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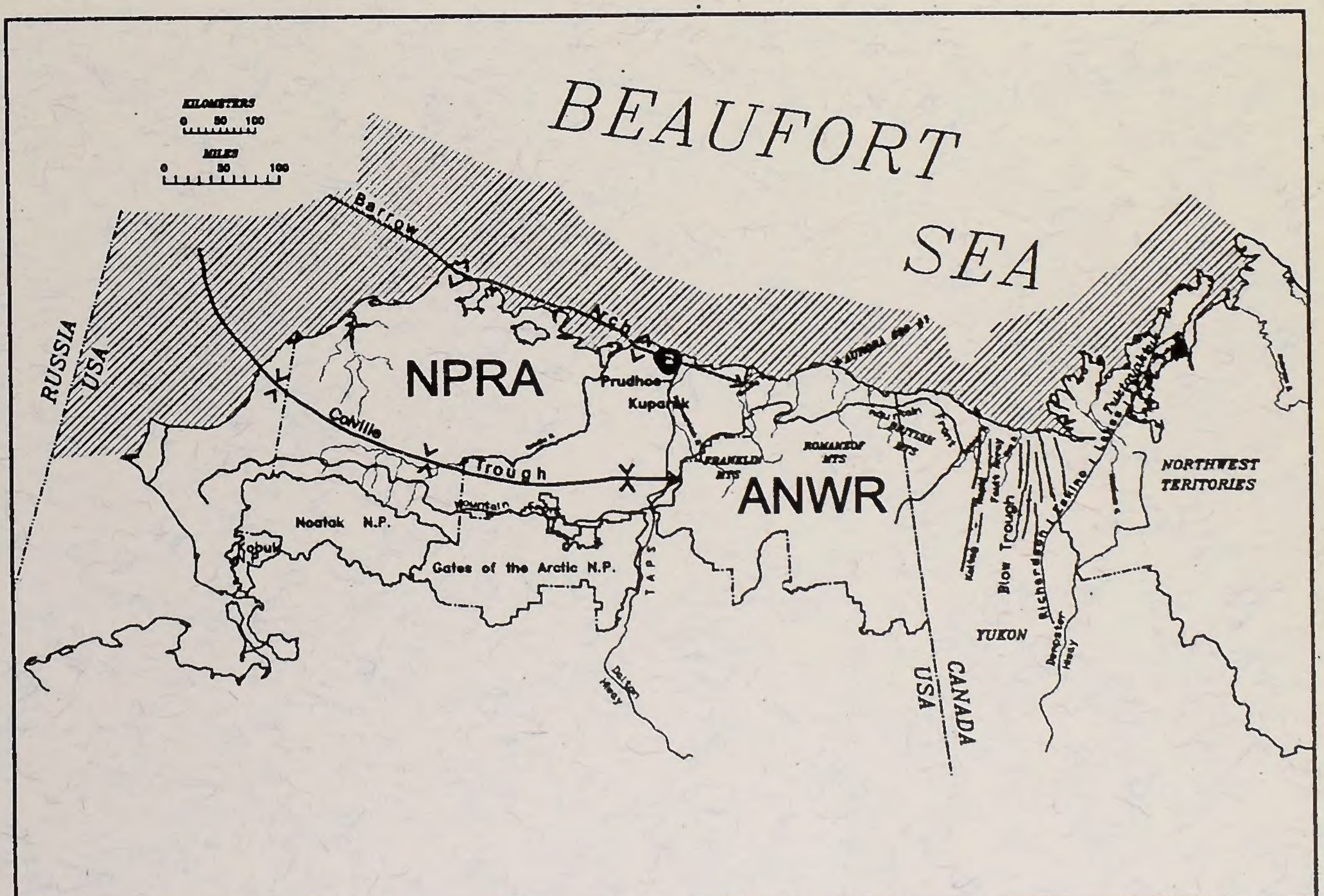
Comparisons Between Petroleum Systems in the Arctic National Wildlife Refuge, Alaska

Arthur C. Banet, Jr. and Thomas C. Mowatt



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COMPARISONS BETWEEN PETROLEUM SYSTEMS IN THE ARCTIC NATIONAL WILDLIFE REFUGE, NORTHEAST ALASKA

The geology of the Coastal Plain of the Arctic National Wildlife Refuge (ANWR) in northeast Alaska indicates that the area has high potential for the accumulation of oil and gas. Discoveries peripheral to, and oil seeps and stains within the area, suggest three petroleum systems are active.

Oil, condensate and gas are present in lower Paleozoic basement, lower Cretaceous sandstones and upper Cretaceous to Tertiary turbidite sandstones at the Point Thomson Unit immediately west of the Arctic Wildlife Refuge. Available analyses indicate the oil in the Cretaceous sandstones correlates to the oil from the Prudhoe Bay field and peripheral fields. This is the Ellesmerian(!) petroleum system. Kinetic modeling of the large seismically mapped structures beneath the coastal plain suggest either Prudhoe oil or oil from other petroleum systems could successfully charge potential reservoirs.

Two distinctly different oils are found at seeps and stained sandstones on the coastal plain. Upper Cretaceous to Tertiary age turbidites, Miocene age siltstones and a currently active oil seep contain a marine, clastic derived oil. This is the JKM (Jago, Katakturuk, Manning) oil type, derived from upper Cretaceous highly bentonitic shales. It is the Hue-Sagavanirktok(!) petroleum system. Heavily weathered bitumen at the Angun Pt. seep has characteristics similar to marine, Tertiary age oils. This is proposed as the Beaufort(.) system.

INTRODUCTION

The Arctic National Wildlife Refuge (ANWR) occupies approximately 19 million acres of northeastern Alaska (fig.1). Subsequent to legislation in section 1002 of the Alaska National Interest Lands Act (ANILCA), geological, geophysical and geochemical studies to assess the petroleum potential for this part of the Alaska North Slope show the Coastal Plain has high potential for economically recoverable accumulations of oil (Clough and others, 1987; Bird and Magoon, 1987; Banet, 1990, 1992, 1994; USGS, 1998). These studies also indicate although there is large range of uncertainty in the assessment approximations, very large volumes of potentially recoverable reserves may exist.

REGIONAL GEOLOGY

Regional studies (Lerand, 1973; Hubbard and others, 1987; Bird and Molenaar, 1993; Moore and others, 1992) describe the North Slope's tectonic-stratigraphic history. The geological framework is reconstructed from exposures in the Brooks Range, exploration drilling and seismic analyses. It covers the breadth of the North Slope from the Brooks Range out to the edge of the Beaufort Shelf (fig. 1). The Brooks Range is the northernmost expression of the North American Cordillera. It has been thrust faulted over the southernmost and deepest part of the Colville Basin. The Colville Basin initially received sediments from a trailing margin (Mississippian through Jurassic) prior to becoming a foreland fold basin to the Brooks Range thrusting (Cretaceous and younger). The Barrow Arch forms the northern border of the Basin, and the Beaufort Shelf consists of sediments prograding over the Arctic Platform (fig. 2).

In northeast Alaska, basement consists of argillite, black shales, schists, quartzite and carbonates. These are generally regarded as upper Proterozoic to lower Paleozoic age. Drill hole and outcrop data show these lithologies vary widely in thickness and extent, recording several tectonic and depositional episodes.

Three major depositional sequences of

northerly derived Ellesmerian clastic and carbonate rocks unconformably overlie the basement (fig. 3). Lowest Ellesmerian strata are not present along the Barrow Arch. However, Mississippian through Triassic, middle and upper Ellesmerian rocks comprise the major North Slope commercial reservoirs. The main oil and gas reservoirs at Prudhoe Bay field are areally extensive and thick sandstones and conglomerates of the Sadlerochit and Endicott Groups and carbonates of the Lisburne Group (Jamison and others, 1980).

