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222 West 7th, #13
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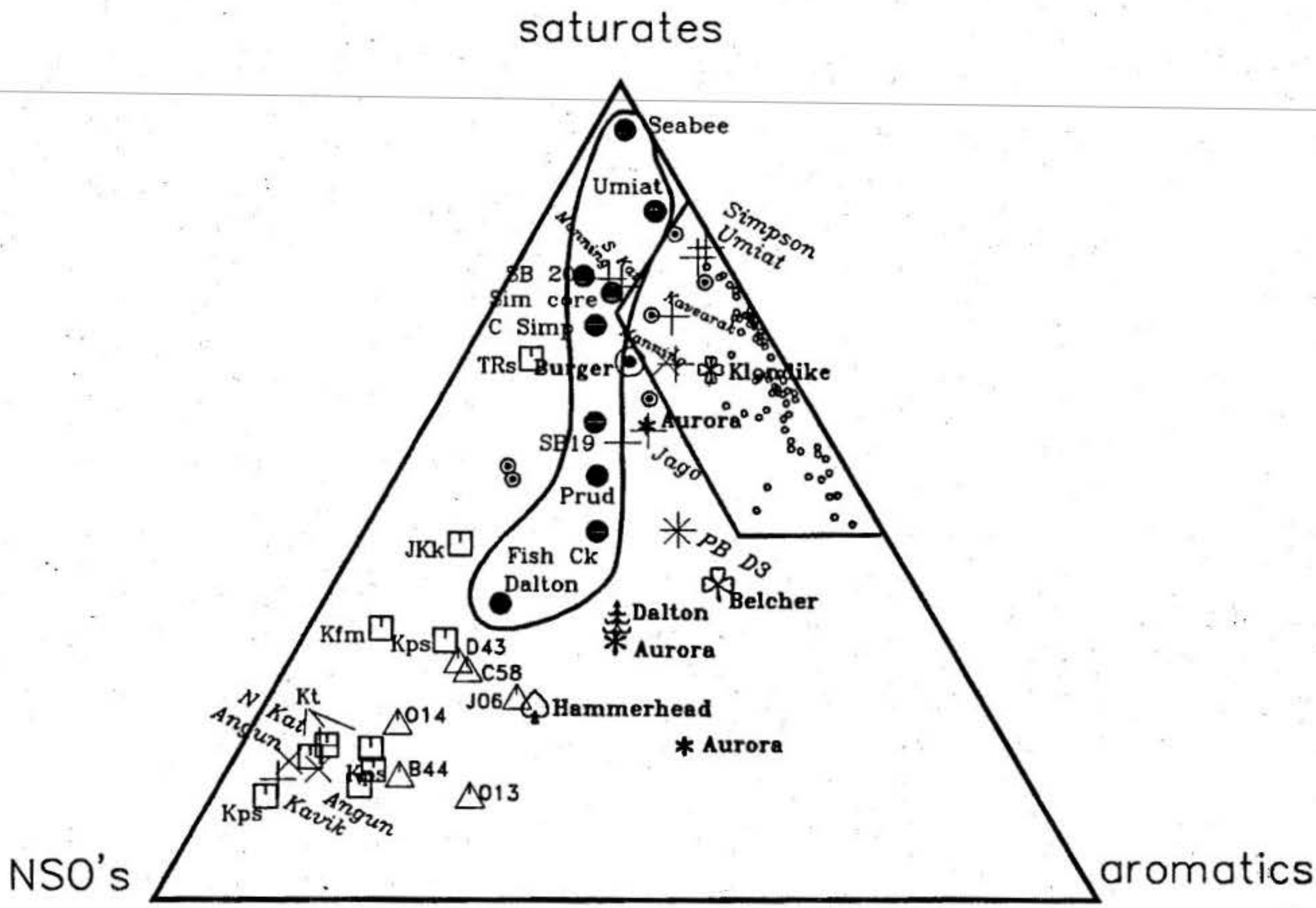
A Comparison of Crude Oil Chemistry on America's North Slope: Chukchi Sea-Mackenzie Delta

Arthur C. Banet., Jr.



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Author

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

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A Comparison of Crude Oil Chemistry on America's North Slope:Chukchi Sea-Mackenzie Delta

Publicly available geochemical data provide the basis for correlating and comparing the major North Slope oil types. These data define ten oil types representing independent petroleum systems. This analysis concurs with earlier work that identifies the major and chemically-distinctive oil types germane to the North Slope.

Prudhoe type oils are shown to extend to immediately west of the Arctic National Wildlife Refguge 1002 area. Also, comparisons of the geochemical data show that considerable mixing of the Prudhoe and Umiat oil types has occurred in reservoirs along the Barrow Arch. Data from the most recent onshore discoveries fit within the Prudhoe or mixed oil siite chemistry. Biological marker analysis of the ANWR 1002 area oils show that there are three types. The Jago-Katakturuk-Manning Pt. type correlates with Mackenzie Type A oils. These oils are derived from the upper Cretaceous Bentonitic, the richest source rock on the North Slope! The Angun Pt. oil is of marine origin and likely derived from multiple sources. The Kavik oil stain is unique. Biomarker data indicate that some nonmarine Mackenzie type C2 oils have migrated into reservoirs which typically yield type C1 oils.

These geochemical data also show that oils from two wells in the Chukchi Sea represent a newly described and independent petroleum system. The multi-faceted chemistry of the Hammerhead oil shows it is the most unique and enigmatic type on the North Slope. It represents another independent petroleum system. Additional data are required to determine how and to what extent the major Kuvlum discovery best correlates to the Prudhoe, Hammerhead, Mackenzie Delta or ANWR suites.

1. Introduction

The North Slope is the major petroleum province of North America. It is located entirely within the harshest of frontier climes; the Arctic, between approximately 132° and 170° W and 69° and 71°N (Plate 1). From the Chukchi Sea on the west to the Tuktoyaktuk Peninsula on the east this area encompasses some 200,000 sq. mi. (518,000 sq km). Distinctive regional geological environments include the Brooks Range and its foothills, the Colville Trough (foreland basin), the Arctic Coastal Plain, the Barrow Arch uplifts and the Mackenzie Delta onshore. The Chukchi Platform and the Beaufort Sea passive margin comprise the offshore (figures 1 and 2).

The stratigraphic record in this region includes rocks of Proterozoic through Recent age. These rocks can be divided into at least 11 depositional megasequences, based on ages of the various units, their depositional polarity, and the amount of data available. The western tectonic regime is predominantly compressional in the south with an abundance of large scale, far- traveled thrust sheets. North of the Colville foreland basin, this regime changes to a relatively undisturbed area beneath much of the Arctic Coastal plain. North of the Barrow Arch, basement-involved extensional deformation is prevalent, particularly in the offshore (figure 2).

Complexity increases eastward. At about Canning River, there is a distinct northward bulge of the mountain front, which superimposes these tectonic regimes (figure 1). Allochthons are also much smaller both in areal extent and thickness of stratigraphic section moved by each.

The eastern region, consisting of the Mackenzie Delta and Canadian Beaufort, is mostly outboard of the large thrust sheet style of deformation. This part of the Beaufort shows a considerable amount of vertical uplift from compression of relatively unconsolidated Tertiary age lithologies and it also has undergone deformation by predominantly listric extensional tectonics (figure 3). Transtensional tectonics also appear to affect the offshore.

Oil, gas or significant shows are present in almost all of the stratigraphic units. However, the major economic reservoirs are of Mississippian, Triassic, Cretaceous and Tertiary ages. The most prolific potential source rocks are found in Triassic, Lower Jurassic, middle and Upper Cretaceous units, and possibly the Tertiary. However, most shales and carbonates in this region have at least fair-to-good hydrocarbon source potential. Current oil and gas assessments identify some fifty distinct and mostly independent exploration plays in this region, based on stratigraphic and structural relationships (Bird, 1991; Craig others, 1985; Thurston and Theiss, 1987; and Dixon and others, 1988).

Exploration interest in this area started about the turn of the century as explorers reported the presence of oil and gas seeps on the Coastal Plain. Later, reconnaissance geological mapping spread out to the Brooks Range foothills. This effort also included some seismic analyses and exploration drilling under the auspices of the U.S. Navy following the second World War and during the Korean Conflict. Industry exploration followed, concentrating first on surface-mapped anticlines in the foothills of the Brooks Range, before turning to seismically mapped prospects beneath the central Arctic Coastal Plain and economic success. Still later, exploration expanded to the offshore regions of the Mackenzie Delta and Beaufort Sea where discoveries to date are still subeconomic.

2. Stratigraphy

North Slope stratigraphy is expansive, with current efforts still unraveling its geological complexity. Dixon and others (1985), Hubbard and others (1987) and Moore and others (1992), offer the most recent, comprehensive and complete regional syntheses of the available data. Bird, (1991), Banet (1990), Thurston and Theiss (1987) Bird and Bader (1987) Bird (1985), Norris (1985) and Lerand (1973) also provide summaries and correlations of available North Slope data.

Crystalline rocks are relatively rare on the North Slope. Exposures and drilling samples of stocks and plutons typically yield isotopic age-dates similar to surrounding sediments, suggesting that they are parts of fault-emplaced allochthons. Undisputable crystalline, or metamorphic basement rock is not known in this region.

Geographically widespread outcrops show that the oldest sediments are of Proterozoic to Devonian age. These units are truncated by a regional sub-Mississippian unconformity (or possibly unconformities). Originally described as the northerly derived Franklinian sequence (Lerand, 1973), later work shows that these lithologies are far more complex in nature and origin. Seismic, well and outcrop data suggest that there are several uncorrelated carbonate sequences which reach several thousands of meters of thickness beneath the Chukchi Platform and in the Bulge, e.g. the Baird Group, the Katakturuk, the Nanook, Mt. Copplestone and carbonate facies within the Neruokpuk Group (Plate 2). Generally, structural deformation has been mostly fault repetitions which comprise large scale, far-traveled, allochthons within the Brooks Range.

The clastic lithologies consist of quartzites, argillites, schists, and volcaniclastics, with some interbedded carbonates. These lithologies are severely folded, fractured and faulted along the Barrow Arch and at the mountain front.

A major regional and angular unconformity with considerable local relief separates these oldest sediments from the overlying Ellesmerian Sequence. Ellesmerian rocks record three depositional sequences of northerly derived, carbonate and clastic sediments (Hubbard and others, 1987). Lower Ellesmerian clastics are present only on allochthons in the Brooks Range. Palinspastic reconstruction of these lithologies suggests that they were deposited hundreds of km south of their present outcrops. Mayfield and others (1991) and Moore and others (1992) describe the extent of shortening recorded in these thrust sheets or "panels."

In contrast, the Upper Mississippian through Triassic, middle and upper Ellesmerian rocks, are thick south of the Barrow Arch and line the Colville basin. Only their fine-grained, distal and condensed section lithologies are exposed on smaller scale thrusts along the front of the Brooks Range. The light colored, cliff-forming Lisburne Group carbonates are also prominent among the other units exposed along the mountain front. In addition, drilling and seismic data shows that the Lisburne carbonates line the Colville trough and are truncated along the Barrow Arch uplifts.

Ellesmerian clastics and carbonates are reservoirs for most of the economically recoverable oil reserves yet discovered in Alaska. Thermally mature facies of the Shublik Formation (Triassic) are the most likely sources for the high sulfur and metals content of the oils at Prudhoe Bay field. The thermal maturity regime indicates that some finer-grained clastics and facies of the Lisburne Group could have also contributed minor amounts of hydrocarbons. However, the available geochemical analyses are not refined enough to identify diagnostic components.

Breakup sequence rocks (Jurassic-mid Cretaceous) record the most recent activation of the Barrow Arch and the stepwise opening/rifting of the Arctic ocean. Multiple local uplifts shed over a kilometer of sediments into the Colville basin south of the Arch, and over three kilometers of sediments to the north, into deep grabens formed by the rifting away of the northern land source (Hubbard and others, 1987). Unconformities are common within this section. At about 128 ma the Lower Cretaceous Unconformity (LCU) removed much of the Ellesmerian section from the crests of the Barrow Arch uplifts.

Hubbard and others (1987) identify a "low velocity" zone within the Lower Kingak Shale (Jurassic) as a potential oil source rock. Carman and Hardwick (1983) identify a High Radioactive Zone (HRZ) or Pebble Shale Unit (Hauterivian - Barremian) as another, organic-rich, potential oil-generating source rock.

Basin depositional polarity subsequently changed to the south, with the deposition of Brookian sediments. This started perhaps as early as Bajocian and proceeded to about lower Pliocene. The Brookian section consists of three distinct pulses of thick clastics. Hubbard and others (1987) cite over 8 km of sediment in the Colville basin and over 10 km of sediment on the Beaufort shelf. These are mostly chert litharenites and shales, with lesser amounts of interbedded coals and siltstones. The coals are widespread, mostly subbituminous and have low sulfur contents. West to east, progressively regressive facies overstep the Arch and deposit onto the Beaufort Shelf (Banet, 1990).

Organic rich condensed facies occur within the Torok Formation (Aptian-Cenomanian), the Colville Shale (e.g. the Turonian-Maastrichtian Bentonitic Shale, the Smoking Hills Formation and Boundary Creek Formation) and likely within the upper Brookian shales on the Beaufort shelf. Creany and Passey (1993) illustrate the sequence stratigraphic occurrence of these multiple and thick sections of organic rich rocks. Their high TOC bases (HTB's) represent maximum flooding surfaces. These HTB's typically have high radioactive zones which have preserved appreciable amounts of sapropelic material. These facies are found in the Brookian sequences in both the U.S. and Canada (Banet, 1990).

3. Oils

Comparative interest in the chemistry of North Slope oils began with the published analyses of Alaskan oils by McKinney and others (1959). Morgridge and Smith (1972), Jones and Speers (1976), Seifert and others (1980) and Carman and Hardwick (1983) offered geological analyses and showed chemical similarities between Prudhoe oil and most other oils in the immediate Prudhoe area. These analyses also demonstrated that the Shublik Formation (Triassic), Kingak Shale (Jurassic - Upper Cretaceous) and Pebble Shale Unit (Cretaceous) are the most likely source rocks of Prudhoe suite oils. Magoon and Claypool (1980) proposed two oil types for the Alaskan North Slope.

In a comprehensive comparison using a wide ranging suite of chemical analyses on samples from NPRA and Prudhoe (Plate 1), various authors (in Magoon and Claypool, 1985) generally concur with two major oil types and offer some minor modifications due to migration, alteration and mixing. Data from Curiale (1987), Sedivy (1987) and Hughes and Holba (1988) suggest additional minor modifications. Analyses of samples from the Arctic Wildlife Refuge indicate three additional North Slope oil types (Magoon and others, 1987) and (Banet, 1990).

Burns and others (1975) presented the original analyses of crude oils from the Mackenzie Delta. Snowdon (1972, 1980, 1987 and 1982), Snowdon and Powell (1979) and Brooks (1986) expanded that database. They demonstrated that there are three major oil types and also established correlations between Mackenzie Delta crude oils and possible source rocks.

Recent thought agrees on five or six oil types in northern Alaska and three in the Mackenzie Delta, with perhaps one oil type common to both areas (Banet, 1992). This report presents and describes the most recent and publicly available geochemical data. These data include analyses from the Chukchi (Burger and Klondike wells) and eastern Beaufort (Belcher, Hammerhead and Aurora wells). In addition, geochemical comparisons are made between all the major oil types.

A. Prudhoe Type Oil

The oil at Prudhoe Bay field is, volumetrically, the most important oil suite on the North Slope. In fact, it is probably the most studied of all oils. Thus, it is the benchmark against which all others are compared. More and different types of analyses are publicly available from the Prudhoe suite than any other. Exploration drilling has found Prudhoe-type oils in a number of accumulations along the Barrow Arch from Barrow to the Pt. Thomson area on the Canning River (Plate 1). Prudhoe-type oil stained rocks and reservoirs range in age from pre-Mississippian at the Pt. Thomson area to the lower Tertiary Ugnu Formation (figure 4 and table 1).

Briefly, Prudhoe oils are dark colored, thermally mature, non- biodegraded, and are marine derived (figure 5). At Prudhoe Bay field, hydrocarbons saturate virtually every available reservoir in the stratigraphic column. Even some of the less permeable units also show considerable oil impregnation. Saturates comprise up to about 60% of the topped oil, with aromatics 10 to 20% and asphaltenes and NSO's usually less than 30% (figure 6). API gravities are usually 25° to 30°, and sulfur contents about 1% or more. Metal contents are greater than about 25 or 30 ppm. Vanadium content exceeds nickel content with V/V+Ni ratio > 0.60. Pristane:phytane ratios are less than 1.5, CPI's less than 1.0 and ^{13}C ratios are about -30 ppt. (tables 1 and 2, figures 5 through 9).

Hopane and sterane biomarkers occur in low concentrations in the Prudhoe oils. Ternary plots of $C_{27-28-29}$ rearranged steranes (m/z 217) show that Prudhoe oils plot as typical marine-derived oils (figure 10). C_{30} sterane is present in Prudhoe oils, supporting marine derivation (Moldowan, 1985). The prevalence of diasteranes supports the contribution of marine shale source rocks rather than just carbonate lithologies.

Terpane concentrations are greater than steranes (Mackenzie and others, 1985). Plates 3 and 4 show that m/z 191 C_{29} hopane is typically equal to or larger than C_{30} in the Prudhoe suite. There is also a series of extended hopanes. Together with the presence of C_{35} hopanes, this suggests the mix of carbonate and marine shale source material (Waples, 1991). Tricyclic terpanes are also prominent, suggesting that the Prudhoe suite oils are thermally mature.

