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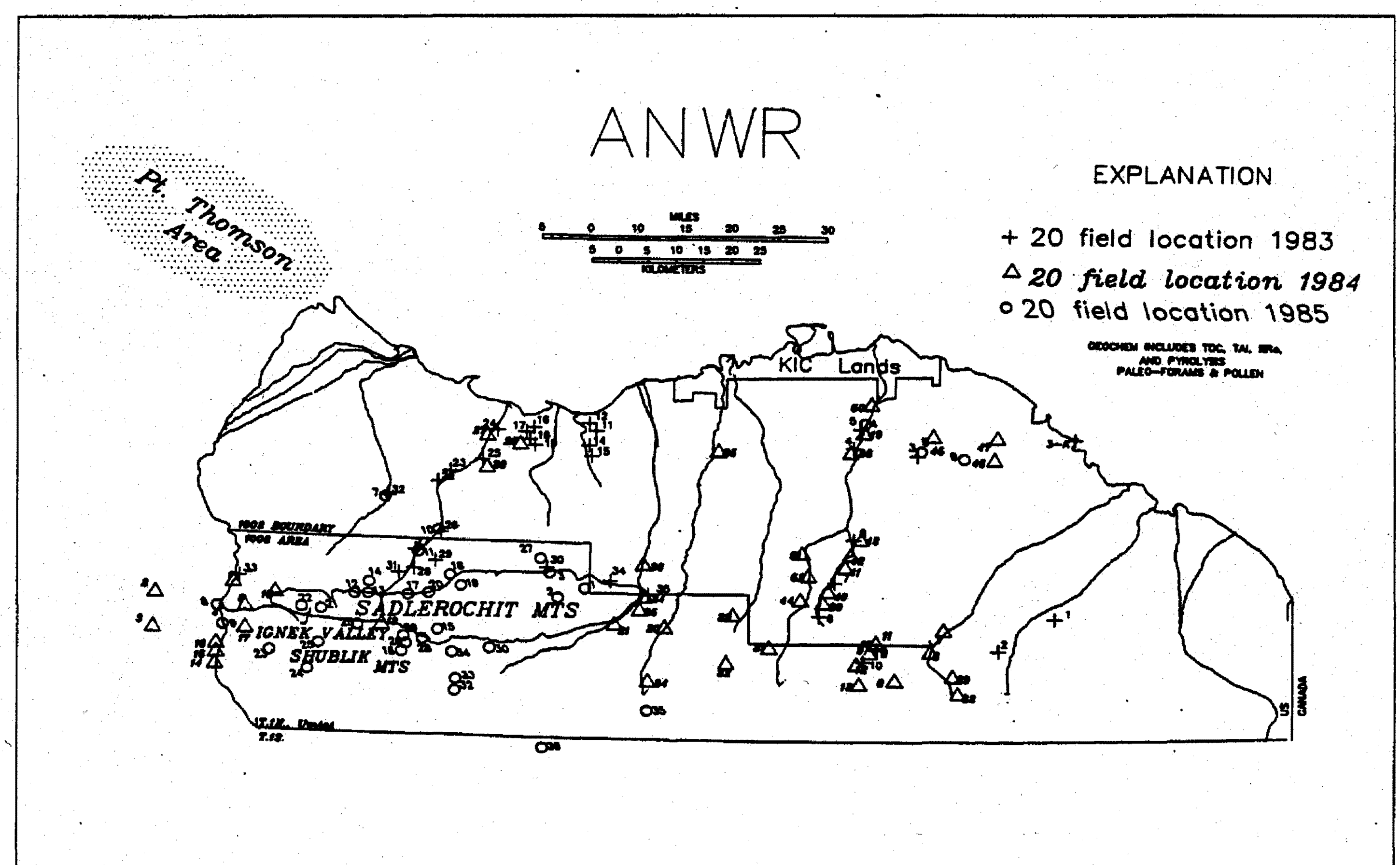
Petroleum Geology and Geochemistry of the Arctic National Wildlife Refuge 1002 Area

Arthur C. Banet, Jr.



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16. Abstract (Limit: 200 words)

A synthesis of field work, geological mapping, sample gathering and testing during 1983-85 identifies the succession of sediments extrapolated to lie beneath the Coastal Plain within the Arctic National Wildlife of northeast Alaska. Complex and diverse assemblages of Upper Proterozoic to Lower Paleozoic mildly metamorphosed sediments underlie most of the region. An angular unconformity separates these older rocks from the overlying northerly derived Ellesmerian Sequence clastics and carbonates which have proven reservoir potential at Prudhoe Bay. Uplift associated with Lower Cretaceous break-up tectonics has removed an undetermined amount of these rocks. A thick, overall regressive, southerly derived Brookian Sequence clastic wedge oversteps all older units.

Compressional tectonics affects all three sedimentary sequences. Major decollements are unique to sequences or along bounding surfaces and typically manifest the effects of multiphasic deformation in the sediments.

Geochemical data identifies several possible hydrocarbon source rocks. These include the basal Brookian shales, the richest potential source rocks of the North Slope and the regionally-known Shublik, Kingak, Pebble Shale, and Seabee formations (Shale Wall member). Timing of hydrocarbon formation, migration and subsequent entrapment is dependent upon structural position.

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Petroleum Geology and Geochemistry of the Arctic National Wildlife Refuge 1002 Area

1. INTRODUCTION

The Arctic National Wildlife Refuge (ANWR) covers approximately 18 million acres of northern Alaska (fig. 1). At present, only the estimated 1.5 million acre portion of the Arctic Coastal Plain, designated the 1002 area (fig. 2), is deemed prospective for petroleum. The Alaska National Interest Lands Conservation Act (ANILCA) mandates the oil and gas resource evaluation of this 1002 area. This geologic analysis has been accomplished through field mapping, geochemical sampling and analyses, and CDP seismic data interpretation.

The subsurface stratigraphy and structural style of the 1002 area are inferred from field mapping programs during 1983, 1984, and 1985, interpretation and correlation of available oil well logs near ANWR, available published material (Bader, 1984; Kososki and others, 1978; and Reiser and others, 1974), and cooperative efforts with the U.S. Geological Survey (USGS). Sedimentary organic richness and thermal maturity are determined T.O.C., pyrolysis, %Ro, TAI, C15+ extractables, and gas chromatographic analyses. These data are displayed as a composite geochemical profile to facilitate evaluation and comparison of the sedimentary units. Both the stratigraphic interpretations and geochemical samples are from oil wells west of ANWR, outcrops in both the 1002 and 1008 areas of ANWR, including the Sadlerochit, Shublik, and front range mountains. All of the material in this report was originally submitted to the U.S. Department of the Interior for inclusion in Clough, N.K., Patton, P.C., and Christiansen, A. C., 1987, Arctic National Wildlife Refuge, Alaska, Coastal Plain Assessment--Report and Recommendations to the Congress of the United States and Final Legislative Environmental Impact Survey; Washington D. C., U.S. Fish and Wildlife Service, U.S. Geological Survey, Bureau of Land Management, v. 1, 208 pp.

Figures 2 and 3 show the major features and nomenclature used in this report. The mountains are referred to as front range, unless specifically identified as the Sadlerochits or Shubliks, and the coastal plain is generally the low relief area between the coast and the mountain front.

An idealized subsurface section (fig. 3) shows the stratigraphic and structural relationship from the Colville Trough and the Barrow Arch. The Colville Trough is lined with Lower Cretaceous and older sediments which have been eroded at the Barrow Arch. The basin is filled by Upper Cretaceous and younger sediments that prograded northward over the Barrow Arch. However, structural deformation is more intense in the 1002 area and the post-Cretaceous stratigraphy is considerably different (plate 1) than the rest of the coastal plain (figure 3); consequently, both the stratigraphy and geochemistry are treated as composite sections for evaluation purposes.