Jurassic through Lower Cretaceous rocks record rifting events and the end of northerly derived sedimentary input. Beaufortian rifting events changed the tectonic regime and subsequent sedimentation. As uplift and rifting progressed from west to east, there were numerous local uplifts, unconformities and sedimentary deposits of mostly limited lateral extent. The reservoir facies of the Kuparuk River formation are typical among these clastic deposits. Sandstones deposited during rifting events are more numerous than the Ellesmerian reservoirs. But their limited areal extent, subordinate thicknesses and distance from infrastructure limit their economically recoverable reserve base. However, the Alpine accumulation east of NPR-A is being developed, with future plans including development at the Point Thomson accumulation, west of ANWR. The lower Cretaceous unconformity (LCU) is the most areally extensive of the Beaufortian erosional events and the most important one in reference to petroleum accumulations. Reservoir potential of uplifted Ellesmerian units has been enhanced along the LCU because of widespread cement dissolution related to subaerial exposure (Shanmugam, and Higgins, 1988).

Jurassic through upper Tertiary, Brookian uplifts to the south generated three distinct and thick pulses of, clastic sedimentation. Initially concordant with the rifting uplifts, these major phases of deposition progressed from southwest to northeast filling the Colville Basin and prograded across the Arctic Platform and Beaufort Shelf. Burial by these Brookian sediments initiated petroleum generation from the major source rock units (Lerand, 1973; Hubbard and others, 1987; Banet, 1990; Moore and others, 1992; Bird, 1995).

Stratigraphic descriptions of reservoirs and source rocks, oil to source rock correlations, the regional dispositon and timing of tectonic events are key elements of petroleum system definitions (Magoon, 1988). In the current classification scheme, Known(!) petroleum systems there have a demonstrated oil:source rock correlation. In, Hypothetical(?) systems regional geology infers an oil:source rock correlation. A Speculative(.) system is postulated where regional geological and geophysical data define the system in lieu of identified source rocks, oil-generation timing and migration pathways. The certainty, and representations of the Petroleum Systems are as follows:

Known(!)
Hypothetical(?)
Speculative(.)

ELLESMERIAN PETROLEUM SYSTEM

The Prudhoe Bay field and ancillary fields (tables 1 and 2) show the exceptional petroleum potential of the North Slope. Magoon (1988) assigns these discoveries along the Arctic coast to the Ellesmerian(!) petroleum system. Most commercial reservoirs are thick, areally widespread and southerly dipping Ellesemerian units which subcrop beneath the LCU. Additional reservoirs are within the overlying Beaufortian sequence (Carman and Hardwick, 1983). Correlative oil-bearing clastics are widespread along the Arch. They include the Kuparuk R. Field, Alpine and Pt. Thomson. Current commercial development of overlying turbidite reservoirs in the Brookian sequence include the Badami and Tarn fields and nonmarine facies are being developed at the West Sak heavy oil accumulation.

Overall, the trapping mechanisms for the Ellesmerian Petroleum System reservoirs are largely stratigraphic rather than anticlinal along the Arch. Bird (1995) posits the Ellesmerian(!) system is low efficiency largely due to lengthy lateral migration.

All depositional sequences have noncommercial reserves outside the Prudhoe area (fig. 1, table 1). However, high infrastructure costs have historically limited, and until recently, precluded their development. Enigmatically, the largest noncommercial reservoirs are Brookian sandstones where large volumes of in-place reserves are producible in only certain areas because of low reservoir temperatures, low formation pressures at shallow depths and potential production problems resulting from unconsolidated sediments (Werner, 1985). Elsewhere on the North Slope only noncommercial, small oil fields and gas fields have been discovered in structural traps.

PETROLEUM GEOCHEMISTRY

Chemical analyses show that ten oil types are present on the North Slope between the Chukchi Sea and the Mackenzie Delta (Banet, 1994). The Prudhoe oil is the most important, volumetrically and areally. It has been generated mostly from the Shublik Formation (Triassic) kerogens, with varying contributions from clastic sources like the Kingak Shale (Jurassic) and Pebble Shale (lower Cretaceous) (Seifert and others, 1979; Magoon and Claypool, 1981). Prudhoe oil has: sulfur contents of at least 1%, metals content greater than 30 ppm, [V]>[Ni], del ^{13}C of about -29.00 ‰, pristane:phytane <1, abundant tricyclic terpanes, C_{31}-C_{35} extended hopane series, 28,30 bisnorhopane and few rearranged steranes (tables 1 and 2). Banet (1994) compares the geochemistry and biomarker distributions of the Prudhoe oil to the other North Slope oil types.

ANWR PETROLEUM SYSTEMS

The ANWR coastal plain shares many petroleum system attributes with the Prudhoe area such as a stratigraphy that includes proven reservoir lithofacies and source rocks. There are three active petroleum systems in the 1002 area. In addition, the 1002 area has other attributes which enhance interest in this area's petroleum potential. These includes multiple source rocks, continuous well defined structural prospects and a burial history which does not require long distance hydrocarbon migration.

Exploration efforts show the Prudhoe Bay field stratigraphy extends to the western border of the ANWR 1002 area (Clough and others, 1987; Bird and Magoon, 1987; Banet, 1990, 1992, 1994). Seismic studies show the subsurface Ellesmerian truncation along the Barrow Arch also extends into the westernmost 1002 area (Foland and Lalla, 1987). However, trends found in field studies in the Sadlerochit mountains and subsequently combined with seismic data (Kelley and Detterman, 1989) suggest the Ellesmerian sequence is present beneath the eastern part of the Coastal Plain. Analyses of the Aurora well stratigraphy and geochemistry (Banet, 1992, 1993) also support the interpretation that thick and extensive Ellesmerian reservoirs underlie the eastern 1002 area. The Aurora well indicates Beaufortian and Brookian sequence reservoirs should also be present. Subsequent assessments increased the probability of success to 46% for finding economically recoverable oil in the 1002 area (BLM, 1991).

Ellesmerian(!) At Point Thomson

The Point Thomson Unit (fig. 4) is immediately west of Canning River, ANWR's western boundary. Its reserves have been reported to include some 200 to 350 million barrels of oil and condensate with 5 Tcf natural gas. The Sourdough discovery (fig. 4) has also been announced as approximately 100 million barrels from Brookian turbidites. In all

probability, these reservoirs extend into both the 1002 area and offshore. Table 3 lists oil recoveries from three different units at Pt. Thomson. The geochemistry of the oil in the Point Thomson sands shows it is part of the Ellesmerian(!) petroleum system (table 2). But the petroleum system here differs from the Prudhoe Bay area because the Ellesmerian stratigraphic section has been entirely eroded and the overlying Brookian section consists of deep-water facies.

Quartzites, phyllites and carbonates comprising the basement rocks at Pt. Thomson yield small quantities of oil (table 3). But, they are not major exploration targets The Cretaceous, Pt.Thomson sandstones and conglomerates are the major exploration objective in this area. They are Beaufortian Sequence sands and roughly equivalent to the Kuparuk River sands which are upsection from the main Prudhoe reservoirs. The Pt. Thomson sands overlie basement at depths between about 3,600 to 3,950m (12,000 and 13,000 ft.). The sands are over 100m (300 ft) thick and consist of quartz, and abundant carbonate rock fragments with lesser amounts of argillite and phyllite. Gautier (1987) reports porosity and permeability are preserved because the unit is relatively free of clays, authigenic mineralization is minimal and there has been carbonate grain dissolution. Overpressuring also contributes to porosity preservation.

The informally named Flaxman sands are upper Cretaceous to lower Tertiary age and are approximately 250m (800 ft) upsection from the Thomson sands. They are, *in sensu lato*, deep-water equivalents to the West Sak and Ugnu sands upsection at Prudhoe. The Flaxman turbidites tested significant volumes of oil at the Pt. Thomson Unit. These sands are dark-colored, fine- to coarse-grained, moderately- to well-sorted, friable, predominantly chert litharenites. Overpressuring is common and porosities are up to 15%. API gravities are variable, and more similar to the Prudhoe oil than to the Pt. Thomson sands (table 3). Reservoirs at the Sourdough discovery are equivalent to these sands.