B. Prudhoe Suite Variations

However, there are several internal variations of note within the Prudhoe suite. Generally, API gravities typically are heavier in shallower reservoirs with lower reservoir temperatures (table 1). ^{13}C isotopes and gas chromatographs of oils from the Kekiktkuk Reservoir (Endicott Group) appear to have some noticeable nonmarine character (figures 5 and 8). Perhaps this reflects some contribution of indigenous kerogens from the Endicott Group nonmarine sediments.

The very high sulfur and metals content, very low gravity oil from the G.W. Dalton well lacks steranes, as if it had been severely degraded. Its triterpane distribution is identical to Prudhoe. It also has the lowest saturate concentration of the Prudhoe Suite (figure 6), but it still has resolvable alkanes, suggesting that some oil mixing postdating degradation has taken place after degradation. Similar oil from the Kavearak Pt. well has high pristane:phytane ratios and the heaviest ^{13}C isotope ratio (figures 8 and 9). It is apparent that a degraded oil has probably been mixed with a nondegraded oil. However, in this case it appears that both oils have chemistries that suggest they are Prudhoe type oils.

The South Barrow #19 oil is a typical Prudhoe suite oil found in an upper Ellesemerian Sand, the Sag River (Triassic). However, its V/V+Ni ratio is slightly lower than the Prudhoe oil. The nearby South Barrow #20 is found in a Breakup sequence sand within the Pebble shale. Its V/V+Ni ratio is identical to Barrow #19. However, the saturates, and the API Gravity are higher. The sulfur content and metal contents are dramatically lower indicating that this is not a typical Prudhoe suite oil. Either the Shublik Formation has not contributed to South Barrow # 20, or more likely, oil type mixing has occurred, affecting South Barrow # 20 more than # 19.

Geochemical analyses show that the Shublik Formation and/or its distal facies; the Otuk Formation, the Kingak Shale and the Pebble Shale Unit, are the likely sources for most of the Prudhoe oil. However, with all of the analyses that have been done on the North Slope, none of these most likely units have been "caught in the act" of actively generating and expelling hydrocarbons.

The Shublik is a phosphatic marine carbonate, rich in sapropelic organic carbon. It contributed the high sulfur, high metal content and triterpanes to the oil (Plate 4). Facies of the Kingak Shale are sufficiently rich in organic matter and volumetrically sufficient to have been a major source for the Prudhoe oil.

Where mature, the Kingak kerogens contribute a considerable amount of diasteranes to the m/z 217 spectra. However, extended hopanes are not prominent (Plate 4). The Kingak Shale is a regionally widespread unit with kerogens that vary in organic richness, geochemical character and burial history. Thus, the Kingak Shale may have contributed to more than one kind of North Slope oil.

The Pebble Shale unit is also a widespread marine shale containing relatively hydrogen-rich organic matter. Like the Kingak, the Pebble Shale m/z 217 spectra have considerable diasterane contribution. In addition the m/z 191 spectra show the extended hopane series, such as that which is so prominent in Prudhoe suite oils (Plates 3 and 4). The Pebble Shale Unit's relatively high TOC, biomarker distribution, and stratigraphic proximity to both carrier beds and major reservoir units, identify it a candidate for a Prudhoe suite source rock where it is thermally mature (Seifert and others, 1979).

C. Umiat Type Oil

The Umiat oils are found both in shallow reservoirs along the Brooks Range foothills, in the Cape Simpson area and at seeps across the NPRA Coastal Plain area. It is commonly referred to as the Umiat-Simpson type oil (in Magoon and Claypool, 1985). These are light colored, high gravity oils and condensate with sulfur contents less than 0.1% (Table 1). Note that sample 105 (table 2) is an Umiat oil and is from a reservoir greater than 14,000 ft. This is the deepest reservoir reported: the location is not indicated.

Gas chromatograms of unaltered Umiat oil samples are generally not distinguishable from the Prudhoe suite. Gross compositional analyses show that the saturate fraction is much higher in the Umiat oils. Attendant pristane:phytane ratios are much greater than 1.5 and CPI's are also greater than 1.0. ^{13}C isotopes are between -29.1 and -27.8 ppt. Metal contents are between 0.1 and 5.0 ppm. Nickel content is typically higher than vanadium with V/V+Ni ratios < 0.50 (figures 6 to 9).

Biomarker concentrations of the Umiat-type oils are less than the Prudhoe suite (Mackenzie and others, 1985). The distribution of $C_{27-28-29}$ steranes reflects more nonmarine kerogen source contribution than the Prudhoe suite (figure 10). The relatively low concentrations and overall sterane distribution also suggest that Umiat oils are more thermally mature than the Prudhoe oils. Neither long migration nor advanced biodegradation alterations are apparent. Plates 3 and 4 also show that the Umiat oils typically have less prominent C_{30} sterane peaks, which suggests dilution possibly due to some terrigenous source material.

The most striking feature of the m/z 191 fragmentogram is that C_{29} is substantially less than C_{30}, which is normal for non carbonate-derived oils (Plate 3). Tricyclics and the partial series of extended hopanes are less pronounced than in the Prudhoe oil. Tm/Ts ratios are also less which could be either attributed to source differences or indicate that Umiat oils may be more thermally mature. Moretanes and oleananes, indicative of nonmarine environments, are not prominent. Thus, nonmarine contributions to the Umiat oils are not manifest as major constituents in the m/z 191 fragmentograms. Umiat oils are derived from mostly marine clastic source rocks.

Stratigraphically, the Torok and Pebble Shale are the most likely candidates, with the Kingak as a less likely source. The m/z 217 spectra show that all three sources have diasteranes similar to the Umiat oil. However, all three sources have a large C_{29} peak, unlike the Umiat oil. This supports the tenet that the Umiat oil is at a high degree of thermal maturity. At m/z 191, Umiat oils have a moretane peak like the Torok, but the Umiat oils have minor amounts of extended hopanes as do the Kingak samples (Plate 4).

Magoon and Claypool (1985) propose that there may be sufficient variation between the Simpson and Umiat oils to indicate that each oil a has different or unique shale source. Alternatively, available analyses suggest that facies and thermal maturity variations within the Kingak and Pebble Shale (and perhaps the Torok) are likely great enough to account for the relatively subtle differences in Umiat oil chemistry.

D. Mackenzie Type Oils

Three major types of oils are found on the Mackenzie Delta and the offshore Canadian Beaufort Sea (Snowdon, 1979; Brooks, 1986; Snowdon and Powell, 1988). These are 16° to 48° API gravity oils and condensates. Brooks (1986) and Snowdon and Powell (1988) report that many are typically biodegraded, some to great depths. These oils frequently lack a "normal" alkane fraction (figure 11). The topped oils lack appreciable amounts of NSO's. Saturates:aromatics:NSO ratios do not separate the Mackenzie oils into definite classes, like the Prudhoe and Umiat suites (figure 6). Sulfur contents are bimodal. The marine derived (Type A) oils have about 1% sulfur while the nonmarine derived (Types B and C) typically have less than 0.2% (table 3). Pristane:phytane ratios are much greater than 1.5 and are higher than any from the Alaskan section of the North Slope (figure 8). ^{13}C isotopes are low (light), dramatically lower than any others encountered in this North Slope study, suggesting considerable nonmarine input (table 3).

Curiale (1991) shows that Type A oils have sulfur contents between about 0.5 and 1.0% with variable metal contents up to about 12 ppm. Vanadium is predominant over nickel. Type C oils have between about 0.01 and 0.2% sulfur with metal contents less than 2 ppm (often nondetectable). Type A oils plot similar to the Prudhoe suite, while Type C are more similar to Umiat-type oils (Figure 7). All Mackenzie oils are isotopically very light. Type B oils and oils in the Kugmallit or Richards Formation reservoirs are $1.2^{0}/00$ heavier than Types A or C (figures 8 and 9).

Brooks (1986) reports on biomarker geochemistry of Mackenzie oils. He uses bar charts (Plate 3) of integrated spectral peaks which facilitates comparison of oil types presented. While useful for comparisons and ratios, this method does not totally replace using spectra as the charts do not show doublets from near-coeluting peaks. In addition, it is not always straightforward in comparing spectra from different laboratories because of differing extraction/isolation/integration methods and analytical hardware.

The $C_{27\text{-}28\text{-}29}$ steranes resolve both a distinct marine oil type and a nonmarine suite (figure 10). The type A marine oils also have a prominent C_{30} peak, and diasteranes are present (Plate 3). Sterane ratios do not separate type B from the C types, the nonmarine oils. Brooks separates Type C oils into two subgroups based on biomarker maturity parameters and diasterane ratios. He proposes a common source. Curiale (1991) subdivides the Type C oils based on reservoir age, the presence of oleananes, terpanes and nor-compounds discerned in m/z 218 spectra. His Kugmallit-Richards oils correlate with Brooks' (1986) C1 subgroup, and are generated from yet unidentified and thermally mature Richards (HTB) facies. The Reindeer-Moose Channel oils correlate with the C2 subgroup. Unlike Brooks (1986), these oils are proposed to be generated from a Paleocene source (Curiale, 1991).

The biomarkers of the Kugmallit-Richards C1 oil fit very well with those identified in the Richards Shale (Eocene). Likewise biomarkers found in the Reindeer-Moose Channel, C2, have been identified in Paleocene sediments of the Canadian Beaufort (Snowdon, 1988). These data suggest that the C1 and C2 oils are separate and distinct groups. There is disagreement, or noncorrelation occurs, where the C2 Issungnak and Tarsiut oils are tested from Kugmallit reservoirs. However, upsection migration of a C2 oil into a C1 reservoir would explain the discrepancies.

Type A marine-derived oils have more tricyclic peaks and lower Tm /Ts ratios than either B or C oils. The m/z 191 shows that C29 norhopane is less than C30 hopane, like most clastic derived oils. Type A oils have well developed C31-35 extended hopane peaks, as expected for marine derived oils. Moretane, possibly indicative of nonmarine rock contributions, occurs in Type A oils, but oleanane was not detected (Brooks, 1986).

Type B oils are derived from pre-Tertiary, predominantly nonmarine source rocks and are found in Lower Cretaceous reservoirs. They also differ from Type A oils because C29 norhopane is almost as prominent as C30 hopane, rather like the Prudhoe suite. This is rather uncommon for nonmarine clastic-derived oils in general. The Tm/Ts ratio is also higher than in the Type A oils. Minor amounts of moretane and oleanane were found (Plate 3). The C31-C35 extended hopanes are present in Type B oils more than in the Type C oils, suggesting a partial marine source contribution (Plate 3).

Type C oils are nonmarine-derived. Both moretane and oleanane, which are typically found in deltaic source rocks, are eluted. Some unidentified peaks also eluted. C_{29} norhopane is less than C_{30} hopane like the type A oils, but Tm/Ts ratios are quite variable. Both tricyclics and extended hopanes are very low. Curiale (1991) reports that only the Kugmallit-Richards (C1) oils contain 24, 28-bisnorhopane, 24-norlupane and perhaps homologous series of lupanes in m/z 177 spectra. These compounds may be indicative of thermal immaturity.

Biodegradation of Mackenzie oils has been severe enough to affect some of the sterane and triterpane distributions at Wagnark and Adgo. However, Curiale (1991) cautions that some biomarker geochemical anomalies may be also be related to source differences. Otherwise biomarker geochemistry concurs that Type A oils found along the basin margins are marine-derived. These Type A are derived from Upper Cretaceous, organic-rich and very bentonitic marine shales (Plate 2). This distinctive source rock facies is found in northeast Alaska as the Bentonitic Shale and as the Boundary Creek and Smoking Hills Formations in the Mackenzie Delta.

Type B oils are probably Lower Cretaceous nonmarine oils and Type C oils are Tertiary nonmarine oils (Snowdon, 1979; Brooks, 1986; Curiale, 1992). However, oil- to actively generating source correlations have not yet been made for Types B, C1 and C2. As yet, only organic-lean and thermally immature possible source rock facies have been tested. Thermally mature, organic rich facies are postulated to exist more basinward and in deeper waters than current drilling techniques permit sampling (Issler and Snowdon (1990).

4. Discussion and Inferences

A. Mixed Oils Along Barrow Arch

Most of the oils found by exploration drilling along the Beaufort Coast of Alaska are Prudhoe suite oils. However, API gravity, sulfur content, percent saturate fraction and metals data from Hughes and Holba (1987) show several significant differences among some of these oils. Figure 7 and table 2 show that the Sadlerochit and Kuparuk oils from Hemi Springs #1, Sadlerochit oil from Gwydyr Bay #1 and Colville oil from Mikkelsen Bay #1 have sulfur contents between 0.2% and 0.6%, with metal contents between 4.0 and 15.4 ppm. These characteristics are between those of the Umiat and Prudhoe oil suites. (Plate 1 shows the geographic distribution of these locations; note that the Badami well is located in Mikkelsen Bay.)

Mixing Prudhoe suite oil with an appreciable quantity of Umiat type oil can obviously explain these observations. Alternatively, these oils may be "less mixed" than the Prudhoe Suite. This means that they have little, or no hydrocarbons contributed from the Shubik Formation. Take particular note of the Hemi Springs fragmentograms. These are nearly identical to the Umiat suite fragmentograms, with relatively low tricyclic content, and C_{29} norhopane much less than C_{30} hopane.

However, important similarities to the Prudhoe suite include the abundance of diasteranes and the well developed series of C_{31}-C_{35} extended hopanes (Plates 3 and 4). Evidently, this is a case of overlapping petroleum systems charging the same reservoirs. The Barrow #19 and # 20 oils are likely a similar situation, but sufficiently quantitative biomarker data are not yet available for comparison.

B. Chukchi Sea Oils

The Shell Western E & P OCS-Y-1413 # 1 Burger well and OCS-Y-1482 #1 Klondike well were drilled off the northwest coast of the National Petroleum Reserve-Alaska (NPRA) (Plate I). At Burger well, Repeat Formation Tests (RFT's) from a reservoir between 5560-5665 ft yielded hydrocarbons from clastic sediments just entering thermal maturity (%Ro about 0.60%). The reservoir is a transgressive sand unit, and is typical of the Breakup depositional sequence, i.e. derived from local uplifts during lower Cretaceous or upper Kingak times.

Oil was recovered at Klondike well at a depth of approximately 9,916 ft. These sediments are a fine-grained facies correlatable to the Sadlerochit Group which is the main Prudhoe reservoir. At this location these sediments are at the threshold of catagenesis. Geochemical analyses of cuttings and sidewall core data show that Burger and Klondike oils are found in lithologies having about 1 to 2% TOC's in both wells.

Analyzed samples include 32° to 57° API gravity oil, condensates and extracts. Chromatograms show Klondike oil with normal, mature, marine-derived character. Some Burger oil has been thermally altered to condensate and some has a prominent n-C_{25} peak (figures 12 and 13). Saturates:aromatics:NSO ratios plot between the Prudhoe and Umiat suites (figure 6). Pristane:phytane ratios are like the Umiat-type (figure 8). Sulfur contents are very low: between 0.06% and 0.4% (table 4). Metal content of the Burger oil is similar to Umiat oils, but (V/V+Ni) ratios are divided (figure 7). Isotopically, Burger is similar to Umiat whereas Klondike plots considerably lower than Prudhoe type oils: more like Kavearak Pt. (figures 8 and 9).

Steranes, at m/z 217, from the Burger well have been altered due to thermal degradation (figure 13). The $C_{27-28-29}$ steranes of shales, sandstones and the oil plot as marine-derived organic material (Figure 10). However, no C_{30} steranes were measured. Small diasterane peaks are also present. The steranes from Klondike have not been so affected. The $C_{27-28-29}$ regular sterane ratios and the presence of C_{30} sterane suggest marine source rocks (figures 10 and 12) for this oil. Diasteranes are also very prominent, probably as a result of maturity affects and because typical carbonate source rocks apparently have not contributed to the oil.

The m/z 191 spectra of Burger and Klondike are practically identical. Tricyclic terpanes are present in appreciable quantities. The C_{30} hopane exceeds C_{29} hopane like the Umiat oils. The C_{31-35} extended hopane series is also present in significant quantities, as would be expected for an oil with a marine clastic source.

Clearly, the sulfur and metal contents indicate that the Chukchi oils are not of the Prudhoe suite. These oils differ from the Umiat oils in their sterane distributions and extended hopanes. They are isotopically lighter, as well. Thus, the Chukchi oils are not a mixture of known oil types and probably represent the product of another petroleum system.

At Klondike, the Shublik overlies the section that yielded the oil sample (Plate 2). This Shublik is a black splintery shale with interbedded limestone. It has TOC values, Hydrogen Indices and a sufficient thermal maturity which suggest that it is a rich souce rock and prime candiate for generating the Chukchi oils. However, known Shublik-derived oils (Prudhoe Suite) typically have high sulfur and metals contents with Vanadium more prevalent. Although the phosphatic facies of the Shublik are absent at Klondike, the carbonate, and probable source of the sulfur, remains. The ^{13}C isotopes are ambiguous.

These data support a marine, or somewhat deltaic shale as the most likely source rock. However, of the marine shales tested and analyzed in the Chukchi exploration, the Kingak, the Pebble Shale and Torok have no source potential or are mostly gas prone. Biomarkers at m/z 191 do not exclude considering the Shublik, the Pebble Shale Unit and, perhaps, certain facies (regionally) of the Kingak to be candidates for the source for such isotopically heavy hydrocarbons. Evidently, the proposed source rocks have significantly different kerogen chemistry from the areas where they are currently quantitatively described. In addition, these same chemical characteristics may also be accountable, perhaps more than mixing with the Umiat oil, for the mixed oil types found along the Barrow Arch uplifts.