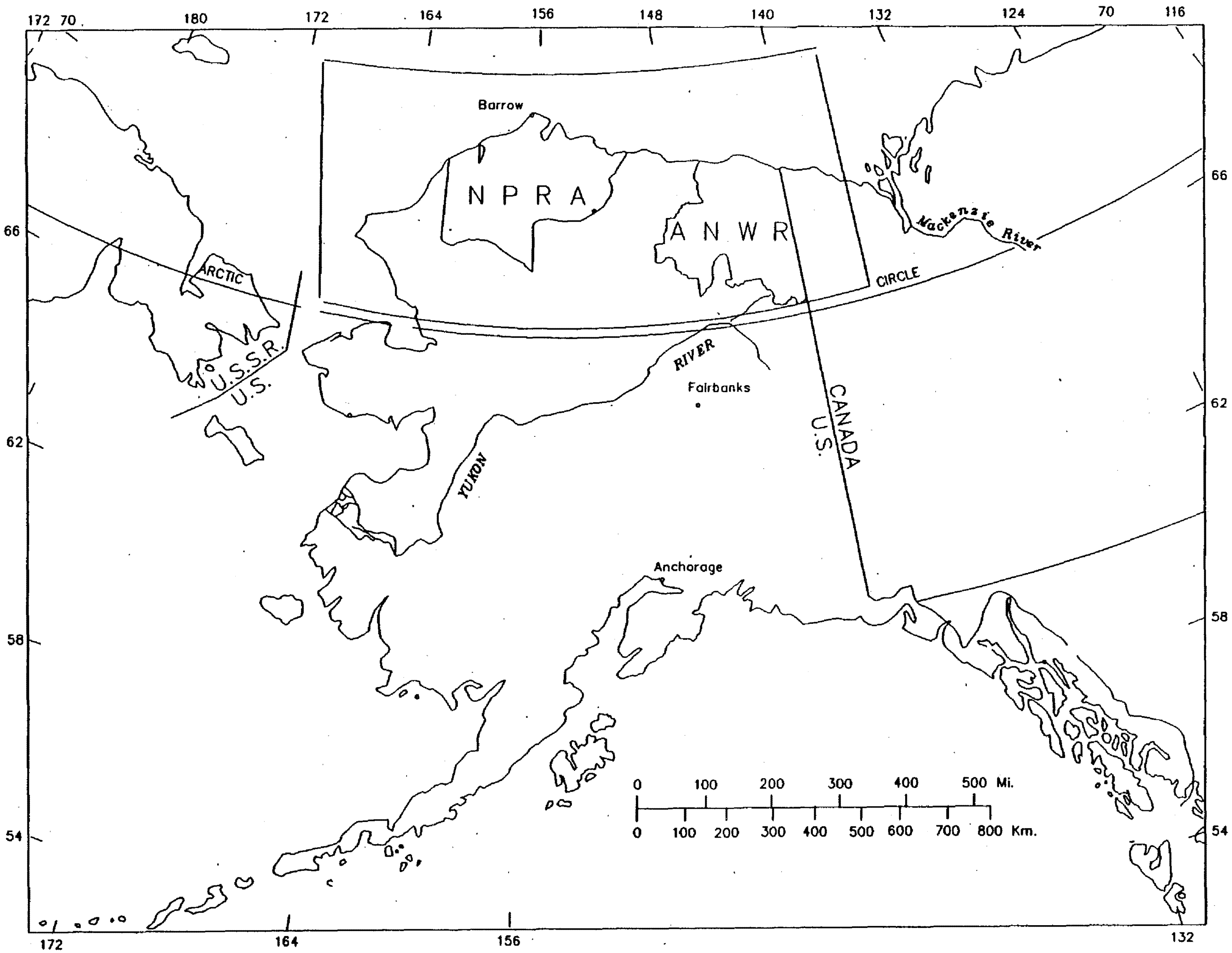

Figure 1. Index map showing Alaska and the North Slope

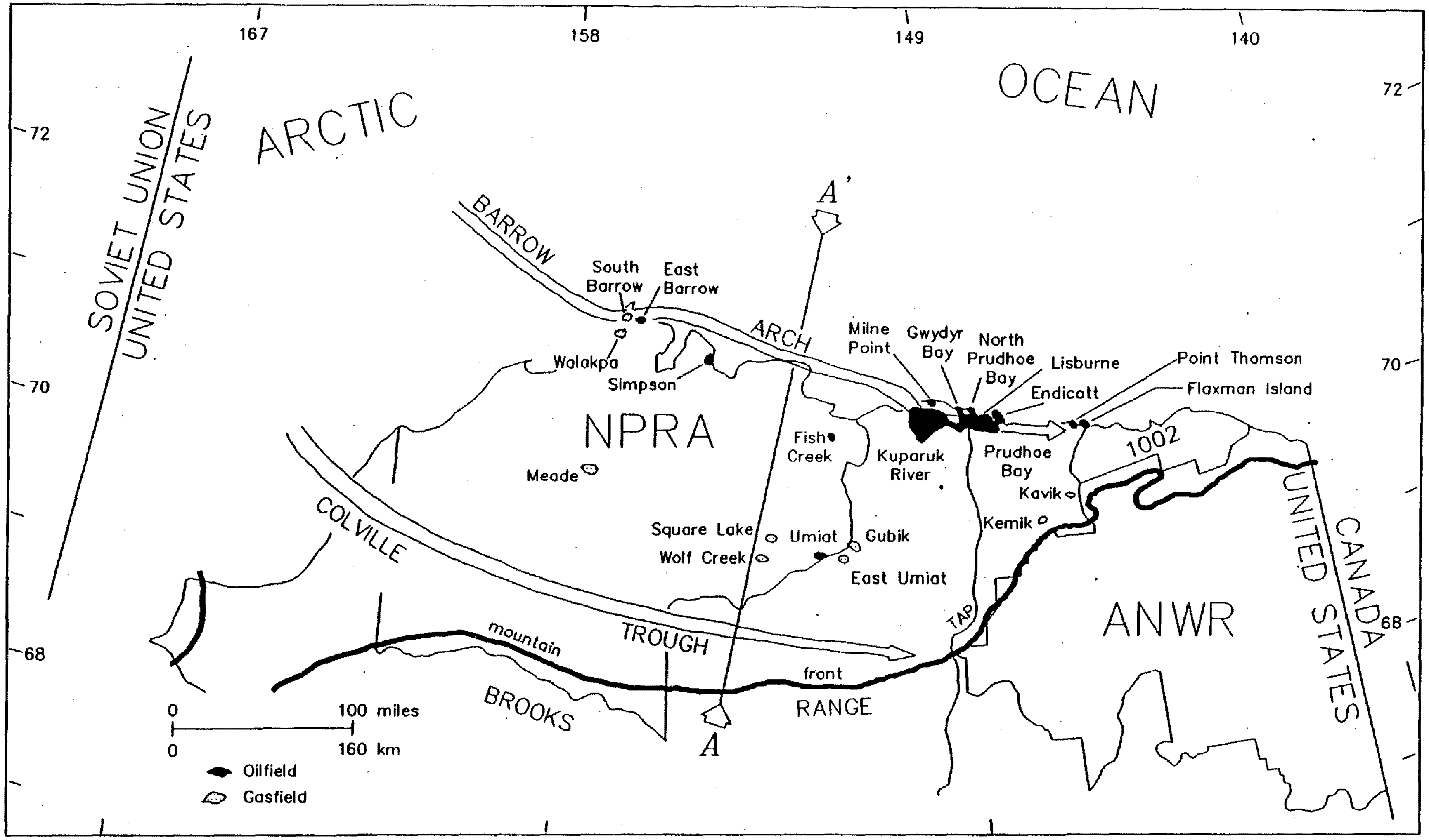

Figure 2. Map showing ANWR,NPRA, major geologic features and oil.gas discoveries (after Bird,1983)

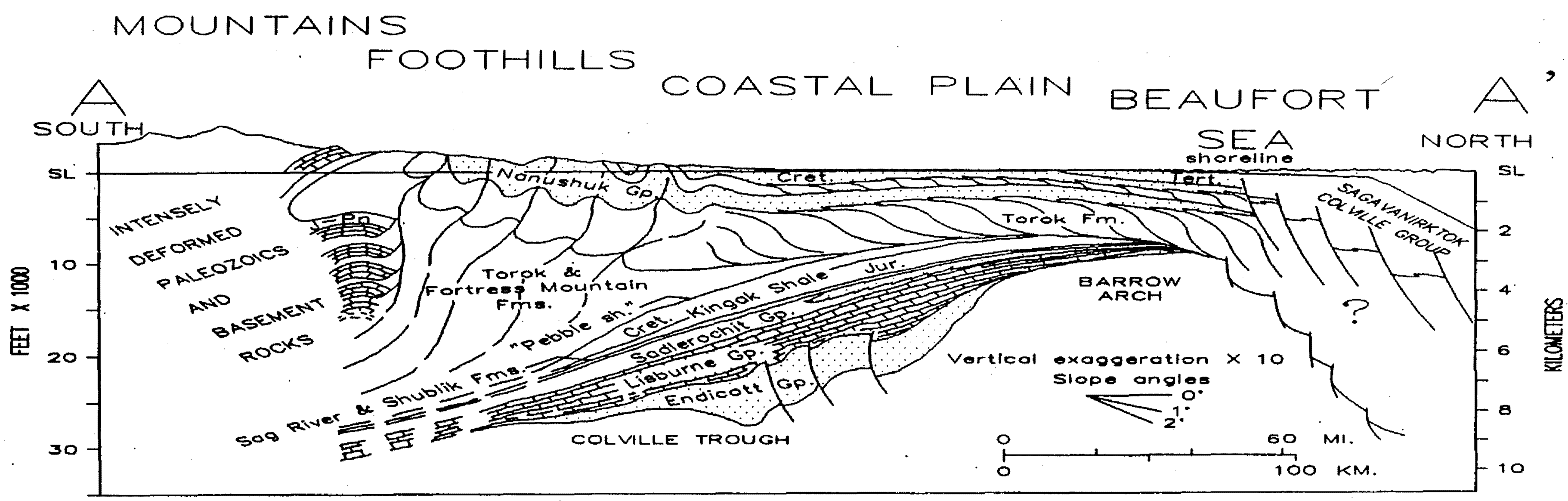

Figure 3. Generalized north–south cross section showing projected stratigraphic and structural relations of North Slope geology; includes basement rocks, Ellesmerian and Brookian Sequences, Overthrust Belt , Collville Trough and Barrow Arch (after Bird, 1983).

2. STRATIGRAPHY

Basement Rocks

The stratigraphy of northeast Alaska is summarized in plate 2. It includes rocks at least as old as pre-Cambrian in or adjacent to the 1002 area. On the North Slope, pre-Mississippian rocks are usually considered as economic basement (Jamison, Brockett and McIntosh, 1980) and are unconformably overlain by Lerand's (1973) Ellesmerian and Brookian sequences (plate 1). The basement sediments, commonly referred to as Franklinian Sequence rocks, are not extensively studied in this area. Consequently, some correlations are tentative, and the structural and stratigraphic relationships are not well known.

In the subsurface along the arctic coast, wells west of ANWR have commonly penetrated the Neroukpuk or the "argillite" beneath the sedimentary section. This unit is commonly described in cuttings and core samples as gray to silvery schist, or gray to black laminated phyllite with abundant quartz filled fractures and veinlets. Wells in the Point Thomson area, however, (fig. 2) penetrated and recovered hydrocarbons from interbedded phyllite and limestones underlying the correlative sediments.

The Katakturuk Dolostone (Proterozoic to Cambrian) and Nanook Limestone (Cambrian-Ordovician) (Blodgett and others, 1986) are the oldest rocks that crop out in the Sadlerochit and Shublik mountains. The Katakturuk is predominantly a gray, massive extensively fractured and vuggy dolostone and silicified dolostone, with abundant vugs, white calcite veinfill, and stromatolites. Angular breccias and pisolites are common and diagnostic of this section. There are also lenses of black to gray volcanic rocks with milky quartz veins at scattered locations. Dutro (1970) reported approximately 3,500 feet of section in the Shublik mountains and more than 10,000 feet of section, which may be faulted, exposed along Katakturuk Creek through the core of the Sadlerochit mountains. The Canning River A-1 well (plate 1) penetrated approximately 600 feet of this section and tested more than 2,000 bfw/day. Cores showed no-to-low interconnected porosity, but abundant open fractures.

