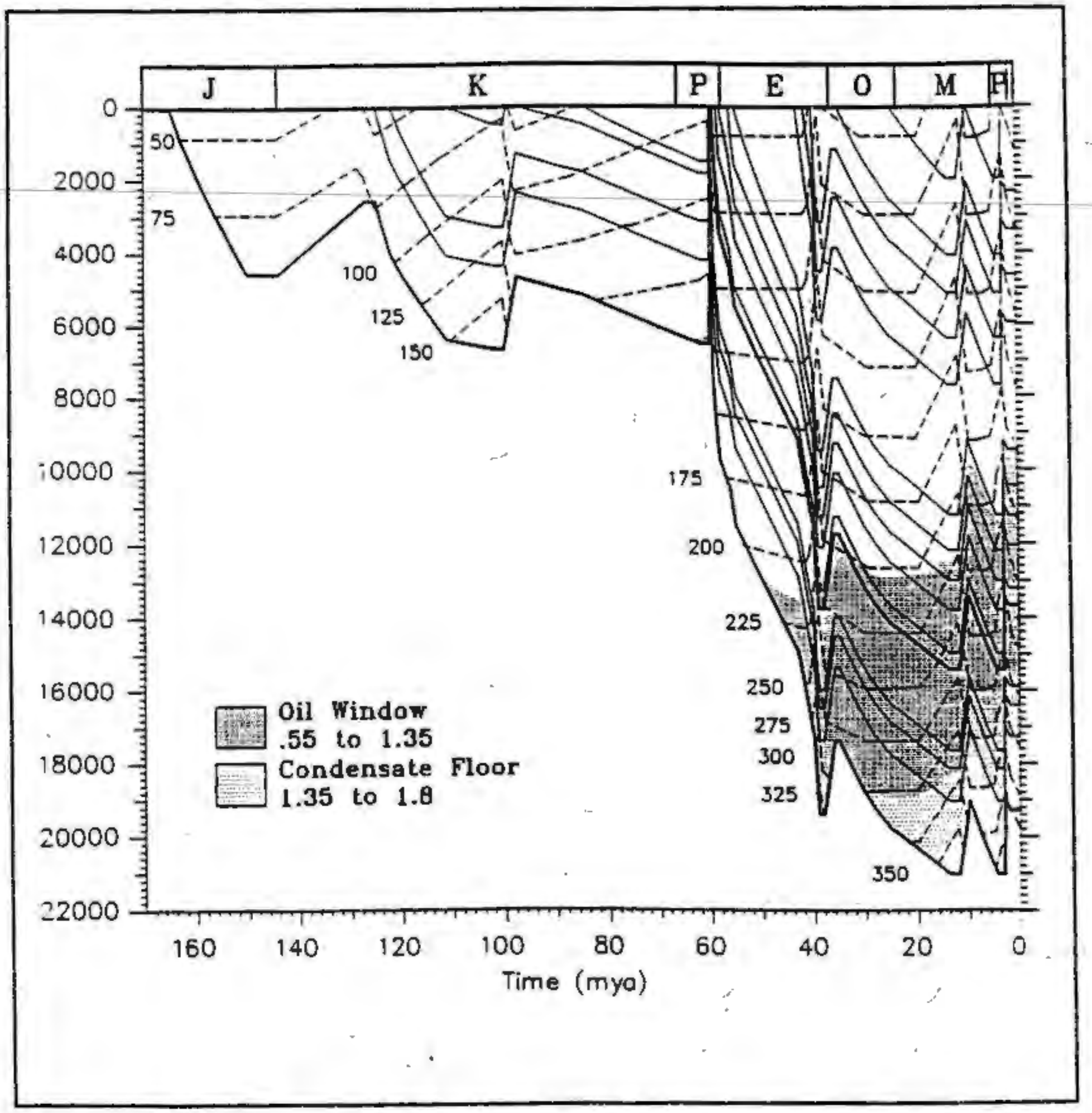
U. S. Department of the Interior
Bureau of Land Management

BLM-Alaska Technical Report 16
BLM-AK-PT-93-018-3045-985

Alaska State Office
222 West 7th, #13
Anchorage, Alaska 99513

A Geochemical Profile and Burial History of Aurora 890 #1 OCS Y-0943 Well Offshore of the ANWR 1002 Area, Northeast Alaska

Arthur C. Banet, Jr.



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.

Technical Reports

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

The reports are available at BLM offices in Alaska, the USDI Resources Library in Anchorage, various libraries of the Unversity of Alaska, and libraries in other selected Alaska locations. Copies are also available for inspection at the USDI Natural Resources Library in Washington, D.C. and at the BLM Service Center Library in Denver.

A Geochemical Profile and Burial History of the Aurora 890 #1 OCS Y-0943 Well Offshore of the ANWR 1002 Area, Northeast Alaska

Arthur C. Banet, Jr.

Bureau of Land Management
Alaska State Office
Anchorage, Alaska 99513

Technical Report 16
January 1993

Table of Contents

List of Figures

List of Tables

A Geochemical Profile and Burial History of Aurora 890 #1 OCS Y-0943 Well Offshore of the ANWR 1002 Area, Northeast Alaska

Abstract: Organic geochemical analyses of the cuttings and sidewall cores from the Aurora well describe the petroleum-generating potential of the Brookian and Breakup sequence rocks offshore of the ANWR 1002 area. Most TOCs are low, and are comparable to sediments from the Beaufort-Mackenzie basin. However, the basal Brookian and Breakup sequences have higher TOCs and are not comparable. Visual and pyrolytic analyses show that indigenous kerogens in Aurora samples are mostly Type IV or inerinite.

Thermal maturity regimes are most accurately defined by %RO and as Wetness data. The catagenetic zone is currently between about 9,518 and 17,500 ft. (2,901-5,334 m). Burial history reconstructions include several periods of uplift and erosion at this location. The source rock analyses and thermal models suggest that the Aurora sediments are not, currently the site of extensive hydrocarbon generation. However, the C-15+ extract data show that hydrocarbons are migrating through these sediments from an as yet unknown and undefined petroleum system.