Limited available chemical analyses show (tables 1 and 2) the oil in the Pt. Thomson and the overlying Flaxman sands most likely contain Prudhoe oil (Banet, 1994). The saturates content, low pristane:phytane ratio, high sulfur content, high metals content, metals ratio (Hughes and Holba, 1988) indicate the Shublik Formation is a major contributing source rock. As such, this marks the most eastern and deepest extent of the Prudhoe oil along the Barrow Arch. This oil and these reservoirs likely extends into northwest ANWR.

Kinetic modeling shows the current depth of the Pt. Thomson sand marks the onset of petroleum generation in this area (Magoon and others, 1987; Banet, 1990). These modeling efforts were on the upper Cretaceous section, rather than for the Triassic source rocks which are not present at Pt. Thomson. Despite these minor differences however, it shows a local "critical moment" (i.e. for generation, migration and accumulation) for the Ellesmerian(!) system which is Pliocene (Magoon, and others, 1987; Banet, 1990) rather than upper Cretaceous and Paleocene as for the Prudhoe oil (Bird, 1995). Consequently, the Pt. Thomson area demonstrates the Ellesmerian(!) petroleum system is viable even though the major Prudhoe reservoirs are not present.

Ellesmerian(?) across 1002 area

Seismic and outcrop data indicate Ellesmerian petroleum system elements probably extend across the 1002 area. However, the petroleum system is considered speculative (?) because geologic and seismic data show truncation of the Ellesmerian units in the northwest portion. In contrast, the Sadlerochit Mountains and the Aurora well demonstrate the existence of the Ellesmerian stratigraphic section in eastern ANWR. In addition oil-stained shale, sandstone and dolostones from the Sadlerochit Mountains suggest some petroleum system, possibly the Ellesmerian, has emplaced oil in the

structurally deformed areas of ANWR.

If the extent of the entire Ellesmerian system is in question, there is a high degree of confidence that portions of it exist across the entire 1002 area. In ANWR, the Kemik and Tapkaurak sandstones approximately correlate to the Pt. Thomson sand (figure 3). Wells and numerous outcrops peripheral to the 1002 area, demonstrate several Kemik depositional facies. Kemik sands are discontinuous, quartzose, fossiliferous, fine-grained to- conglomerate and poorly sorted. Thickness is up to about 50m (150 ft). Where exposed at thrust-faulted mountain-front crops, the Kemik is typically silicified and shows no reservoir potential. However, it is a gas reservoir at the W. Kavik field and the gas was likely generated from the Shublik. Mowatt and Banet (1991 and 1992) report the Kemik sand should have potential as a reservoir where it has not been too deeply buried.

The informally named Tapkaurak sand of the Aurora well has stratigraphic and petrographic similarities to both the Kemik and Pt. Thomson sand (Banet, 1992,). It is over 53m thick (173 ft), mostly quartzose, fine to coarse-grained, has few clay minerals and dolomite cement (Mowatt and others, 1994). The Tapkaurak reservoir potential is poor at Aurora because it has been buried to about 4,900m (16,300 ft). The local geothermal gradient is also higher than at the Pt. Thomson area and thermal maturity for the Tapkaurak is in the gas and condensate range. Seismic data however, suggests the Tapkaurak horizon is shallower in the eastern 1002 area where diagenetic conditions are less severe. Because of this, its thickness and its relationship to source rocks, it has reservoir potential.

Large seismically mapped prospects

In contrast to the largely stratigraphic traps in and around the Prudhoe Bay fields, the tectonic history of the 1002 area has resulted in large, distinct, seismically-mapped, anticlinal exploration targets (Foland and Lalla, 1987). These demonstrate structural closures for petroleum entrapment rather than a subcrop seal beneath the LCU. However, depending upon the timing of formation of these structures, the LCU or other unconformities, which are common along the Barrow Arch, may play important roles in the development or enhancement of reservoir conditions or the timing of potential trap formation.

The largest of the twenty-six seismically-mapped, anticlinal structures are in the eastern part of the Coastal Plain (figure 4). They are among the most important features in the assessment of the 1002 area's potential petroleum resources. Based on the mapping of continuous, well-defined reflectors, two structures, identified as nos. 18 and 19, are distinct large and illustrate the area's petroleum system elements. For comparison, the Prudhoe Bay field is about (160,000 acres; 64,000 ha). This makes it smaller than prospect number 18 (220,000 acres; 88,000 ha) and larger than prospect number 19 (52,000 ha, 130,000 acres) (Clough and others, 1987). The crestal depths of these prospects are about 4,100 m (13,500 ft) and 3,050 m (10,000 ft.), respectively. Total vertical closure in these two large prospects exceeds 3,050 m (10,000 ft.) (Clough and others, 1987).

These large prospects are significant because there is a high probability that they share the same stratigraphy with the Prudhoe Bay field. Regional geology suggests the Sadlerochit sands, Lisburne carbonates and Endicott sands having depositional environments similar to Prudhoe are potential reservoirs. These are extensive and thick lithologies juxtaposed to important source rocks. There are also several thick shale units with sealing properties.

Limited available data show the Ellesmerian petroleum system source rocks test as having gas-generating potential towards the 1002 area (Magoon and others 1987). This is partly due to facies changes. However, these data also reflect advanced stages of thermal maturity along the mountain front where considerable tectonic deformation and uplift have occurred. Where not too deeply buried, the upper Cretaceous

bentonitic shale unit (the distinct and mappable portion of Molenaar's Hue Shale) and Shublik Formation demonstrate the richest potential for generating oil on the North Slope. Subsequent and conservative volumetric calculations show that the large structures, because of their size, source rocks, temperature regime and burial history have the potential for Prudhoe-sized reserves with oil being generated from in situ source units (fig. 5). Long distance, inefficient migration is not necessary to charge potential reservoirs in either the Ellesmerian, Beaufortian or Brookian sequences.

From Pt. Thomson to the Aurora well, data show the tectonic history and thermal regime vary across the 1002 area (Banet, 1992). At the Aurora well, the main phase of oil generation begins at about 2,895m (9,500 ft). This is similar to the Prudhoe Bay area. Oil generation proceeds to about 4,570m (15,000 ft) with condensate stable to perhaps 5,335m (17,500 ft). At the Aurora well location, only hydrocarbons in the Brookian sediments are not undergoing thermal degradation. By contrast, oil generation at the Pt. Thomson area begins about 3,600m (12,000 ft), at the base of the Brookian section.

Burial history reconstructions incorporating stratigraphic and geochemical data garnered from the Pt.Thomson area, the 1002 area and modified with data from Aurora well, demonstrate limits of petroleum generation for source rocks in eastern ANWR. Figure 6 shows the main phase of petroleum generation for Triassic through upper Cretaceous source rocks is initiated no earlier than during the Upper Cretaceous to lower Tertiary Middle Brookian sedimentation.

At the more deeply buried Prospect 18 (fig.5), source rocks at the lowest closing contours around the periphery of the structure are at thermal maturity for the gas and condensate phase. Only the upper part of the structure and younger potential source rocks are within the oil window. At prospect 19, all source rocks are within the oil window. Although the burial history diagrams are generalized, they indicate petroleum generation and preservation are probably ongoing at the current depths of these structures. Seismic mapping shows both structures command relatively large drainage areas. Consequently, either the Ellesmerian or upper Cretaceous, Brookian source rocks could have generated appreciable amounts of hydrocarbons. The richness, thermal regime, minimal migration distance from this favorable source rock:reservoir geometry demonstrates that the large structures are attractive exploration targets.

Timing of trap formation is critical to petroleum entrapment. Source rocks were not buried deeply enough to generate hydrocarbons until the deposition of the Middle Brookian sediments. Depending on the geothermal gradient, major generation of hydrocarbons may not have started until Upper Brookian deposition (Late Oligocene - Early Miocene time). Consequently, burial history reconstructions suggest even traps formed as late as Pliocene could receive hydrocarbons from this system. Even more favorably towards entrapping an accumulation, both Clough's biostratigraphic analyses (personal communication, 1996) and structural reconstructions of Kelley and Foland (personal communication, 1996) suggest the large structures are reactivated older positive features. This is favorable relationship because most if not all the generated hydrocarbons would be able to migrate into the large structures. An earlier interpretation (Kelley and Detterman, 1989) suggested the large structures were earliest Cretaceous. This scenario would predate the onset of thermal maturity and perhaps enhance the development of porosity and permeability, similar to that along the LCU.