The Nanook Formation unconformably overlies the Katakturuk, where exposed, in the Shublik mountains. There, it is mostly light gray, fine-grained limestone with minor amounts of gray shale. Kososki and others (1978) estimated 3,000 to 3,300 feet of section in the Shubliks. Porosities and permeabilities have not been tested, but hand specimens appear tight.

Ellesmerian Sequence

The Ellesmerian sequence is a northerly derived package of sediments that unconformably overlies the older basement rocks (Lerand, 1973). This sequence is widespread across the North Slope; exposed throughout the Brooks Range from Cape Lisburne to Canada, and correlated through the subsurface from NPRA and the Prudhoe Bay fields to wells adjacent to ANWR. The basal Kekiktuk Conglomerate is up to 400 feet of fluvial deposits composed of black and white chert pebbles, quartzose sandstones, mudstones, and minor amounts of shale and coal. Outcrops in ANWR commonly show very little porosity or permeability. Although the Kekiktuk is discontinuous, it is found throughout the Brooks Range and in the subsurface of NPRA (South Meade No. 1 and Topogoruk No. 1). Offshore from the Prudhoe field, the Endicott field has estimated reserves of 1.4 billion barrels of 23° API gravity oil and 0.5 billion reservoir barrels of gas (Behrman and others, 1985). The Kayak and Itkilyariak shales overlie the Kekiktuk or are present in its place. The Kayak is up to 1,300 feet of gray fissile shale, in well cuttings, and phyllitic shale at outcrop (Brosge and others, 1962). The Itkilyariak is a similar lithology except that it is red at the

Prudhoe field and in the eastern Brooks Range of the 1008 area (Mull and Mangus, 1972).

The Lisburne Group (Mississippian-Pennsylvanian) unconformably overlies the Endicott clastics. The Lisburne limestones are gray to light gray, massive, cherty, partially dolomitic, oolitic, and commonly fossiliferous with bryozoan chrinoids and corals. The Alapah is the lower member and the Wahoo is the upper, more resistant member. At outcrop, these rocks are massive, dense, hard, usually fractured and partially vuggy. These rocks also correlate across the Brooks Range and in wells from NPRA to wells adjacent to ANWR where the unit is approximately 2,000 feet thick. Although both outcrop and core samples have very little porosity, the Lisburne at Prudhoe produces oil with reserves estimated at approximately one billion barrels from rocks that have very low porosities and permeabilities (Okland and others, 1985).

The Sadlerochit Group (Permian-Triassic) is a predominantly fluvial-deltaic sequence of sandstones and shales which unconformably overlies the Lisburne rocks. The basal Echooka is predominantly thin interbedded prodelta sandstones and shales, with some massive bedded sandstones up to approximately 25 feet thick. These sandstones are typically fine-grained, quartzose, well sorted, and weather to brown. The overlying Kavik is a dark gray marine shale estimated to be approximately 400 feet thick where exposed on the north side of the Sadlerochit mountains. Upsection, the Ivishak sandstones are thick-to-massive bedded, laterally extensive, amalgamated channel sands that range in thickness from 350 to 400 feet along the back of the Sadlerochit mountains. The sandstones are quartzose, white to light gray on fresh fracture, fine-grained to coarse-grained, with some matrix-supported chert-pebble conglomerate. Outcrops of the Ivishak are rust to brown rubble piles with the individual blocks characteristically several feet across. Hand specimens are very hard and very dense. Most sand grains have been recrystallized, and yellow limonite grains are common on fresh fracture. The Fire Creek siltstone is a localized unit consisting of 100 to 200 feet of thin interbedded siltstones and shales which overlie the Ivishak.

The Sadlerochit sandstones are correlatable from NPRA to the wells adjacent to ANWR; they are the major reservoirs of the Prudhoe field, where porosities in the oil producing zone range from 10 percent to 35 percent, and permeabilities are up to 4,000 md (Jamieson and others, 1980). These lithologies are equivalent to those that show no reservoir characteristics at outcrop ANWR.

The Shublik Formation (Lower Triassic) is mostly a dark gray, nodular phosphatic organic rich marly limestone, and black nodular phosphatic shale with minor amounts of very fine-grained sandstone or siltstone. The abundance of phosphate, glauconite, and high T.O.C. indicate that the Shublik represents preservation of an oceanic updwelling zone where currents create an organic rich productive ecology (Tothman-Parrish, 1985) essential for a good oil source rock. It ranges in thickness from 90 to 250 feet at outcrops in ANWR and nearby wells.

The Sag River sandstones of the western part of the North Slope and the Karen Creek sandstones (Lower Triassic) of the eastern part of the North Slope are equivalent units. The sandstones are very fine-grained to fine-grained, commonly glauconitic, with no observable porosity at outcrop, and are gray, weathering to tan. Thicknesses vary from 17 feet in ANWR, to 55 feet near Prudhoe where it is a minor oil reservoir.

The Kingak Shale (Jurassic - Lower Cretaceous) crops out in drainages along most of the mountain front and in one location on the coastal plain. The Kingak is mostly a monotonous sequence of gray and silty to very silty shale, with minor amounts of concretions, sandstone lenses, and bentonite layers deposited on a trailing continental margin. Detterman and others (1975) described the Kingak "type section" in the Sadlerochit mountains and reported sections measured from 150 to some 1,400 feet in ANWR. Measured thicknesses vary due to fault repetitions, erosion, or poor exposure.

The end of Kingak deposition also marks the end of a major period of predominantly quiescent deposition in northern Alaska. Regional uplift and tilt in the north made the Barrow Arch a positive element. Lower Cretaceous erosion removed the Ellesmerian sequence from the Arch. South of the Arch, the progressively younger Ellesmerian rocks are truncated southward by the Lower Cretaceous Unconformity (LCU) (plate 1 and figure 2) which disappears southward Molenaar (1983).

Local tectonic events resulted in the deposition of infra-rift marine clastic units which are generally petrologically mature, similar to the Ellesmerian rocks and designated as Barrovian Sequence (Carmen and Hardwick, 1983). At present, these rocks are only described in the Kuparuk Field near Prudhoe, but there are similar nonassigned post-Ellesmerian sands in the Point Thomson area.

Across most of the North Slope, the Kemik sandstone and the informally named pebble shale unit, of the Kongakut Formation directly overlie LCU. The Kemik is exposed around the Sadlerochit mountains, and has been found in nearby wells (plate 1). Well and field correlations show that near ANWR it is an elongated sandstone body, at least 6 miles by 20 miles, and generally less than 100 feet thick; analogous to a modern platform bar/barrier island sand body. In hand specimen, the Kemik is quartzose, mostly fine-grained to medium-grained, and petrologically similar to the Ellesmerian sequence. Ripple marks, large-scale trough crossbeds, mud bands, and clam shell impressions, are common features, as are clast supported black and white chert pebble conglomerate lenses. The Kemik is usually hard, blocky to flaggy, with outcrop porosities in the 3 percent to 6 percent range (Lyle and others, 1980).

The Pebble Shale is an informally named unit, correlatable from NPRA across the North Slope. It overlies the Kemik sandstone where present, or the older rocks. The lithology is predominantly black, fissile, pyritic, organic rich shale with floating sand grains, rare to common chert pebbles (up to three-inch diameter), and minor amounts of siltstone and bentonite. It crops out along Canning River, around the Sadlerochit mountains, along the front range, and at one location on the coastal plain. In wells, it is usually between 200 feet and 400 feet thick. Exposures in ANWR usually do not include a complete uninterrupted section. The upper part of this unit is characteristically radioactive, usually called the GRZ (gamma ray zone) or HRZ (high radioactive zone). It is a commonly used marker bed in North Slope stratigraphy. Fossils indicate a Hauterivian-Barremian age for the lower part of this unit on the coastal plain, and Molenaar (1983) reports that the upper part is typically barren of diagnostic fossils.

Wells in the Pt. Thomson Unit penetrate a localized sandstone body, directly overlying the basement rocks. This sandstone is mostly quartzose and clean, like the Kemik, but unlike the Kemik the lithologic logs from this interval include a high percentage of large angular carbonate grains and breccia. The sandstone reaches a thickness of approximately 400 feet in the Pt. Thomson Unit, but it thins out southward, and is completely gone at West Staines No. 1 (plate 1). Wilson (1977) cites discovery flow rates of 2,000 bopd of 18.5° API gravity oil and gas in excess of 10 MM cfd from these sandstones in the Pt. Thomson Unit. These rocks are likely derived from localized northern tectonic events rather than being part of the Ellesmerian sequence. Thus they may be similar to Carmen and Hardwick's (1983) Barrovian Sequence.

The areal extent of Ellesmerian Sequence truncation at the Lower Cretaceous Unconformity is a major problem in the ANWR analysis and evaluation. If the Ellesmerian rocks are truncated in the subsurface of ANWR, important reservoir rocks will not likely be very extensive, and thus the petroleum potential would be lowered. Evidence for a truncation along the Barrow Arch is from well log correlations (plate 1) and seismic mapping of reflectors (Foland and Lalla, in press). These methods show the truncation of Ellesmerian in western ANWR in the area of the Canning River. The easternmost expression may possibly be an isolated outcrop of Kemik sandstone overlying Sadlerochit sandstone along upper Marsh Creek on the north side of the Sadlerochit Mountanins.

However, Ellesmerian rocks, especially the Sadlerochit Group, are found on the south flanks and northeast ends of both the Sadlerochit Mountains, the Shublik Mountains and across the front range of ANWR immediately south of the 1002 area. These sands are 300 to 400 feet thick along the approximately 90 miles of outcrop.

Seismic mapping of the eastern half of ANWR, which is approximately 50-90 miles east of the mapped truncation near the Canning River, shows coherent to semi-coherent seismic reflectors underlying the deformed Brookian Sequence. These underlying reflectors have characteristics and interval velocities that are unlike the overlying Brookian rocks and underlying basement rocks. Their character and interval velocities do, however, resemble the Ellesmerian rocks, where mapped and tied with outcrops and good well data. Thus, even though the presence of Ellesmerian rocks in the subsurface of the eastern part of the 1002 area cannot be confirmed withouth well or outcrop ties, their existence, or the existence of hitherto unknown rocks in this interval must definitely be considered.