1. Introduction

The Aurora 890 #1 well OCS Y-093, offshore of the Arctic National Wildlife Refuge (ANWR) 1002 area, is the most recently available publicly released data pertinent to northeast Alaska *(figures 1 and 2)*. This report presents the geochemical interpretation of the Aurora data. It is also ancillary to BLM Alaska Technical Report 15 "Log Analysis of Aurora 890-#1, OCS Well, Offshore of the Arctic National Wildlife Refuge 1002 area, Northeast Alaska" (Banet, 1992). This geochemical profile expands and updates interpretation of the upper Brookian and Tuktoyaktuk depositional sequences at this location, based on the burial history reconstruction.

BLM-Alaska Technical Report # 15 describes, in detail, the geology of the sedimentary section at Aurora well, based on log and cuttings samples analyses and interpretations. *Plates 1, 2, and 3* are directly from BLM Technical Report 15. They show the logs at reduced scale, the mudlog and log interpretation and the geochemical profile, respectively. Some of the figures and tables referring to regional geology and specific intervals of the Aurora well are also from BLM TR #15. However, most figures, plates and tables are unique and germane to only this report.

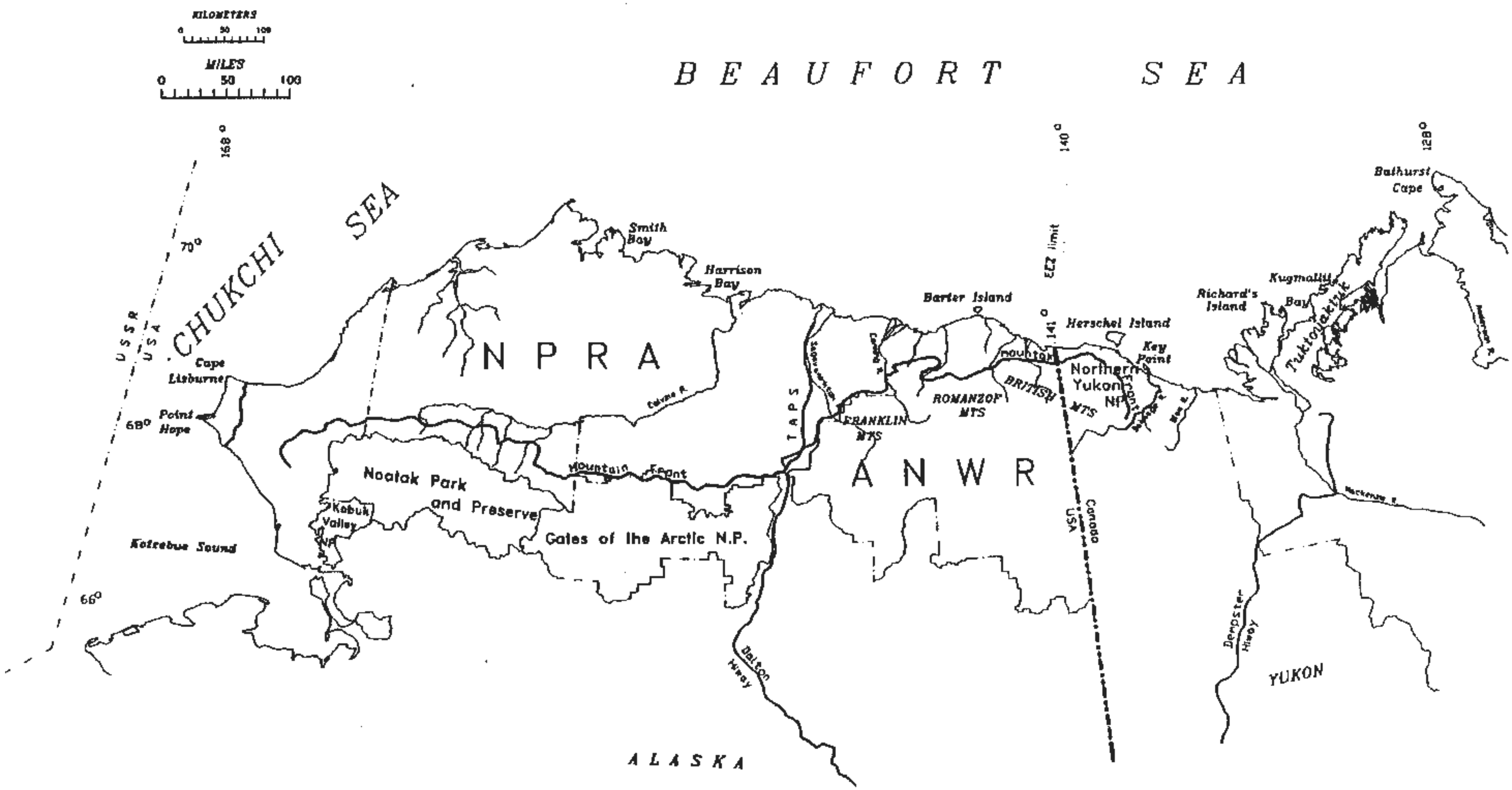


Figure 1
Index map of the Arctic showing major geographic features in Alaska, Yukon Territory and Northwest Territories

