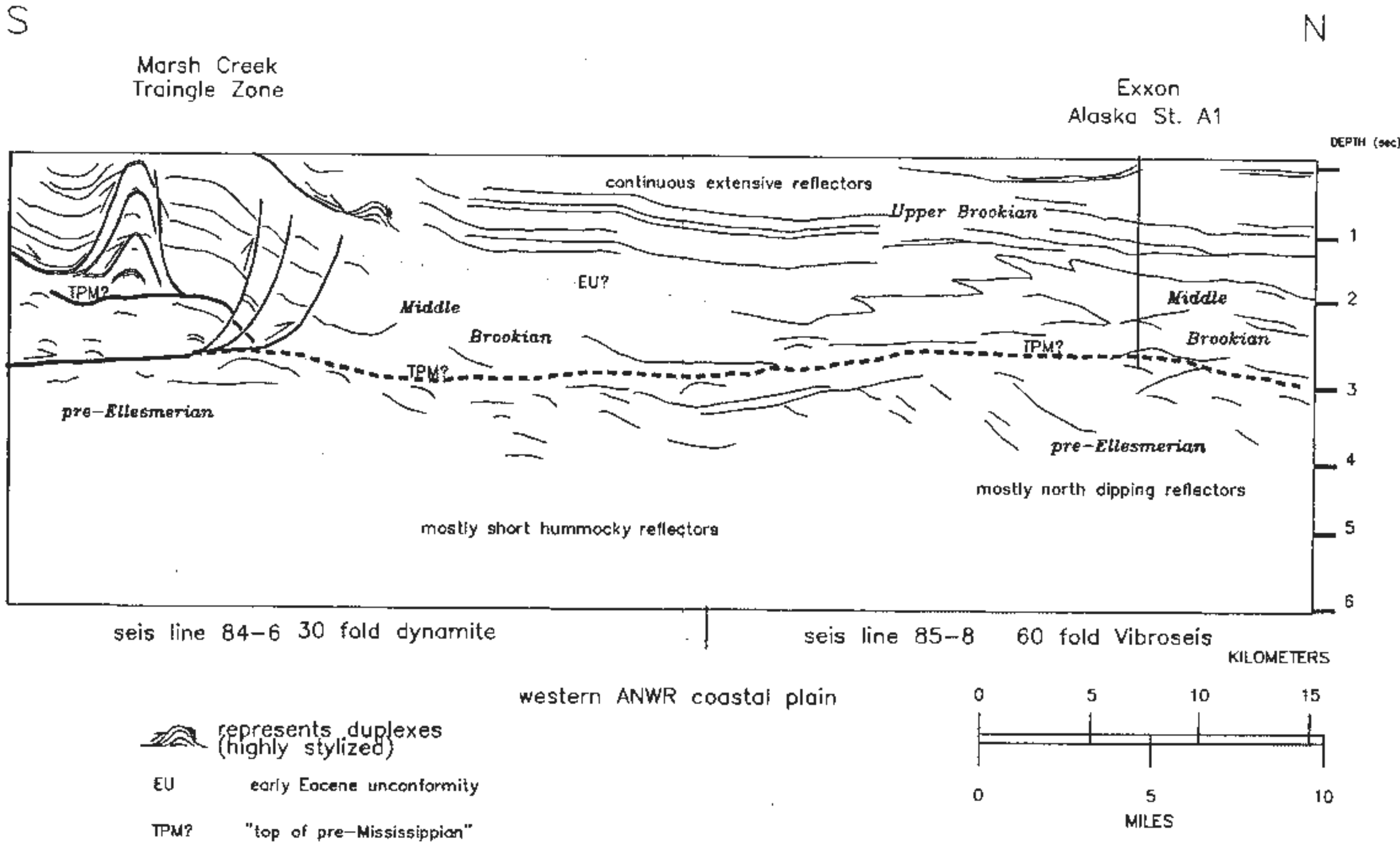


Figure 14. Seismic profile across western ANWR 1002 area

showing Marsh Creek anticline triangle zone, extent of Brookian megasequences, and disposition of reflectors in the pre-Ellesmerian section

(note: substantial vertical exaggeration; arrows show throw on faults, representative reflectors shown; unconformities weighted) megasequence rocks from the Central Arctic area.

Seismic interpretation of the upper Brookian megasequences shows somewhat poorly resolved or interfingering foresets and flat-lying well-developed topsets unconformable on progressively deeper water sediments of the Middle Brookian megasequence (figure 14). The western upper Brookian sediments are mostly undisturbed by the compressional tectonics that affects the rocks southeast of the Marsh Creek anticlinorium and and those that form the offshore Camden Anticline and Demarcation Ridge (plate 3, figures 7 and 14). Syndepositional listric normal faulting which is typical in this and other progadational wedges is commonly seen at outcrops along the Marsh Creek anticline.

Eastward from approximately the location of Barter Island and into Canada, the stratigraphy of the third Brookian megasequence is more complex. It may represent as many as five distinct depositional sequences of southerly derived sediments in the Eastern Beaufort basin. These sequences are related to the sporadic and episodic uplifts of the Brookian foreland, and the ensuing deformation within the offshore basins owing to resulting diapirism or shale flowage.

Available seismic data show that the basal mid-Eocene unconformity of the Upper Brookian megasequence is deformed in ANWR and offshore (figures 15, 16 and 17). Fault-cored folds are breached onshore in ANWR downsection to the Jurassic. Offshore, major uplifts occur on the Camden anticline, the Demarcation and Herschel ridges, but the mid-Eocene unconformity is not breached. "Piggy-back" basins formed by these uplifts are filled with unconsolidated, reworked, Upper Brookian megasequence sands and silts (figure 16).

Overall the data from cores and outcrops shows that the sediments consist of mostly subrounded-to-angular, fine-grained litharenites. Well-rounded, mostly chert-rich, coarse-grained and pebble conglomerates are locally common to abundant. The lithic constituents are mostly fine-grained quartz with black or white cherts. The most common large clasts (up to several centimeters) are floating angular to well rounded cherts. These litharenite sandstones are friable or poorly cemented, which usually leads to poor cuttings and core sample recovery. The finer-grained deltaic lithologies are typically laminated to very thin bedded and have a tendency to be carbonaceous.

Organic debris is common and includes large pieces (meter+ length) of brown to black partially fossilized wood and carbonaceous material forming finer grained lamina on bedding surfaces. Lignite is reported from cuttings descriptions, and centimeter-size pieces are noted in some cores. The finer-grained, deep-water lithologies are light gray to tan, soft, plastic muds with varying amounts of floating grains, coaly material and chert pebbles.