Brookian Sequence

The Brookian rocks are a southerly derived clastic sequence that record the uplift of the Brooks Range. These rocks are of Aptian age in NPRA, and generally become progressively younger east northeastward towards ANWR. However, the turbidite sequence at Kingak Hill, southeast of the Sadlerochit mountains, is, apparently, an exception. This sequence is approximately 90 feet of thin to massively bedded, very fine-grained to fine-grained, noncalcareous, hard, flaggy siliceous sandstone. Flute casts and crossbeds are common and indicate current direction towards the northwest. This unit is mostly gray weathering to tan. It overlies a gray, silty shale with minor siltstone lenses and bentonitic beds. Faults and steep dips complicate the stratigraphic relationship. Detterman and others (1975) reported Albian age (?) fossils. This suggests that these are the oldest Brookian rocks in northeast Alaska. Structural complications, limited exposures, and no well correlations preclude determining the extent of this unit in the ANWR subsurface.

The Seabee Formation or Colville Group shales (Upper Cretaceous - Tertiary) overlie the pebble shale in nearby wells and at outcrops in ANWR (plates 1 and 2). The basal shale (Shale Wall Unit) is black with a papery/cardboard texture. It is rich in T.O.C. Its abundant tuffaceous bentonite beds record the widespread volcanism associated with initial stages of the Brooks Range uplift. These bentonites range in thickness from less than one inch to up to three feet. Where exposed around the Sadlerochit mountains, a thin, hard sinter layer weathers to a distinctive orange. Well lithologies and logs record abundant bentonite and high gamma log readings through this 250- to 500-foot thick section. Structural deformation is easily seen at outcrops in ANWR in the folding and fault offset of the bentonites and platy shale.

The bentonite beds are thin and are less prevalent upsection. Along Niguanak Creek, a soft, light-gray, smectitic shale with large, round concretions overlies the bentonitic unit.

In western ANWR, along the Canning River and Katakturuk Creek and its tributaries, the Colville shale consists of interbedded sandstone/silty shale turbidite sequences. The shales are gray to dark gray, very silty and soft. The sandstones range in thickness from lamina to stacked channels up to 25 feet thick. The thinner sandstones are closer to the mountain front, are more continuous and uniform than the thicker channel sandstones. At outcrop, specimens are generally gray on fresh fracture, weathering to tan, mostly very fine to fine-grained, with minor amounts of matrix supported conglomerate. Angular, black and white chert is common in the sandstones. In addition, there is a lot of coal deposited as distinct lamina, as the highest parts of the fining upward units, as intact plant remains and tree stumps. One tree stump, approximately one foot in diameter, was found upright. The abundance of preserved coaly material, the lack of marine shale, and the presence of cross cutting channels rather than distinct fining-upwards sequences suggest that at least part, if not a lot, of this sequence may be a deltaic/near pro-deltaic deposit rather than a turbidite deposit.

In central ANWR, there is a very thick sequence of interbedded conglomerate and shale of Paleocene age exposed between the Okpilak and Okerokovic Rivers (Detterman and others, 1975; Lyle and others, 1980). This Paleocene unit may be coeval with the turbidites and is perhaps the fluvial deltaic equivalent. The exposures are east-west trending and dip to the north; approximately 45° north at the south end of the crops, decreasing to approximately 10° north at the north end. The conglomerate is mostly matrix supported, angular to subangular, black and white chert, pebbles and cobbles, with minor amounts of igneous and metamorphic rocks. The matrix consists of poorly sorted, coarse sandstone and angular chert grains that weather to brown or tan. There are thin coals mostly near the base of the section and there are casts of tree trunks and large-scale crossbeds that show cross-cutting channels throughout the section. Although these rocks are mostly hard, commonly breaking across grains and pebbles and show little visible porosity, some sections are friable. The interbedded shales are black, very silty, platy and carbonaceous, with numerous siltstone beds. The entire section is approximately 10,000 feet thick and is not repeated by faults. However, the base of the section is a thrust fault contact.

Well logs (plate 1) show that the Turbidite sequences, where present, are overlain by 1,200 to 4,000+ feet of gray, smectitic shale interbedded with minor amounts of marine sandstone. There is no well data or outcrop data to determine the stratigraphy directly above the conglomerate. At the E-56 Natsek well in the Canadian Beaufort (approximately 30 miles ENE), a probably correlatable Upper Cretaceous-Paleocene of similar non-marine fluvial sandstone and conglomerates are overlain by approximately 6,500 feet of Paleocene marine shales (figure 4).

In western ANWR, the Colville shale is overlain by a thick, northeasterly prograding, nonmarine sequence, the Tertiary Sagavanirktok Group (Colville nonmarine, Molenaar, 1983). The Sagavanirktok is up to approximately 6,000 feet of poorly to non-consolidated sandstone, siltstone, mudstone, and gravel. These rocks are exposed along the flanks of the Marsh Creek anticline in western ANWR. Lyle and others (1980) divided the Sagavanirktok into three members. The Sagwon (Eocene) is the basal unit, and it consists of soft gray smectitic shale, carbonaceous shale, ironstone nodules, thin discontinuous lignite beds, and poorly sorted, unconsolidated conglomerate and sandstone, with abundant, partially fossilized wood. The overlying Franklin Bluffs Member consists of a thick section of brown carbonaceous clay and silt varves; thin interbedded units of unconsolidated sand, silt and clay, with common floating, rounded chert pebbles (1/2 cm diameter); and local poorly consolidated sands and conglomerate. More poorly consolidated, crossbedded

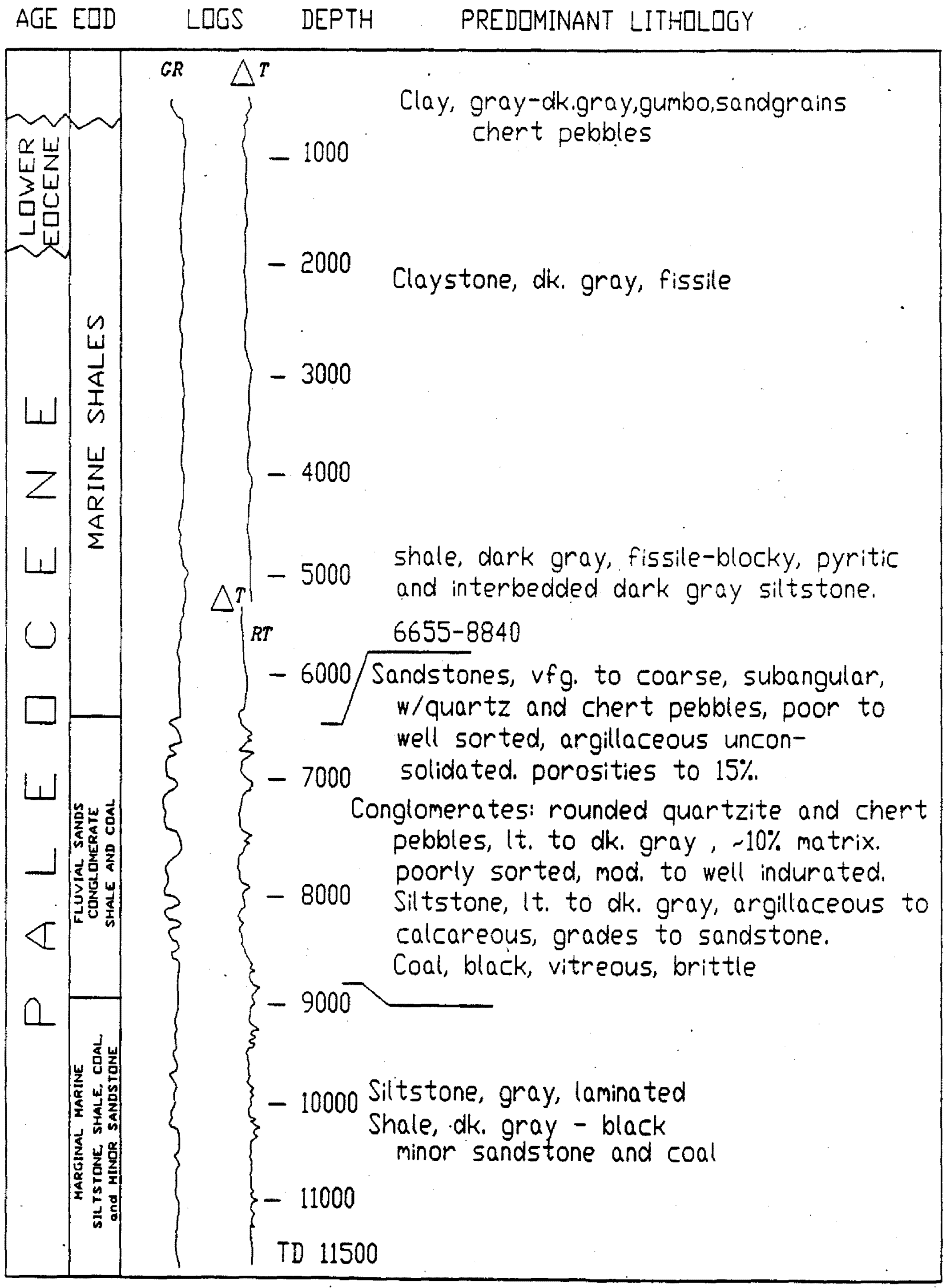

Figure 4. Log profile and generalized lithology of Natsek E-56 well (Dome Petroleum Limited)

sandstone, pebble conglomerate and mudstone, with floating pebbles comprise the overlying Nuwok Member.

Much of the coastal plain is covered by the predominantly easterly derived sands, pebbles, and cobbles of the Gubik Formation. The Gubik has a distinctive, higher percentage of igneous and metamorphic rocks and a wider size variation than rocks of the underlying units. Glacial runoff, alluvium, and colluvium from the front ranges cover much of the upland areas, limiting outcrops mostly to stream cuts.