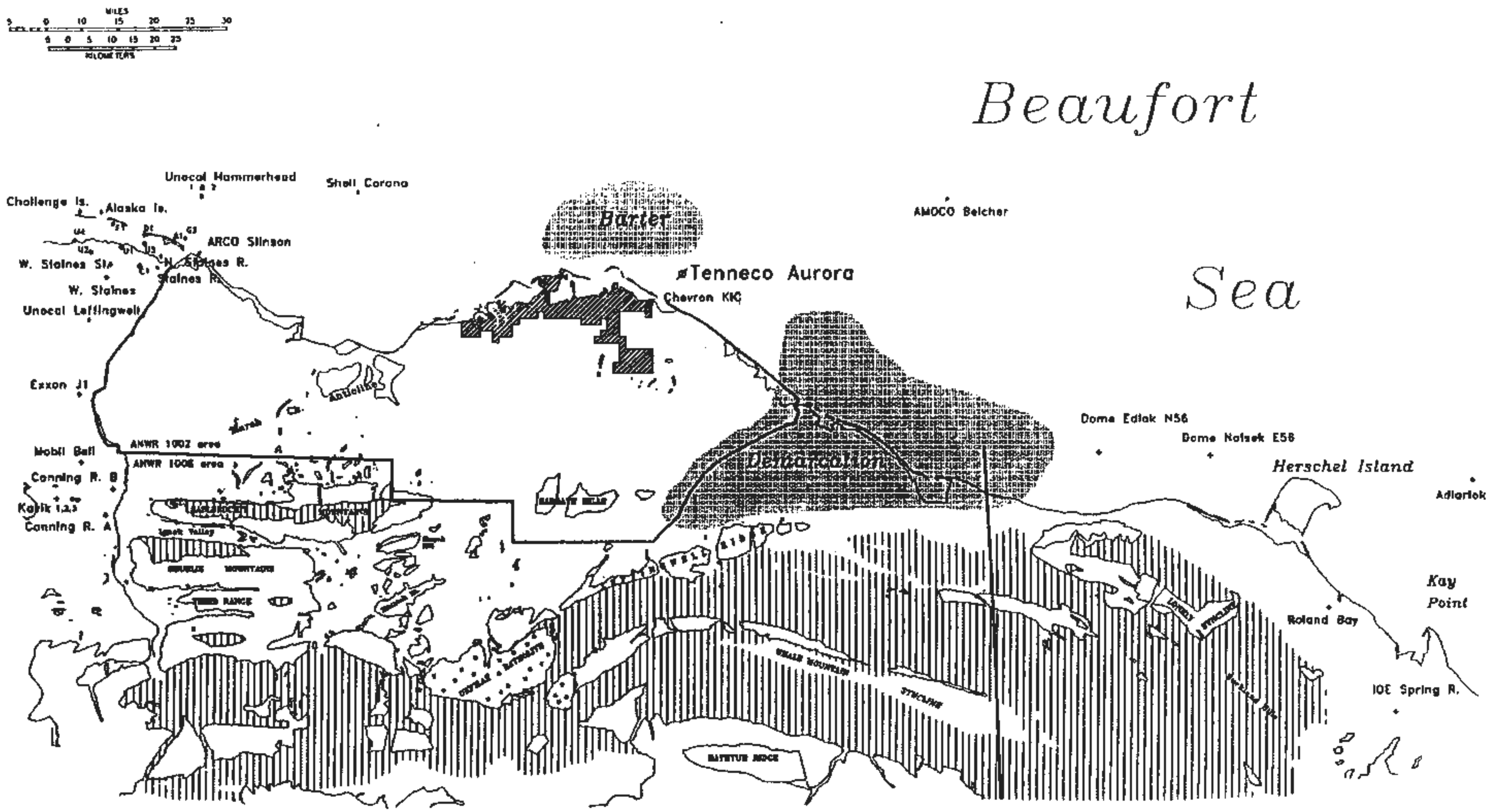


Figure 2
Aurora well location, outcrops and major geographic features including ANWR 1002 area and nearest exploration wells

Key:

shaded areas	Barter and Demarcation sub-basins
hatched areas	pre-Ellesmerian rocks

2. Stratigraphy

Briefly, the Aurora well penetrated some 18,325 feet of sedimentary section. All log units identified belong to Hubbard and others' (1987) Beaufortian or Brookian depositional sequences *(tables 1 and 2)*. The Beaufortian sequence is redefined as the Breakup sequence which stresses the nature of the temporally and spatially separate pulses of clastic deposition shed from several localized uplifts along the Barrow Arch (Banet, 1990, 1992 and Banet and Mowatt, 1992).

The Tapkaurak Unit of the Breakup Sequence is expanded from just the Tapkaurak sand to include the sandstone and shale beneath it. Likewise, the Middle Brookian Oruktalik Unit is expanded to include the shales below the Oruktalik Sand of Unit IV. The Tuktoyaktuk sequence sediments are not discernable from the log suite, but are inferred at this location from regional geology (Banet, 1990).

Breakup Sequence

Banet (1992) interprets Unit I, the deepest section penetrated, (18,325 - 17,325) as Breakup sequence shales and sandstones that are correlative to the Kingak Formation (Jurassic-upper Cretaceous) of onshore nomenclature. Regionally, the Kingak represents up to about 4,000 ft of predominantly fine- grained, shaley, shelf deposits. Sands of local extent are more common along the Barrow Arch. The interbedded Kingak shales and thin sands at Aurora are terminated by a lower Cretaceous unconformity, the LCU of onshore terminology.

Unit II, the Tapkaurak, overlies the Kingak. It is an overall coarsening upwards sequence of interbedded sandstones and shales. These sandstones become thicker-bedded upsection, culminating in the informally named Tapkaurak sandstone unit, 16,620 - 16,446. The Tapkaurak has some similar depositonal and petrological characeristics as the other predominantly sandstone Breakup sequence units; the Kuparuk Formation, the Kemik sand and the Pt. Thomson sand (*table 2*; Banet 1992)

Unit III is the top of the Breakup Sequence. It consists predominantly of dark-brown to dark-gray shale, with some minor carbonaceous laminations and thin-bedded siltstones or sandstones. A lower Tertiary unconformity (LTU) terminates the Breakup sequence which is manifest by the dramatic log break at 15,937. This stratigraphic relationship of a lower Tertiary

Table 1.

A brief synopsis of nomenclature used for rifting-related sandstones and shales encountered along the Barrow Arch.

sequence	*investigators*	*comments*
Barrovian	Carman and Hardwick,	•infra-rift and rift sediments from a northern source •4 distinct depositional units •2 limited areal extents; •~1,500 km² active reservoir area •multiple sand bodies
Rift	Craig and others, 1985	•clastics shed into infra-rift basins like Dinkum Graben. •may be very thick •related to locality and time intervals •does not include Barrovian sedimants
Beaufortian	Hubbard and others, 1986-1987	•rift event sedimentation includes all clastics on Arch, Jurassic - mid Cretaceous •northern source, with multiple uplifts •transitional basin geometry rifting younger to east
Breakup	Banet, 1990	•rift event sedimentation from multiple local uplifts along arch axis •separated geographically and temporally •unique sand petrologies reflect basement lithologies

Table 2

A comparison of lower Cretaceous sands and shales from northern Alaska

HRZ AT KUPARUK

4 - 9 %TOC
shale w/ paper fissility
~200'
Albian - Aptian

KALUBIK FORMATION

below HRZ- 150 API
internal, local HRZ
overlies Kuparuk sands
mudst & slst
carbonaceous
moderately fissile
pyritic & sideritic
200 ft. to 300 ft.
marine deposition

Barremian - Aptian
BREAKUP SEQUENCE

PEBBLE SHALE

GRZ
LCU basal unconformity
No. Slope regional
silty shale
black, fissile, pyritic
minor bentonite
200 ft. to 300 ft.
floating pebbles/grains

rich source rock
TOC to ~ 5%

Haut. to Barr.
BREAKUP SEQUENCE

KONGAKUT FM.