C. NPR-A

Approximately 23 million acres comprise the National Petroleum Reserve-Alaska (NPRA). This area was set aside because of the numerous oil and gas seeps along the coast and favorable geologic structures in the foothills. Government exploration started in the 1940's with a drilling program in the 1950's, testing areas of known seepages and anticlines. These efforts found several small oil and gas fields at relatively shallow depths. Later drilling programs, based largely on the results of modern CDP seismic interpretations during the 1970's tested a wider area, but found only oil shows and gas (Gryc, 1988). Four lease offerings have resulted in only one Industry test well, Brontosaurus, in northwest NPRA. Plate I shows the extent of NPRA exploration. Drilling density is not high, even along the Arctic coast. The results indicate that there is probably no Prudhoe-style Ellesmerian truncation accumulation to be found along the coast. However the regional geology and drilling immediately east of NPRA suggests that Breakup sequence sandstones are probably prospective in the subsurface of the northern coastal plain. (Table 1 describes what is known about these oil discoveries.) Also, the minimal amount of exploration of the foreland foldbelt and overthrust belt of the Brooks Range has been far from conclusive: in reality, it's just barely informative.

The numerous authors in Gryc (1988) present the synthesis of various NPRA geological and geochemical investigations. Magoon and Claypool (1988) identify three oil types: the Prudhoe suite; the Umiat oils; and they separate the condensates into a third group based on migrational effects. Potential oil prone source rocks include the Torok Formation, Pebble Shale, Kingak Shale and the Shublik Formation (Magoon and Bird, 1988), but none of these units was found to be actively generating hydrocarbons where tested.

Although the NPRA studies are extensive, there are still some areas which need additional analyses. Data are sparse from the Skull Cliffs seep in northwestern NPRA. It has low sulfur content and low API gravity (Magoon and Claypool, 1982). Perhaps it is part of the Chukchi oil system. If so, then parts of western NPRA may warrant additional resource estimation analyses.

The variations found in the thermal maturity of outcrops along the foreland foldbelt are of particular interest in determining which potential source rocks are viable in NPRA analyses (Johnsson and others, 1991; Howell and others, 1992). The nature of oil emplacement at Umiat is of particular interest. At present, this petroleum system is poorly understood. Umiat type oils are found across a large area in a number of structural and stratigraphic environments. If the Umiat type oils are related to the enigmatic dead oil shows from the Cretaceous clastic section at Lisburne well (Plate I), it greatly expands the area of an exploration play into the foothills region.

Kleist and others (1983) report on oil-stained Lisburne limestones in the central foothills of the Brooks Range thrust belt. Certainly, these oil stained carbonates and the black, ignitable, organic-rich "blubber rock" found locally on Lisburne allochthons warrant further geochemical evaluation. Current data suggest that these rocks are too thermally mature to host their hydrocarbons (Johnsson and others, 1991; Howell, 1992). Either one of the known petroleum systems has been able to put hydrocarbons in these rocks, or there may be another, as yet, undefined petroleum system in operation. Additional geochemical data may help to determine the areal extent and productive lifespan of the petroleum system emplacing hydrocarbons along the mountain front.

D. Colville Delta Discoveries: The Kuukpik Unit

Recent drilling west of the Prudhoe-Kuparuk area has resulted in several oil and gas discoveries (Plate 1) immediately east of NPRA. This is the Kuupkik Unit. As of yet, the operators have not released much pertinent data on their recent discoveries. Table 1 shows that these wells have tested between 180 and 1200 BOPD of 26° to 32° API gravity oil with GOR's of 250 to 500 from multiple reservoirs (table 1). Current speculation from the publicly available well depths and the API gravities is that these are Prudhoe suite oils or a mixture tested from the Breakup sequence sands.

E. Seal Island

The Seal Island discovery represents about 300 million barrels of condensate and oil found offshore, north of Prudhoe Bay field (Plate I). Hydrocarbons are tested from the Sadlerochit Group sands. The North Star accumulation is a continuation of this trend, onshore. The Shell E & P OCS-Y-181 well (table 4) shows high API Gravity oil/condensate. It also yielded high levels of H_2S, which is more commonly associated with Prudhoe suite oils produced from sea water-injected and microbial-affected areas of the Prudhoe field, or the Lisburne field carbonate reservoirs.

F. Badami

The Badami discovery is approximately 30 miles east of Prudhoe Bay field (Plate 1). It tested approximately 4250 BOPD of 27° to 28° API gravity oil and 1.2 MMCFD gas from middle Brookian sands. Without additional geochemical data, speculation is that this is a Prudhoe oil, or possibly a mixed suite.

Oil is found in basement rocks, the Pt. Thomson sands of the Breakup sequence and Flaxman sands of the middle Brookian sequence. These are 18^{o} to $>40^{o}$ API gravity oils with GOR's between 400 and 22,705. The sections which were tested are from depths between about 11,500 and 14,300 ft. (Banet, 1992). Table 2 shows that sample DZE, from a Cretaceous sand, has API gravity, sulfur and metal contents that place it within the Prudhoe suite (figure 7). This is the deepest, and the maximum down dip occurrence yet known along the Barrow Arch uplifts and furthest east identified extent of the Prudhoe suite oils. It expands the geographic range of the Prudhoe oils right to the very western border of the highly prospective Arctic National Wildlife Refuge 1002 area.

The Flaxman sands (Paleocene) are upsection of the Pt. Thomson sands and they also tested oil, up to 2500 BOPD. Anders and others (1987) posit that the variability in API gravity oil in Pt. Thomson area is because there are two different oils in these respective reservoirs. Deasphalting causes both a high gravity oil (35° to 45°) and low gravity residue (18^{o}) in the Cretaceous Thomson sands. The Flaxman sands (Banet, 1990 figure 7) then, have a genetically different 21° to 27° gravity oil. Anders and others (1987) also propose that some 44° gravity oil has migrated vertically into the Flaxman sands.

This report demonstrates two oil types are present along the Barrow Arch, and where/how mixing of these oil types occurs. Note that the analytical variations, documented by publicly available data within the Prudhoe suite alone, could account for all the differences between the Pt Thomson and Flaxman reservoirs. These oils are present in near-economic accumulations, additional and definitive crude oil chemical analyses should be (hopefully) forthcoming to the literature.

G. Hammerhead Oil

The Hammerhead discovery is offshore, north of the Pt. Thomson area (Plate 1). The discovery well tested almost 1,000 BOPD from mostly unconsolidated early Oligocene sediments (figure 14). These are thermally immature, upper Brookian sands, silts and mudstones. The sediments have high TOC's, high Genetic Potentials from oil staining and high Oxygen Indexes from the predominantly terrigenous indigenous kerogens (figure 15).

Hammerhead oil has a greenish color. Analyses show a dramatically higher sulfur content than the Prudhoe suite or even the Dalton oil. API gravity is low, 17° to 20° (table 4). The alkane:aromatic:NSO's ratios (figure 6) and alkane distribution indicate that this oil has been extensively degraded (figure 15). ^{13}C isotopes of Hammerhead kerogens and extracts are low (figure 8) which is probably more indicative of the extract from its nonmarine reservoir sediments than the oil. Sterane distributions vary significantly with depth representing thermal or migrational alteration. Note the dramatic loss of C_{29} with depth, which reflects increasing thermal maturity. Diasteranes, which are typically rare in high sulfur crudes, are prominent in all samples and also increase with depth (figure 15).

The high sulfur content, the $C_{27-28-29}$ sterane ratios and the possible elution of C_{30} sterane (figures 10 and 15) suggest that this crude oil is derived from marine shales and carbonates, with noticeably less (or no) nonmarine source contribution than the Prudhoe suite (figure 10).

The triterpanes (m/z 191) also show intriguing distributions and changes with depth. In shallower samples C_{29} hopane is less than C_{30} hopane. In deeper samples there is more C_{29}, which like the Prudhoe suite, suggests marine carbonate source rock. The extended hopanes become prevalent down section. Also the concentration of C_{35} extended hopane in the deepest sample supports marine carbonate-derived oil. Tricyclics are more prominent with depth suggesting, like the sterane chemistry, that detectable thermal maturation changes occur down section. Tm>Ts in all samples. This ratio decreases down section, reflecting thermal maturity and the marine derivation of the oil. Also, peak ratios of the C_{31} extended hopanes of the Hammerhead oil (figure 15; N:O) are rather similar to those attributed to marine oils leaching biomarkers out of Tertiary coals (Philp and Gilbert, 1986). Both moretane and bisnorhopane, which are usually associated with nonmarine-derived oil, are eluted from the Hammerhead samples.

The sybillistic chemistry of the Hammerhead oil makes it the most enigmatic on the North Slope. Biomarkers show appreciable thermal maturity changes with a relatively small increase of depth. The high sulfur content and biomarkers indicate derivation, at least in part, from marine carbonates; perhaps more so than the Prudhoe oils and Dalton oil. However, high diasterane content, the presence of moretane and bisnorhopane are more typical of terrigenous source input. Also, the Hammerhead oil is found in upper Brookian sediments deposited during a transgressive high stand. Known marine carbonate possible source rocks are more distant areally and stratigraphically from Hammerhead than from any other North Slope discovery.

H. Kuvlum

Kuvlum is an offshore discovery approximately 15 miles east of Hammerhead (Plate 1). It tested 3400 BOPD of 34° gravity oil and 2.04 MMCFD of gas from middle or upper Brookian sands. These limited data show that the Kuvlum oil chemistry differs from the nearby Hammerhead oil. Initial speculation is that it may be a high gravity Prudhoe suite oil, similar to the Pt. Thomson oil(s). However its juxtaposition to Hammerhead, ANWR and Mackenzie areas with their multiple petroleum systems mandates the exercise of caution in predicting oil type at this stage. With initial reserves estimated at 1 BBO, perhaps marginally economic, additional data should be forthcoming.

I. ANWR 1002 AREA

The 1.5 million acre Arctic National Wildlife Refuge 1002 area, in northeast Alaska, has high potential for the discovery of significant oil and gas reserves. The stratigraphy shows that there are numerous prospective petroleum source rocks and reservoir rocks in this area (Bird and Molenaar, 1987; Banet, 1992). There are also numerous mapped prospects (Foland and Lalla, 1987). Volumetric estimates for the 1002 area rival those estimated for the entire NPRA (Dolton and others, 1987; Bird, 1991).

Outcrops are uncommon across the featureless Arctic Coastal Plain. However, these relatively few Coastal Plain exposures yield a number of oil seeps, oil stained sediments and organic-rich lithologies. Due to its Arctic environment, intense weathering and biodegradation has affected the oil seep samples and sediment samples from locations on Katakturuk R., Jago R., and Kavik Ck. (figure 16. - The Kavik Ck. location is technically outside the 1002 area but is included in the analyses.).

Chromatograms of the C_{15+} fraction show that some samples are altered to varying degrees. Consequently, definitive interpretations made from them may be arguable. However, figure 16 shows that eluted elements have general similarities between the surviving nonresolvable portions of the Bentonitic Shale (Upper Cretaceous) on Jago R. and nearby (immediately downstream) very odorous, oil-stained Eocene siltstone. There is also minor similarity between the nonresolvables of the lower Katakturuk Ck. oil stained sandstone and the Kavik Ck. oil stained sandstone. These latter two sandstones are from the upper Brookian Sagavanirktok Formation. The same degree of similarity may also extend to the oil stained middle Brookian turbidite samples found along upper Katakturuk Creek and Canning River. In addition, the resolvable alkanes show that these samples appear to have some nonmarine character and high pristane:phytane ratios (Banet, 1990).

Chromatograms from the remaining samples resemble typical extracts of mature, marine derived hydrocarbons. All have low pristane:phytane ratios.

No identifiable alkanes or iso-alkanes were resolved from the oil seep samples. Manning Pt. appears to have a unimodal marine character, whereas the Angun Pt. seep may have some bimodal nonmarine character (figure 16). Saturate:aromatics:NSO distributions show that the Manning Pt., South Katakturuk Ck. and Jago samples are similar to the Prudhoe and Umiat oils whereas the North Katakturuk and Angun samples plot like source rocks because weathering has removed much of the saturate fraction (figure 6). Variations of the pristane:phytane ratio separate the North from South Katakturuk samples (figure 16). ^{13}C isotope variations (figure 9) place the Kavik sample out by itself. Angun Pt. samples are similar to oils generated from marine clastics, while the others are closer to the Prudhoe suite. The Manning Pt oil seep has isotope ratios which suggest mixed source materials (figure 9).

Biomarker analysis shows that regular sterane concentrations are low and diasteranes are very prominent in the m/z 217 spectra. Like so many of the Mackenzie oils this is probably due to thermal maturity or possibly biodegradation, weathering, and derivation from clastic source rocks. Only the Kavik sample has no quantitatively resolvable steranes (plate 4) The $C_{27-28-29}$ distribution shows that the Manning Pt. seep plots between the nonmarine Mackenzie (types B, C1 and C2) and Prudhoe suites. The Katakturuk, Jago and Angun samples and Manning Pt. stain plot as marine-derived oils (figure 10). However, C_{30} sterane is not readily resolved in any of these spectra (Plates 3 and 4).

Tricyclics are present in all m/z 191 spectra. As in the Umiat m/z 191 spectra, the tricyclic concentrations are very minor. However, degradation leaves the relatively stable tricyclics as the only readily identifiable peaks in the Kavik and Angun samples. Oddly, both Angun seep and stain samples retain their steranes relatively intact albeit mostly altered. In the Jago, Manning Pt. and Katakturuk samples, C_{29} norhopane is much less than C_{30} hopane and Tm slightly larger than Ts. These samples also have well resolved extended C_{31}-C_{35} hopane series, like the Prudhoe suite, suggesting marine clastic source derivation. Overall, their m/z 191 spectra are nearly identical.

Both the Kavik and Angun Pt. samples are severely altered in the hopane spectra. They also lack the extended hopanes. However, unidentified peaks in their spectra elute where oleanane and moretane, indicative of Tertiary deltaic source material, should be suspected.

The chromatograms show considerable nonmarine source character that is not particularly coincidental to the biomarker geochemistry. With the severity of degradation, the biomarker interpretation is probably less compromised than the chromatograms. Thus, the available data show that the 1002 area samples have predominantly marine source rock characteristics. The biomarker data define the Jago-Katakturuk-Manning Pt. group, which includes all of the samples from the middle Brookian turbidites and the Pebble Shale and Kemik samples, too (figure 16). The Upper Cretaceous Bentonitic Shale is the predominant source rock, whereas the biomarker distributions suggest Kingak and the Pebble Shale are also minor contributors (Plates 3 and 4). In some wells immediately west of the 1002 area the Bentonitic shale has high resistivities and low sonic velocities suggesting that oil is actively being generated and filling pore space, thus altering the petrophysical properties. The Bentonitic Shale correlates to the Smoking Hills and Boundary Creek Formations which are the most likely source of the Mackenzie Type A oils (Snowdon and Powell, 1979; Snowdon 1980; and Brooks, 1986).

Kavik stain is severely weathered and mostly unlike the other samples. It may be related to the oil stained, nonmarine, Sagavanirktok sandstone found along north Katakturuk Creek. The presence of steranes at Angun where alkanes and triterpanes have been severely altered, may be due to mixing of two or more oils. Otherwise it appears to be a severely altered marine derived crude oil.

K. Aurora Well

The Aurora well provides the most recent, publicly available geological data for northeast Alaska. This well tested a thin upper Brookian sequence, a thick middle Brookian sequence, and Breakup sequence rocks. Indigenous hydrocarbon potential is very poor,- to gas prone (Banet, 1993). However, there were appreciable amounts of extractable hydrocarbons that migrated into the system. Chromatograms show that alteration and degradation are common (figure 17). There is minor similarity with 1002 area samples derived from marine shales: the Katakturuk-Jago-Manning Pt. and Angun Pt. samples. High and variable pristane:phytane and high CPI's show that there are also nonmarine source characteristics. The geochemistry and geographic proximity suggests a possible mixing connection with the Manning Pt. samples.

L. Belcher Well

The Belcher well is the furthest offshore test in the Beaufort, to date. It penetrated thermally immature Tuktoyaktuk and upper Brookian sequences. Chromatograms show that immature or biodegraded, isoprenoid-rich saturates are present. Ternary plots of saturates:aromatics:NSO's show that Belcher extracts are unique; most likely related to the Mackenzie Type C1 and C2 oils (figure 6). Pristane:phytane ratios are low, covering the range of marine-derived clastic rocks. No isotope data are available.

5. Summary and Conclusions

The North Slope is a large petroleum province, with oil in rocks of all represented ages and several different depositional histories. Multiple petroleum generating, migrating and preserving systems have been active. Analytical caveats aside, available data suggest the following ten oil types are present: Prudhoe, Umiat, Chukchi, Hammerhead, ANWR/ Mackenzie Type A (marine derived), Kavik, Angun, Pt Mackenzie Type B, Mackenzie Type C1, and Mackenzie Type C2.

The publicly available data shows that the Prudhoe and Umiat oils are distinctively different types. The Prudhoe type differs from the Umiat type in that it has high sulfur content, high metals content, and heavier ^{13}C isotopes. Biomarker differences include low pristane:phytane ratios, more tricyclic terpanes, more extended hopanes, few rearranged steranes, C_{30} sterane and sterane ratios which indicate that the Prudhoe type oils are derived from marine clastic source rocks (Pebble Shale Unit and Kingak Shale) with considerable contribution from a carbonate source (Shublik). The Prudhoe type oil API gravity ranges from about 6o to over 40o or condensate, whereas that of the Umiat type oil is typically greater than about 35o.