Sagavanirktok Formation

Lyle and others (1980) divided the Sagavanirktok Formation into three members based on ANWR Coastal Plain outcrops between Katakturuk River and Carter Creek. The basal Sagwon Member (Eocene) is mostly interbedded, lower delta-plain, bentonitic and carbonaceous shales and siltstones with some lignite

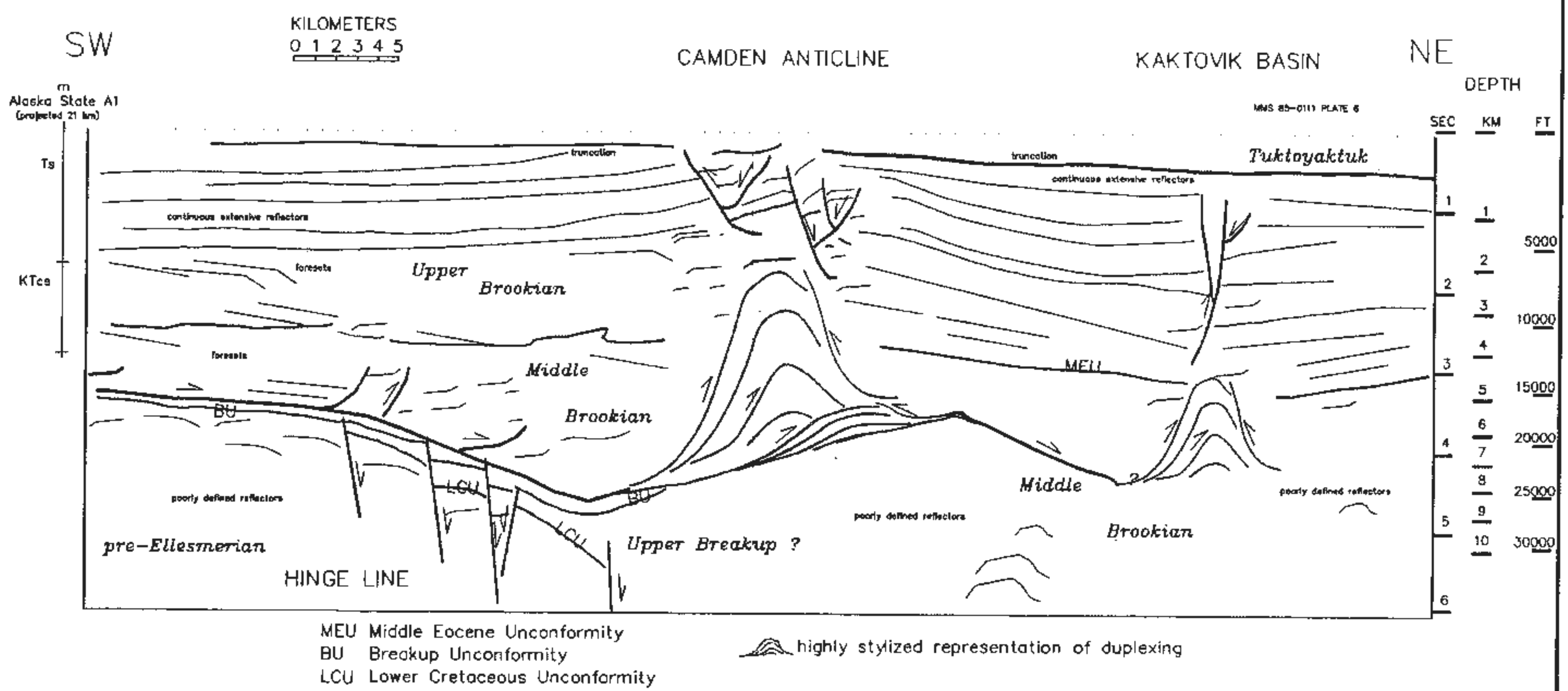


Figure 15. Seismic profile across Camden anticline to Kaktovik Basin

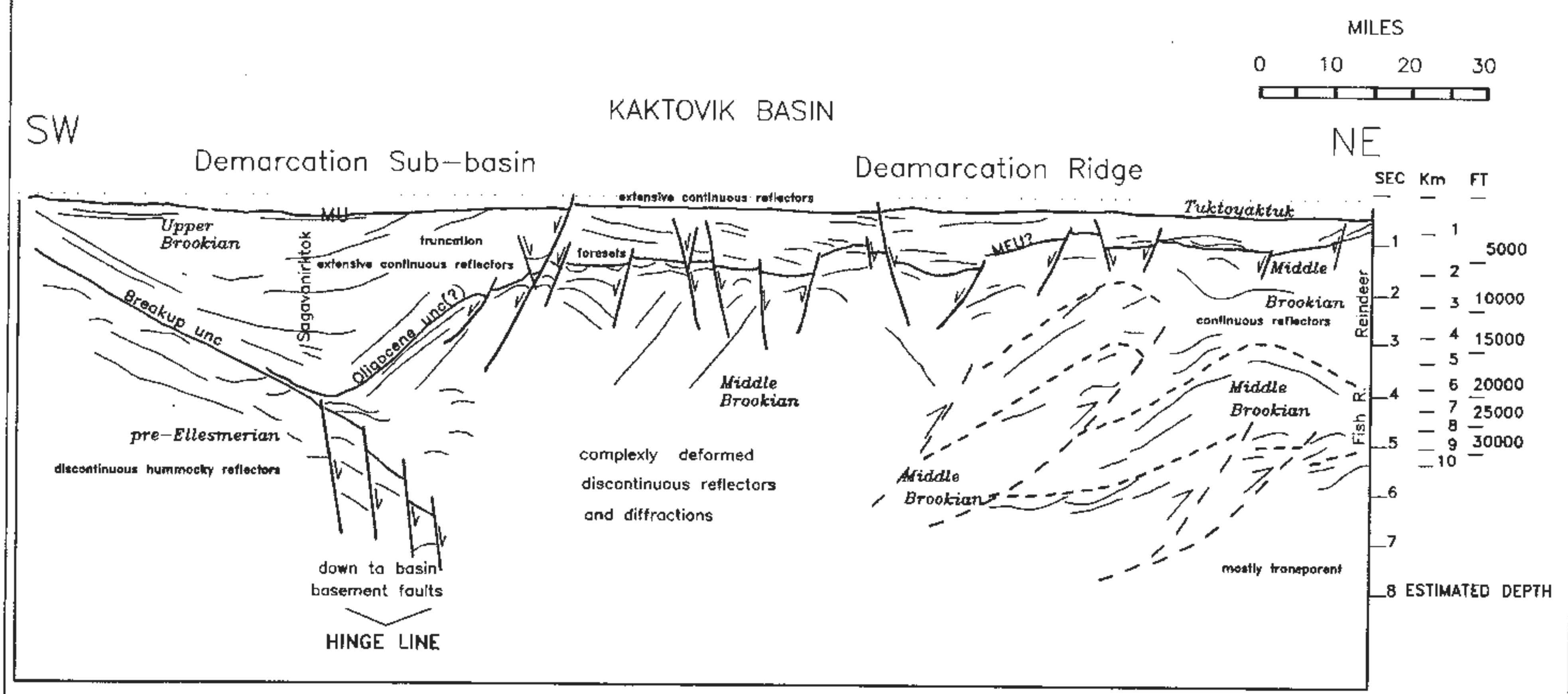
showing duplex style compressional folding and faulting of Brookian megasequences forming offshore structures