Hue-Sagavanirktok(!)

Fault-emplaced, oil-stained, turbidite sandstones and interbedded shales crop out along a northeast trend extending across the 1002 area (fig. 4). The sandstones are fine to medium-grained chert litharenites in beds ranging in thickness to about 20m (from inches to tens of

feet). Outcrop porosities are typically low except where oil staining is evident. Several shales and siltstones are also oil stained. Geochemical analyses of the widespread oil staining shows it is unlike the Prudhoe oil (Magoon and others, 1987). Geochemical differences (e.g., metals contents <10 ppm, [S]<1%, etc.) and biomarker distributions (fig. 7) show these sands have been charged by the Jago-Katakturuk-Manning (JKM) oil (Banet, 1994). Upper Cretaceous, highly bentonitic shales from the turbidites' distal depositional environment (i.e. condensed section) are the source for this oil. TOC's and pyrolysis data show this papery- to cardboard-texture shale, where thermally mature, is the richest petroleum source rock on the North Slope.

This JKM oil is present at oil-stained sands and seeps from upper Katakturuk Creek to Manning Pt. on the Arctic coast and Jago River, i.e, across most of the 1002 area. JKM oil is found in sediments as young as Miocene along the crest of the Marsh Creek anticline and along Jago River. The seep at Manning Pt. is active and leaking liquid hydrocarbons into the Beaufort Sea. Correlative, Upper Cretaceous, highly bentonitic shale source rocks cover a large area, with outcrops extending across ANWR and through the Mackenzie Delta, in Canada. There, where sufficiently mature, it is also the source of oils found around the basin periphery (Snowdon, 1979; Brooks, 1986). The JKM oil found across the Coastal Plain, and the strong indications of microseepage of hydrocarbons in the same area (Cunningham and others, 1987), demonstrate this source rock is actively expelling hydrocarbons into the stratigraphic system. Magoon (1988) assigns this the Hue-Sagavanirktok/Canning(!) petroleum system.

By contrast to the large seismically mapped structural traps of the Ellesmerian(?) system, currently identified seeps and potential traps of the Hue-Sagavanirktok(!) system are occur in the structurally detached, post-upper Jurassic section (Foland and Lalla, 1987). These are smaller "roll overs", features which show two-way closure on available seismic data. These "roll over" structures are relatively shallow and most are not buried deeply enough to generate hydrocarbons in situ. However, they are structural culminations and in position to accommodate hydrocarbons generated where source rocks are thermally mature, down dip. These charging areas are extensive and the roll overs are numerous with an estimated 150 drillable prospects (Clough and others, 1987; Dolton and others, 1987). These features vary in size from about 8 km^2 (3 $mi.^2$) to as much as 25 km^2 (15 $mi.^2$). These source rock:reservoir relationships mitigate some of the inherent inefficiencies due to lateral migration.

The extent of oil stained sands and seeps across the 1002 area indicate the highly organic and bentonitic Cretaceous shales exist across most of the ANWR subsurface, are thermally mature and are expelling oil. There are two known areas where the bentonitic shale is missing. Well data show the upper Cretaceous highly bentonitic shale unit is not present across the entire Pt. Thomson area because it is locally eroded from the northern extent of the field by a lower Tertiary unconformity. A similar localized erosional event, rather than a regional event, is likely to have removed the upper Cretaceous bentonitic shale from the Aurora well area.

Beaufort(.) petroleum system

The third possible petroleum system which affects ANWR is manifest along the coast. It is defined as Hypothetical (.) because there is no petroleum-source rock correlation. The solidified oil seep at Angun Pt. east of Manning Pt. is severely degraded, such that even the biomarker spectra (fig.7) provide no means to correlate to Prudhoe oils of the Ellesmerian system, the JKM oils of the Hue-Sagavanirktok petroleum systems or the three families of nonmarine oils found in the Mackenzie Delta (Banet, 1994). Limited isotopic data suggest the Angun oil has the geochemical signature of a marine oil. It may be derived from distal depositional environments of Upper Brookian,

Tertiary source rocks offshore. The Barter and Demarcation sub-basins (Craig and others, 1985) located north and east of the 1002 area are possible depositional centers and areas where potential source rocks may have been buried sufficiently to generate hydrocarbons. Current information suggests this petroleum system is restricted to upper Brookian sediments in the northeast portion of the 1002 area. The extent are undetermined.

The upper Cretaceous(?) - early Tertiary, Oruktalik sand of the Aurora well (table 3) correlates to the Flaxman sands of the Pt. Thomson-Sourdough area. Petrographic descriptions (Mowatt and others, 1994) show the Oruktalik sand is also similar to the Middle Brookian Sabbath Creek Conglomerate found in the eastern part of the 1002 area (fig. 3). It is probably a distal equivalent. Extractable hydrocarbons from the Brookian section at Aurora, and the minor tar and gas in the Oruktalik indicate hydrocarbons have moved through this area. Data show the hydrocarbons have been altered and do not readily correlate to hydrocarbons shows, onshore (Banet, 1993, 1994; Paul and others, 1994). Proximity suggests these hydrocarbons may have the same source as the Angun seep.

SUMMARY

Exploration drilling and seismic interpretations demonstrate that the Ellesmerian(!) petroleum system, extends to the westernmost border of the Arctic Wildlife Refuge 1002 area. Although the major Prudhoe Bay reservoirs are absent at Pt. Thomson, significant volumes of Prudhoe suite oil were tested from both Beaufortian and Brookian sequence sands upsection. Seismic analysis shows there are no significant subsurface obstacles to these petroleum system elements to also extend into the northwest portion of the Arctic Refuge.

Large seismically mapped structures in the eastern part of the 1002 area are the most important features to the petroleum potential of the Arctic Refuge. Interpretations of regional geology, the Aurora well, seismic lines and geochemical data suggest that the entire or partial components of Ellesmerian petroleum system are present in these large prospects. Without drilling the large prospects however, the Ellesmerian petroleum system is comparatively speculative in the eastern 1002 area subsurface.

Although the thermal regime varies across the 1002 area, the large structures are mostly within the oil window. Tectonic history reconstructions suggest the large mapped features may be as old as lower Cretaceous and possibly reactivated at later times. Burial history modeling shows that pre-Eocene structures would be open to receive a full charge of hydrocarbons from any of the source rock units. Burial history modeling shows that structures as young as Pliocene could receive a partial hydrocarbon charge from source rocks within the immediate drainage area.

Oil stained Brookian sands and seeps across the 1002 area show a second petroleum system is also active and expelling liquid hydrocarbons. This is the Hue-Sagavanirktok(!) system which has generated and emplaced oil in sands of the middle Brookian sequence. It consists of organic-rich and bentonitic, upper Cretaceous shales supplying liquid hydrocarbons to the overlying clastic section across much of the 1002 area.

In addition, the degraded oil from the Angun Pt. seep in the eastern part of the 1002 area and possibly the extracted hydrocarbons present in the Brookian section Aurora well do not correlate to either of the aforementioned petroleum systems. A third petroleum system, the Beaufort(.) is postulated. It's source and reservoirs are Tertiary aged. Its extent and petroleum potential are not yet determined.

The juxtaposition of the major and multiple petroleum system elements reinforces geologic analyses suggests the Arctic Wildlife Refuge 1002 area, may have appreciable quantities of

economically recoverable hydrocarbons. Accumulation efficiencies are enhanced because there are multiple source rocks and reservoirs, short predominantly vertical, migration distances, large structural features overlain by lithologies with known sealing capacity and a thermal history which suggests favorable timing for the migration of hydrocarbons into the large prospects. In addition, the 1002 area has potential for accumulations in stratigraphic traps, but these possibilities have not yet begun to be explored.