3. STRUCTURE

Compressional deformation is the predominant structural style in ANWR. The majority of outcrops show sediments with steep dips, fault offsets, fault contacts, repeated units, or tightly folded marker beds. Only the small area northwest of the Marsh Creek Anticline has the relatively undisturbed "layer cake" stratigraphy that is usually found on the arctic coastal plain west of ANWR.

Kelly (1985) and Rattey (1985) mapped and identified three major detachments in this area. The decollement in the Kingak is the oldest detachment, and the source rock geochemistry is distinctively different on either side of the decollement. Immature to marginally mature source rocks are found above the Kingak decollement. These sediments are commonly deformed and offset by subsidiary high angle thrust faults and fault duplexes that sole into the Kingak decollement. This is the typical style of a structural, prograding leading edge, where the faults are younger away from the mountain front, or origin of deformation. Each later fault deforms and uplifts the previous faults and fault bounded rock units (Kelly and Foland, 1987). The result of this deformation is multiple repetitions of the sedimentary section which has not yet been buried enough for large-scale hydrocarbon generation. ANWR coastal plain outcrops are typically deformed in this manner. Thus, it can be difficult to make exacting stratigraphic correlations or thickness measurements on these outcrops.

The next oldest detachment is at the base of the Ellesmerian section (Kelly, 1985). This detachment emplaces the allocthonous Ellesmerian rocks over the younger rocks and autocthonous Ellesmerian rocks, as observed in the Sadlerochit mountains, the Shublik mountains, and much of the northeast Brooks Range (plate 1). It also deforms the Kingak decollement and older faults. Upsection cutting splays of this decollement are also progradational. Thus, rocks between this decollement and the Kingak decollement that are at the surface have been laterally transported miles, and uplifted more than 15,000 feet from their previous downdip position. Sparse geochemical data available for these rocks indicate that they have been buried beyond petroleum-generating environments prior to this phase of uplift and emplacement. Extrapolation of this faulting style suggests that the Ellesmerian section may be thrust over the younger rocks, at least along the mountain front and perhaps over additional Ellesmerian rocks if they are present in the coastal plain subsurface.

Bedding parallel thrusting within the pre-Ellesmerian stratigraphic section, is the third major detachment in this area (Kelley, 1985; Rattey, 1985). This is the most recent phase of thrusting, and it deforms the previous detachment surfaces. It is confined to the basement rocks and apparently does not affect the source rock potential in ANWR because source rocks are not identified in that part of the section.

4. SOURCE ROCKS

Introduction

Geochemical analyses of well cuttings samples, outcrop samples, seismic line shot hole samples, oil stained rocks, and oil seeps in and around ANWR are shown on plates 3 and 4. These data identify the major petroleum generating souurce rocks and compare the organic richness, type of indigenous organic matter, and thermal maturity ranges of the sedimentary section expected in the ANWR subsurface.

Evaluation

Plate 3 is a composite of T.O.C., %Ro, TAI, kerogen type, Hydrogen Index (S2/TOC), and Genetic Potential (S1 + S2) data from wells and outcrops. The wells are immediately west of ANWR, and the cuttings samples are essentially fresh samples. The outcrop data are from exposures in both the Sec. 1002 and nearby 1008 areas of ANWR and are plotted as accurately as possible from field work to their true stratigraphic positions.

There is good agreement between T.O.C. values from outcrops vs cuttings, despite possible weathering or thermal maturity effects. Also, there is overall fair to good comparison of vitrinite reflectance data. The Brookian rocks are generally immature to mature and the Ellesmerian rocks are mature to over-mature. Pyrolysis data, Hydrogen Index and Genetic Potential, however, differ widely between well cuttings and outcrop samples; the outcrop samples are usually much lower than the drill cuttings samples (plate 3). Also, there is more data available on the Brookian rocks because they have been drilled and sampled more than the Ellesmerian sequence, except for the extensively studied lower Cretaceous pebble shale.

The source rock data on the basement and lowest Ellesmerian sequence is minimal because these rocks have not been sampled extensively and were only drilled at Canning A-1. T.O.C. is mostly less that one percent, and there is no direct data on thermal maturity (plate 3). However, samples from upsection in the same well are in the metagenetic stage, and anthracite rank coal has been described in the overlying Endicott Group. As elsewhere on the North Slope, this section demonstrates no real source rock potential.

The Ellesmerian Lisburne carbonates have low to average T.O.C. values for carbonate rocks. The kerogens are predominantly coaly (likely recycled material or Inertinite) and one sample is amorphous kerogen. All are hydrogen poor and the maturity indicators are in the metagenetic zone. Consequently, the source potential of the Lisburne carbonates is poor, where it has been sampled. However, all the samples are from allocthnous blocks that have been thrust from the deeper parts of the basin into their present positions. Some source potential may exist where these rocks are not, or are less deformed, but to what extent is undetermined.

The fluvial-deltaic sandstones and shales of the Sadlerochit (Echooka, Kavik, and Ivishak formations) have between approximately 0.5 percent and 6 percent T.O.C. from kerogens described as coaly, woody, or inertinite (plate 3). These T.O.C. values are comparable to the Sadlerochit Group shale (Kavik) at the Prudhoe Bay field (Siefert, Moldowan, and Jones, 1980), where the bulk of the oil production is from the overlying and underlying sandstones. Pyrolysis data show that these kerogens are mostly hydrogen poor, but have a fairly high genetic potential at %Ro maturities that are in the catagenetic range. This suggests that the indigenous kerogens from the Sadlerochit part of the section are predominantly gas prone, which is common for most fluvial-deltaic deposits.

The Shublik Formation is distinct on geophysical logs because it is considerably more radioactive than the overlying and underlying formations. Recent studies (Siefert, Moldowan, and Jones, 1980; Carmen and Hardwick, 1983; and Magoon and Claypool, in press; Curiale, 1985) demonstrate that the Shublik, where mature, is a major source rock of North Slope oil because it is rich in T.O.C. and oil prone kerogen types.

Although not extensively sampled and tested near ANWR, the Shublik Formation has between 0.5 percent and 5 percent T.O.C. and kerogen types described as woody, amorphous, herbaceous, and inertinite. All of these samples are in the late catagenetic to metagenetic range with low Hydrogen Indexes and low Genetic Potentials. These data indicate that the Shublik has uncharacteristically low-to-no source potential. However, all samples tested are from allocthnous blocks that have been thrust faulted into the area and, consequently, are not necessarily representative of the Shublik in undisturbed, or less deformed parts of the basin (plate 2). Because the Shublik is considered a major North Slope source rock and because there are no available data on this formation in undeformed areas, the Shublik cannot be ruled out as a possible source rock in the ANWR coastal plain.

The Kingak Formation averages approximately one percent T.O.C., and ranges in value to almost five percent T.O.C. Plate 3 shows that the Kingak shale has the widest variation of kerogen types of any of the formations that were tested. Thermal maturities also show a wide range of values from immature to overmature with respect to major hydrocarbon generation. This is due to the large scale compressional faulting in ANWR, which has emplaced allocthonous basinal Kingak shale justaposed to less thermally altered and more paralic Kingak shale.

The pyrolysis shows that Kingak kerogens are mostly hydrogen poor and have mostly no-to-low Genetic Potentials with a few exceptions (plate 3). These results indicate that the source potential of the Kingak is a function of both geochemistry and thermal maturity. This is similar to the previous work by Siefert, Moldowan and Jones (1980) that demonstrated a limited source potential of the Kingak in the Prudhoe Bay area.

The pebble shale unit has a distinct, uniformly organic rich lithology across most of the North Slope. Visual kerogen is reported as predominantly amorphous with lesser amounts of herbaceous, woody and inertinite types. In the ANWR area, there is a wide range of thermal maturities. It is in the diagenetic to catagenetic stage in the wells just northwest of ANWR, where it is presently at its approximate maximum depth of burial and has not undergone major structural deformation.

Maturities from outcrop samples and interpolated maturities from wells to the southwest (Canning River A-1, B-1, and Beli Unit 1) are at all levels because these samples are from allocthonous rocks that have been emplaced by the compressional faulting. This means that rocks from various deeper parts of the basin, to the south, have moved horizontally (miles) and vertically (thousands of feet) and are now exposed as allocthonous blocks in the structurally deformed areas of ANWR. This is why the pyrolysis data indicates that the Hydrogen Index and Genetic Potential have such widely differing values. Samples from the unfaulted and immature pebble shale unit are hydrogen rich and have a very good Genetic Potential, while the very mature samples have Hydrogen Indexes and Genetic Potentials too low to be a petroleum source rock. Thus, in the 1002 area, the pebble shale should be a good source rock in areas where it has not been greatly affected by large scale tectonic dislocation.

The black, bentonitic, papery Upper Cretaceous shale (the Shale Wall Unit of the Seabee Formation, Colville Group) unit is distinct in logs at wells in the Central Arctic, where it has a high gamma ray log reading, commonly a high resistivity, and lower interval transit time than the adjacent lithologies. The high gamma ray log reading becomes more intense and occurs lower in the section, eastward across the central arctic area, owing to the progradational nature of the Colville Group rocks.

In and around ANWR, the unit is very rich in T.O.C., and has predominantly amorphous type kerogens. This unit is mostly in the catagenetic stage or high diagenetic stage. Therefore, the pyrolysis data shows the source rock characteristics rather than the affects of thermal maturity. The Hydrogen Index values are typically greater than 200, and range in value to over 500, and the Genetic Potentials are all good to excellent (plate 3). These data indicate that the Upper Cretaceous shales should be definitely considered as source rocks in ANWR.

The Uppermost Cretaceous to Tertiary shales (Seabee Formation) have uniform T.O.C. values of approximately one percent with kerogens that are herbaceous, woody, or inertinite types (plate 3). Abundant coaly material and coalified plant parts occur, interbedded as distinct lamina and intermixed in the sandstones. This entire unit is about equally in the diagenetic and catagenetic stages. Hydrocarbon Indexes are generally 100 or less, and Genetic Potentials are mostly moderate to good, from the woody herbaceous and coaly material that are prone to generate gas.