At both seeps and in the subsurface, the Umiat type oils have low sulfur and metal content, light 13C isotope ratios, and high pristane:phytane ratios. These parameters and the biomarker distributions of steranes and triterpanes suggest that the Umiat type oils are derived from marine clastic source rocks, with perhaps minor contribution, from terrigenous kerogens Available data suggest that the source of the Umiat oil is the Kingak Shale, with possible contribution(s) from the Torok or Pebble Shale Unit. Marine carbonate source rocks do not appear to have contributed to the Umiat type oils.

Variations and cross plots of these same geochemical data also show that considerable mixing of oil types has occurred along the Barrow Arch uplifts in reservoirs previously thought to contain only Prudhoe type oil. These mixed oils have sulfur contents, metal contents, and pristane:phytane ratios between the Prudhoe and Umiat types. They are found from the Barrow area to the Mikkelsen Bay area. Alternatively, the variation may be from no, or very minor, contribution of oil from the Shublik formation. Either way, there is mixing of different oil types. The J.W. Dalton oil is an exception. It has the lowest API gravity, highest metal and sulfur contents. It lacks identifiable steranes, yet retains resolvable alkanes. Triterpanes are like the Prudhoe suite oils. Thus Dalton is a mixture, and appears to be composed of degraded Prudhoe oil commingled with a later phase of relatively nondegraded Prudhoe oil.

The oils from the Chukchi Sea exploration do not match either the Prudhoe type or the Umiat type oils. They are low sulfur, low metals content, high saturate content, and high pristane:phytane ratio like the Umiat type oils. Chukchi oils are isotopically variable. The chemistry, the chromatograms, and the m/z 191 and m/z 217 spectra indicate that the Chukchi oils are generated from marine or deltaic clastics, rather than a marine carbonate. Current data indicate that regionally important petroleum source rocks are considerably different in the Chukchi than in other parts of the North slope. These differences are sufficient to suggest that the Chukchi oils belong to a different petroleum system from the Prudhoe or Umiat oils.

Diagnostic geochemical data from the recent discoveries east of NPRA (Kuupik Unit) and east of Prudhoe (Badami and Kuvlum) are lacking. API gravities and geography indicate that they may be Prudhoe type oils or mixed types.

API gravity, metal and sulfur contents of oil from the Cretaceous Pt. Thomson sand correlate best to the Prudhoe type. Its API gravity is at the high end of the Prudhoe type range. Geochemical data are not available for oils found in the basement rocks, or the upsection Flaxman Sands, within the Pt. Thomson Unit, but their API gravities are variable and are within the range of the Prudhoe Type. Oil type mixing, or a separate oil type are possible, but such migrational pathways and timings are difficult to effect.

The Hammerhead oil is the most enigmatic oil on the North Slope. It has a chemical composition, chromatograms and fragmentograms that are indicative of its having multiple hydrocarbon sources, which have subsequently undergone degradation and thermal alteration. The geochemistry suggests derivation from both marine carbonates and possibly Tertiary age, deltaic sources. Stratigraphically, neither scenario is more likely than the other. The conclusion is that Hammerhead is a mixed suite oil, but perhaps not necessarily mixture of Prudhoe and Umiat types.

The Kavik oil, from immediately west of the 1002 area, is so severely altered that gross chemical composition, distributions and biomarkers do not reveal much of its origin. Isotopes show that it does not resemble any of the other oils, and thus it is still considered as a separate type at this time. In the 1002 area, the Angun Pt. stain and seep has sterane distributions and isotopes suggesting that it is derived from predominantly marine source rocks. However, both alkanes and pentacyclics triterpanes are severely altered. Thus, further correlations cannot be made with a high degree of comfort.

The oils extracted from stained sediments and seeps along Katakturuk Creek and along Jago River are derived from marine sources. Their geochemistry, chromatograms and fragmentograms correlate well with the Mackenzie Type A oils. The Manning Pt. oil has sterane distributions and isotope ratios indicating that it also has a significant nonmarine source component. Resolved m/z 191 terpane distributions, however, place it with the Katakturuk and Jago samples. The source of these oils is most probably the highly radioactive, organic-rich, Upper Cretaceous, paper- to cardboard texture, HTB shale facies which represents the distal portion of the maximum, middle Brookian transgressional event. This facies is locally called the Bentonitic Shale Unit, Smoking Hills Formation or Boundary Creek Formation.

The majority of Mackenzie oils are nonmarine. They are isotopically light, have low NSO contents, low metal and low sulfur contents. The pristane:phytane ratios are the highest of any on the North Slope. Type B oils are found in Cretaceous reservoirs and have terpane biomarkers distinctly different from the Type C oils. Two type C oils are differentiated on their reservoir age and biomarkers. Type C1 oils are found in Richards or Kugmallit (mid Eocene - Oligocene) reservoirs. Bisnorlupane, oleananes and some *nor*-compounds are eluted in their m/z 218 spectra. Type C2 oils are found in the older Reindeer and Moose Channel Formations (Maastrichtian - early Eocene) and lack the aforementioned biomarker compounds. The apparent lack of these biomarkers suggests that oils at Issungnak and the Tarsiut areas appear to be type C2 oils that have migrated up into the Richards and Kugmallit reservoirs.

In summary, at least 10 oil types are differentiated on the basis of bulk geochemistry, isotopes, ratios, chromatograms and biomarkers. These data indicate that some mixing of oil types has occurred and that there are likely multiple phases of oil emplacement from single sources. Also, one oil type is common to both the U.S. and Mackenzie area. Limited data show two oils (the Angun and Kavik) are severely degraded, but are also different from the other types.

These 10 oil types represent different petroleum systems operating independently or in concert. Some oil types are found across a wide geographic area. Known reserve estimates for this area approach 100 billion barrels. This is a tremendous amount of oil. In addition, oil stained sediments and oil seeps suggest that much remains to be learned, particularly in the lightly explored areas away from the Barrow Arch uplifts.

With at least 10 different petroleum systems in operation to draw from, the task at hand is to determine which petroleum systems were in action (or interaction) at specific times, which migration pathways were available, and the timing of the trapping mechanisms. The next logical step to assist successful exploration is to identify, quantify and rank the source rock facies involved and then to determine when and where in the North Slope basin's burial history they were most active and in which plays their products are still preserved.

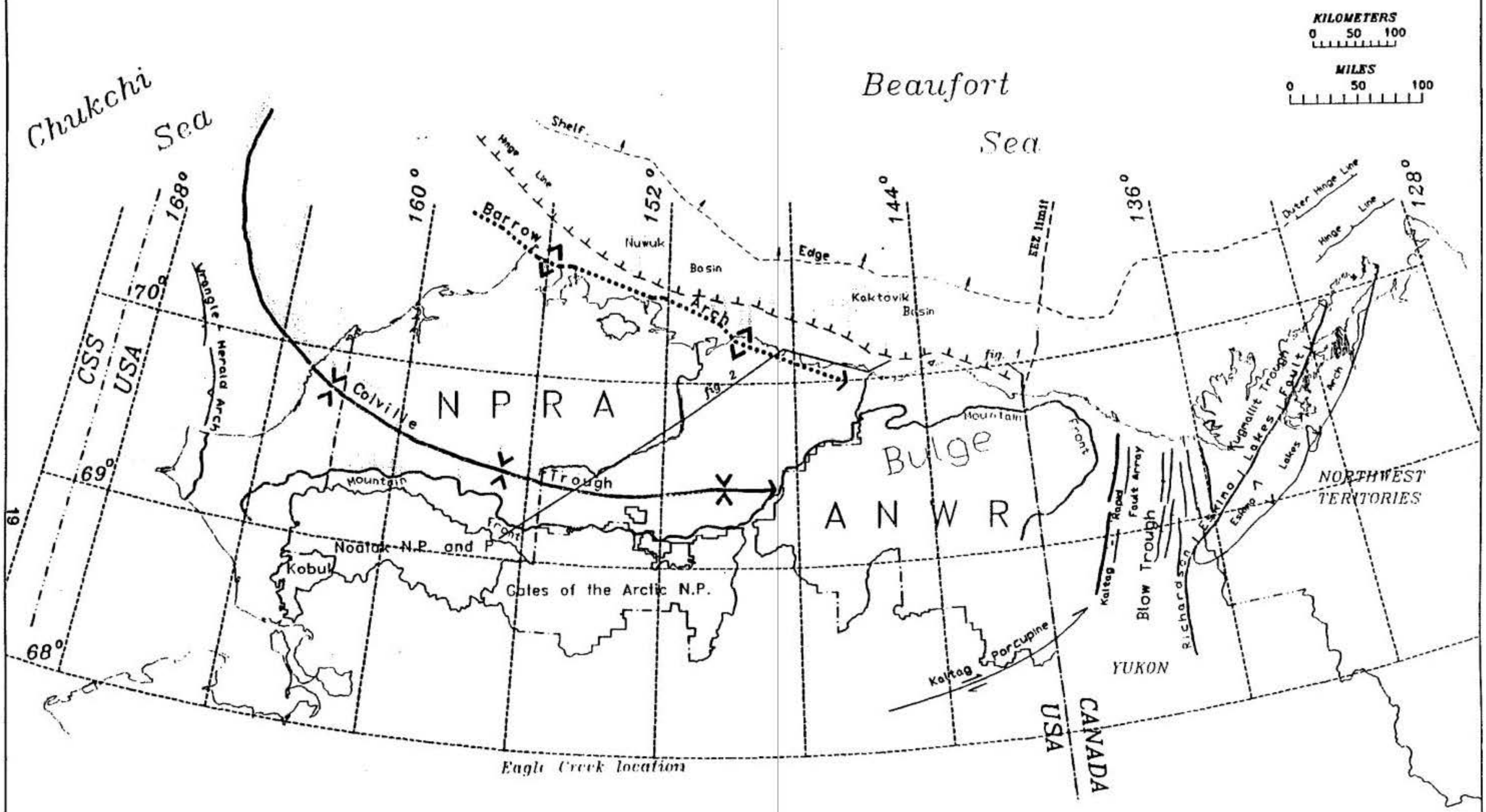


Figure 1
Geographic and major tectonic features of the Arctic
(with emphasis on the Shelf edge, axis of the Barrow Arch uplifts, Colville Trough and mountain front)

(depocenters >~8 km. shaded; after Hubbard and others, 1987; Craig and others, 1985)

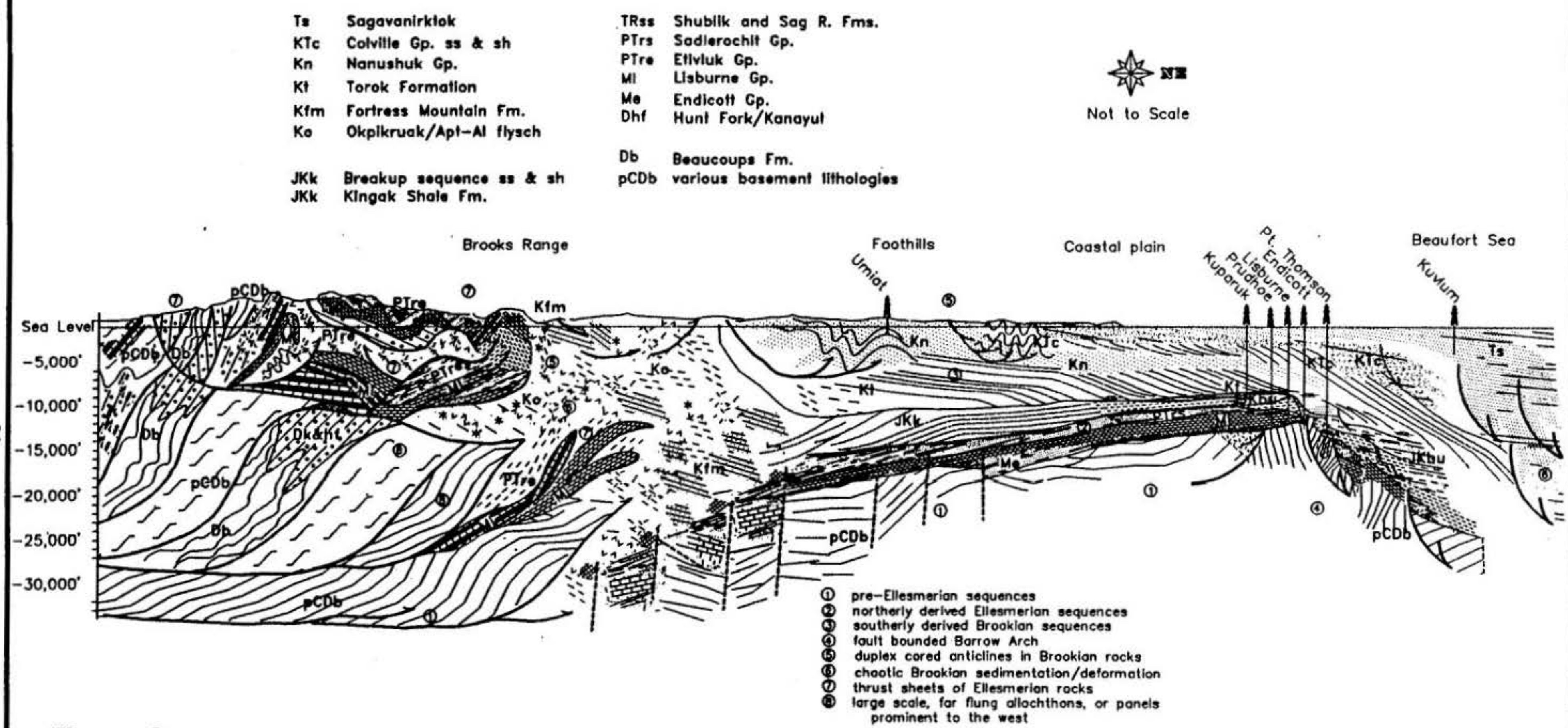
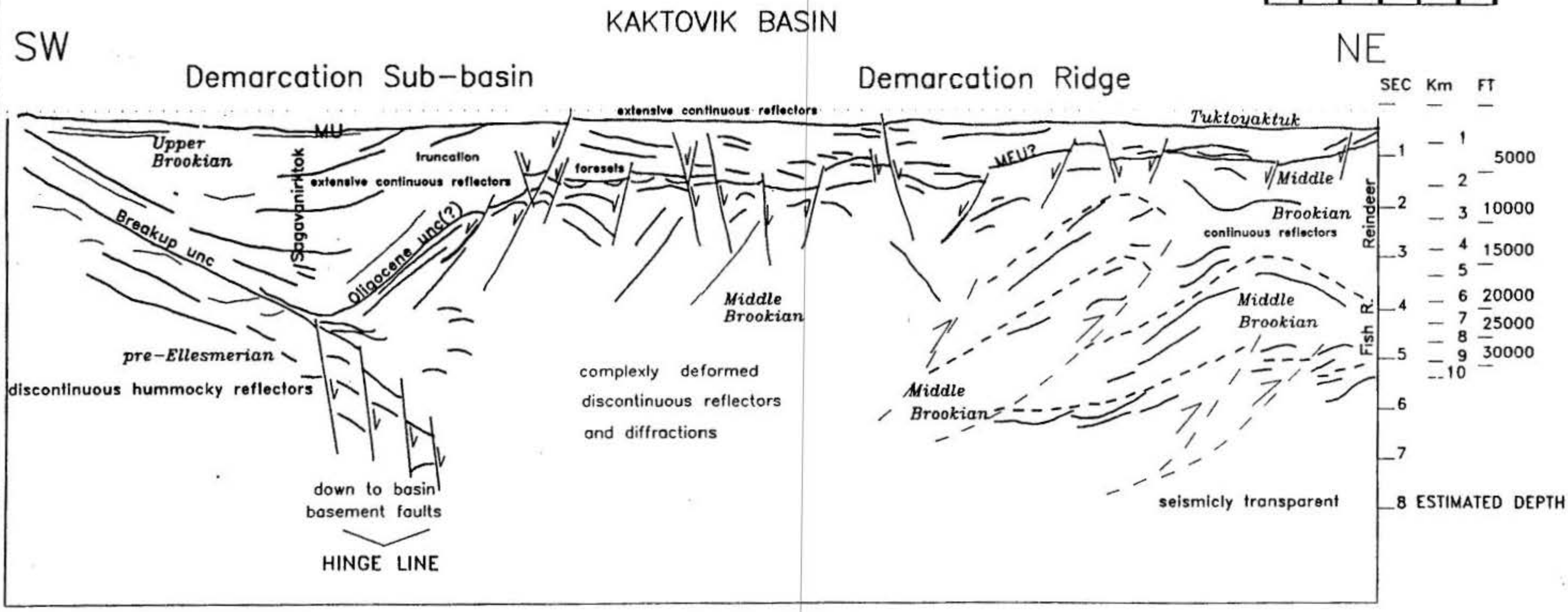


Figure 2
Schematic structural-stratigraphic cross section of the North Slope

(a collage of major tectonic and depositional styles; vertical exaggeration approximately 15x)

Figure 3
Seismic line offshore of ANWR 1002 area showing deformation styles affecting Brookian sediments