sh, slst, minor ss
4 members
deep water turbidite
~ 1900 ft. thick
internal unconformities
GRZ in Pebble Sh.
black, manganiferous
few fossils
floating chert pebbles
Kemik sand ~ 260 ft.
quartz arenite to-
feldspathic wacke
very fine-grained
basal contact conformable

Berriasian - Barremian
BROOKIAN

ARCTIC CK.

ss & sh
vf. to fine grained
quartzose
5 ft. to 90 ft. beds
~ 250 ft. total sand
thins eastward
siliceous , hard
100% recrystallized
deep marine & turbidites
flutes, grooves & load casts
blk. fissile shale
minor bentonites

Albian Aptian
BROOKIAN

AURORA UNIT III

LTU at top
sh, slst & carb sh
gray to dk. gray
very thin beds
very silty cuttings
500 ft.
~SE-NW transport

lean source rock

lower - mid Cretaceous
BREAKUP SEQUENCE

KUPARUK

below GRZ
multiple beds
sand & shale
shallow marine
fine-grained, rounded
glauconitic, sorted
intraformational
unconformities
distinct contacts
areally limited unit
~ 5 mi. X ~15 mi.
Haut. - Barr.

oil & dissolved gas
BREAKUP SEQUENCE

KEMIK

below GRZ
LCU basal unconformity
sands to ~ 150 ft.
sand & shale
distinct to interbedded
fine-grained, rounded
well sorted, marine
No. Slope Regional
~6mi.X 24mi. units
northeast trend
commonly imbricated
mega-fossils
Hauterivian

gas
BREAKUP SEQUENCE

POINT THOMSON

below GRZ
LCU basal unconformity
thick single unit
sand, conglomerate, breccia
angular dolostone fragments
sits on basement
poorly to well sorted
nonmarine
limited lateral extent
~ 3mi X 5mi
east-southeast trend?
distinct contacts
barren of fuana

oil & condensate
BREAKUP SEQUENCE

AURORA UNIT II

no GRZ
LCU at base
distinct contacts
interbedded ss & sh
coarsens & thickens upwards
174 ft. massive sand at top
Tapkaurak sand
fine to coarse-grained
clear to white grains
subrounded/subangular
dolomitic cement
unconsol to med. hard

BREAKUP SEQUENCE

KEY: GRZ = gamma ray zone; HRZ = highly radioactive zone; LCU = lower Cretaceous unconformity, LTU = lower Tertiary unconformity. Stratigraphic position and geography emphasized. Some age relationships uncertain.

unconformity eroding through the Breakup sequence is similar to the stratigraphy at the Pt. Thomson-Flaxman area. However, at the north side of the Pt. Thomson-Flaxman area, the LTU erodes all of the Breakup sequence.

Brookian Sequence

Middle Brookian

Southerly-derived, middle Brookian sediments comprise the section 15,937 - 2,385. These sediments are mostly shales and soft clays with predominantly thin interbedded siltstones and sandstones. Many of the individual sandstones and siltstones are too thin to be resolved on the geophysical logs. However, log Units IV through XIII are differentiated based upon log responses and their geochemistry.

Log Unit IV, the Oruktalik Unit, is the most notable of the Middle Brookian units. This unit includes the Oruktalik Sand, a thick, composite, sandstone unit, between 14,828 - 14,685. The Oruktalik Sand had the most prominent gas show in the well and some oil staining.

Interpreted paleontological data from the Aurora well are not yet available so the Middle-to-Upper Brookian sequence boundary is implied from the well logs and regional correlations. As at the Pt. Thomson area, the Brookian stratigraphy is considered to be entirely Tertiary and younger above the lower Tertiary unconformity (LTU). Log Units IV - XIII, between 15,937 and 2,385, correlate best with the middle Brookian lithologies. Consequently, regional data constrains them to be Paleocene to upper(?) Eocene age. The Flaxman Sands (Paleocene) have tested near-commercial amounts of oil and condensate immediately west of the 1002 area *(figure 2)*.

Data from Aurora well describes a Middle Brookian section that differs significantly from the Middle Brookian rocks found in the western and central parts of the 1002 area. Both the basal Bentonitic Shale Unit and overlying Colville Group shale are missing at Aurora. The Bentonitic Shale Unit is typically found across the 1002 area. Similar and largely coeval lithologies of the Boundary Creek and Smoking Hills formations are found as far east as the Tuktoyaktuk Peninsula (Banet, 1990; Dixon and others, 1985). In wells and at outcrop, all these units consist of 600 to 1,000 ft of black, fissile, organic rich (to 14% TOC), paper/cardboard, shale and interbedded bentonites. The Bentonitic Shale Unit is overlain by up to 5000 feet of gray, silty shales with some interbedded turbidite sandstones (in the west) and gray, smectitic shales (central 1002 area). These units correlate to Detterman and others (1975) Shale Wall Member and Colville Shale and Molenaar's (1987) upper part of the Hue Shale and Canning Formation, respectively, of western ANWR nomenclature.

Craig and others (1985) describe the upper Cretaceous to Eocene section of the Arctic margin consisting of up to approximately 18,000 ft of prodelta and shelf sediments. These are the diapiric or mobile shales (Grantz and May, 1983). Tectonic compression along the Hinge Line has folded and uplifted these sediments along a ridge which separates the Barter Island subbasin from the Demarcation subbasin *(figure 2)*. Middle and upper Brookian sediments at Aurora have a very marked south-southeast provenance, rather than from the west-southwest as more commonly found across the rest of the North Slope (Molenaar, 1983). Nonmarine and shallow marine facies of coeval westerly derived middle Brookian rocks contain large reserves of low reservoir temperature oil in the West Sak and Ugnu (upper Cretaceous - Tertiary) deposits near Prudhoe.

Seismic stratigraphy of the Canadian portion of the Beaufort basin identifies over 15,000 ft of middle Brookian sequence rocks with lithofacies that are typically more proximal than those identified at Aurora. The seismic sequences are the delta plain and delta front facies of the Fish River (Paleocene), the Aklak (lower Eocene) and the nearshore/pro-delta facies of the Richards (upper Eocene). Near the international border, these distal lithology sediments sediments have been deformed by both synde postional and tectonic folding and faulting. Major offshore discoveries such as Adgo, Adlartok and Taglu are in the middle Brookian prodelta and delta front sands facies (Deitrich and others, 1985 and 1992).