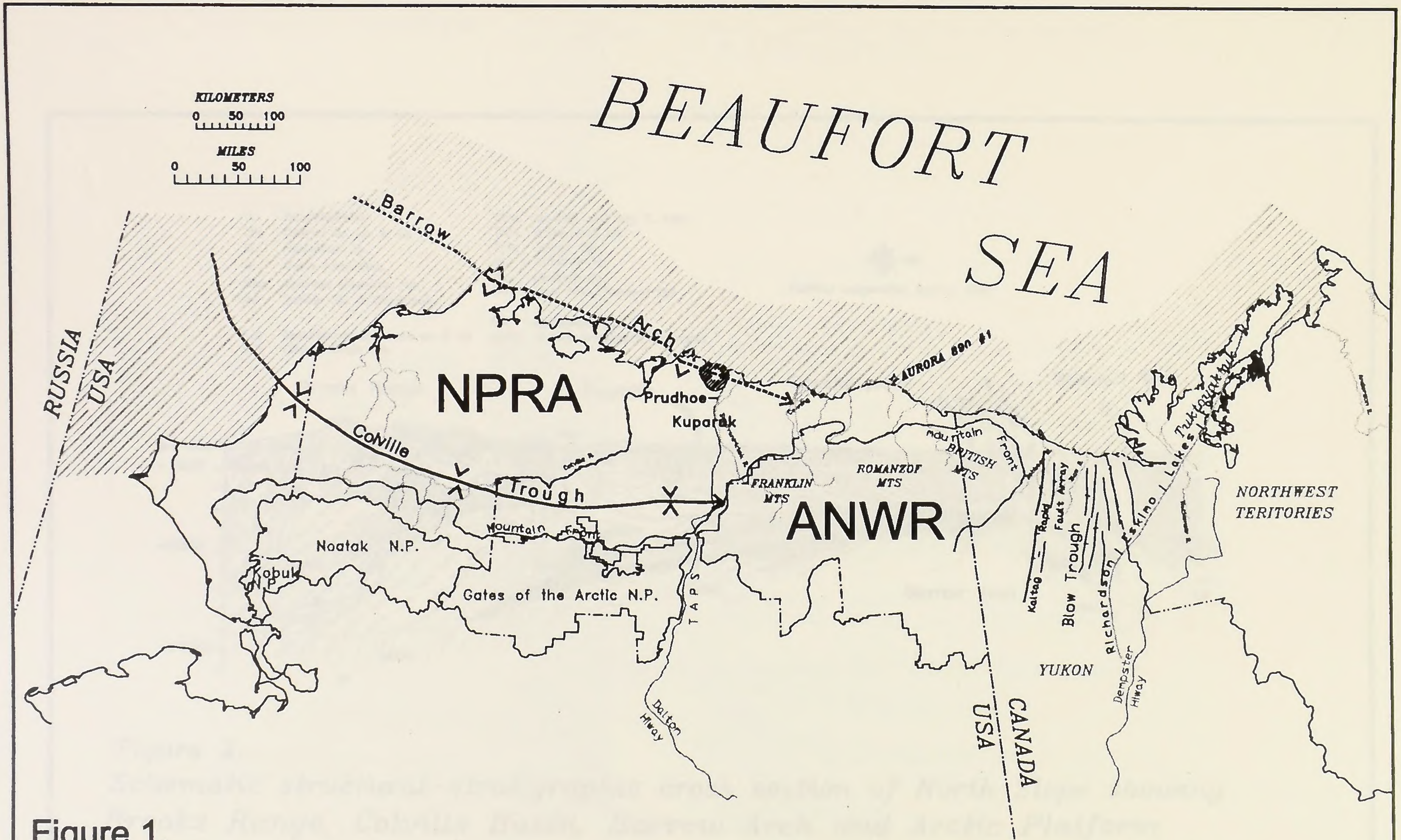


Figure 1.
Major tectonic features of Arctic Alaska and adjacent Canada.
(Beaufort–Chukchi Shelf hatched)

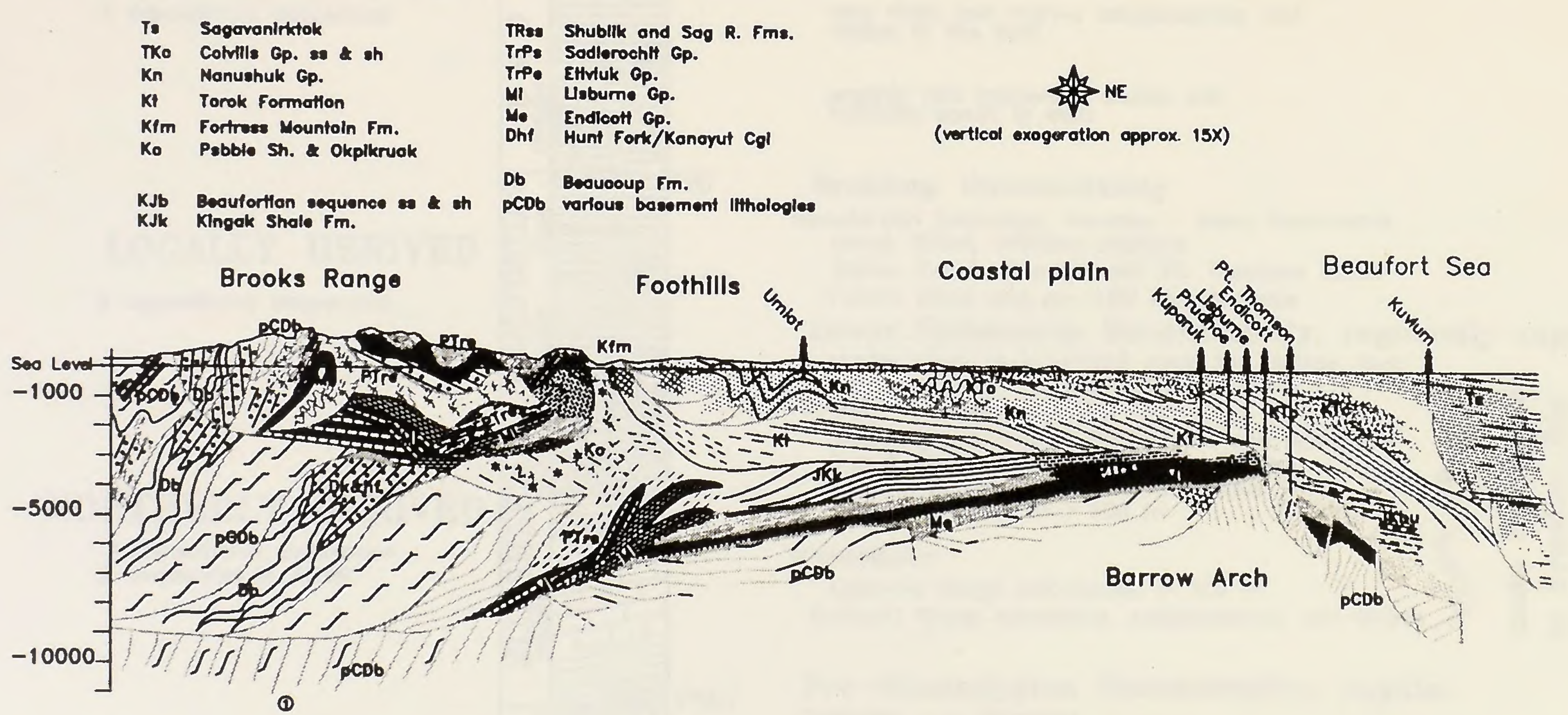


Figure 2.

Schematic structural–stratigraphic cross section of North Slope showing Brooks Range, Colville Basin, Barrow Arch and Arctic Platform.

Figure 2

Schematic stratigraphic-structural cross section of North Slope Mountain Range, Colville Basin, Barrow area and Arctic Platform.