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



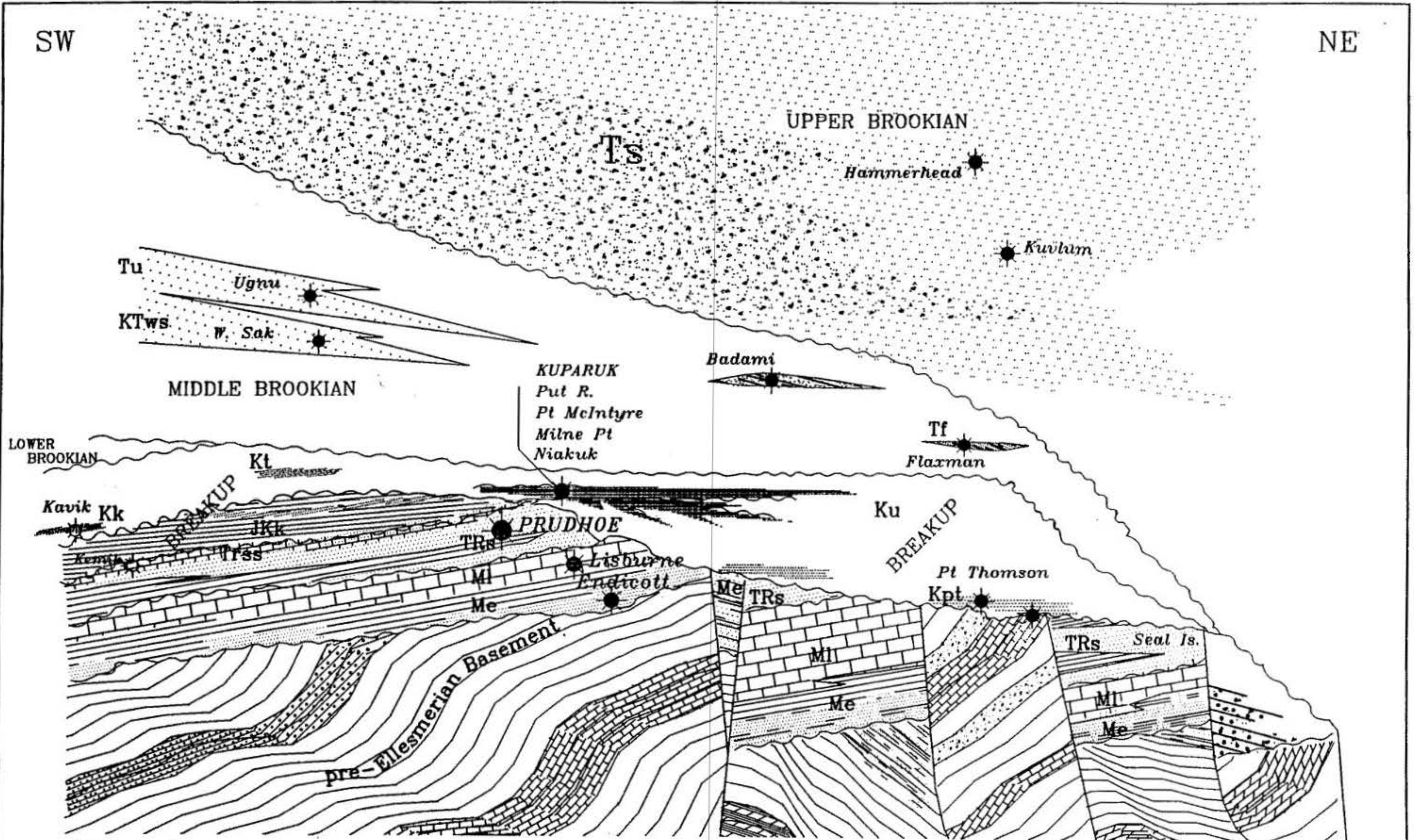


Figure 4
Generalized SW-NE cross-section, superimposing North Slope petroleum traps

(faults, unconformities, thicknesses and stratigraphic geometries highly stylized)

Gas and oil discoveries on coastal plain, highlighted.
Locally deposited Breakup Sequence sands:

Tapkaurak (Kt), Kuparuk R., Put R., Pt. Thomson (Kpt), Pt. Mc Intyre, Kemik (Kk), Simpson, Walakpa.

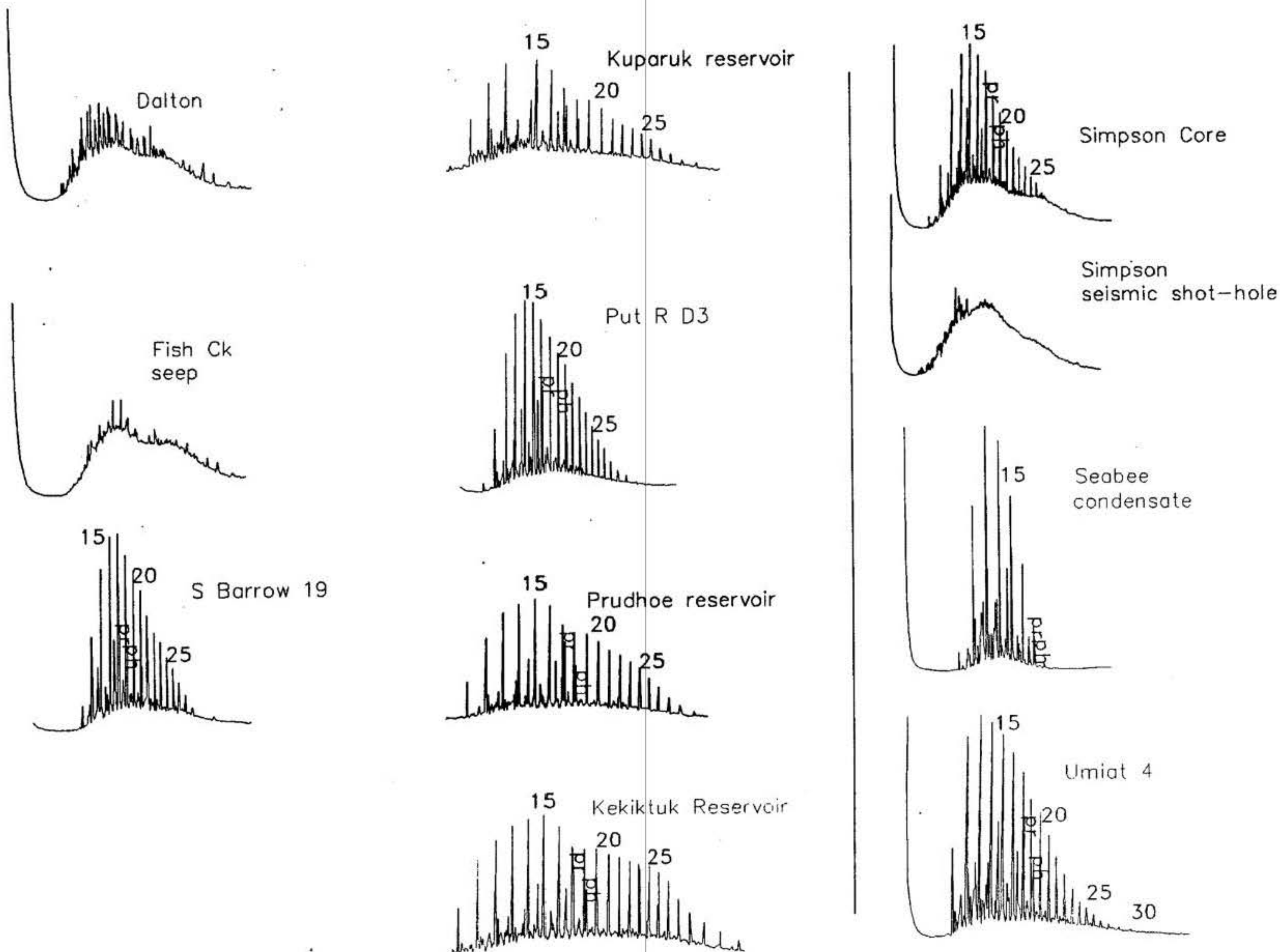


Figure 5
Comparison of chromatograms from Prudhoe and Umiat oil suites

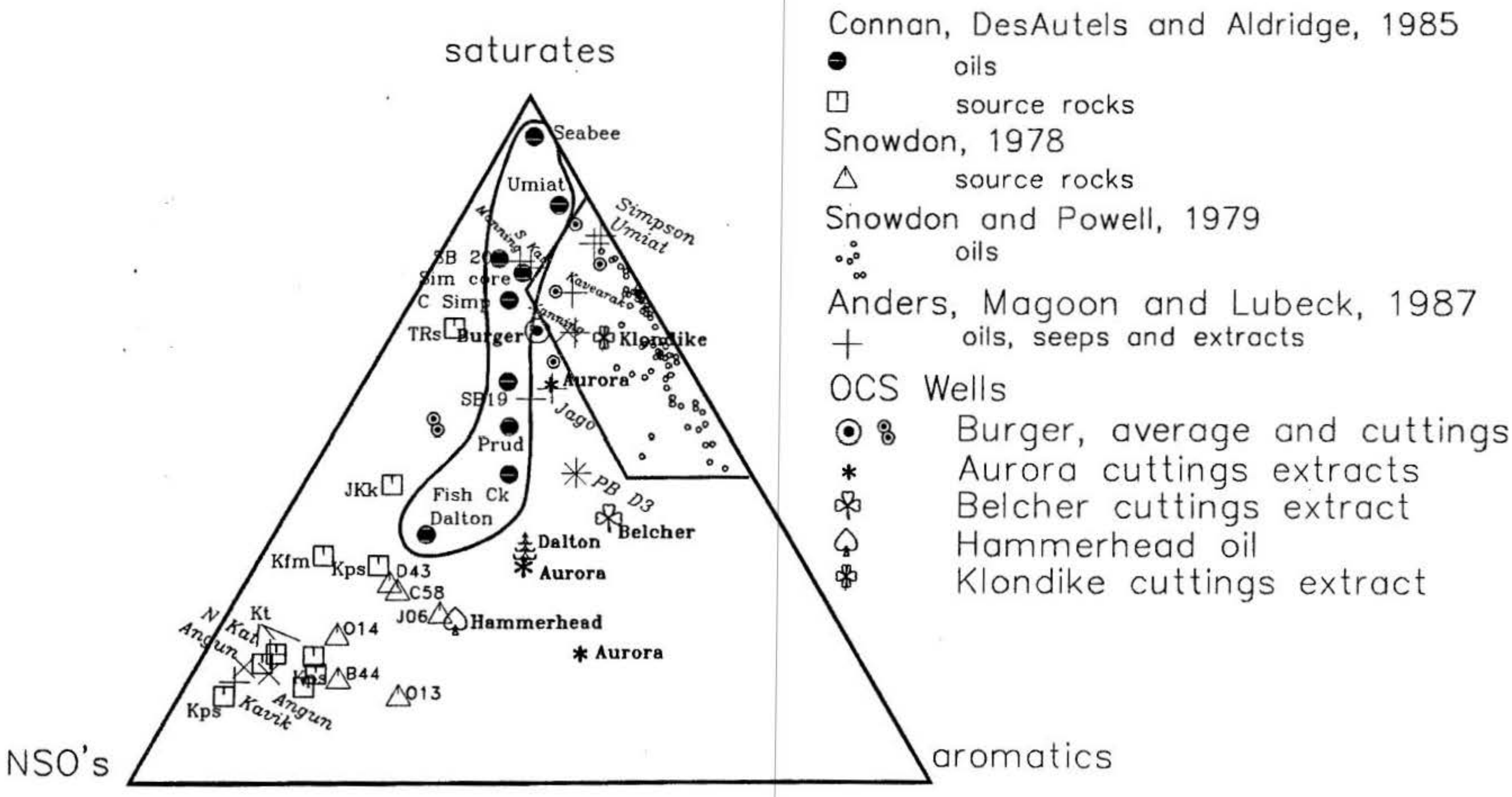


Figure 6
Saturates: aromatics: NSO ratios of North Slope oils and source rock extracts

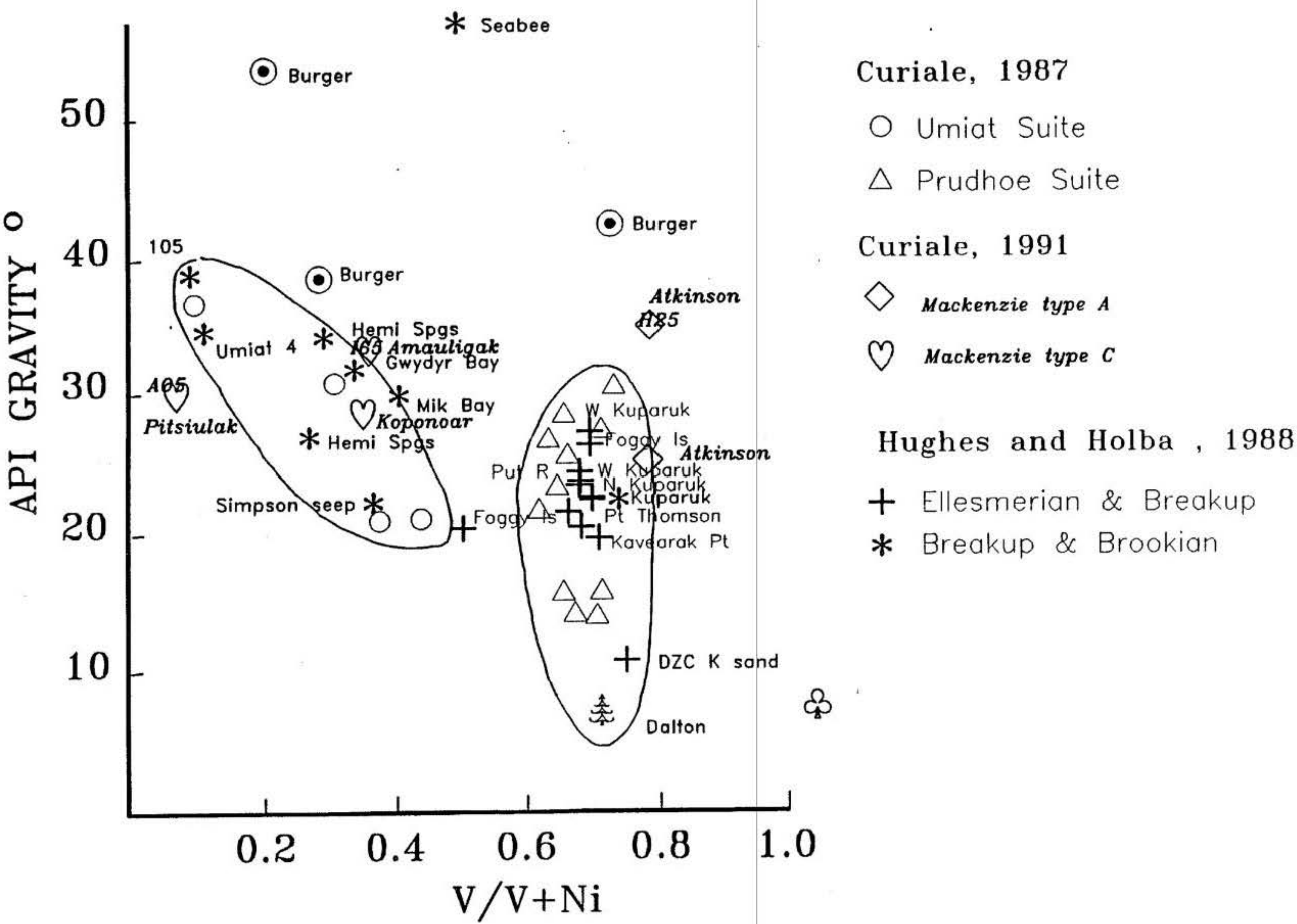


Figure 7
Metals ratios vs. API gravity separate the Prudhoe from Umiat Suites

(note that some Barrow Arch oils plot with Umiat Suite)