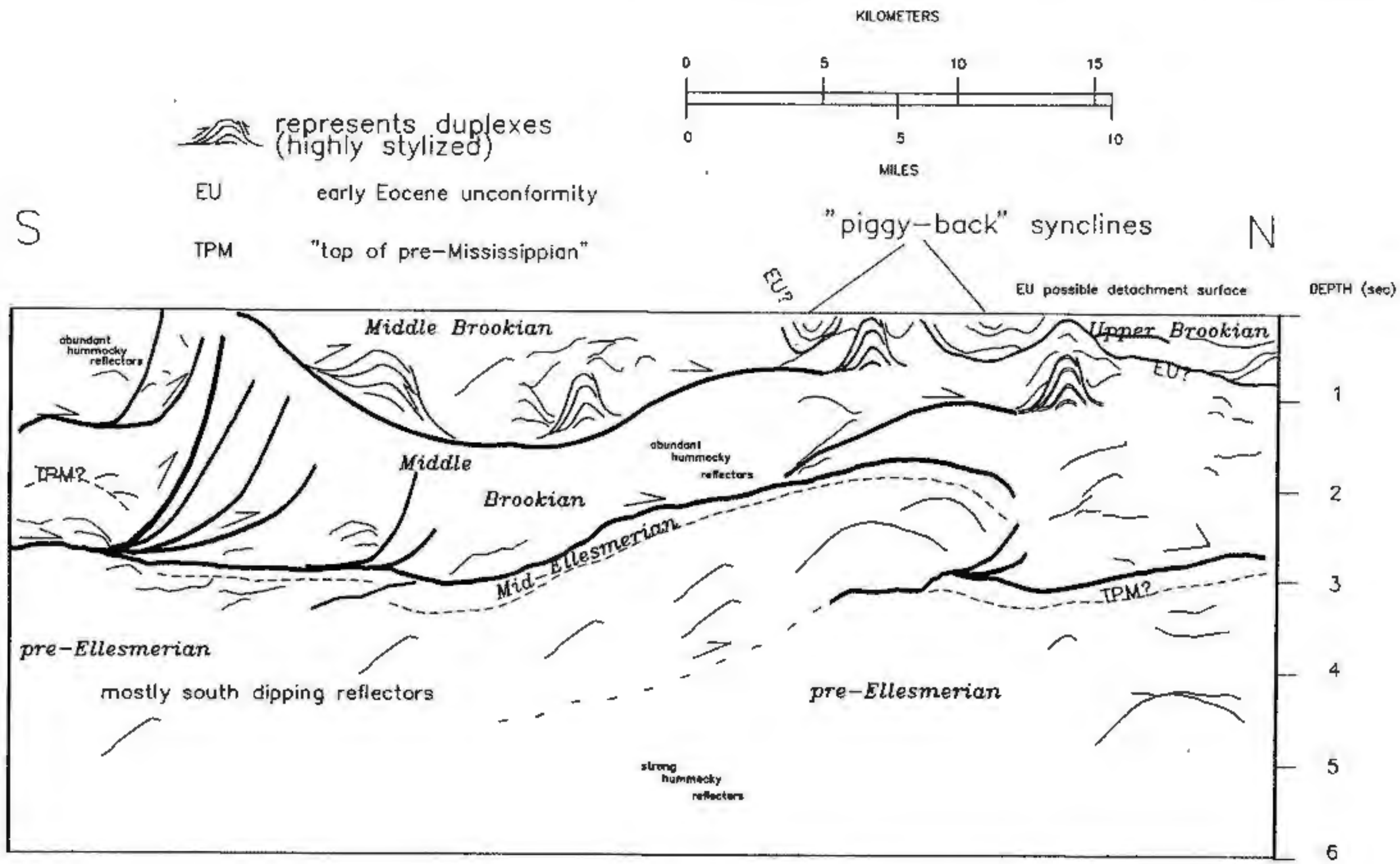
(Note: substantial vertical exaggeration; arrows show throw on faults, representative reflectors shown; unconformities weighted.

Figure 16. Seismic line offshore from ANWR

showing the major megasequences, unconformities and faulting styles

(Note: substantial vertical exaggeration; arrows show throw on faults, representative reflectors shown; unconformities weighted)





seis line 85–50 60 fold Vibroseis

eastern ANWR coastal plain

Figure 17. Seismic 85-50 across eastern ANWR 1002 area

showing compressional deformation within megasequences and to megasequence uniformity boundaries

(Note: substantial vertical exaggeration; arrows show throw on faults, representative reflectors shown; unconformities weighted) beds and massive channel sands. The north dipping channel sands along Katakturuk River are are cross-bedded and have floating, rounded, chert pebbles (~1 cm) and abundant lignitic debris. At an outcrop along Katakturak Creek, these sands are oil-stained, and have up to 22.8 percent porosity with more than 600 md permeability (Lyle and others, 1980). Along Jago River, Eocene age siltstones have concretions that are oil-stained with a distinctly petroliferous odor on fresh fracture.

The overlying Franklin Bluffs Member (Oligocene ? - Miocene ?) consists of cyclic, lacustrine deposits. Most outcrops are alternating gray, yellow and tan varves of clay, silt, fine- to medium- grained sand and carbonaceous shale. Volcanic ash, limonitic concretions and lenses of mostly poorly consolidated sand with floating, rounded chert pebbles are present upsection.

The Nuwok Member (late Miocene ? - early Pliocene) is exposed on the flanks of the Marsh Creek anticline. The Nuwok consists of thick, unconsolidated poorly-sorted sands and chert and igneous-pebble conglomerates. Pebbly siltstones and carbonate concretions occur between the sands and conglomerates. There is a distinct, angular unconformity between the uppermost Sagavanirktok and the younger Gubik Formation (Quaternary).

Richards Sequence

In the Canadian Beaufort, the Richards Sequence (mid- to late- Eocene) is unconformable on the Reindeer sequence of the Middle Brookian megasequence (plate 2, figure 13). Dietrich and others (1985) show that the maximum thickness is some 200 m in the Richards Island area. Figure 13 shows a very thin Richards section consisting of predominantly mud rich delta front shales, and the extent of uplift between Dome's Edlok N-56 and Natsek E-56 exploration wells. Like many thick and predominantly shale sequences, especially on the North Slope, exploration drilling shows that the Richards is typically overpressured.