Upper Brookian

Log Unit XIV, from the unconformity at 2,385, to at least, the end of data at 930, is considered to be upper Brookian. This section is composed of gray, gummy, clay, with unconsolidated silts sands, and minor amounts of floating pebbles or gravels.

Onshore, the west-southwesterly derived Sagavanirktok Formation (latest Eocene or Oligocene - early Pliocene) is time equivalent to Unit XIV. Well and outcrop data show that the Sagavanirktok consists of up to 8,800 ft of nonmarine, interbedded and poorly consolidated sands and silts with floating chert pebbles, varved clays and silts, poorly sorted gravels and bedded sandstones. Partially coalified wood is common. The Hammerhead discovery, west of the Aurora is from early Oligocene sands from this section (Banet, 1990; Scherer and others, 1991).

The upper Brookian section at Aurora is south-southeasterly derived (*Plates I and II*). These sediments are lithologically most similar to the marine facies of the upper Kugmallit (Oligocene), Mackenzie Bay (upper Oligocene - Middle Miocene) and Akpak (middle - upper Miocene) seismic sequences (Dixon and others, 1985 and 1992). Multiple transgresssions and regressions mark the upper Brookian depositional sequence in the Canadian Beaufort. Deitrich and others (1985) estimate that the sediment thickness on the Canadian side of the border may exceed 20,000 feet. Craig and others (1985) estimate similar upper Brookian thicknesses in the Demarcation and Barter subbasins juxtaposed to the Aurora location *(figure 2)*.

Unlike the Sagavanirktok onshore, numerous unconformities of local to regional extents, especially a major mid- to upper- Miocene unconformity, are prominent in the seismic records of this Upper Brookian section offshore. Many of the Mackenzie Delta-Beaufort Sea discoveries are in upper Brookian sands, including the largest at Amauligak (Enachescu, 1990; Dixon and others, 1992).

Tuktoyaktuk Sequence

Analysis of regional data indicates that at least some of the predominantly east-derived Tuktoyaktuk sequence (Pliocene - Pleistocene) rocks should be present at Aurora (Banet, 1990). These rocks are commonly referred to as the Gubik Formation (mid- Pliocene and younger) across much of the North Slope coastal areas. The Gubik is usually composed of clays, mostly gray, poorly sorted, unconsolidated, silts and sands, with cobbles and boulders of igneous origin; some originating from as far away as the Canadian Arctic Islands. These lithologies represent both nonmarine and marine depositional environments.

Dinter (1987) describes multiple marine transgressions from outcrops within this section between Barrow and the Canadian border. An angular unconformity separates the Gubik from the underlying Sagavanirktok at outcrops along the Marsh Creek Anticline in the ANWR 1002 area southwest of the

Aurora location. Compilations of both onshore and off- shore data suggest that the Gubik may be as thick as 300 ft in this area (Carter, 1987 and Dinter, 1987).

In the Canadian Beaufort, Iperk sediments and the overlying Shallow Bay are partially proximal equivalents of the coeval Gubik. Both glacial and tectonic events have effected much of these units' sedimentation. Like the Gubik, the Iperk is mostly undeformed and overlies folded and faulted middle and upper Brookian sequence units. However, the Iperk is over 15,000 feet thick in the central part of the Canadian Beaufort Basin. This rapid influx of sediments and the lowered temperature from glacial periods have dramatically affected hydrocarbon generation in much of the central part of the basin. Kinetic modelling shows the oil window substanstially depressed into higher temperature regimes in areas unaffected by the compressional mobilization of the middle Brookian shales (Issler and Snowdon, 1990).

Figures 1 and 2 show that the Aurora location is between areas of the U.S. and Canadian Territories where well and outcrop data are available. Major geologic domain changes occur going from onshore to offshore (south to north) in addition to the increasing complexity of Brookian depositional sequences receiving sedimentary input from the Tuktoyaktuk area (west to east). This necessitates using and extrapolating from the available public data from both areas to reconstruct the burial history at Aurora (Banet, 1990; Kelley and Detterman, 1989; Dixon and others, 1988; Hubbard and others, 1987; Dixon and others, 1985; Dietrich and others, 1985; Craig and others, 1985; Grantz and May, 1983; etc.). Consequently, the data from the Aurora well and its interpretation ties together an important part of the regional geology.

3. Organic Geochemistry

Cuttings and sidewall cores are analyzed using standard organic geochemical procedures. The displays on plate 3 show the variations vs. depth for TOC (total organic carbon), %Ro (vitrinite reflectance in oil), Gas Wetness (headspace ∑C2-C4/∑C1-C4), C15+ extractables, and indigenous kerogen types. Kerogen pyrolysis analyses produces the Genetic Potential (S1+S2), Production Index (S1/(S1+S2)), Hydrogen Index (S2/TOC), Oxygen Index (S3/TOC) and Tmax data. The characteristics of these analyses determine each log unit's oil or gas source potential and extent of thermal maturity with respect to generating and preserving mobile hydrocarbons. Chromatographic data (*Plate 4*) show the distribution of n-alkanes, isoprenoids (pristane/phytane) and the unresolved hydrocarbons. Quantatative hydrocarbon ratios (Carbon Preference Indexes and Pristane/phytane ratios), and the amounts of solvent extracts are also listed. These data are correlated to other other North Slope hydrocarbons.

Sample descriptions accompany the analytical data to facilitate comparison with the lithology determined from the geophysical logs, and to compare with the mudlog, to determine whether sloughing, caving or sample mixing occurred and may have caused apparent extraneous data. This also offers an opportunity to see what, if any, differences occur between cuttings samples (with a large sample population) and side wall cores (with a stratigraphically specific sample population).

Tuktoyaktuk and Brookian Rocks

Total Organic Carbon

Organic richness is the most important aspect of source rock analyses (*tables 3 and 4*). Organic richness is a function of the TOC, the type of indigenous kerogens and the level of thermal maturity. A critical minimum concentration of organic carbon, approximately 0.3% TOC, is necessary for accurate and precise quantitative detection, especially for pyrolysis (*tables 3 and 4*). Also, different kinds of kerogens yield different ranges and amounts of hydrocarbons at different levels of thermal maturity (*figures 3 and 4*). The side by side display of the organic geochemical analyses facilitates the comparison of these aspects to the lab results, the cuttings vs. sidewall core, the mud descriptions and the log interpretation (*Plates 3, 4, and 5*).