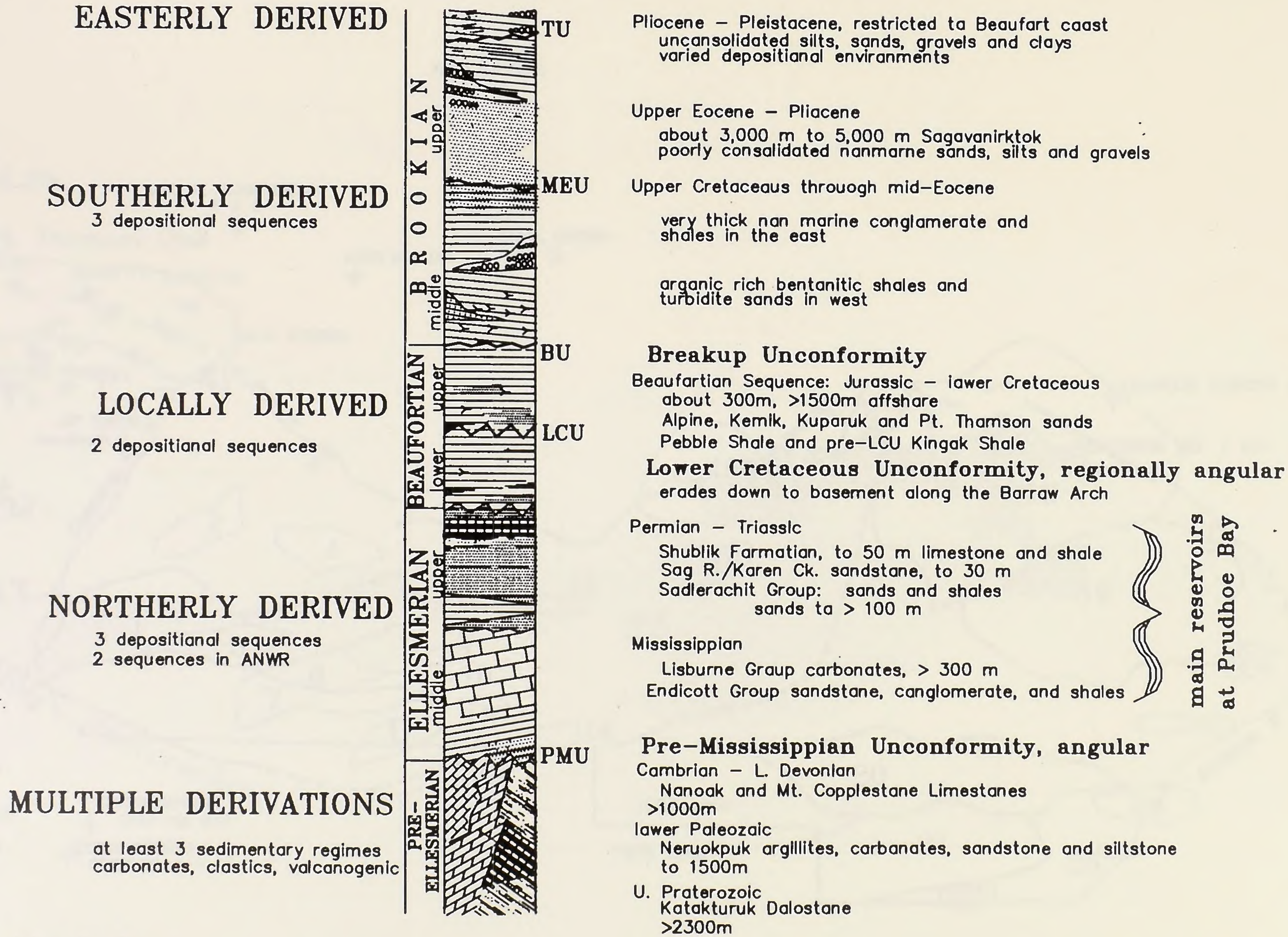


Figure 3.

Generalized stratigraphy of northeast Alaska.

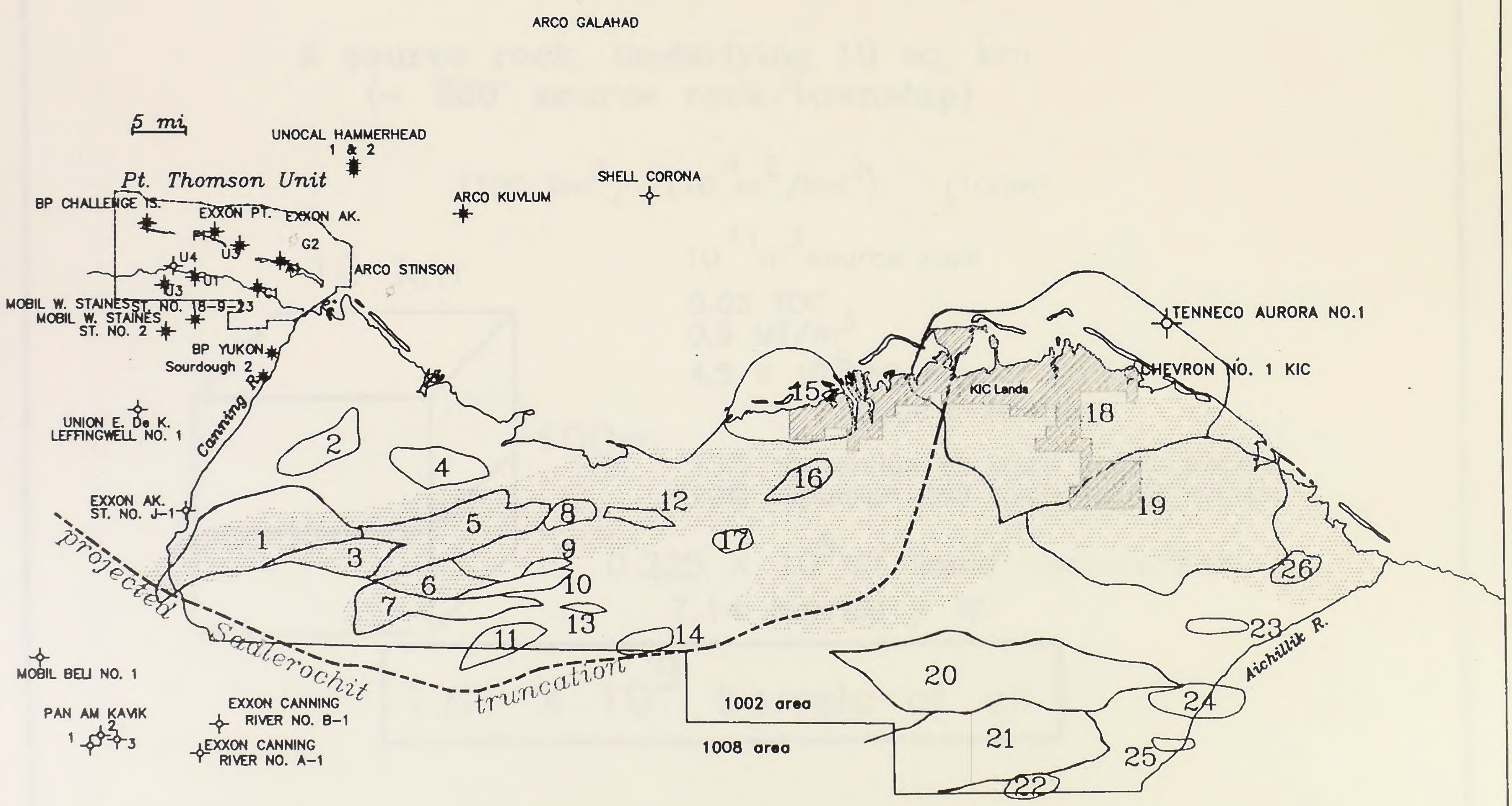
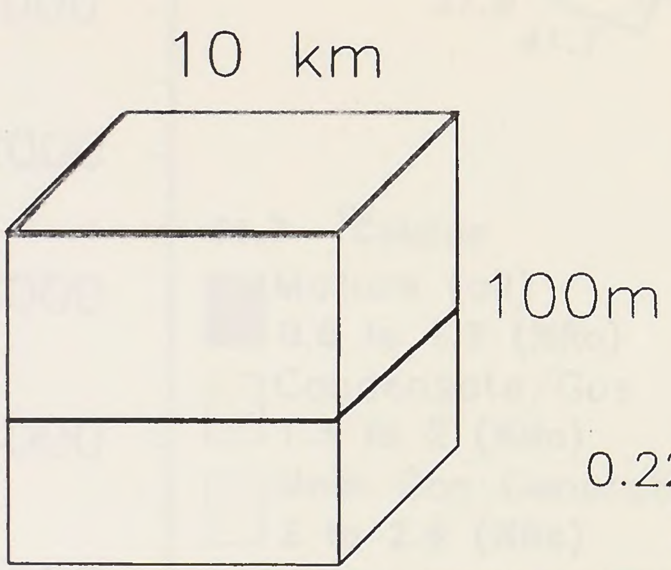


Figure 4.