Koponoar Sequence

Drilling at the Koponoar Field and surrounding seismic stratigraphy shows the existence of a thick mudstone and siltstone unit in the Central Beaufort shelf area (figure 18). This unit of late Eocene to possible early Oligocene age is preserved only in the far offshore and it is not yet clearly correlated with coeval nearshore and nonmarine facies in Canada and ANWR. It is unclear how much areal erosion has taken place, although it is tentatively identified in the Edlok N-56 well (figure 13).

Kugmallit Sequence

The Kugmallit depositional sequence is a very thick and areally extensive, mostly well-preserved, well-drilled and well-studied sequence consisting of a sand-dominant prograding delta and coeval mud-dominant shelf and basinal facies (Dietrich and others, 1985). It is mostly poorly lithified, but it has abundant lignite, partially fossilized wood and significantly more sand and silt than the underlying Richards sequence (Dietrich, 1985). There are two main pulses of pro delta and delta plain sediments. These are the Ivik and Arnak formations, respectively (plate 2). Drilling data and seismic data indicate that they are restricted in areal extent, encountered approximately in the area of the present Mackenzie delta (figure 12). Owing to poor sample recovery and long ranging species the Kugmallit is tentatively determined to be late Eocene-Oligocene.

Mackenzie Bay Sequence

The Mackenzie Bay sequence records the return to southerly derived sedimentation (figure 12). It is predominantly north and northeasterly prograding Brookian derived sediments with only minor amounts of clastic input from the Tuktoyaktuk Peninsula. The Mackenzie Bay sediments consist of unconsolidated mudstones, siltstones and fine-grained, predominantly quartzose sandstones. These Mackenzie Bay sands and silts are known only in the subsurface and typically yield abundant forams of Oligocene to Miocene age.

Ancillary lithologies include abundant bentonites, lignitic material, floating quartz grains and pea gravels. The basal contact is always abrupt and unconformable with the underlying Kugmallit (plate 2). The Mackenzie Bay pro delta and delta plain facies overlie the fine-grained Kugmallit shelf muds (Dietrich and others, 1985). Dietrich and others (1985) show seismic evidence of north-northeasterly progading clinoforms and suggest that deltaic strata are also present west of Herschel Island and in the Demarcation sub-basin across the international border. Recent divisions of the Canadian Beaufort siesmic stratigraphy (Dietrich and others, 1985) correlate the Mackenzie Bay sequence to the Mackenzie Bay Formation.

Akpak Sequence

There is a widespread mid-Miocene unconformity between sediments around the margins of the Beaufort basin. This separates the more proximal facies of the Mackenzie Bay and Akpak sequences. The Akpak (middle - late Miocene) depositional sequence is the youngest of the southerly derived sequences. The basal contact with the Mackenzie Bay sequence is abrupt and locally unconformable due to the basin margin and local uplifts. In the Demarcation sub basin, proximal, sand-rich Akpak facies overlie tectonically deformed "mobile shales" (figure 16) (Craig and others, 1985; Grantz and May, 1983). Dietrich and others (1985) describe it as a deep-water, estimated to be as much 1000 m from foresets, mud dominant facies. They (Dietrich and others, 1985) estimate that it thins from 2000 m near the international border to ~800 m in the central Canadian Beaufort.

I. Tuktoyaktuk Megasequence

Iperk Sequence

I suggest the inclusion of an additional megasequence in this part of the Arctic. The Tuktoyaktuk megasequence describes a period of regional, unconformity-bounded sedimentation. This megasequence reflects a change again in basin polarity as sediments are mostly directed from the Tuktoyaktuk Penninsula on the eastern side of the Beaufort Sea. These sediments are Dietrich and others' (1985) Iperk depositional sequence (figure 18). This sequence is described as extensive, westward-prograding deltaic, nonmarine- to marginal-marine sands and gravels that extend as far seaward as the

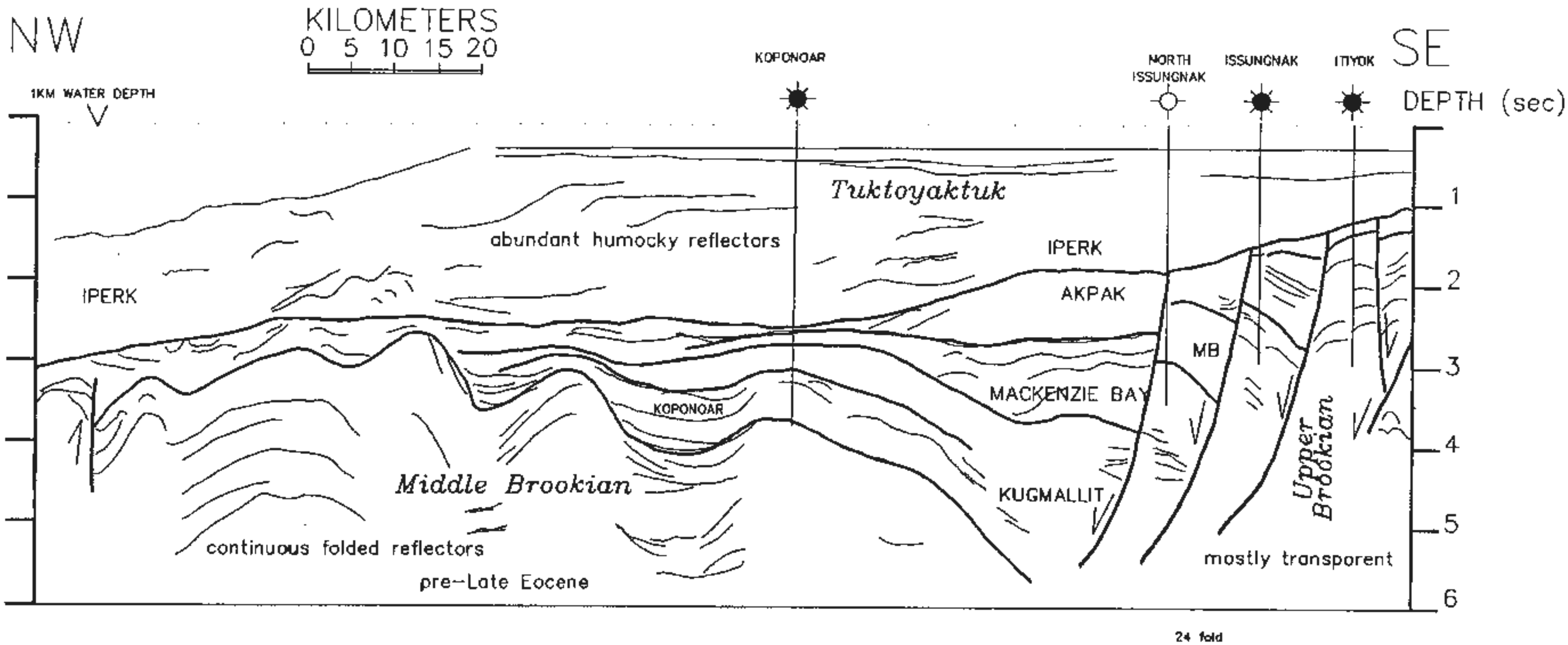


Figure 18. Seismic interpretation profile of Eastern Beaufort Shelf

showing Upper Brookian and Tuktoyaktuk megasequences

(Note: substantial vertical exaggeration; arrows show throw on faults, representative reflectors shown; unconformities weighted)
(modified from Dietrich and others, 1985)

present shelf edge, before grading into predominantly offshore sands and muds (figures 12 and 18) .