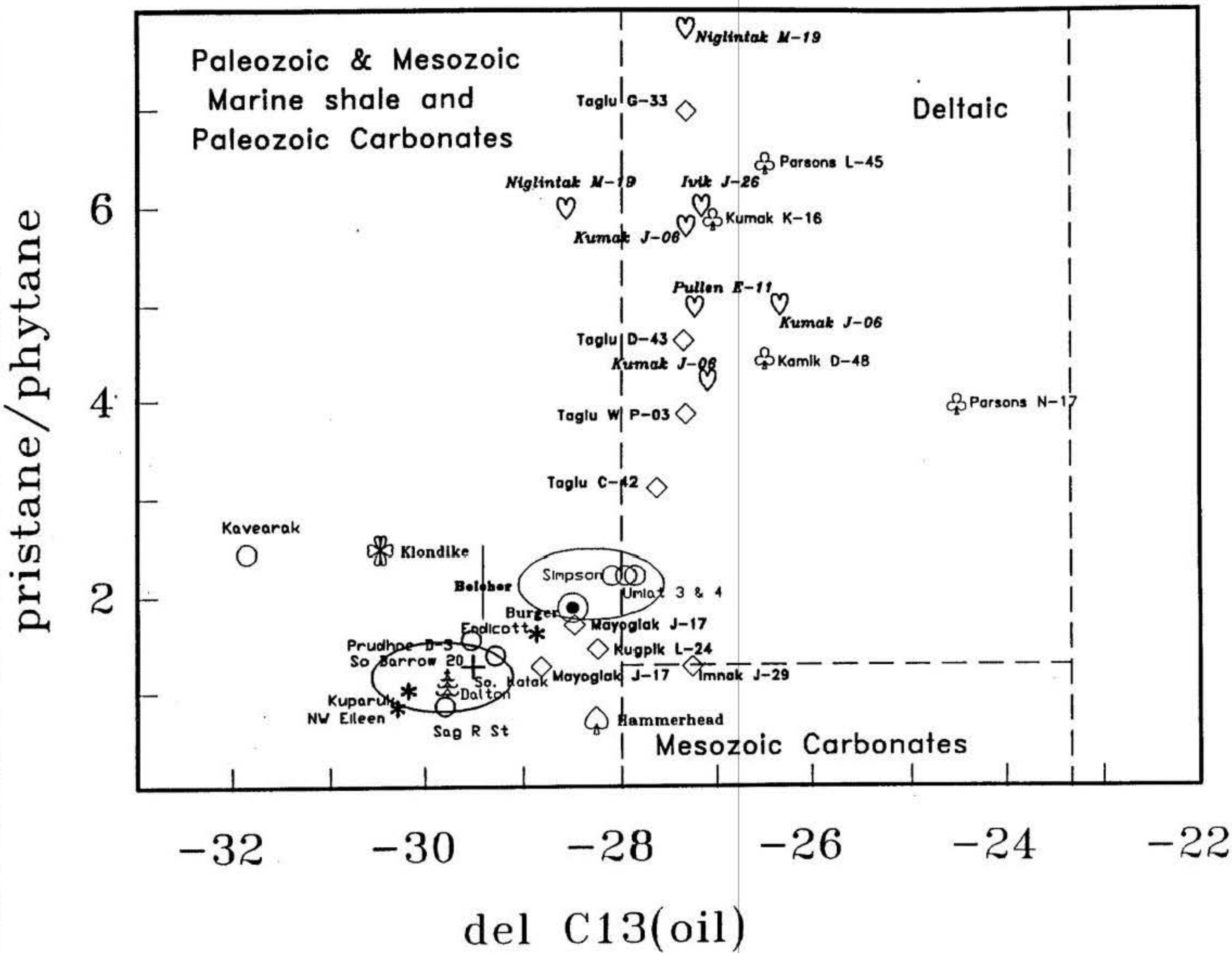


Figure 8
Oil source determined from carbon isotopes vs pristane:phytane ratio

(modified from Chung and others, 1992)

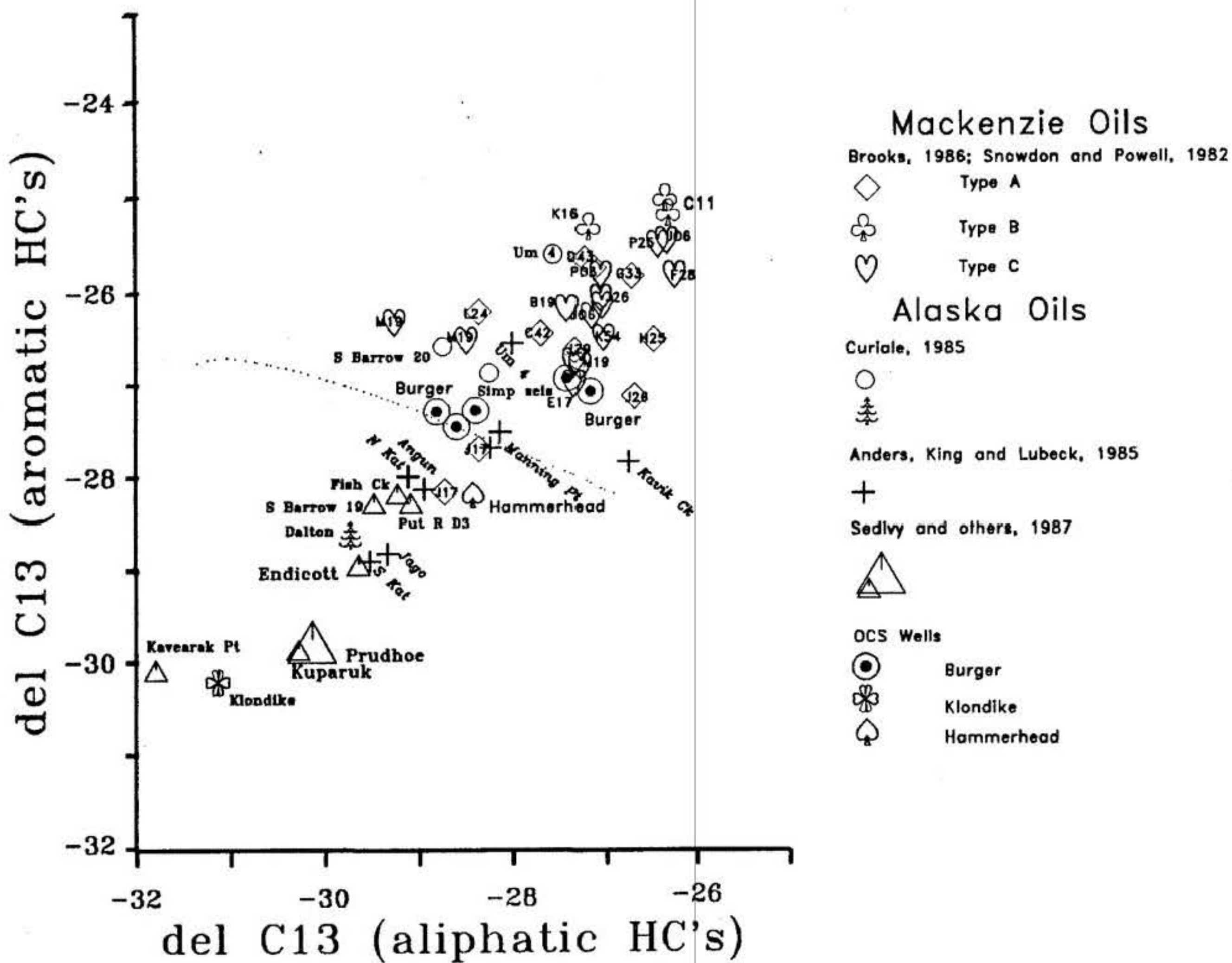


Figure 9
Aromatic:aliphatic isotope ratios for U. S. and Mackenzie oils (dotted line approximately separates Prudhoe suite from others)

(modified from Curiale, 1985)

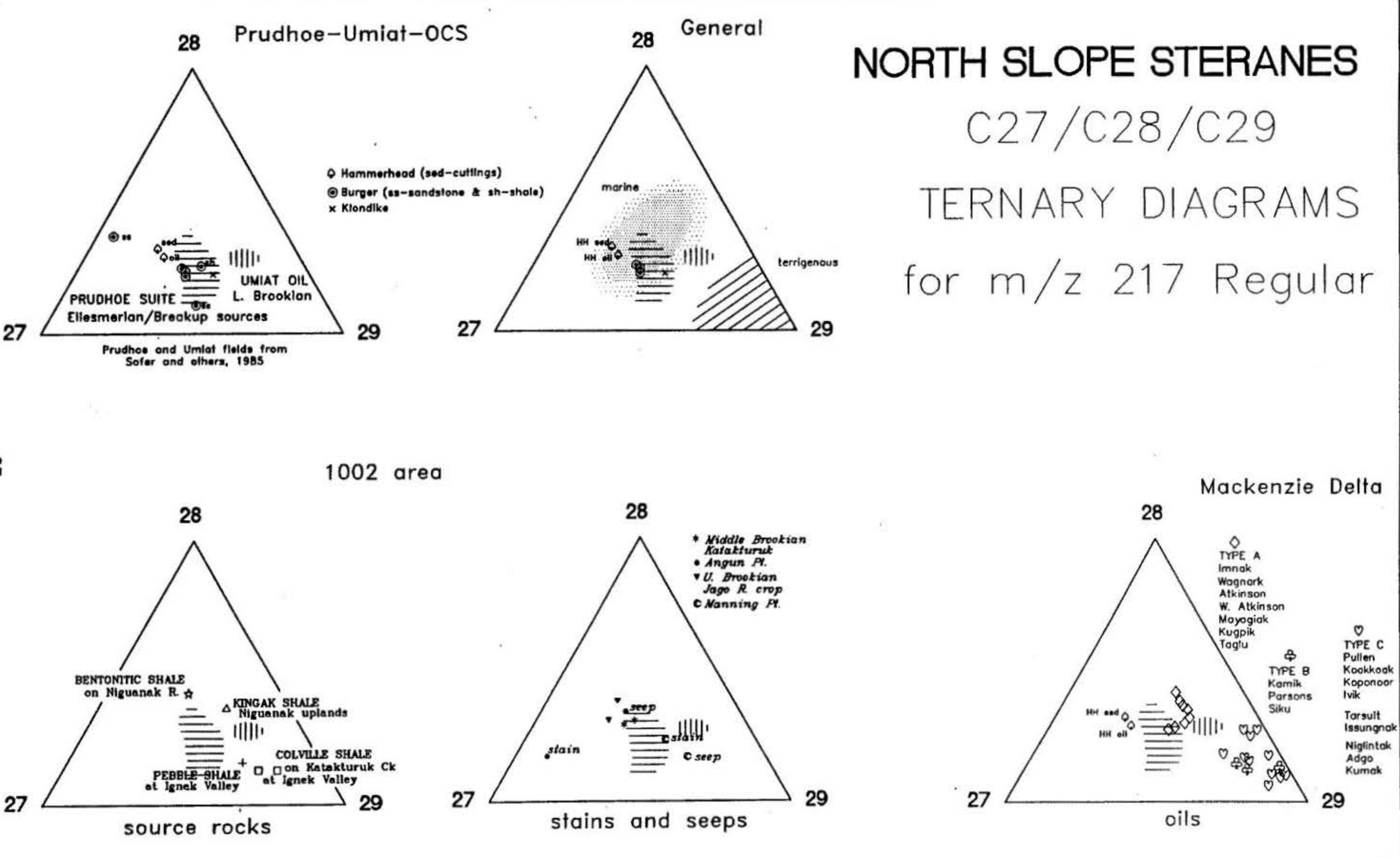


Figure 10
C27-28-29 ternary diagrams for North Slope oils and some source rocks

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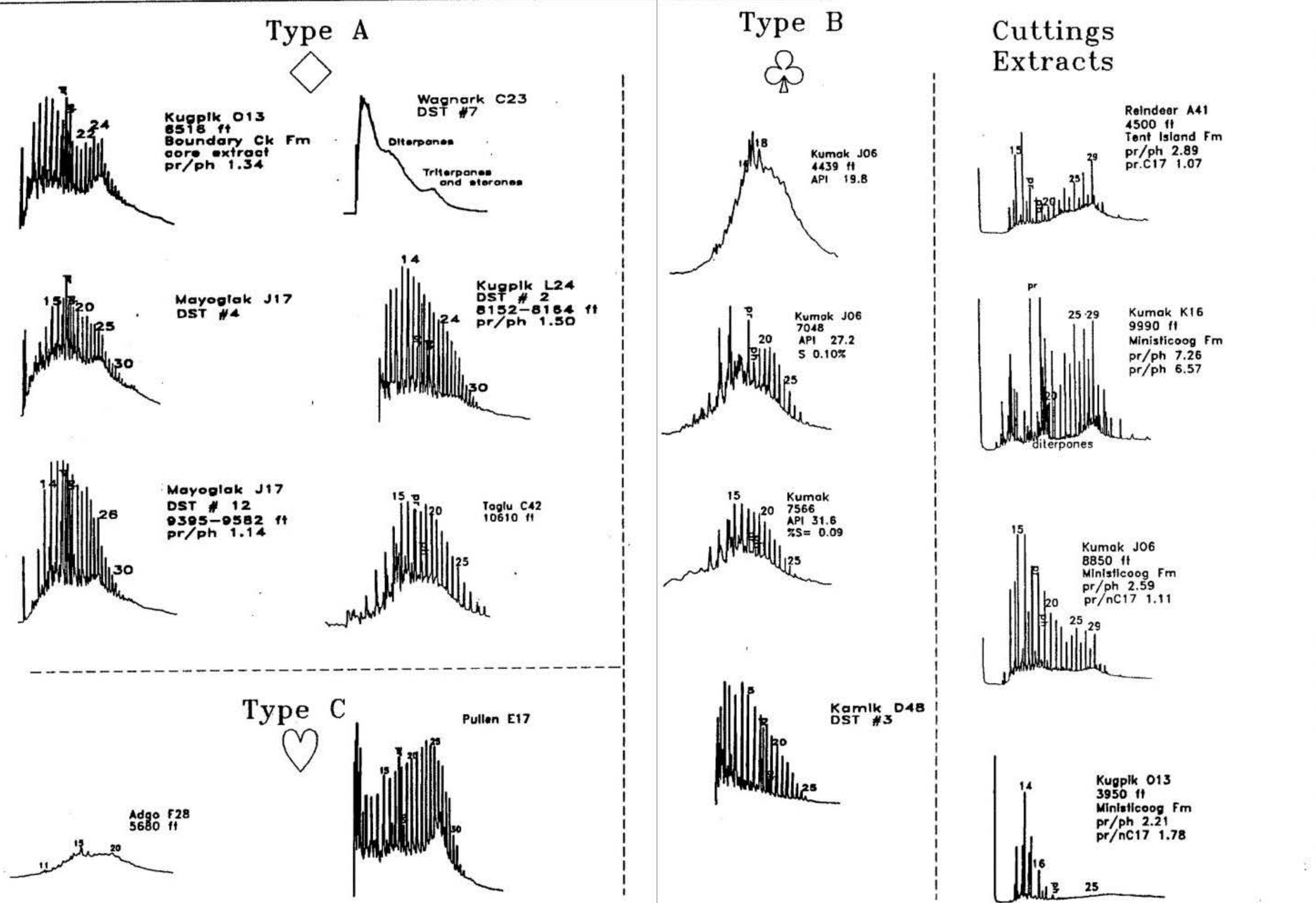


Figure 11
Chromatograms of the the three major Mackenzie oil types and source rock extracts

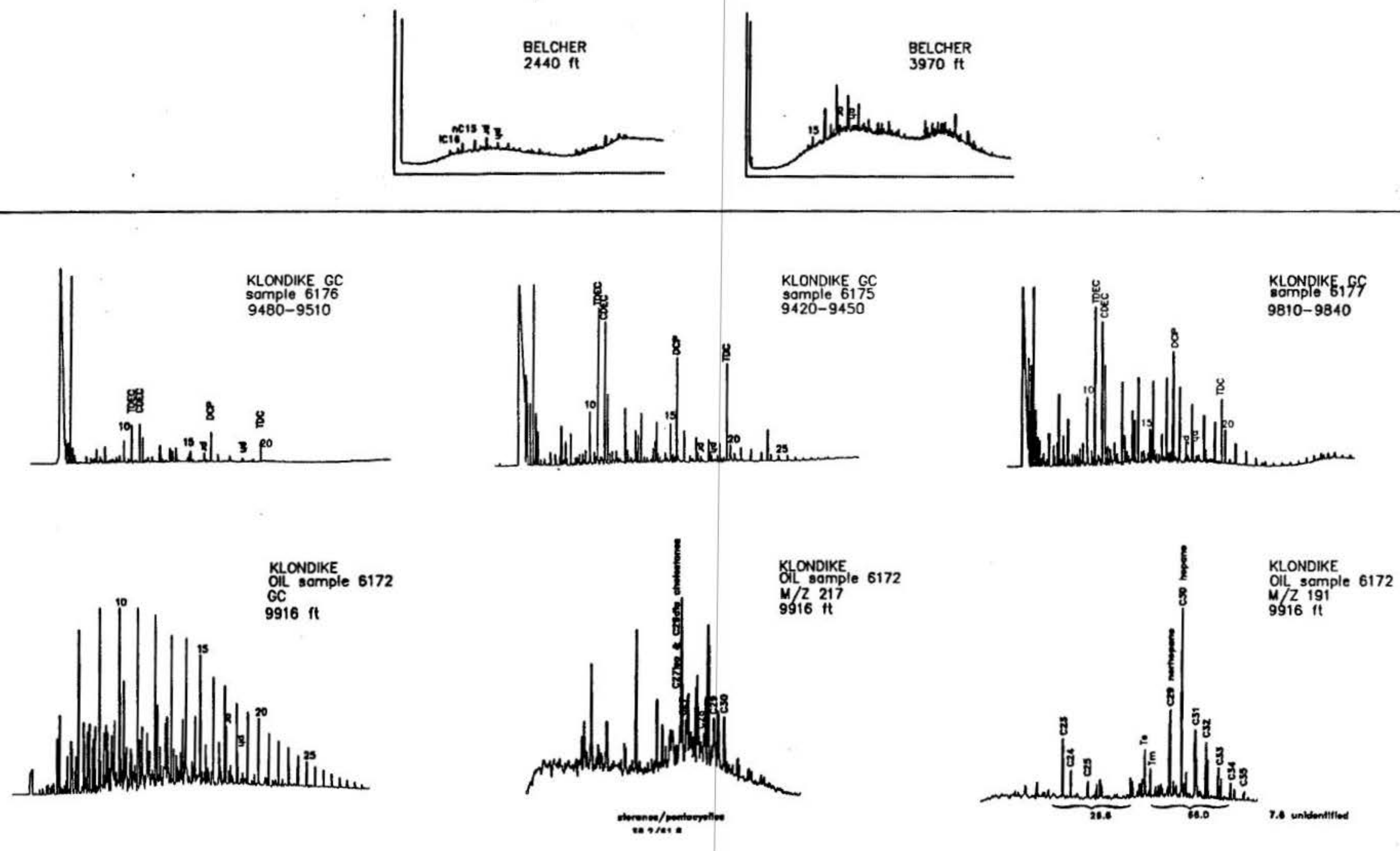


Figure 12
Chromatograms and fragmentograms from Belcher and Klondike well samples