Overall the Tuktoyaktuk and Upper Brookian samples from Aurora well have mostly 1 to 2% TOC. These values are fairly uniform with a few widespread, but notable differences (*Plates 3 and 5*). These are considered typical values for the lithologies tested (*tables 3 and 4*). In addition, they are rather similar to the predominantly marine, middle Brookian lithologies analyzed from well cuttings from and around the ANWR 1002 area (Magoon and others, 1987; and Banet, 1990). But, the Aurora well samples have lower TOC's than outcrop measurements from the 1002 area (Banet, 1990; and Lyle and others, 1980). Both Aurora and the outcrop samples have notably high TOC's in the basal parts of the Brookian lithologies.

Table 3
Comparison of organic source rock potential by Total Organic Carbon (TOC) and Pyrolysis

TOC %

CLASTIC	CARBONATE	SOURCE POTENTIAL
0 – 0.50	0 – 0.12	POOR
0.5 – 1.00	0.12 – 0.25	FAIR
1.00 – 2.00	0.25 – 0.50	GOOD
2.00 – 4.00	0.50 – 1.00	VERY GOOD
4.00 –10.00	1.00 – 2.00	EXCELLENT

(Source-Rock Evaluation Manual , Geochem Laboratories Houston , Texas)

PYROLYSIS

Genetic Potential (S1 + S2)

S1 + S2	*equivalent extractables*	
2 Kg/ton	*2000 ppm*	*no source potential*
2 to 6 Kg/ton	*2000 to 6000 ppm*	*moderate source potential*
greater than 6 Kg/ton	*> 6000 ppm*	*good source potential*

(from Tissot and Welte , 1984)

Table 4
Characteristics, common classifications and nomenclatures of sedimentary organic matte (from Hunt, 1978)

	SAPROPELIC	HUMIC		
Kerogen (by transmitted light)	Algal/Amorphous	Herbaceous	Woody	Coaly (Inertinite)
	Liptinite	**Vitrinite**	**Inertinite**	
Coal Macerals (by reflected light)	Alginite (Amorphous)	Sporinite Cutinite Resinite	Telinite Collinite	Fusinite Micrinite Scleratinite
Kerogen (by evolutionary pathway)	**Types I & II**	**Type II**	**Type III**	**Types III & IV**
H/C	1.7 to 0.3	1.4 to 0.3	1.0 to 0.3	0.45 to 0.3
O/C	0.1 to 0.02	0.2 to 0.02	0.4 to 0.02	0.3 to 0.02
Organic Source	Marine / Lacustrine (restricted & anoxic environments)	Terrigenous	Terrigenous	Terrigenous
Maturation Product	Oil, Oil Shale, cannel coal	Oil and Gas	Coal and Gas	Gas and residual carbon

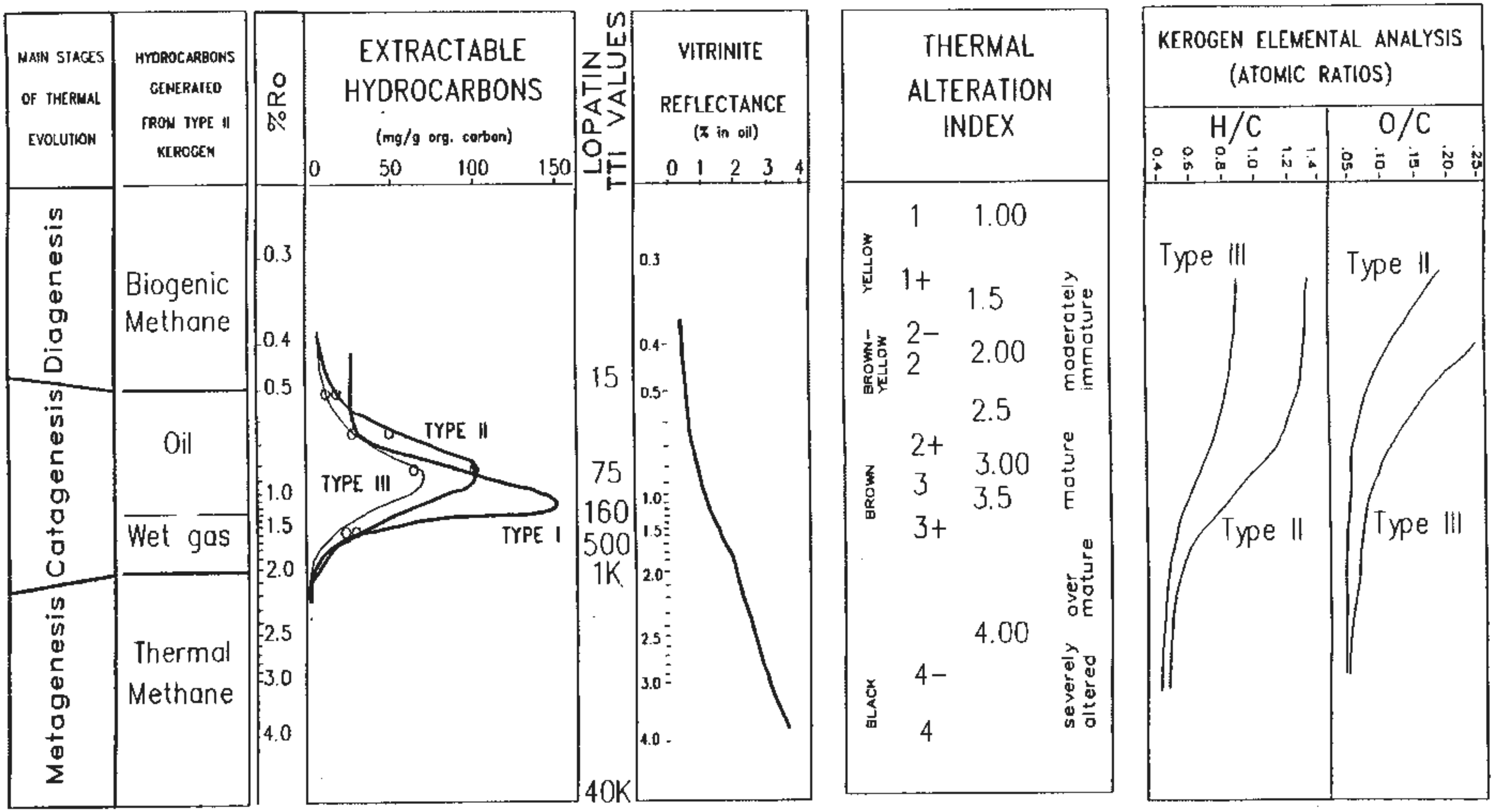


Figure 3
Comparison of maturity indicators
(after Tissot and Welte, 1984)