Over most of the basin there are marked lithological, grain-size, and seismic velocity contrasts between the underlying southerly derived, predominantly flat lying distal sediments, and the overlying Iperk sediments which have well developed seismic forsets. In the tectonically undisturbed regions of the central Beaufort basin the Iperk sequence may be some 5000 m thick (Dixon and others, 1986). But the amount of deformation increases westward, towards international border. And this precludes accurate estimation of the areal extent or total thickness of Tuktoyaktuk megasequence sediments overriding the Upper Brookian sediments.

Shallow Bay and Gubik Formations

There is a thin veneer of unconformably overlying late Pleistocene to Holocene age sediments on both sides of the border. This is the Shallow Bay sequence (Dixon and others, 1985) on the Canadian side of the internatioal border. From the border to the Barrow area these rocks are the Gubik Formation (Quaternary). In ANWR, they are unconsolidated, poorly sorted sands, rounded pebbles and cobbles.

Although these rocks have a Brookian clast component, they also have a distinct provenance which includes igneous and volcanic rocks of eastern origin that are unlike any present in the underlying Upper Brookian megasequence rocks. There is also a distinct angular unconformity between the Gubik and Upper Brookian rocks exposed along the north flank of the Marsh Creek Anticline. The Gubik thickens to ~100 m offshore and is present to the present shelfbreak (Dinter, 1982) . Carter (1987) and Dinter (1987) describe several marine trangressions represented in these glaciomarine sediments.

Uplift from recent tectonic activities has resulted in no Gubik deposition on the crests of shallow folds in the Kaktovik basin (Dinter, 1982). These same uplifts have carved radial style drainage patterns into the 1002 Coastal Plain area.

Current depositional patterns since the Pleistocene glaciations are mostly from the south and are probably driven by some degree ofisostatic rebound. The most notable features are the fans at the base of front range hills, and the small gravel deltas building out into the Beaufort Sea.

4. Summary and Conclusions

The northernmost bulge of the Rocky Mountain Cordillera exposes very thick assemblages of sediments. These sediments are as old as Proterozoic, and probably represent at least two distinct megasequences of regional predominantly pre-Cambrian sedimentation. The regionally exposed Neruokpuk represents both clastic and carbonate sedimentation from south (in present directions). The uppermost Neruokpuk units are Cambrian.

The Katakturuk is a northerly derived platform carbonate sequence having limited exposure. It is Proterozoic. The overlying Nanook limestone is more areally restricted to exposures in the Shublik Mountains. It ranges in age from lower Cambrian to middle Devonian. The Nanook is definitely a separate depositional sequence, but like the Katakturuk is also a northerly derived platform carbonate sequence, and may retain its close tectono-stratigraphic association with the Katakturuk into the subsurface. The extent of these megasequences in the subsurface is still unknown. But, sesimic data indicate that there are at least two domains of reflectors which may represent these Proterozic to Cambrian megasequences. Drilling has penetrated mildly metamorphosed basement sediments regionally across the North Slope. Drilling also indicates that some of these units are still able to provide migrational pathways for oil and gas resources.

A marked angular unconformity separates both the Neruokpuk, and Katakturuk/Nanook rocks from overlying sediments. Lerand's (1973) lower Paleozoic, northerly derived and overlying Franklinian sequence may not extend across the area of the Bulge as previously thought. Sediments overlying the Neruokpuk consist mostly of lower Paleozoic volcanics, black graptolitic shales, interbedded chert and phyllites, with lesser amounts of carbonates, slate and phyllites which may have a southern provenance. These sediments are known only from widely diverse locations across the North Slope, but little is known about the continuity. The Nanook has a very compatible lithology to the Franklinian sequence, but these limestones are widely separated from known Franklinian equivalents, and may not have a similar depositional style.

Two sedimentary megasequences of northerly derived Ellesmerian rocks unconformably overlie the older lithologies in the bulge. The Endicott clastics and the Lisburne Group carbonates represent middle Ellesmerian sedimentation and the Sadlerochit Group, Shublik Formation and Sag/Karen C. sandstone represent the upper Ellesmerian sequence. Shales and localy conglomeratic sands of the Endicott Group typically overlie the Neruokpuk and Katakturuk/Nanook. Both the middle and upper Ellesmerian megasequences are well represented lithologically and well exposed in the Brooks Range, but their existence in the subsurface of the Arctic Coastal Plain is debatable, owing to possible lower Cretaceous erosion at the Barrow Arch or other similar rift associated uplifts. These are, at present, the major producing North Slope oil and gas reservoirs at Prudhoe

Bay. Thus, their existence may have considerable importance to possible resource estimates of the entire area.

The Breakup megasequences associated with rifting are northerly derived and diachronous pulses of localized coarse clastic sedimentation. The rifting events are restricted to the area of the Barrow Arch, which is roughly subsurface of the present coastline. Further south, coeval lithologies are mostly deep water, typical trailing margin shales. On allocthons in the Brooks Range, there are isolated occurrences of deep water shales interbedded with volcanics, probably recording the initial pulses of southerly derived sedimentation. Reservoirs unique to these megasequences are, only recently, coming into their own at Kuparuk River and (perhaps soon) the Point Thomson areas.

Brookian megasequence sediments are very thick, clastic and diachronous. They record three distinct and separate phases of the Brooks Range uplift which filled the Colville Trough and eventually overstepped the Barrow Arch. Elements of all three phases were deposited and are preserved in the area of the bulge.

Brookian megasequences of the Canadian Beaufort have varying contributions from the Tuktoyaktuk Peninsula. Although both the volume of Brookian sediments is very large, and they have in-place reserves identified greater than those at Prudhoe Bay, the hydrocarbon accumulations are not yet developed owing to small (by world class standards) deposit size and technical difficulties associated low reservoir temperatures. This is in addition to the ubiquitous added development expenses resulting from harsh Arctic conditions and environmentally sensitive caveats. I propose that the most recent pulse of sedimentation in the Canadian Beaufort, and perhaps crossing the international border in its distal lithologies, be referred to as the Tuktoyaktuk megasequence.

This terminology reflects its major provenance and it reflects somewhat of a quiet stand of Brookian deposition. Also, glacially derived sediments across much of Arctic Alaska have considerable clasts of igneous and metamorphic rocks derived from Canada, rather than from the Brooks Range. There are local angular unconformities between the Tuktoyaktuk rocks and the underlying Brookian sequences.