ANWR 1002 area showing nearby wells, large mapped prospects (area of smaller, Jurassic–Tertiary culminations shaded).

A source rock, underlying 10 sq. km
(~ 300' source rock/township)

(100 km^2) ($10^6 m^2/km^2$) (100m)



$10^{11} m^3$ source rock

0.05 TOC
0.9 MT/m^3
4.5 X 10^9 MT organic matter
(type II kerogen)

25% conversion to liquid hydrocarbon
20% expulsion and migration efficiency

0.225 X 10^9 MT liquid hydrocarbon
7.14 barrels / MT

1.61 X 10^9 barrels of oil

Figure 5.

A calculation of generated hydrocarbons.

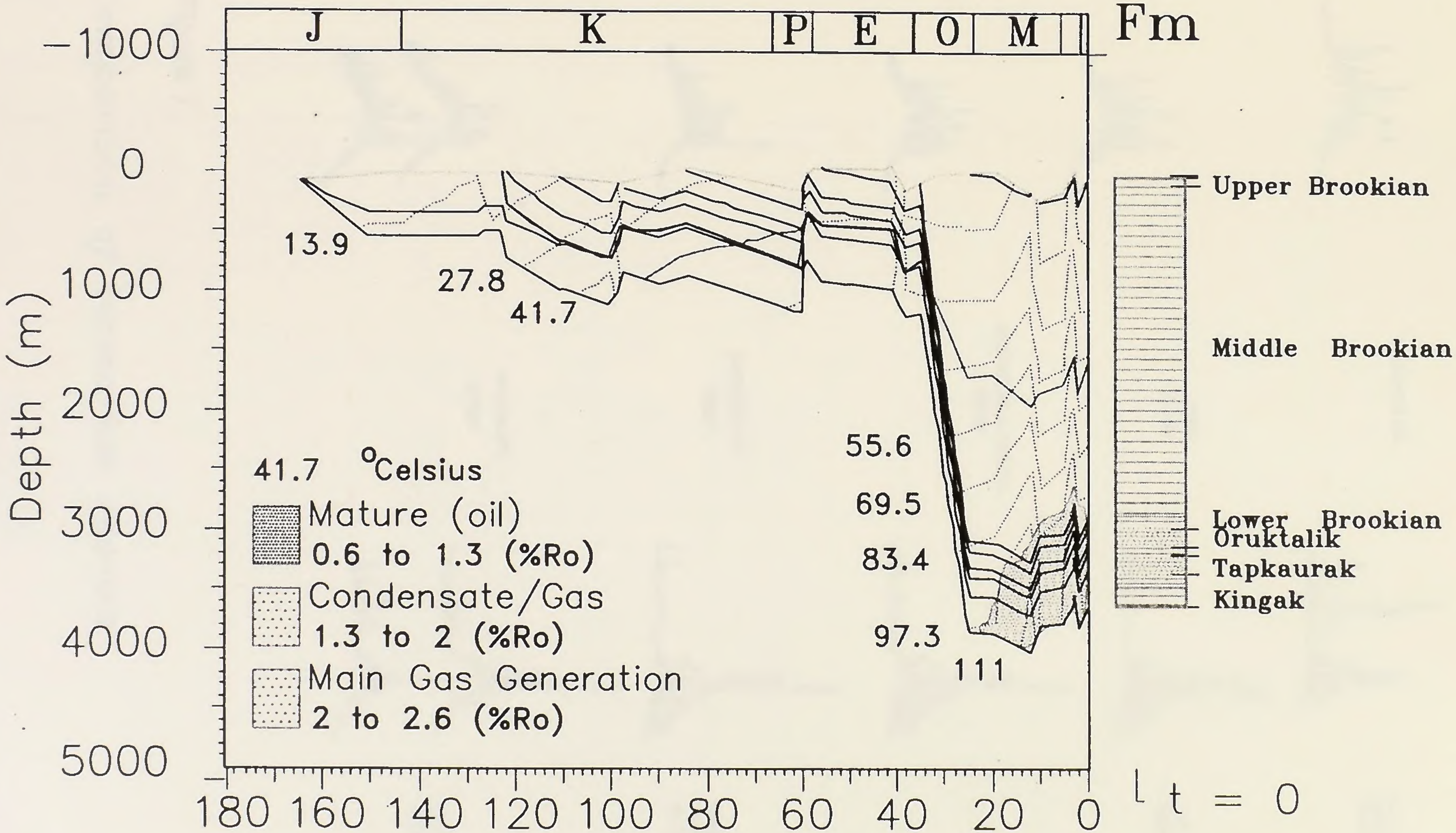


Figure 6.

Burial history diagram for large seismically mapped prospects in eastern 1002 area.

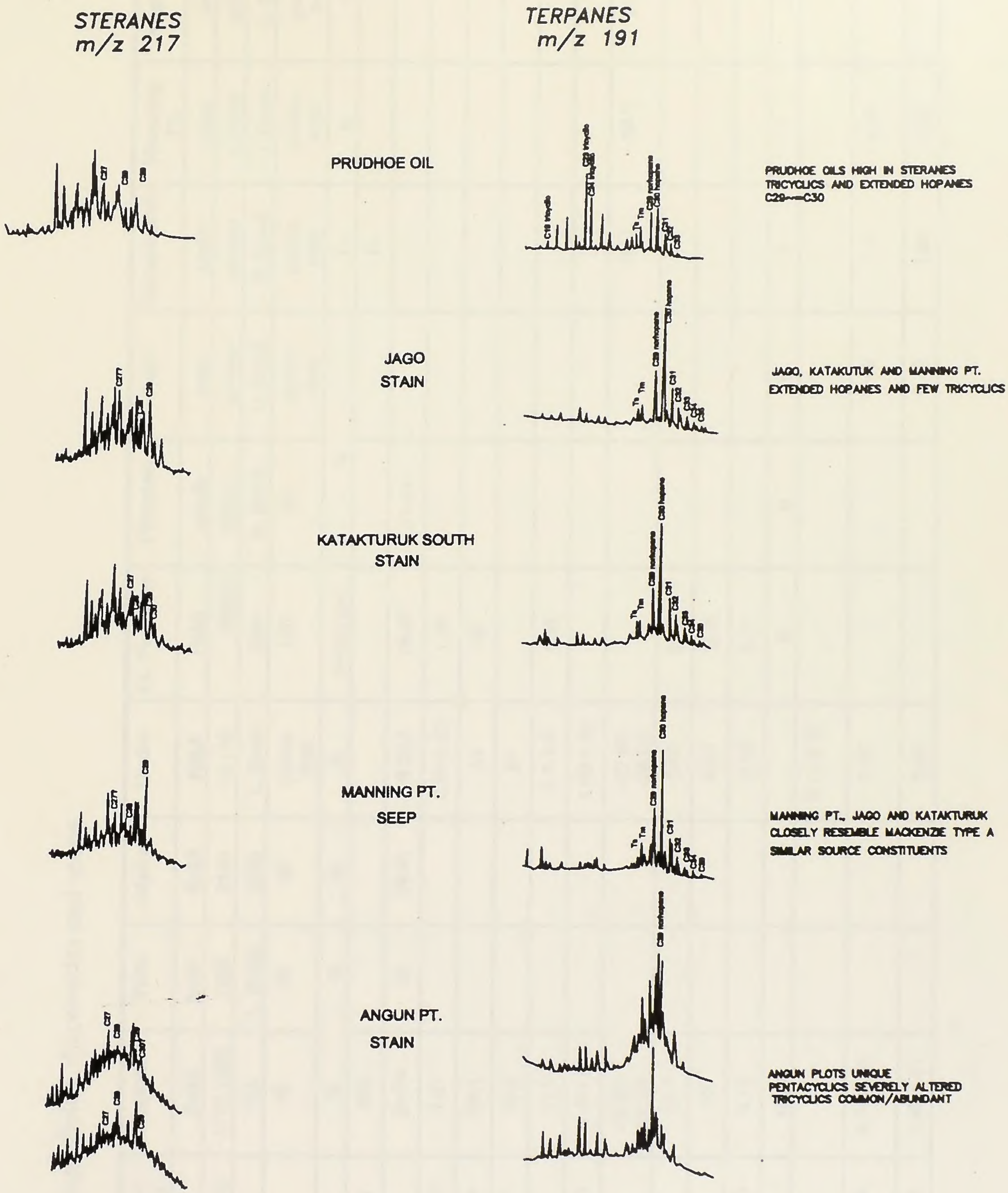


Figure 7.