The unconsolidated gravel sandstones, siltstones, and claystones of the predominantly non-marine Tertiary clastic wedge of sediments have an appreciable percentage of coal and partially fossilized wood pieces and fragments included in the lithology. Thus, the T.O.C. values are mostly in the one percent to two percent range, but are also greater than 10 percent where the coal and the partially fossilized wood are more common (plate 3). The entire section is still very much in the diagenetic stage. Pyrolysis data shows that most of these samples have Hydrogen Indexes less than 100, and Genetic Potentials that are mostly low to moderate. However, some samples have good source rock potentials, and there are several oil seeps in ANWR in rocks of this sequence.

Summary

The organic geochemical data (plate 3) shows that the Upper Cretaceous shales and the pebble shale unit have high T.O.C. values, predominantly amorphous kerogen types, and thermal maturities in the diagenetic and catagenetic ranges. Consequently, these black shales, which probably constitute approximately 400 to 500 feet of section, are considered to be good to excellent petroleum source rocks in the subsurface of ANWR. In addition, regional data indicate that the Shublik Formation, which is a well-known major source of North Slope oil, may also be a good to excellent source rock in ANWR where present, and that the Kingak has fair to good source potential.

5. EXTRACTABLE ORGANIC MATTER

Approximately half of the ANWR samples (Lyle and others, 1980) that had extractable hydrocarbons plotted in the dry gas or the poor to fair source fields (figure 5). Noticeable exceptions are the Tertiary oil stained sandstones and siltstones from along the Katakturuk and Jago Rivers, respectively (figure 5, table 1). Another lightly oil stained conglomeratic sandstone, sample 11, plotted as very good. Chromatograms (plate 4) show that these samples are very biodegraded with no correlatable n-alkanes remaining, and roughly similar shapes of the nonresolvable background hydrocarbons.

Paper/cardboard shale samples 7 and 14 are not biodegraded, have resolvable n-alkanes and single mode "humps" of nonresolvable hydrocarbons (plate 4). This is different from the oil stained nonmarine sandstones (Nos. 3, 11, and 22) and the Jago paper/cardboard shale (23) which suggests a different source. Because shale samples 7 and 14 are much more thermally mature than sample 23 (table 1), the extracted hydrocarbons are probably indigenous, whereas the immaturity and the amount of extractable hydrocarbons of the paper/cardboard shales on the Jago suggests, at least in part, the presence of similar migrated bitumen in both the shale (23) and sandstone (22).

Other good and very good potential source rocks include samples from the pebble shale unit where it is interbedded with the Kemik sandstone (No. 20) along Canning River, and the turbidite samples (Nos. 4, 6, 8, and 13) (figure 4). The Pebble shale-Kemik samples have resolvable alkanes with pristane/phytane ratios of 1.00 or less and single mode humps of nonresolvables. The turbidites are distinctly different. They have high pristane/phytane ratios ranging in value from 2.67 to 4.26 and have a definite bimodal distribution of the nonresolvable hydrocarbons (plate 4).

Most of the poor to fair oil source rocks and the gas source rocks are nonmarine sediments and turbidite samples (figure 4). Exceptions are from the Pebble shale and Kingak shale. Both (Nos. 18 and 9, respectively) are at high stages of thermal maturity, both have resolvable n-alkanes with low pristane/phytane ratios, and both have single mode, nonresolvable hydrocarbon background.

Gas chromatographic analysis of cuts from the oil seeps at Angun Point and Manning Point (Magoon and Claypool, 1980) show that both oil seeps are very biodegraded, with no identifiable n-alkanes. The nonresolvable backgrounds are not similar, nor do either resemble the ANWR samples from Lyle and others (1980) (plate 4).

In summary, the bitumen analyses indicates that the black, paper/cardboard Upper Cretaceous shale and Lower Cretaceous pebble shale are good to very good potential source rocks. The Tertiary nonmarine sandstones and the paper/cardboard shale on the Jago River have high levels of migrated bitumens and misleadingly plot as source rocks. Gas chromatrographic analysis shows that the oil seeps at Angun Point and Manning Point, the oil stained sandstones along Kavik Creek, the Katakturuk River, the Jago River, and the paper/cardboard shale along the Jago are all extremely biodegraded. The oil seeps are also unlike the bitumen extracts from the rocks and probably from different sources.

The rock extracts show three essentially different distributions in ANWR. The biodegraded samples are similar. Samples from the paper/cardboard shale, pebble shale, and Kingak have low pristane/phytane ratios and single mode distributions of the nonresolvable fraction. All the turbidite samples have a high pristane/phytane ratio and bimodal distribution of nonresolvables hydrocarbons.

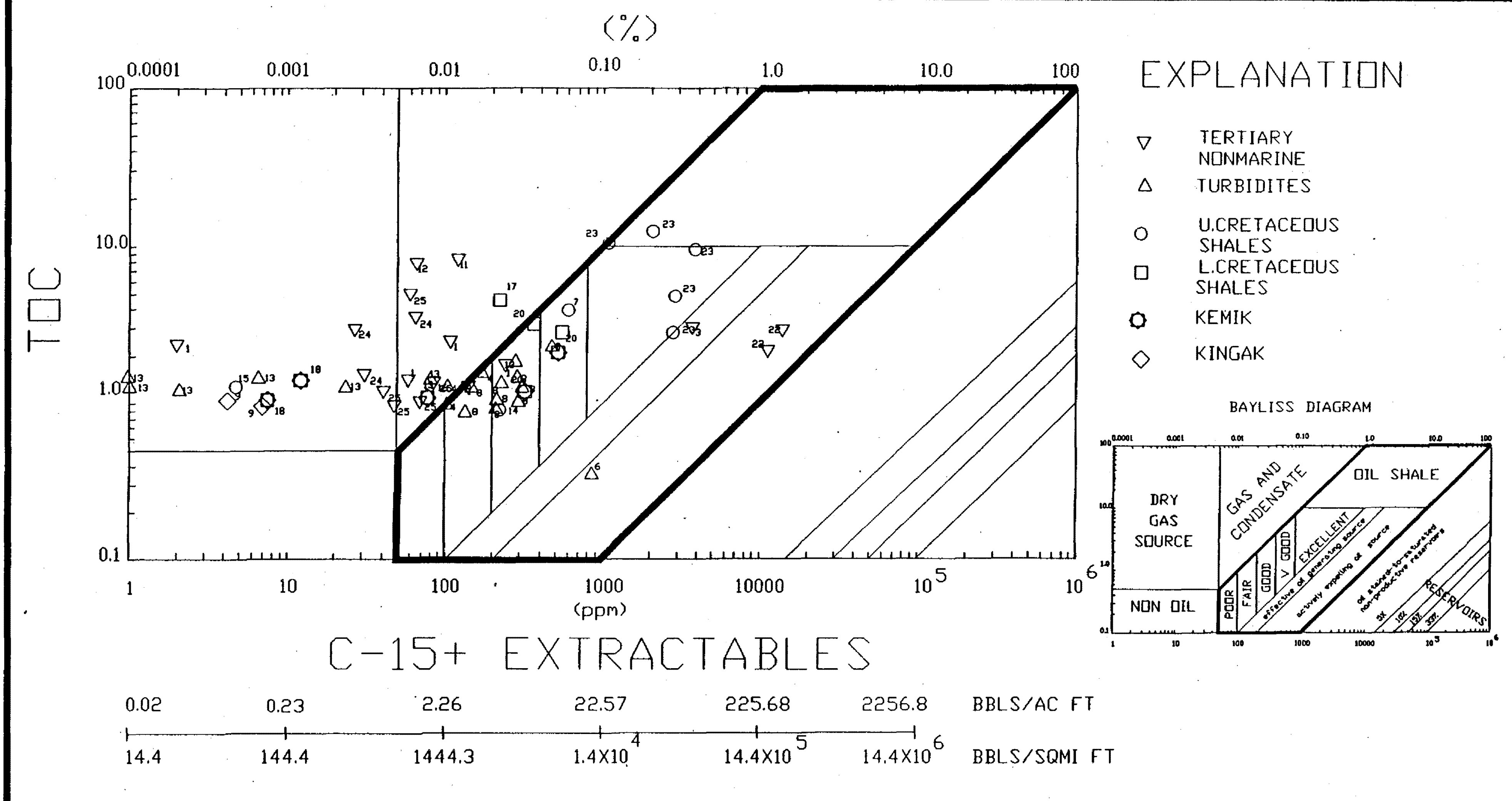

Figure 5 Bayliss Diagram showing TOC vs C15+ extractables data from Lyle and others, 1980

6. THERMAL MATURITY GEOTHERMAL GRADIENT

Figure 6 shows data compiled from 13 wells adjacent to ANWR, including the Dome Ltd. Natsek (nearest Canadian well; offshore Beaufort) and a 12°F/1,000' (22°C/km) geothermal gradient. There are some deviations, but this gradient appears to be good for both the Brookian and Ellesmerian rocks (plate 5). Overall, this geothermal gradient is low. It is similar to the gradient observed in the U.S. Gulf Coast (12°F/1,000' to 13°F/1,000', in Louisiana, Tissot and Welte, 1984).

7. TIME TEMPERATURE RELATIONSHIPS

First order reaction kinetics predict that the zone of oil generation is time and temperature (depth) dependent. Table 5 and plates 3 and 5 show that the zone of oil generation (%Ro = 0.60) begins deep, ranging from approximately 10,000' to 13,000' (average 11,500') in wells that penetrate the relatively tectonically undeformed stratigraphic sections. They also show that major structural deformation has uplifted thermally mature sediments to the surface, which is more than 11,000' of uplift. Consequently, source rock modelling must account for both normal burial thermal maturation and tectonic deformation overprinting as is shown on plate 2.

There are various methods to model the time temperature dependencies of thermal maturation (Lopatin, 1971; Waples, 1980; Zhijon, 1983; Pigott, 1985). These are applicable to basin analyses with varying degrees of success. Waples (1980) improved on the Lopatin method, and it is widely used. Also, it is versatile enough to model some of the large scale effects of regional tectonics (Furlong and Edelman, 1984). Figure 8 is a Lopatin diagram of the pebble shale unit source rock (Late Cretaceous, Barremian-Hauterivian, ca., 125-130 Ma). The time temperature index (TTI) calculated for this unit is 15.4, which is just at the beginning of the oil generating zone (table 2). This value agrees favorably with the %Ro data (plate 3 and table 1) and probably represents a lower limit of the onset of oil generation for the tectonically undisturbed section.