Thus there are sediments spanning the time from Upper Proterozoic to Recent in the area of the bulge. While additional work is surely warranted, a sufficient amount has been done to demonstrate the tantalizing prospects of hydrocarbon resources in this area.

Bibliography

Ahlbrandt, Thomas, S., Huffman, A., H., Fox, J., E., and Pasternack, Ira, 1979, Depostional framework and reservoir-quality studies of selected Nanushuk Group outcrops, North Slope, Alaska. in Ahlbrandt, T., S., ed. Preliminary geologic, petrologic and paleontologic results of the Nanushuk Group rocks, North Slope, Alaska. U.S. Geological Survey Circular 794.

Banet, Arthur, C., Jr., Petroleum geology and geochemistry of the Arctic National Wildlife Refuge 1002 area, Bureau of Land Management, Alaska State Office Technical Report 12, March 1990, 33pp.

Banet, Arthur, C., Jr., 1983, A geochemical profile of Tunalik No. 1 Well (NPRA): U.S. Geological Survey open-file report 83-0627, 20p.,2 oversize sheets.

Barnes, D., 1976. Bouguer gravity map of Alaska: U.S. Geological Survey Open-File Report 76-60, 1 sheet, 1:250000.

Bartsch-Winkler, S., 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, North Slope, Alaska, in Ahlbrandt, T., S., ed. Preliminary geologic, petrologic and paleontologic results of the Nanushuk Group rocks, North Slope, Alaska. U.S. Geological Survey.

Bird, K. J. 1977, Memorandum to G. Gryc Chief ONPRA cf. Granitic basement in Husky NPR East Teshepuk Lake #1 well.

Bird, K.J. and Jordan, C.F., 1976, Lisburne Group (Mississippian and Pennsylvanian), Potential major hydrocarbon objective of Arctic Slope, Alaska: AAPG Bulletin V.61, no. 9, p.1493-1512.

Bird, K.J., Connor, C.L., Tailleur, I.L., Silberman, M.L., and Christie, J.L. Granite on the Barrow Arch, northeast NPRA. 1978, in Johnson, K.M. ed. The U.S. Geological Survey: Accomplishments during 1977 Geological Survey Circular 772-B.

Bird, K.J., and Magoon, L., B., eds., 1987, Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska, U.S. Geological Survey Bulletin 1778.

Bird, K.J., and Molenaar, C.M. 1987, Stratigraphy (Chapter 5) in Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska. Bird, K.J., and Magoon, L.M. eds. U.S. Geological Survey Bulletin 1778.

Blodget, R.B., Clough, J.T., Dutro, J.T., J. Thomas Dutro, Jr., Ormiston, A.R., Palmer, A.R., Taylor, M. E. (1988) Age revision of the Katakturuk Dolomite and Nanook Limestone, northeastern Brooks Range, Alaska. abstract Geological Society of America.

Bodnar, Dirk, A., 1985, Age and Correlation of the Otuk Formation, north-central Brooks Range, Alaska. abstract, AAPG Bulletin, V.69, no.4 p 657.

Brabb, E., E., and Churkin, M., 1969, Geologic map of the Charley River quadrangle: U.S. Geological Survey Miscellaneous Geological Investigations I-573.

Brosg'e, W.P., Dutro, J.T., Mangus, M.D. and Reiser, H.N., 1962, Paleozoic ssequence in eastern Brooks Range, Alaska. AAPG Bulletin V.46, no. 2, p 2174-2198.

Buckingham, M.L. 1987, Fluvio-deltaic sedimentation patterns of the U. Cretaceous to L. Tertiary Sabbath Creek section, Arctic National Wildlife Refuge (ANWR), northeastern Alaska, in Tailleur, I.L and Weimer, Paul: Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V.50 p.529-540.

Callahan, J., E., and Martin, G.C., 1980, Coal occurrences of the Nanushuk Group-an update, in Rao, P.D. and Wolff, E.N., eds Focus on Alaska's coal '80, pp. 32-60.

Campbell, R.H. 1967, Areal geology in the vicinity of the Chariot site, Lisburne Penninsula, northwestern Alaska, U.S. Geological Survey Professional Paper 395, 71p.

Carman, G.J. and Hardwick, Peter, 1983, Geology and regional setting of the Kuparuk oil filed, Alaska: AAPG Bulletin, V.67, no. 6, pp. 1014-1031.

Carter, Claire and Laufield, Sven, 1975, Ordovician and Silurian fossils in well cores from North Slope, Alaska, AAPG Bulletin, V.59, no.3, pp.457-464.

Carter, L.D., 1987 Late Pleistocene marine transgressions of th Alaskan Arctic Coastal Plain in Tailleur, I.L and Weimer, Paul: Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V.50 p.541.

Churkin, Michael, Jr., 1975, Basement rocks of the Barrow Arch, Alaska, and circum-Arctic Paleozoic mobile belt: AAPG Bulletin, V.59, no. 3, pp. 451-456.

Clough, J.G., 1986, Peritidal sedimentary facies and stromatolites of the Katakturuk Dolomite (Proterozoic), northeastern Alaska: abstract 12th International Sedimentological Congress, Canberra, Australia, p.64.

Clough, J.G. 1989, General stratigraphy of the Katakturak Dolomite in the Sadlerochit and Shublik mountains Arctic National Wildlife Refuge, Alaska: Alaska Division of Geological and Geophysical Surveys, Public Data File 89-4a. 9p.

Clough, J.G., Reifenstuhl, R.B., Imm, T.A., Pavia, E.A., 1988, Depositional environments of Katakturuk Dolomite and Nanook Limestone, Arctic National Wildlife Refuge, Alaska, abstract: AAPG Bulletin, V.72, no. 2., p.172.

Clough, J.G., Robinson, M.S., Pessel, Garnett, H., Imm, T.A., 1990, Geology and age of Franklinian and older rocks in the the Sadlerochit and Shublik Mountains, Artic National Wildlife Refuge, Alaska, (abs.) GAC-MAC annual meeting, May, 1990.

Craig, J.D., Sherwood, K.W. and Johnson, P.P., 1985, Geologic report for the Beaufort Sea planning area, Alaska: regional geology, petroleum geology, environmental geology: U.S. Minerals Management Service OCS Report MMS 85-0111, 192p.

Crowder, R.K. 1987, Cretaceous basin to shelf transition in northern Alaska: deposition of the Fortress Mountain Formation: in Tailleur, I.L and Weimer, Paul:

Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V.50 pp.449-458.

Detterman, R.L.,Reiser, H.N., Brosge, W.P. Dutro, J.T.,Jr. 1975, post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46p.

Detterman, R.L. and Spicer, R.A., 1981, New stratigraphic assignment for rocks along Igilatvik (Sabbath) Creek, William O. Douglas Arctic Wildlife Range, Alaska, in Albert N.R.D., and Douglas, Travis, eds. The U.S. Geological Survey in Alaska Accomplishments during 1979: USGS Circular 823-B, pp.B11-B12.