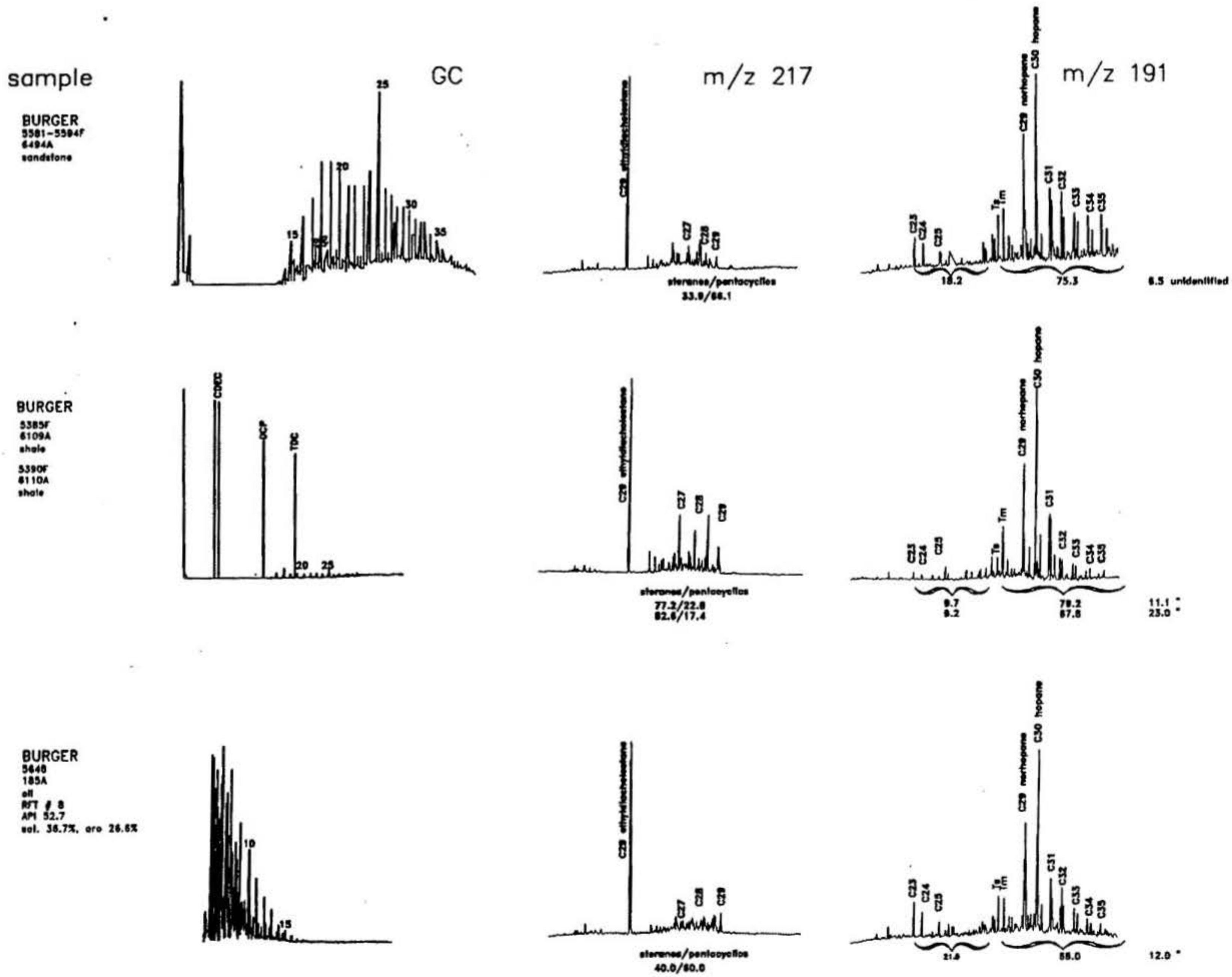


Figure 13
Chromatograms and fragmentograms for Burger well lithologies and oil

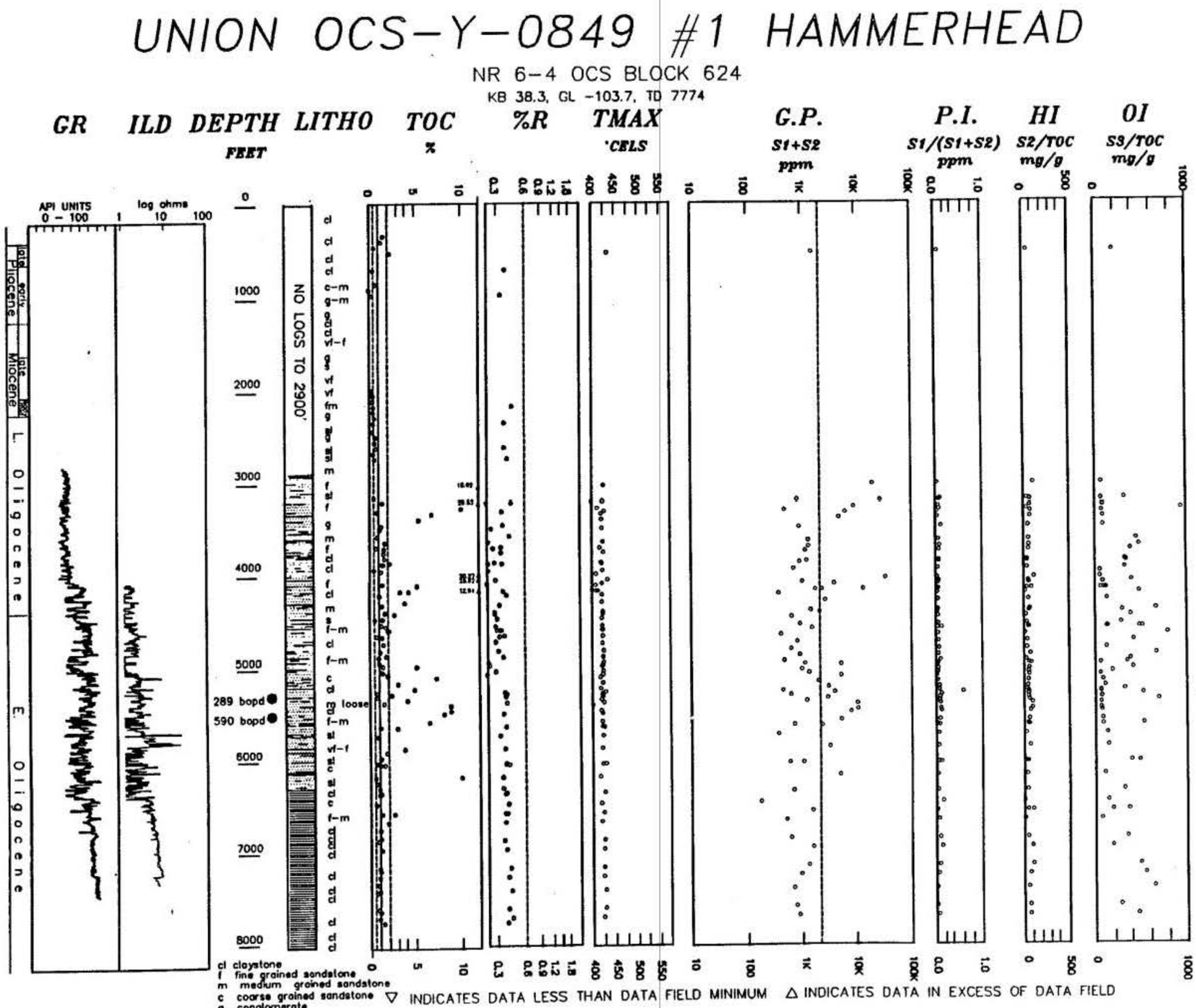
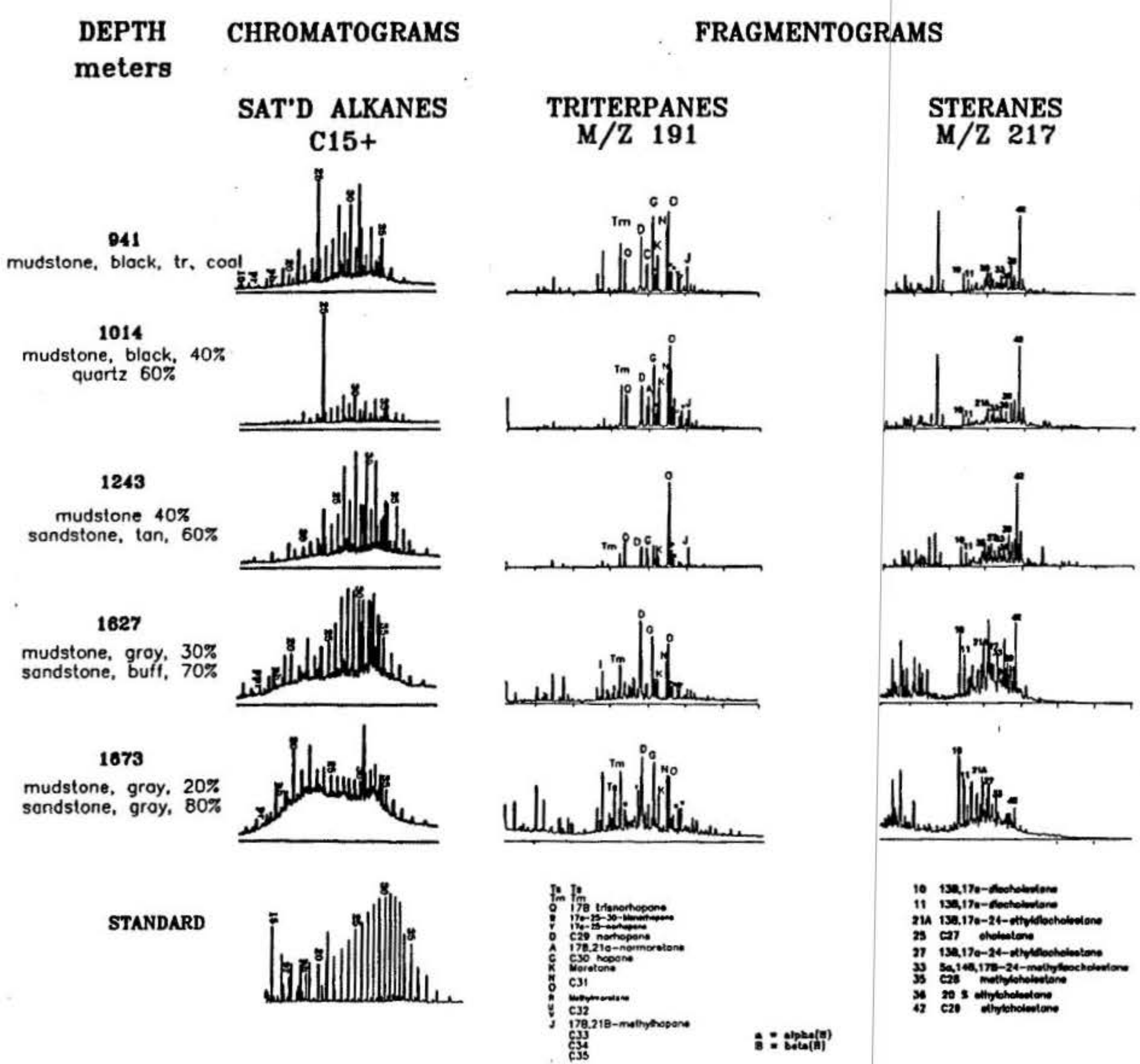


Figure 14
Geochemical profile of Hammerhead well



CHEMICAL DATA

Depth (m)	EXTRACTS CH_2Cl_2/Soxhlet (%) total	sat's	aro	res	SULFUR (%)	C-13 ppmil (o/oo) extract	kerogen
941	0.449	23.8	24.8	51.5	1.7	-25.0	-28.8
1014	0.633	18.4	20.1	61.5	1.6 - 3.5 avr. 2.7	-25.0	-27.6
1243	0.286	19.4	22.8	57.7	0.8 - 3.4 avr. 1.9	-28.4	-25.2
1627	0.202	22.8	38.5	38.8	3.3 - 3.6		
1673	0.249	32.6	42.3	25.1	avr. 3.45		

Figure 15
Lithologies, chromatograms, fragmentograms and geochemical data from Hammerhead well.

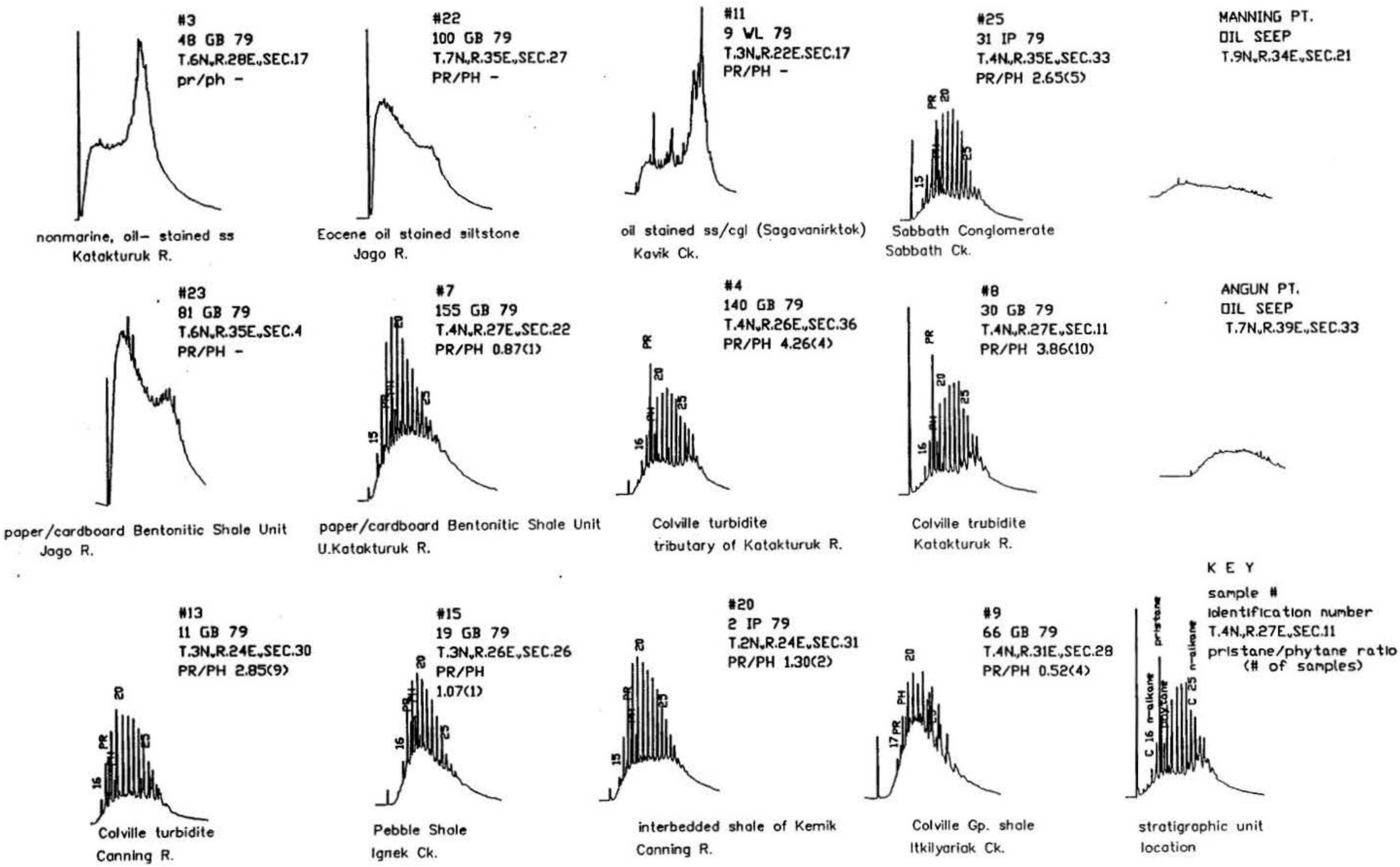


Figure 16
Comparison of C15+ chromatograms of rock extracts and oil seeps from ANWR

(data from Lyle and other, 1980; Magoon and Claypool, 1981)