With a geothermal gradient of 12°F/1,000', the end of oil generation is calculated to be approximately 19,000' and the base of the categenetic zone at 23,500'. For comparison, the higher gradient, 15°/1,000' puts the base of the oil generating zone at approximately 15,600' and the base of preservation at 19,000'. This implies that areas of ANWR, where the Brookian Sequence may be underlain by Ellesmerian, oil could be preserved through most of the section and that both the Shublik and Kingak Formations would still be capable of oil generation.

8. THERMAL MATURITY IN ANWR

Plate 6 shows the contoured thermal maturity maps %Ro, TAI, and Tmax. The vitrinite reflectance maps shows the coastal plain to be immature (%Ro 0.40) except along the crest of and envechelon to the axis of the Marsh Creek anticline and in the Niguanak Uplands area. The mountain front, however, is well into the metagenetic stage with no samples of transitional catagenetic stages of maturity; this is a partial indication of the structural deformation styles in ANWR.

The Tmax map shows that data acquisition was poor and roughly limited to the crop or subcrop of the Eocene rocks in the western part of ANWR. In the east, Tmax maturity is mostly similar to the %Ro maps except that there are elongated east-west trends rather than small isolated areas of more mature rocks on the coastal plain and overmature rocks in the mountains. In addition to resembling the %Ro maturity trends, the Tmax data indicate a somewhat higher degree of maturity than the %Ro data.

The TAI map is less similar and more varied than the previous two maturity maps. Trends are less distinct. Overall, rocks of the coastal plain are immature except for some unique areas on seismic lines 1 and 4, and the mountain front is very overmature. Most differences are probably due to sample inhomogeneity, different lab procedures and techniques, and the degree of subjectiveity in analyses. It also shows that the mountain front is much more thermally mature than the coastal plain.

TABLE 2

Depths to Oil Generating Zone and Metagenetic Zone
(* indicates that the section has not been severely structurally deformed)
Average Approximately 11,500 Feet

Thermal Maturity

Well		%Ro = 0.60	Formation	%Ro 2.00	Formation
Alaska State D1	*	12,030	Colville Shale	TD	Nanook(?)
Beli		5,000	Colville Shale	14,161	Lisburne
Canning River A		surface	Colville Shale	3,000	pebble sh
Canning River B		surface	Colville Nonmarine	10,781	Lisburne
E. Mikkelsen Bay	*	10,300	Colville Shale	TD	Argillite
Kavik		surface	Colville	4,300	Shublik
Pt. Thomson Unit 1	*	10,000	Colville Shale	TD	Argillite
West Kavik		10,000	Colville Shale	16,613	Lisburne
West Staines No. 2	*	13,000	pebble shale	TD	Argillite

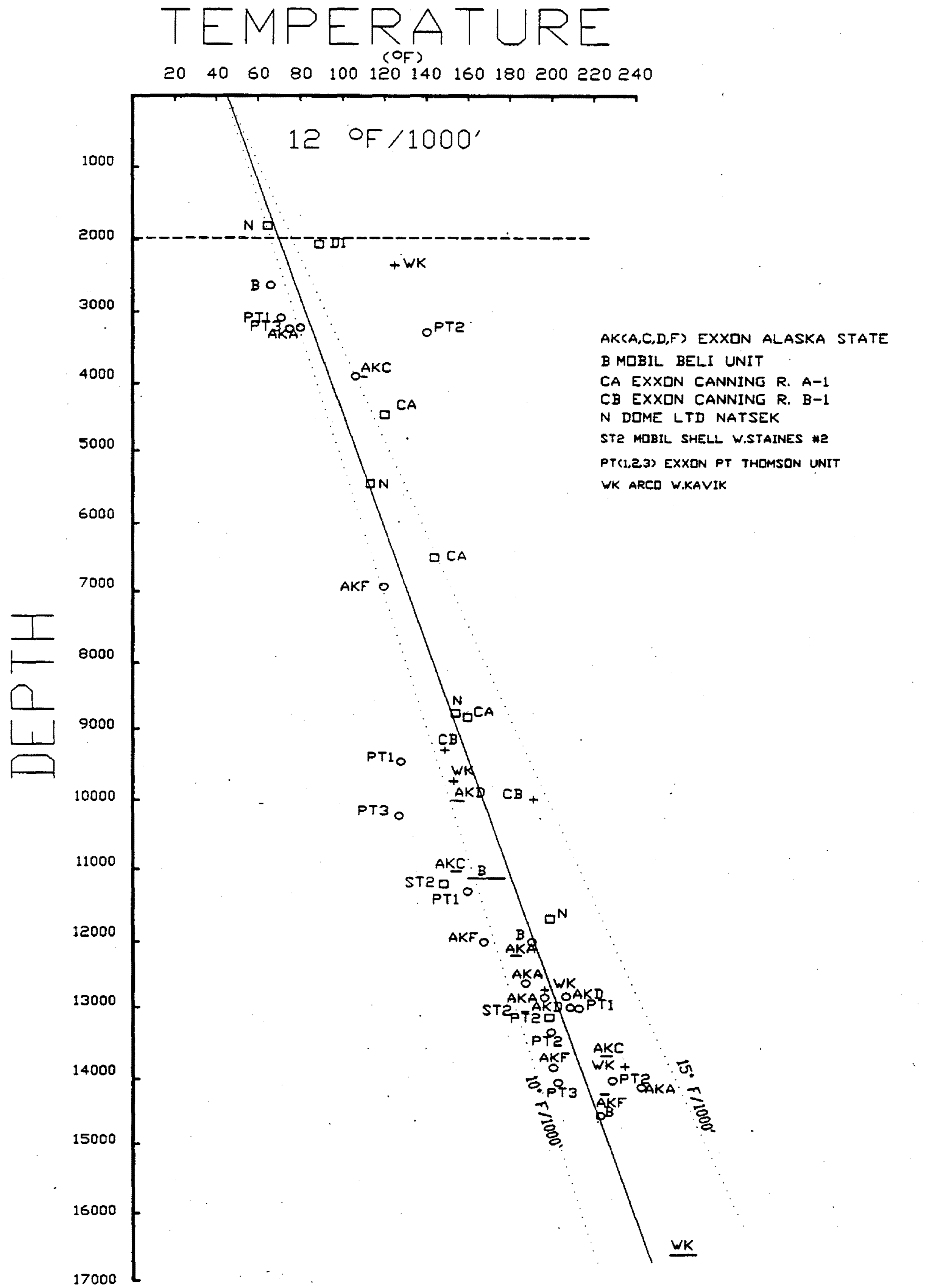

Figure 6. Showing well temperature data from wells nearest ANWR

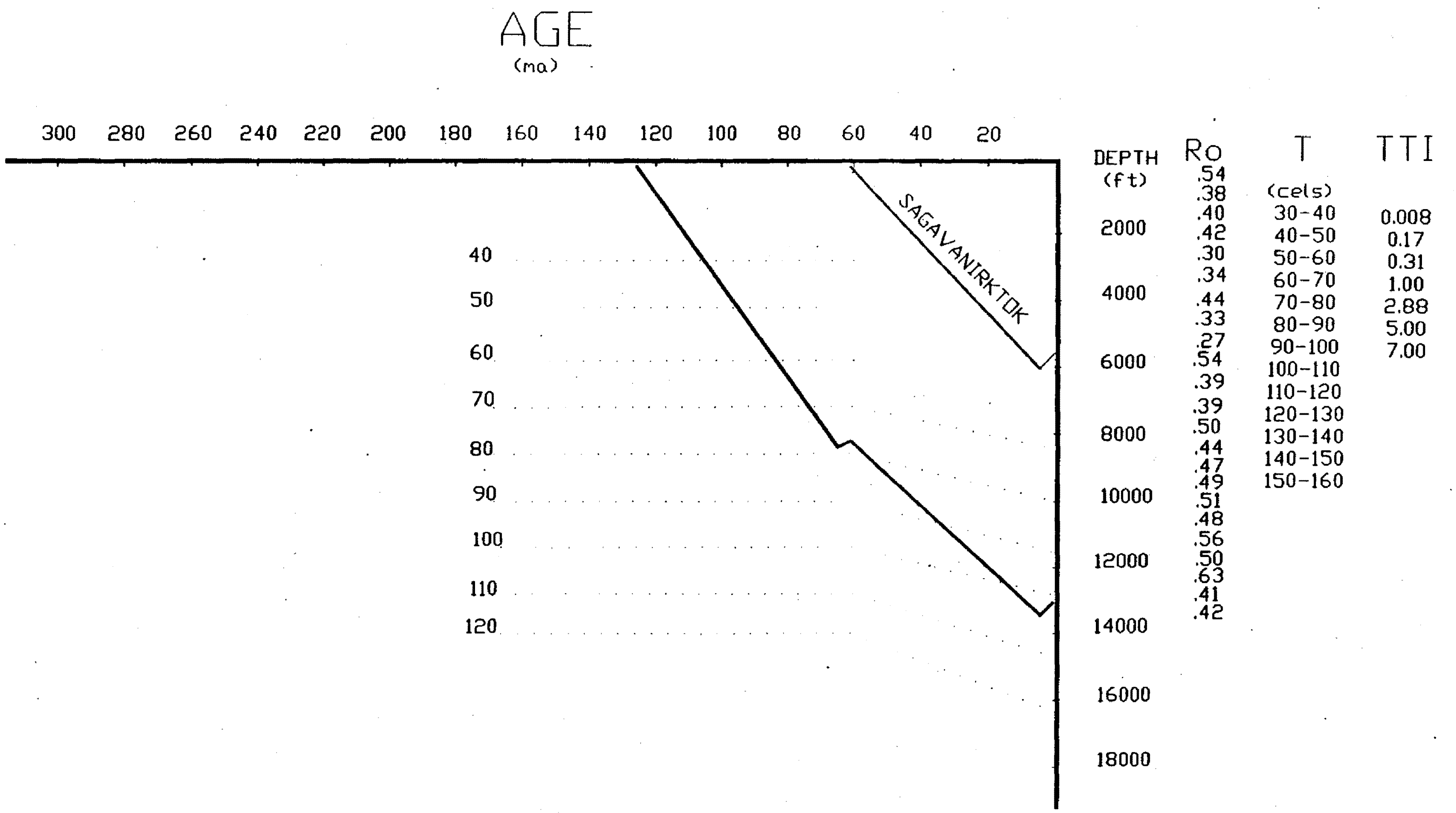

Figure 7. Lopatin diagram for the Pebble Shale Unit at W. Staines No. 2

9. SUMMARY AND CONCLUSIONS

Well-log interpretation, correlation, and field work indicate that there are at least three major and one minor sedimentary rock sequences in ANWR and in the 1002 area subsurface. The basement rocks are predominantly pre-Cambrian to Devonian carbonates with minor clastics where exposed in the mountains south of the 1002 area. Wells on the coastal plain immediately northwest of ANWR penetrated a section of interbedded pre-Devonian argillite and limestone.