Dietrich, J.R., Dixon, J., and McNeil, D.H. 1985, Sequence analysis and nomenclature of U. Cretaceous to Holocene strata in the Beaufort-Mackenzie basin, in Current research, part A: Geological Survey of Canada, Paper 85-1A pp. 613-628.

Dillon, J.T., Tilton, G.R., Decker, J., Kelly, M.J. 1987, Resource implications of magmatic and metamorphic ages for Devonian igneous rocks in the Brooks Range. in Tailleur, I.L and Weimer, Paul: Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V.50 pp.713-723.

Dinter, D.A., 1982, Holocene marine sediments on the middle and outer continental shelf of the Beaufort Sea, north of Alaska: U.S. geological Survey Miscellaneous Investigations Series, Map I-1182-B, 1:500000, 2 sheets.

Dinter, D.A. 1987, Late Quaternary depositional history of the Alaskan Beaufort shelf: in Tailleur, I.L and Weimer, Paul: Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V.50 p.541.

Dixon, J. 1982, Jurassic and L. Cretaceous subsurface stratigraphy of the Mackenzie delta-Tuktoyaktuk Peninsula, NWT Geological Survey of Canada Bulletin 349.

Dixon, J., Dietrich, J.R, McNeil, D.H., McIntyre, D.J., Snowdon, L.R., and Brooks,P. 1985, Geology, biostratigraphy, and organic geochemistry of Jursassic to Pleistocene strate, Beaufort-Mackenzie area, northwest Canada: Course notes, Canadian Society of Petroleum Geologists, Calgary, Albera, 64p.

Dixon, J., 1986, personal communication, Calgary, Alberta.

Dixon, J., Morrell, G.R., Dietrich, J.R., Proctor, R.M. and Taylor, G.C. 1988 Petroleum Resources of the Mackenzie Delta-Beaufort Sea. Geological Survey of Canada Open File 1926.

Dutro, J.T.,Jr., 1970, Pre-Carboniferous carbonate rocks, northeastern Alaska: in Adkinson, W.L. and Brosge, M.M. eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, Calif. AAPG Pacific Section, pp. M1-M8.

Dutro, J.T.,Jr., Brosge, W.P. and Reiser, H.N., 1972, Significance of recently discovered Cambrian fossils and reinterpretation of Neroukpuk Formation, northeastern Alaska: AAPG Bulletin V.5, no.4, pp. 808-815.

Dutro, J.T.,Jr., 1981, Geology of Alaska bordering the Arctic Ocean, in Nairn,A.E.M., Churkin, M.,Jr., and Stehli, F.G. eds., The ocean basins and margins, V.5, The Arctic Ocean: Plenum Press, pp. 212-36.

Fisher, M. A., and Bruns, T.R., 1987 Structure of pre- Mississippian rocks beneath the coastal plain: in Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska. Bird, K.J., and Magoon, L.B. eds. U.S. Geological Survey Bulletin 1778.

Foland, R.,F., Bascle, R.,J., Brougham, G.,B., and Banet, A., C., 1988, Oil and gas exploration in Alaska: a brief perspective, Bureau of Land Management, Alaska State Office, Division of Minerals Mineral Assessment report, unpublished.

Fritz, W.H., 1985, The basal contact of the Road River Group- a proposal for its location in teh type area and in other selected areas in the Northern Canadian Cordillera, in Current Research Canadian Geological Survey, Paper 85-B1, pp. 205-215.

Grantz, Arthur and May, S.D., 1983, Rifting history and structural development of the continental margin north of Alaska, in Watkins, J.S., and Drake, C., eds., Studies in continental margin geology: AAPG Memoir 34,pp.77-100.

Gryc, George, 1951, Northern Alaska, (in) Petroleum possibilites in Alaska: Alaskan Science conference 2d. Mt. McKinley National Park 1951, Proc., 184-188.

Gryc, George and Mangus, M.L., 1947, Preliminary report on the stratigraphic and structure of the area of the Shaviovik and Canning Rivers, Alaska: U.S. Geological Survey Inv. Naval Petroleum Reserve and adjacent areas. Preliminaly report 10, 7p. openfile 1954.

Gryc, George, Miller, D.,J., and Payne,, T.G. 1951 Alaska, in Possible petroleum pronvinces of North America: AAPG Bulletin, v.35, no. 2, pp. 151-168.

Hubbard, R.J., Pape, J., and Roberts, D.G., 1985, Depositional sequence mapping as a technique to establish tectonic and stratigraphic framework and evaluate hydrocarbon potential on a passive continental margin, in Berg, O.R., and Wolverton, D., eds., Seismic Stratigraphy II: AAPG Memoir No. 39, pp.79-91.

Hubbard, R.J., Edrich, S.P., and Rattey, R.P., 1987, Geologic evolution and hydrocarbon habitat of the 'Arctic Alaska Microplate': in Tailleur, I.L and Weimer, Paul: Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V.50 pp.797-830.

Jamison, H. C., Brockett, C.D., and McIntosh, R.A., 1980, Prudhoe Bay: A ten year perspective, in Halbouty, M.T. ed. Giant oil and gas fields of the decade 1969-1978: AAPG Memoir no. 30, pp.289-314.

Keller, A.A., Morris, R.H., and Detterman, R.L., 1961, Geology of the Shaviovik and Sagavanirktok River region, Alaska, part 3: U.S. Geological Survey Professional Paper 303-D, pp.169-222.

Kelley, John, 1989 personal communciation.

Kososki, B.A., Reiser, H. N., Cavit, C.D., and Detterman, R.L., 1978, A gravity study of the northern part of the Arctic National

Wildlife Range, Alaska: U.S. Geological Survey Bulletin B-1440, 21p.

Kumar, Naresh, 1989 3-D seismic applications showing enhanced porosity developed in the Lisburne Field, North Slope, Alaska. presentation at Alaska Geological Society monthly meeting.

Leffingwell, E. de K., 1919, The Canning River region, northern Alaska: U.S. Geological Survey Professional Paper 109, 251p.

Lerand, Monti, 1973, Beaufort Sea in McCrossan, R.G. ed., The future petroleum provinces of Canada–Their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, pp.315-386.

Lyle, W.M., Palmer, I.F., Bolm, J.G. and Maxey, L.R., 1980, Post-Early Triassic formations of northeastern Alaska and their petrokleum reservoir and source-rock potential: Alaska Division of Geological and Geophysical Surveys, Geologic Report 76, 100p.

Magoon, L.B. and Claypool, G.E., 1985 Alaska North Slope oil-rock correlation study: AAPG Special Studies in Geology No. 26, 678p.