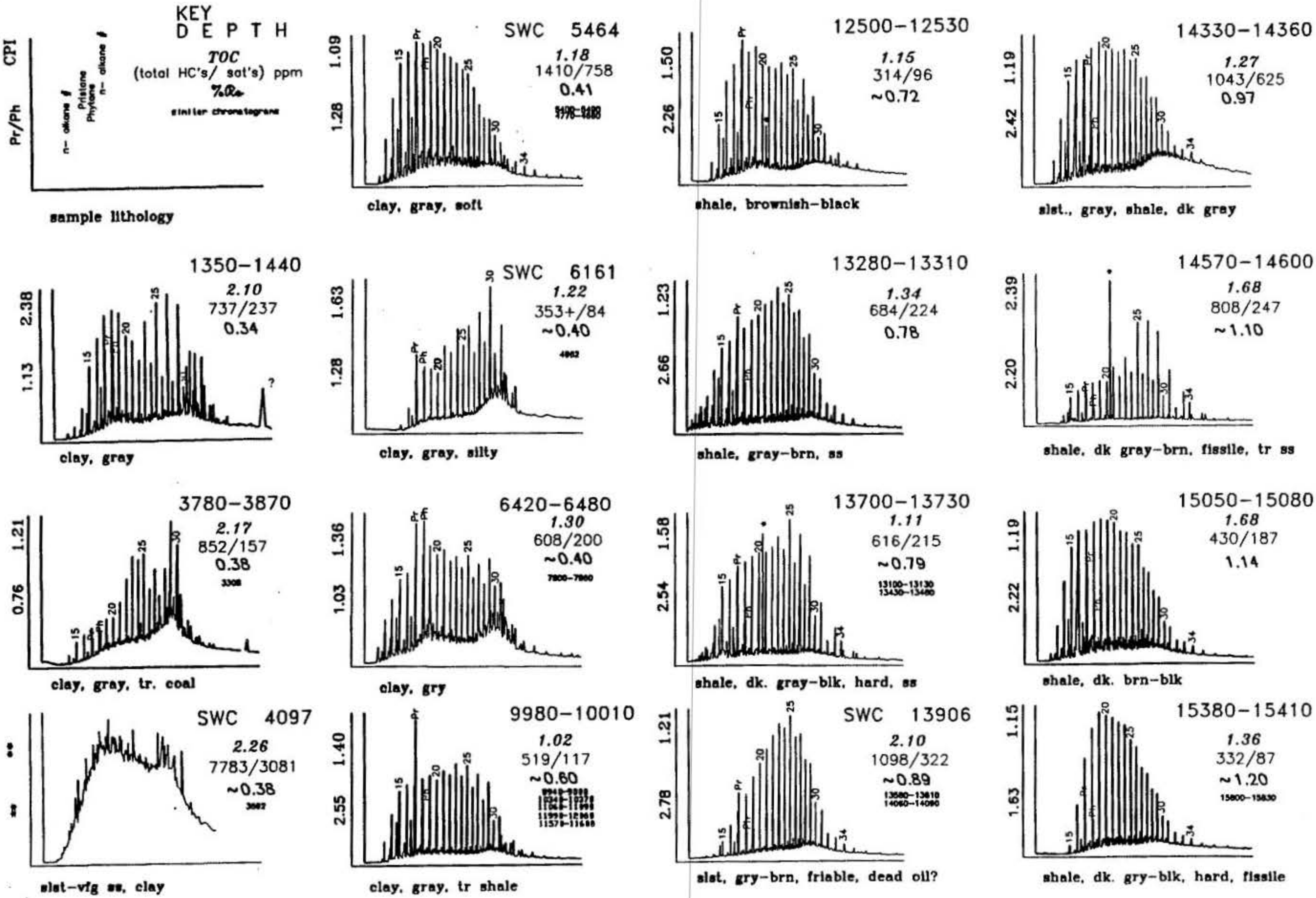


Figure 17
Representative chromatograms from Aurora well cuttings extracts

Table 1.
Compilation of geochemical data from North Slope, Alaska oil discoveries and seeps

	UGNU & WSAK	KUPARUK	PRUDHOE	LISBURNE	ENDICOTT	KUUKPIK (Fiord, Colvile, Delta 1-3, Kalubik)	UMIAT	SEABEE	SIMPSON
DEPTH	2700-3250 / 2500-6500	5800-6300	8400-9000	8500-9500	9600-10200		to ~900	5338-5394	<300
RESERVOIR	Ugnu/W Sak	Kuparuk	Sadlerochit	Lisburne	Kekiktuk	Kuparuk?	Nanushuk	Torok	Nanushuk
TEMPERATURE	45-100	150	200	185	200-225		<32	-	-
GAS CAP	N	N	Y	Y	Y	Y	N	-	-
API GRAVITY	5-11/17-26	24	22-32	25.1	17-23.7	26-32	19-39.2	52.6	18-22.7
% SULFUR	1.56	1.67	0.79-1.49	1.27	0.72-1.53		0.04-0.29	0.01	0.2-0.48
GOR		450	730	830	750	400-500			
% saturates	35.86	38.9	38.9	36.5	38.42			84.1	51.7
% aromatics	55.12	55.1	54.4	~55	56.12			16	48.1
pr/ph	~1.5	<1.50	1.0	1.2	1.71		1.7-2.0	12.0	-
CPI	1.00	1.0-1.5	0.97	0.97	1.05		1.02-1.05	-	-
Ni	14.8	21.7	10-30	26.8			0.2-4.5	0.2	na
V	35.4	58.0	20-60	60.0			0.2-0.7	0.2	na
V/V+Ni	0.71	0.73	.62-.74	0.69			0.11	0.50	0.38-0.46
δC ppt		-30.2	-29.89	-29.83	-28.90				-28.90
STERANES									
TRITERPANES tricyclics/pentacyclics			0.83				0.11-0.27		0.32-0.79
BIODEGRADED	Y	Slight	N	N	N		N		Y

	BARROW #20/#19	FISH CH	PT THOMSON	FLAXMAN	SKULL CLIFFS	KAVIK	MANNING PT	ANGUN PT
DEPTH	1600/2245	892-933	12834-13885	11392-12635	W NPRA	W ANWR	1002 coast	1002 coast
RESERVOIR	Pebble Sh/Sag R. ss	Nanushuk	Thomson ss	Flaxman ss	Nanushuk	Sagavanirktok	Eocene?	Eocene?
TEMPERATURE		<32	205	195				
GAS CAP								
API GRAVITY	28.8/21	13-22.6	18-45	21-44	18.4		26.7	solid
% SULFUR	0.21/	1.15-1.92	1.16		0.32		0.14	0.22
GOR								
	1.34							
% saturates	84.8/48.1		36					
% aromatics								
pr/ph	1.32/1.22		1.35					
CPI	0.99/0.97							
Ni	4.2/14.8		4.2/					
V	4.7/20.8		4.7/					
V/V+Ni	0.45/0.71	0.71	0.45/					
δC ppt	30.03/29.95	-30.09	30.03/			-26.7/-27.8	-28.23	-28.71
STERANES								
TRITERPANES tricyclics/pentacyclics	0.82	0.51						
BIODEGRADED					Y	Y	Y	Y

Data from:
Magoon and Claypool, 1982
Carman and Hardwick, 1983
Alaska Oil and Gas Conservation Commission Statistical Report, 1983
Werner, 1985
Curiale, 1985, 1987
Sedivy and others, 1987
Banet, 1992

Table 2
Cheochemical data from wells along Barrow Arch Uplift and foothills

(modified from Hughes and Hoba, 1986)

Type	sample	well name	res. depth ft.	Reservoir	AGE	API°	%S	Ni ppm	V	V/V+Ni %	Sats	pr/ph
U	80	Seabee #1	5366-5394	Torok	K	52.6	0.01	0.2	0.2	0.50	90.7	12.00
U	105	Well A	14126-14144	not listed	K	39.6	0.23	2.6	0.3	1.10	64.7	1.43
U	108	Umiat #4	299	Nanushuk	K	36.5	0.06	4.5	0.5	0.10	69.3	1.77
M	AYZ	Hemi Spgs #1	7196-7245	Kuparuk	K	34.4	0.25	6.0	2.2	0.27	51.8	2.17
M	GGN	Gwydyr Bay S #1	10053-10105	Sadlerochit	Tr	33.6	0.30	9.0	4.3	0.32	55.9	1.74
M	DZG	Mikkelesen Bay St #1	10468-10550	Colville	K	33.2	0.83	8.5	6.9	0.45	48.1	1.18
M	76	S Barrow 20	1629-1639	Pebble Sh	K	28.8	0.21	4.2	4.7	0.53	64.8	1.32
P/M	CGN	W Kuparuk St #1	8880-8924	Shublik	Tr	28.0	0.60	10.0	21.6	0.68	46.3	1.49
M	BHW	Hemi Spgs #1	9538-9582	Sadlerochit	Tr	27.8	0.22	2.9	1.1	0.28	57.1	1.56
P	CGM	Sag R St #1	8890-9008	Sadlerochit	Tr	27.0	1.01	9.9	22.5	0.69	40.0	1.53
P	DZF	N Kuparuk St #1	8890-8984	Sadlerochit	Tr	26.0	1.00	11.2	22.2	0.66	42.3	1.42
P	GGK	N Kuparuk St #1	3708	Colville ss	KT	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	0.73	38.9	1.30
U	79	Simpson core test	near surface	Nanushuk	K	23.0	0.24	1.2	0.7	0.64	58.0	1.57
P	GGM	Foggy Is Bay St #1	10092-10209	Lisburne	Mis	23.1	1.27	22.8	40.9	0.78	38.1	1.45
P	GGL	Mikkelesen Bay St #1	11870-12200	Lisburne	Mis	22.7	1.28	30.8	71.1	0.70	35.1	1.10
P	77	S Barrow 19	2200-2245	Sag R. ss	Jur	21.1	1.34	21.2	20.8	0.50	48.1	1.22
P	GGJ	Kavearak Pt #1	3794-3845	Ugnu ss	T	20.9	1.56	14.8	35.4	0.71	39.0	1.56
P	DZE	Pt Thomson #1	12063-13050	Thomson ss	K	20.0	1.16	23.8	58.6	0.71	36.0	1.35
P	DZC	Well B	not listed	not listed	K	12.4	0.87	17.0	48.4	0.74	29.3	1.18
P	ASN	Mukluk OCS-Y-0334	7360-7385	Kuparuk R	K	12.1	NA	NA	NA	-	28.3	1.54
DP/M	81	J.W. Dalton #1	8568-8665	Lisburne	Mis	6.5	3.12	43.9	141.1	0.76	23.5	1.37

U Umiat
P Prudhoe
M Mixed
D Dalton

Table 3
Geochemical data from Mackenzie Delta wells

Type	well name		reservoir	depth	temp	API	%S	Pr/Ph	^{13}Caro	^{13}Caliph	^{13}Ctot	GOR	%V	%Ni
C2	Adgo F28	bdg	Reindeer	5680	116	16.5	0.1		25.86	26.32		235		
	Adgo F28	bdg		4090	85	18	0.1							
	Adgo F28	bdg		5625										
C2	Adgo P25	bdg	Reindeer	4408					25.46	26.36				
C2	Adlartok P09		Moose Ch			30	0.05		25.06	26.88	26.03		0.6-	
C1	Amauligak I6	oil/cnd	Kugmallit			28-35	0.1		26.44	28.14	27.55		0.2	0.6
A/m	Atertak E41		Brookian	4030	78	20	1.4							
	Atertak E41			4460	80	23								
	Atertak E41	oil		4049	78	22								
A	Atkinson H25	bdg	Breakup	5700	118	24	1.0		26.49	27.49		284		
A	Imnak J17	oil		9336				1.3	26.73	27.22				
C2/m	Issungnak J29?		Kugmallit			35-35	0.88		26.28	28.02	27.36		8.90	3.0
C2	Ivik J26			10072				4.6	25.68	27.19				
	Ivik J26			9640				7.9						
	Ivik J26			9926				9.8						
	Ivik J26			8605	121	23	0.1							
	Ivik J26			8350	120	26	0.1							
	Ivik J26			8656				8.1						
	Ivik J26	cnd		8797	122	42	0.1							
	Ivik J26	dgd	Brookian	8080	58	23	0.2		25.97	27.09				
	Ivik J26	dgd		8080				8.3						
	Ivik J26	prbdg	Brookian	9122	126	33	0.1	5.9	26.06	27.09		262		
C2	Ivik K54	dgd		8280					26.39	27.11				
	Ivik K54	dgd	Brookian	8584	120	24	0.1					610		
B	Komik D48	oil	Cretaceous	9397				4.3	25.87	26.56				
C1	Koakoak O22		Kugmallit			28	0.66		26.66	28.06	27.59		0.1	-
C1	Koponoar 21-44	oil	Richards?				0.04		26.59	28.23	28.39		0.2	0.6
A	Koponoar M13		Cretaceous			33-38	0.12		26.67	28.37	28.43		0.4	
C2?	Kugpik L24	oil	Reindeer	8152				1.5	26.22	28.36				0.8
A	Kugpik O13	oil	Breakup	7202	156	48	0.05							
B	Kumak J06	con	Reindeer	8145				5.0	25.36	26.41				
	Kumak J06			7048	144	27	0.1	4.6	25.84	27.04		319		
	Kumak J06	bdg	Brookian	4439	120	20	0.2	4.5				640		
	*Kumak J06	con		8145	184	47	0.1	5.0	25.36	26.41	27.29		0.6	
	Kumak J06	pbdg	Brookian	7566	152	32	0.09	5.9	26.27	27.37		496		
B	*Kumak K16		Reindeer	9732			0.14	6.0	26.05	27.16	27.26		0.2	
	Kumak K16	con		9618			0.02	5.3	25.95	27.67	26.42		-	-
	Kumak K16	con		9932				5.8	25.67	27.01				
A	Mayogiak P17	oil	pre Elles	9395	184	32	0.3	1.9	27.57	28.25		270		
A?	Mayogiak P17	oil	Brookian	3790	96	32	0.2	1.3	26.49	27.49				
C2	Niglintak B19	bdg		5234				9.0	26.21	27.38				
	Niglintak M19	bdg	Kugmallit	4547					26.64	27.82				
	Niglintak M19	bdg	Reindeer	6560				9.0	26.86	27.23				
	Niglintak M19	bdg		5730					26.85	27.36				
	* Niglintak M19	bdg		5647			0.06		26.04	27.12	26.15			
	Niglintak M19	bdg		4345					26.31	29.16				
	Niglintak M19	con/bdg		6910				5.3					0.55	0.15
	Niglintak M19	oil						6.0	26.42	28.54				
B	Parsons D20	cnd		11300				3.7						
	Parsons D20	cnd		11798				3.4						
	Parsons D20	cnd		12168				3.5						
	Parsons L43	cnd		9332				6.4	24.38	26.54				
	Parsons N17	cnd		9762				4.0	24.9	24.54				
C1	Pitsiulak A05	oil	Kugmallit			31	0.11							
C1	Pullen E17	oil	Kugmallit	11694	158	30	0.1	6.0	26.66	28.19	27.68		0.1	0.15
	Pullen E17	oil	Brookian	11781	159	27	0.2	5.0	26.71	27.39				
B	Siku C11			9710				3.6						
	Siku C11	cnd		9622				4.6	24.9	26.25				
	Siku C11	cnd		9486				3.9	25.1	26.28				
C2	Taglu C42	conbdg	Reindeer	9450				6.1						
	Taglu C42	conbdg		9405				5.7						
	Taglu C42	oil	Brookian	10610	172	29	0.1	3.2	26.25	27.72				
	Taglu D43			9598				5.0						
	Taglu D43	conpdgd		8380				4.8	25.25	27.30				
	Taglu G33			9209				5.1						
	Taglu G33			8216				5.3						
	Taglu G33			9340				9.7						
	Taglu G33			8473				6.7						
	Taglu G33	bdg		9759	160	46		6.9						
	Taglu G33	con		8164	136	38		7.0	25.86	27.22				
	Taglu W P03	con		9759				6.9						
	Taglu W P03	con		9340				9.7						
	Taglu W P03	con		8656				8.1						
	Taglu W P03	conbdg		9209				5.1						
	Taglu W P03	conpdg		8490				8.3						
C2	Tarsiut A25		Kugmallit				0.14		27.01	27.44	27.21		0.10	-
C2	E Tarsiut N4		Kugmallit			26-29	0.08		27.85	27.79	27.85		-	-
A	Wagnark C23	pdgd	Cretaceous	3513					27.79	27.36				
C1	Uviluk P66		Richards				0.14		28.41	26.47	28.02		0.2	0.5

bdg biodegraded
con condensate
pbdg partially biodegraded
prbdg probably biodegraded
A/m: type A oil, migrated into younger reservoir

* data from multiple sources
sources include Burns and others, 1975; Snowdon and Powell, 1979; Brooks, 1986; Curiale, 1991)

Table 4
Geochemical data for selected offshore wells (U.S.)

	BURGER Y-1413	KLONDIKE Y-1482	SEAL ISLAND Y-0181	HAMMERHEAD Y-0849	BELCHER Y-0917	AURORA Y-0943	BADAMI*	KUVLUM Y-0866
	OIL	OIL/EXTRACT	OIL/COND	OIL	cuttings	cuttings	OIL	OIL
HC zone	5560-5665	9916		5300-5500	2214-3970	2380-15930		
TOTAL DEPTH	6702	12008	13078	8034	13150	18325		8500
Reservoir		Sadlerochit	Sadlerochit	Sagavanirktok		Oruktalik		
Dep Sequence	Breakup	Mid Elles	Mid Elles	U Brook	U/M Brook	M Brook	M Brook	U Brook
API°	46.4	35.3	40.0	18.5				
range	32.0-57.2		39.0-41.1	17-20			27-28	34
Sulfur (%)	0.4-0.6	0.18	(<15ppm H_2S)	3.3-3.6				
Saturates (%)	64.1	66.2		32.6	39.3	34.4		
range	36.7-81.0				38.5-40.5	18.4-59.9		
Aromatics	17.9	26.1		42.3	41.1	35.9		
range	11.0-21.3			39.0-42.5		0.73-53.6		
Pristane/phytane	1.84	1.92			1.66	1.91		
range	0.77-2.6	1.90-1.94			1.25-1.41	0.73-3.38		
Pristane/nC-17	2.83	0.47			0.68	1.15		
range	0.3-12.0	0.35-0.58			0.63-0.72	0.51-2.57		
del C-13								
whole	-28.30			-28.4				
aromatics	-27.06	-30.28						
saturates	-27.88	-31.03						
Metals (ppm)								
Ni	0.9							
V	0.35							

(*Badami was drilled from onshore to an offshore bottom hole location)

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