The basement rocks are unconformably overlain by northerly derived Ellesmerian sedimentary rock which range in age from mid-Mississippian to Lower Cretaceous. All the clastics tend to be petrologically mature and quartzose sands deposited in non-marine to paralic conditions with interdeltaic and shelf shales. The Lisburne carbonates are thick platform type deposits and the Shublik is organic rich marl from a restricted marine environment with interbedded shales. The extent of these rocks in the subsurface is uncertain. Well data indicate that they are truncated by a Lower Cretaceous unconformity along the Barrow arch beneath the coastal plain immediately west of the 1002 area. However, outcrops in the 1008 area, the eastern part of the 1002 area, and seismic analyses indicate that they may also be present in some parts of the 1002 subsurface.

Well data indicate the possibility that post-LCU and pre-Brookian, northerly derived (Barrovian) rocks may be present in ANWR. Southerly derived Upper Cretaceous and younger clastic Brookian rocks are present across most of the 1002 area in ANWR. They unconformably overlie the Ellesmerian and older rock where present. The basal predominantly deep water shales and turbidites grade into deltaic, fluvial, and non-marine facies upsection owing to the well developed progradational nature of the sediments in the western part of ANWR. Paleocene outcrops of non-marine conglomerates overlain by shales may indicate a different depositional regime for the east part of the 1002 area during the Tertiary. Quarternary periglacial gravels of the easterly derived Gubik Formation and collovium comprises a great deal of the land surface in ANWR.

Sparse outcrops on the Coastal Plain and the exposures in the mountains show that ANWR is structurally complicated. Most outcrops are completely faulted or have steeply dipping sediments with no preferred orientation. At least three major levels of stratigraphically related decollements are suspected in this part of northeastern Alaska. Total deformation is estimated in miles of lateral movement and over ten thousand feet of vertical displacement.

Source rock geochemistry shows that organic rich, oil prone source rocks are found in and around ANWR. The analyses also indicate that the stratigraphic position and structural environment are the prime factors affecting source rock potential. The richest source rocks are the basal U. Cretaceous, tuffaceous papery/cardboard Brookian shales (Shale Wall Formation), and the pebble shale unit. Both are widespread across ANWR. Good source rocks include the Kingak Shale and some of the deep water Brookian shales (Seabee Formation). The Shublik Formation showed no potential, but was sampled only from allocothnous thrust plates. If it is autocthonous in the subsurface, regional considerations dictate that it should be considered as a good to very good source rock.

Source rock thermal maturity is a function of structural position. The Brookian shales predominantly sampled from only thrust sheets above the Kingak decollement are immature. The pebble shale and Kingak Shale samples are from thrust sheets above and beneath the Kingak decollement and consequently range in thermal maturity from immature to almost overmature. Most, if not all, overmature samples are from allocthonous thrust blocks.

Extractable hydrocarbons from the oil stained sediments and oil seeps are extremely biodegraded but chromatographically similar. Extracts from the Kingak, pebble shale and paper/cardboard shale have low pristane:phytane ratios and a single mode distribution of the nonresolveable fraction. All the turbidite samples have high pristane:phytane ratios and bimodal nonresolveable distribution. Crude oils from the Prudhoe Bay field are dissimilar. This indicates that two, perhaps three, types of hydrocarbons have been generated and have migrated into/from ANWR sediments. Source rock geochemistry shows that organic-rich oil-prone rocks are present in ANWR and are also likely to be in the catagenetic zone in proximity to the 1002 area.

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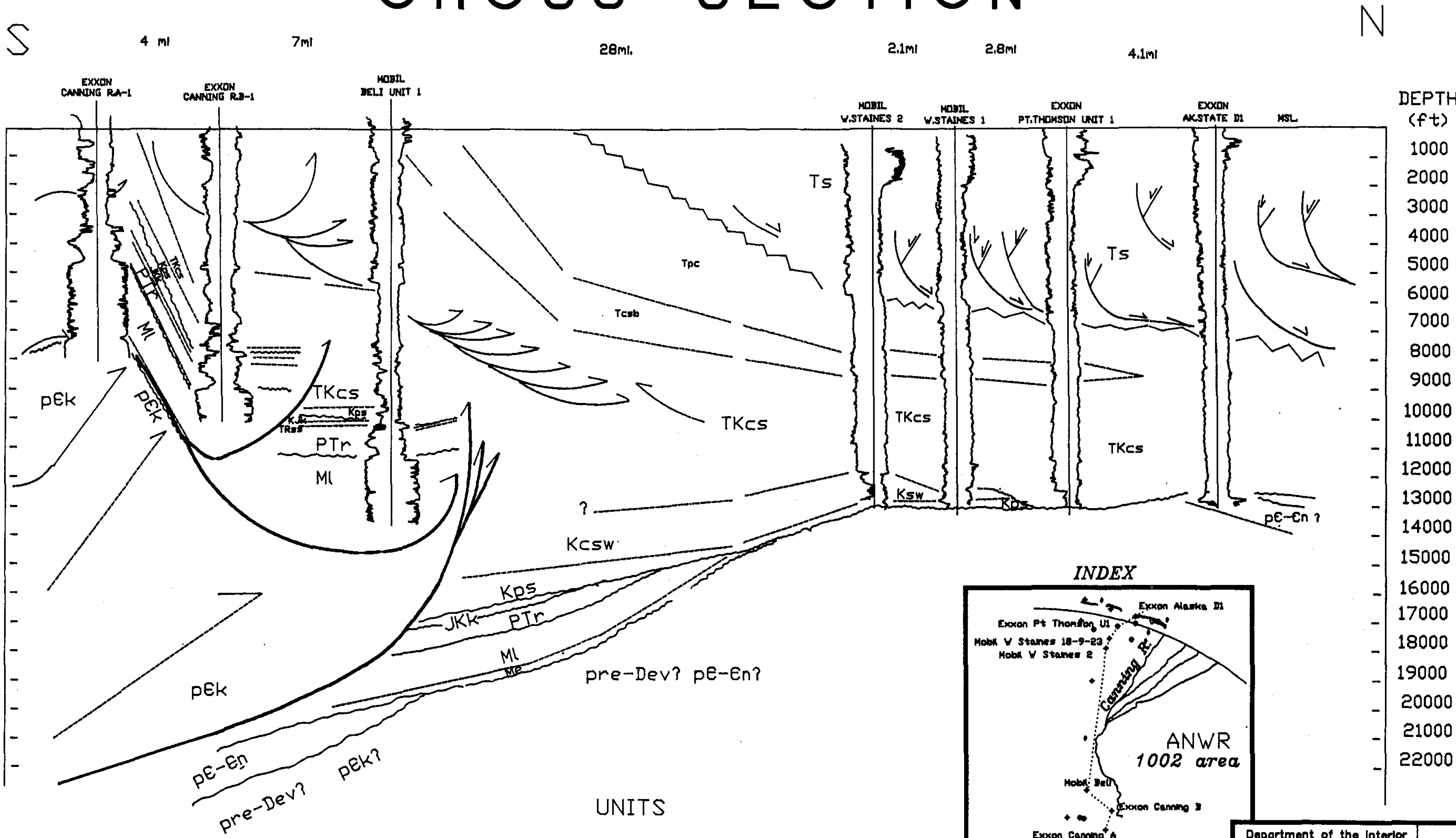
CROSS SECTION



UNITS

Ts	Sagavanirktok, mostly marine Eocene and younger
Tpc	Prince Creek, marine shale Paleocene – L. Eocene
Tcsb	Colville Gp. Schrader Bluff Fm. marine predomnantly turbidite sands
TKcs	Colville Gp. Seabee Fm. marine shale
Kcsm	Colville Gp. Shale Wall bentonitic shale
Kps	Pebble Shale, black, pyritic fissile shale
JKk	Kingak Shale, gray silty
Trss	Shublik Fm. & Karen Ck./Sag R. sandstone silty sandstones & black phosphatic limestones and shale
PTr	Sadlerochit Gp. deltaic sandstone & shale
Ml	Lisburne Gp. thick massive carbonates & minor shale
Me	Endicott Gp. fluvial sandstones, conglomerate & shale
pre-Dev	Nerokpuk. Argillite or meta sediments
pЄ-Єn	Nanook Limestone, massive, minor shale
pЄk	Katakturak Dolostone, massive, silicified, vuggy stromatolitic, brecciated, very thick

Department of the Interior
U.S. BUREAU OF LAND MANAGEMENT
Branch of Mineral Assessment
ALASKA STATE OFFICE

Mineral Assessment

Arctic National Wildlife Refuge
OIL AND GAS ASSESMENT

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lead geophysicist:
lead geologist: Arthur C. Banet
compiled by:
date: January,1988

Plate 1.

PLATE 1 GENERALIZED GEOLOGIC CROSS SECTION SHOWING STRAGITRAPHY, PREDOMINANT FAULTING STYLES AND MAJOR UNCONFORMITIES PROJECTED FROM WELLS WEST OF ANWR