Magoon, L.B., Woodward, P.V., Banet, A.C.,Jr., Griscom, S.B., and Daws, T.A., 1987, Thermal maturity, richness, and type of of organic matter of source rock units: in Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska. Bird, K.J., and Magoon, L.M. eds. U.S. Geological Survey Bulletin 1778.

McClean, Hugh, 1987, Petrology and reservoir potential of the Jago River Formation: in Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska. Bird, K.J., and Magoon, L.M. eds. U.S. Geological Survey Bulletin 1778, pp.123-126.

McWhae, J., R., 1989, Tectonic history of northern Alaska, Canadian Arctic and Spitsbergen region since Early Cretaceous. AAPG Bulletin, v.40, no. 4, pp. 430-450.

Mertie, J.B.,Jr. 1923, Geology and gold placers of the Chandalar district: in Brooks, A.H. ed. U. S. Geological Survey Bulletin 773, p 215-265.

Molenaar, C.M., 1981, Depositional history and seismic stratigraphy of L. Cretaceous rocks, National Petroleum Reserve and adjacent areas: U.S. Geological Survey Open File Report 81 01084, 42p.

Molenaar, C.M., 1983, Depositional relations of Cretaceous and L. Tertiary rocks, northeastern Alaska: AAPG Bulletin V.67, no.7, p. 1066-1080.

Molenaar, C.M., and Bird, K., B., 1987, Stratigraphy, Chapter 5 in Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska. Bird, K.J., and Magoon, L.M. eds. U.S. Geological Survey Bulletin 1778.

Moore, T.E., and Nielsen, T.H., 1984, Regional variations in the fluvial U. Devonian and L. Mississippian Kanayut Conglomerate, Brooks Range Alaska, in Nielsen, T.H. ed., Fluvial sedimentation and related tectonic framework, Western North America: Sedimentary Geology, V. 38, pp.465-497.

Mull, C.G, Tailleur, I.L., Mayfield, C.F., Ellersieck, I and Curtis, S.M., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: AAPG Bulletin v.66, no.3, pp. 348-362.

Nielsen, T.H., 1981, U. Devonian and L. Mississippian Endicott Group, Brooks Range Alaska, U.S. Geological Survey Open File Report 80-1066, 1:1000000, 2 sheets.

Norris, D.K., 1981, Geologic Map 1541-A Geology Herschel Island and Demarcation Point, 1:250000 Geological Survey of Canada.

Norris, D.K., 1984, Geology of northern Yukon and northwestern District of Mackenzie: Geological Survey of Canada Map 1581A 1:500000.

Norris, D.K. 1985a Eastern Cordilleran foldbelt of northern Canada: Its structure, geometry and hydrocarbon potential: AAPG Bulletin, V.69, no 5, pp. 788-808.

Norris, D.K. 1985b, The Neruokpuk Formation, Yukon Territory and Alaska, in Current research part b: Geological Survey of Canada Paper 85-1B, pp. 223-229.

Palmer, I.F., Bolm, J.R., Maxey, L.R. and Lyle, W.M., 1979, Petroleum source-rock and reservoir quality data from outcrop samples, onshore North Slope of Alaska east of Prudhoe Bay.: U.S. Geological Survey Open File Report 79-1634, 52p.

Poulton, T.P., 1982, Paleogeographic and tectonic implications of the Lower and Middle Jurassic facies patterns in northern Yukon Territory and adjacent Northwest Territory. in Embry, A.F., and Balkwill, H.R., eds., Arctic Geology and Geophysics, Canadian Society of Petroleum Geologists, Memoir 8, pp. 13-28.

Reed, B.L., 1968, Geology of the Lake Peters area, northeastern Brooks Range, Alaska, U.S. Geological Survey Bulletin 1236.

Reiser, H.N., 1970, Northeastern Brooks Range: a surface expression of the Prudhoe Bay section; in Proceedings of the geological seminar on the North Slope of Alaska, AAPG Pacific Section, pp. K1-K3.

Resier, H.N., Brosge, W.P., Dutro, J.T. and Detterman, R.L. , 1971, Preliminary geologic map , Mt. Michelson quadrangle, Alaska: U.S. Geological Survey Open File Report, 71-237, 1:200000.

Resier, H.N., Brosge, W.P., Dutro, J.T. and Detterman, R.L., 1980, Geologic map of the Demarcation Point quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Map I-1133, 1:250000.

Robinson, M.S. Decker, John, Clough, J.G., Bakke, Arne, Reifunsthul, R.R., Dilon, J.T., and Rawlinson, S.E., 1989, Geology of the Sadlerochit and Shublik Mountains, Arctic National Wildlife Refuge (ANWR), northeastern Alaska: Alaska Division of Geological and Geophysical Surveys Geologic Report 100, 1 sheet, 1:63600.

Sable, E.G., 1965, Geology of the Romanzof Mountains, northeastern Alaska: U.S. Geological Survey open file report, 218p.

Sable, E.G., 1977, Geology of the western Romanzof Mountains, Brooks Range, northeastern Alaska: U.S. Geological Professional Paper, 897.

Smith, D. G., 1987 Late Paleozoic to Cenezoic reconstruction of the Arctic: in

Tailleur, I.L and Weimer, Paul: Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V. 50 pp. 785-795.

Teseneer, R.L., 1985, Teshekpuk Lake Special Study Area Mineral Evaluation Bureau of Land Management proprietary report.

Werner, M.J., 1987 West Sak and Ugnu sands: low-gravity oil zones of the Kuparuk River area, Alaskan North Slope: in Tailleur, I.L and Weimer, Paul: Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V.50 pp. 109-118.

Werner, M.J., 1985, West Sak and Ugnu: low-gravity oil zones of the Kuparuk River area, North Slope, Alaska. abs. AAPG Bulletin v. 64, no. 9 p.682.

Woidneck, K., Berhman, P., Soule, C. and Wu, J., 1987, Reservoir description of the Endicott Field, North Slope, Alaska: in Tailleur, I.L and Weimer, Paul: Bakersfield Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, V.50 pp. 43-60.

Yorath, C.J., 1973, Geology of the Beaufort-Mackenzie Basin and western part of Northern Interior Plains, in Pitcher, M.D., ed., Arctic Geology, AAPG Memoir 19, pp. 41-47.

Yorath, C.J., and Norris, D.K., 1975, The tectonic development of the southern Beaufort Sea and its relationship to the origin of the Arctic Ocean Basin, in Yorath, C.J., Parker, E.R., and Glass, D.J., eds., Canada's Continental Margins, Canadian Society of Petroleum Geologists, Memoir 4, pp. 589-612.

Young, F.G., and McNeil, D.H., 1984, Cenozoic stratigraphy of Mackenzie Delta, Northwest Teritories NTS107B,107C, Geological Survey of Canada Bulletin 336, 63p.

Young, F.G., Myhr, D.W., and Yorath, C.J., 1976 Geology of the Beaufort-Macknezie Basin, Geological Survey of Canada, Paper 76-11, 63p.