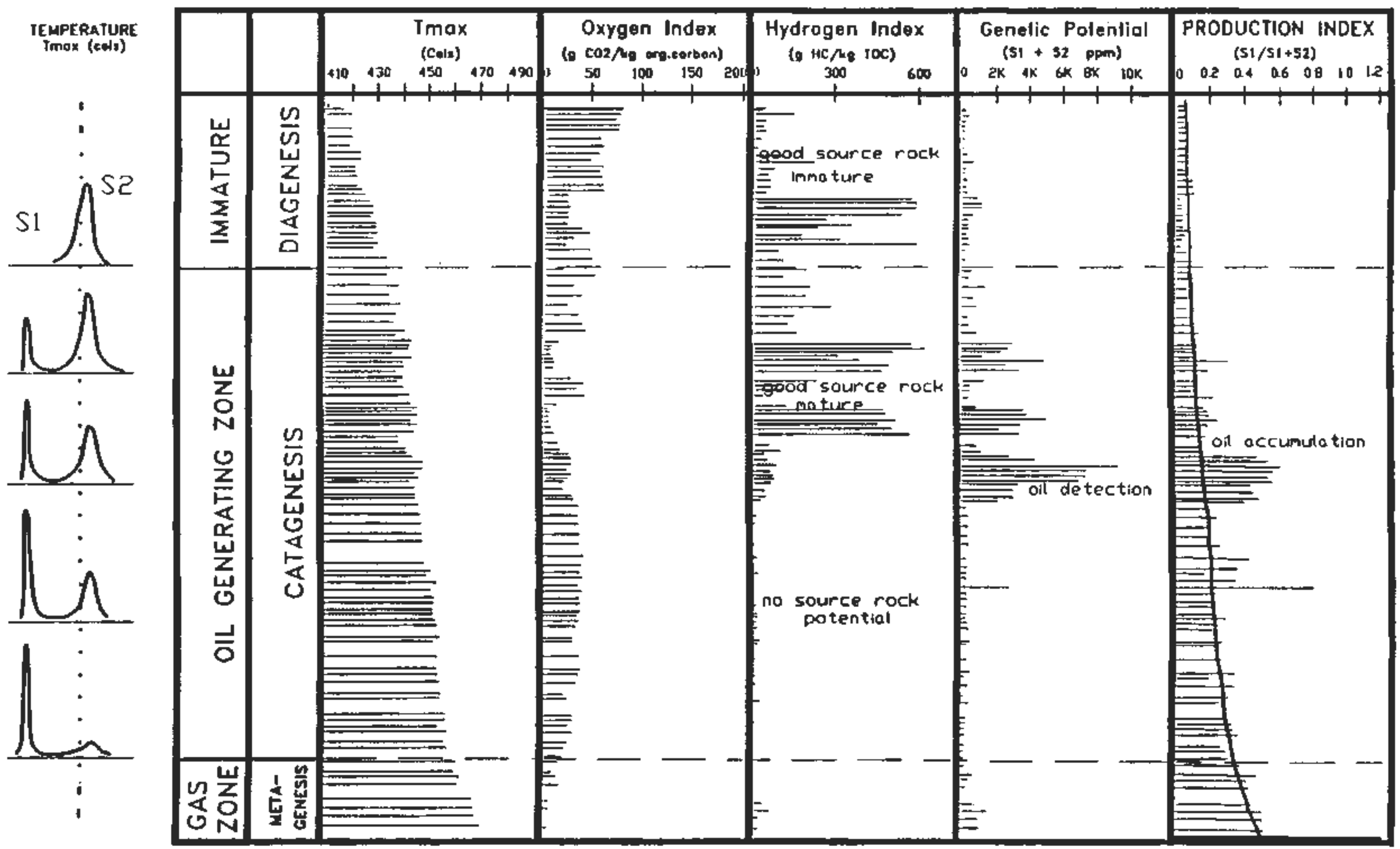


Figure 4

Pyrolysis information

(variations of peak heights and Tmax with increased burial; the threshold temperatures of Tmax maturity; and the Oxygen and Hydrogen Indexes and Genetic Potential of immature and mature source rocks)

Much of the Brookian section at Aurora can be described as having mostly monotonous log response (Banet, 1992). Most of the geochemistry for the Tertiary section is as monotonous as its lithology (plates 2 and 3). TOC values are almost all approximately 1% to a depth of about 15,600. This is not quite coincident with the Lower Tertiary Unconformity picked from the logs at 15,937.

There are several notable, but widespread exceptions to the predomoinantly uniform TOC's. The Upper Brookian between 930 (where sample data are available), and 2,385 has higher TOC's that range in value from 1.5 - 2.0%. These TOC's generally decrease downsection to the average Brookian values of about 1%. Exceptionally high TOC's of 3.5% and 7.5% are at approximately 13,400 (Unit V). The highest TOC values from the Brookian units are in the basal part of the Oruktalik Unit. Side wall core data are particularly noticeable where several samples from the 15,500 - 15,937 interval are as high as 5%; considerably higher than the 1 to 2% TOC's of the cuttings. *Table 3* shows TOC's exceeding 4% can be typically considered to have excellent source-rock potential.

In summary, most of the Brookian section has approximately 1% TOC which could be considered fair to good source rock potential. The upper Brookian samples average greater contents than most of the middle Brookians samples. There are also a few widely scattered, exceptionally rich samples having TOC's between about 2% and 7.5% which could have very good- to excellent potential. However, these higher-potential samples are generally few and widely separated (*Plate 3*). *Table 5* compares Aurora TOC's to onshore wells (Banet, 1990) which typically have higher values for coeval predominantly marine lithologies.