Comparison of biomarker spectra

Table 1.

Geochemical data for North Slope fields, discoveries and seeps.

	Ugnu-W. Sak	Prudhoe/ Lis/End	Kuparuk	Tarn	Alpine	Umiat	Pt. Thomson	Flaxman	Jago	Katakturuk	Manning Pt.	Angun Pt
	fields	**fields**	**field**	**field**	**field**	**field**	**field**	**sands**	**seep**	**stain**	**seep**	**seep**
DEPTH (m)	760-1400	2560-3110	1770-1920	1580	2190	10-110	3960+/-	3660+/-	surface	surface	surface	surface
SEQUENCE	M. Brook	Elles	Rift	L. Brook	Bfrtn	L. Brook	Bfrtn	M. Brook	U. Brook	M. Brook	U. Brook	U. Brook
TEMP (C)	5 to 40	95	65	65	60	perma frost	100	95	perma frost	perma frost	perma frost	perma frost
GAS CAP	N	Y	N	N	N	N	mostly gas	N		N	N	N
GOR		730-830	450							N		
API GRAVITY	5 - 26	17-25	24-34	38	39-41	19-39.2	18-45	21-44				
% SULFUR	1.56	0.79-1.53	1.67			0.04-0.29	1.16					
% AROMTICS	35.86	36.5-38.4	55.1			33	36					
% SATURATES	55.12	54.4-56.1	38.9			67						
Pr/Ph	~1.5	1.0-1.7	<1.5			1.7-1.9	1.35					
CPI	1	0.97-1.03	1.0-1.5			1.02-1.05						
del 13C oil		-28.90 -29.83	-28.89 -30.20			-27.80 -28.82				-26.7	-28.3	28.71
Ni (ppm)	14.8	10-30	21.7			0.06	23.8					
V (ppm)	35.4	20-60	58			4.51	58.6					
V/V+Ni	0.71	0.62-0.75	0.73			0.12	0.71					
biodegraded	Y	N	slight				N	N	Y	Y	Y	Y
TERPANES: tri/pent		0.63				0.11-0.27						
C29norhop/ C30 hop	0.56-0.65	0.35-0.94	0.74-0.85			0.47			0.46	0.4	0.54	
C35/C34 hop	1.19-1.35	0.80-1.43	1.40-1.51			0.62			0.12	0.83	0.63	

Table 2.

Geochemical data for western North Slope wells.
(modified from Hughes and Holba, 1986; and Banet, 1994)

Sample	Well Name	Depth	Reservoir	Age	API	%S	[Ni]	[V]	V/[Ni+V}	%Sats	pr/ph	Type
80	Seabee #1	5336-5394	Torok	K	52.6	0.01	0.2	0.2	0.5	90.7	0.12	U
105	Well A	14126-14144	not listed	K	39.6	0.23	2.6	0.3	1.1	64.7	1.43	U
108	Umiat #4	299	Nanushuk	K	36.5	0.06	4.5	0.5	0.1	69.3	1.77	U
AYZ	Hemi Spgs #1	7196-7245	Kuparuk	K	34.4	0.25	6	2.2	0.27	51.8	2.17	M1
GGN	Gwydyr Bay S. #1	10053-10105	Sadlerochit	Tr	33.6	0.30	9	4.3	0.32	55.9	1.74	M1
DZG	Mikkelsen Bay S. #1	10468-10550	Colville	K	33.2	0.83	8.5	6.9	0.45	48.1	1.18	M1
76	S. Barrow 20	1629-1639	Pebble Sh	K	28.8	0.21	4.2	4.7	0.53	64.8	1.32	M1
CGN	W. Kuparuk S. #1	8880-8924	Shublik	Tr	28.0	0.60	10	21.6	0.68	46.3	1.49	M1
BHW	Hemi Spgs #1	9538-9582	Sadlerochit	Tr	27.8	0.22	2.9	1.1	0.28	57.1	1.56	M1
CGM	Sag R. S. #1	8890-9008	Sadlerochit	Tr	27.0	1.01	9.9	22.5	0.69	40	1.53	P
DZF	N. Kuparuk S. #1	8890-8984	Sadlerochit	Tr	26.0	1.00	11.2	22.2	0.66	42.3	1.42	P
GGK	N. Kuparuk S. #1	3708	Colville	K	25.8	1.00	9.3	18.9	0.67	32.7	1.44	P
75	Put R. D-3	10417-10536	Sadlerochit	Tr	24.9	0.99	8.4	16.7	0.66	43.5	1.42	P
BCY	Kuparuk R. 1Y-2	7638-8012	Kuparuk	K	23.9	1.67	21.7	58	0.73	38.9	1.3	P
79	Simpson core	surface	Nanushuk	K	23.0	0.24	1.2	0.7	0.64	58	1.57	U
GGM	Foggy I. Bay S. #1	10092-10209	Lisburne	M	23.1	1.27	22.8	40.9	0.78	38.1	1.45	P
GGL	Mikkelsen Bay S. #1	11870-12200	Lisburne	M	22.7	1.28	30.8	71.1	0.7	35.1	1.1	P
77	S. Barrow 19	2200-2245	Sag R.	Tr	21.1	1.34	21.2	20.8	0.5	48.1	1.22	P
GGJ	Kavereak Pt. #1	3794-3845	Ugnu	T	20.9	1.56	14.8	35.4	0.71	39	1.56	P
DZE	Pt. Thomson #1	12063-13050	Thomson	K	20.0	1.16	23.8	58.6	0.71	36	1.35	P
DZC	Well B	not listed	not listed		12.4	0.87	17	48.4	0.74	29.3	1.18	M2
ASN	Mukluk Y-0334	7360-7385	Kuparuk	K	12.1		NA	NA	NA	28.3	1.54	M2
81	J.W. Dalton	8568-8665	Lisburne	M	6.5	3.12	43.9	141	0.76	23.5	1.37	M2

Table 3.
Oil and gas tests from Basement rocks, Beaufortian Seqence and Brookian Sequence sands in the Point Thomson area..

Well	Interval m from KB	GAS Mm^3/day	OIL m^3/day	GOR	API°
BASEMENT COMPLEX					
Sohio AK Is 1	4570-4580	62	175	354	>40
Exxon AK St F	4205-4365	69	152	454	35
Exxon AK St A1	3960-4018	salt water			
PT THOMSON SANDS					
Exxon AK St C1	4092-4232	95	139	683	37
Exxon AK St F1	4228-4232	119	45	2644	35
Exxon Pt Thomson U1	3912-3924	108	27	4000	45
	3951-3978	373	363	1028	18
Exxon Pt Thomson U3	4228-4232	178	76	2342	38
FLAXMAN SANDS					
Exxon AK St A1	3830-3847	62	398	156	23
Exxon AK St C1	3498-3536	2	and gas	cut	mud
Exxon AK St F1	3660-3682	3	22	136	22
	3929-3934	2			
Exxon Pt Thomson U2	3530-3559	63	21	3000	44
	3672-3744	32m with	oil shows		
Exxon Pt Thomson U2	3530-3559	3	39	77	21
Mobil W. Staines	3551-3406	gas flow	1		

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