Pyrolysis Data

Pyrolytic analyses of the Brookian section shows some interesting pecularariaties germane to these kerogens. Data from the upper Brookian section have TOC's between 1 and 2%. Pyrolytic analysis shows these samples have generally low organic richness values and low Tmax thermal maturities. Only a few Genetic Potentials exceed 2,000 ppm which is the base of hydrocarbon generating potential. The derivative data, Genetic Potential (G.P.), Production Indexes (P.I.), Hydrogen Indexes (H.I.), and Oxygen Indexes (O.I.) are low, but not exceptionally low because the rocks are thermally immature. Kerogens from this interval plot on

Table 5
Comparison of pyrolysis data from nearby wells and outcrops

Well Name		TOC	MATURITY	G.P.	P.I.	HI	OI
CORONA offshore	n	0.4 - 2.78	immature	6000 12000	<0.20		
HAMMERHEAD offshore	n	1.5% 30% stains	immature	6000 20000	~0.50	100	200 - 800
AK Island	n m	2.0 - 26.0 0.4 - 2.4			.3 -3.0 .3 -3.0	60 - 180 60 - 180	
AK State A	n&m	1% +/-0.5	immature/	~10000 nonmarine	0.2 - 0.3	50 - 200	100 - 400
AK State C	n&m	40% in coals	mature	1000			
AK State D	n m	0.35 - 11	immature - marginally	1000-5000	.05 - .20 .1 - .25	55 - 180 100 - 350	
AK State F	n m	0.3 - 4.0 0.5 - 1.8	marginal/ mature		.1 - .50 .1 - .25	30 - 100 100 -350	
Pt Thomson 1	n	1.2 - 2.2	immature mature	<2000	.2 - .6	50 - 300	
Pt Thomson 2	n m	.7 - 7.0 0.6 - 2.25	immature mature	1000 5000	0.1 - 0.6 .1 - 1.0	30 - 300 50 - 200	
Pt Thomson 3	n m	.5 - 5.0 1.0 - 7.0	immature mature	~1000	.1 - .4 .1 - .35	30 - 300 75 - 150	
Pt Thomson 4	n m	.3 - 7.0 1.5 - 4.0	immature mature	~1000 10000	.1 - .4 .1 - .15	50 - 75 75 - 100	
E. Mikkelsen Bay	n m	0.5 - 7.0 1.2 - 1.8	marginal mature	1000- 3000	0.20 - 0.40	<150	~200
W. Mikkelsen Bay 1	n m	0.2 - 17.0 0.1 - 22.0	immature- mature	1000 3000	0.10 - 0.30	<100 400	<400
W. Mikkelsen Bay 3	n m	0.2 - 11.0 0.4 - 4.3	mature	<1000 5000+	0.90	<100	<<100
Leffingwel							
Bell	n m	0.2-8.5, >30 in coal 0.5 - 2.0	marginal - mature	>10000 2000 - 5000	.05 - .15 .13 - .36	34 - 422 79 - 215	96 - 674 138 - 270
Canning A	m	1.0 - 3.0	mature	2000 - 5000	.2 - .4	<50	<50
Canning B	n m	1.0 - 2.0 0.5 - 3.0	marginal - mature	<1000 1000 - 3000	.2 - .3 .2 - .5	<50 50 - 150	100 - 200 50 - 200
Kavik	m	1.0 - 4.0	mature	<4000	.2 - .9		
W. Kavik	n m	0.5 - 1.0 >> in coal 1.0 - 3.0	marginal mature	1000 5000	.1 - .7 .2 - .3	<100	<<100
Kemik	m	0.5 - 2.0	mature	1000 - 3000	.1 - .3	50 - 400	<400
Kemik 2	m	1.0 - 2.5	mature	1000 - 5000+	.90	<100	<<100
Fin Ck.	m	1 - 2	marginal mature	1000 - 10000	.1 - .3	<100	100 - 200
OUTCROPS IN 1002		0.3 - 20.0 .05 - 3.0	immature marginal	<2000 - 10000 <2000 - 20000		50 - 150 50 - 350	
BENTONITIC SHALE	w c	1.5 - 7.0 0.5 - 12.0	mature	1000 3000	0.10 - 0.30	<100 400	<400
PEBBLE SHALE	w c	1% - 2% 1% - 2% 1% - 2%	mature/ over	5000+		<100 <100 <100	
KINGAK SHALE	w c	1.2 - 2.3 0.6 - 3.4 0.5 - 3.0	mature- over	<5000		50 - 100 0 - 35 25 - 350	

w wells c crops

modified van Krevlen diagrams as typical immature, gas prone, Type III *(figure 5)*.

Most of the kerogens from the middle Brookian interval demonstrate very low potential to generate hydrocarbons, irrespective of thermal maturity *(Plates 3 and 4 and figure 5)*. In addition to low G.P. and P.I. the Hydrogen and Oxygen Indexes plot so low on modified van Krevelen diagrams *(figure 5)* that they indicate the indigenous organic matter is composed of predominantly recycled or residual organic material which has essentially no potential to generate hydrocarbons (Tissot, 1984). Much of the material identified as amorphous and shown on *Plate 3* should be more properly considered as part of the Inertinite maceral.

Overall, the hydrocarbon indicator values for most of the middle Brookian rocks are low - quite low considering that the lithologic log recorded minor occurrences of peat, partially coalified wood fragments, coal and some oil staining. Onshore outcrop samples from the ANWR 1002 area which are typically severely weathered have similar low pyrolysis values. By contrast middle Brookian sequence well samples, from immediately outside the ANWR 1002 area, typically have much higher hydrocarbon generating potential than either the Aurora samples (*figure 5*) or the onshore outcrop data (Banet, 1990).

Tmax thermal maturity is within the diagenetic and catagenetic ranges throughout both the upper and middle Brookian sections. However, pyrolysis shows that most of these samples are lean, which means that they yield few hydrocarbons during pyrolytic induced catagenesis. Two Genetic Potentials, at about 3,500 and at about 4,000 showed good source rock potential *(figures 3 and 4, Plate 3)*. The single sample from about 3,500 also had an oil-prone Hydrogen Index, and a high Production Index, which, considering the diagenetic level of thermal maturity, suggests that the hydrocarbons were migrated or contaminants. There are a few widely scattered (stratigraphically) samples with Genetic Potentials having moderate hydrocarbon generating potential at about 9,800, 11,000, 13,400 and 14,300. Low Hydrogen and Oxygen Indexes indicate that these samples represent organic facies that are apt to produce gas, rather than liquid hydrocarbons.

Correlative lithologies, onshore, have considerably more potential to generate liquid hydrocarbons (Banet, 1990). The nonmarine lithologies have comparable, or higher average Hydrogen Indexes than most of these predominantly

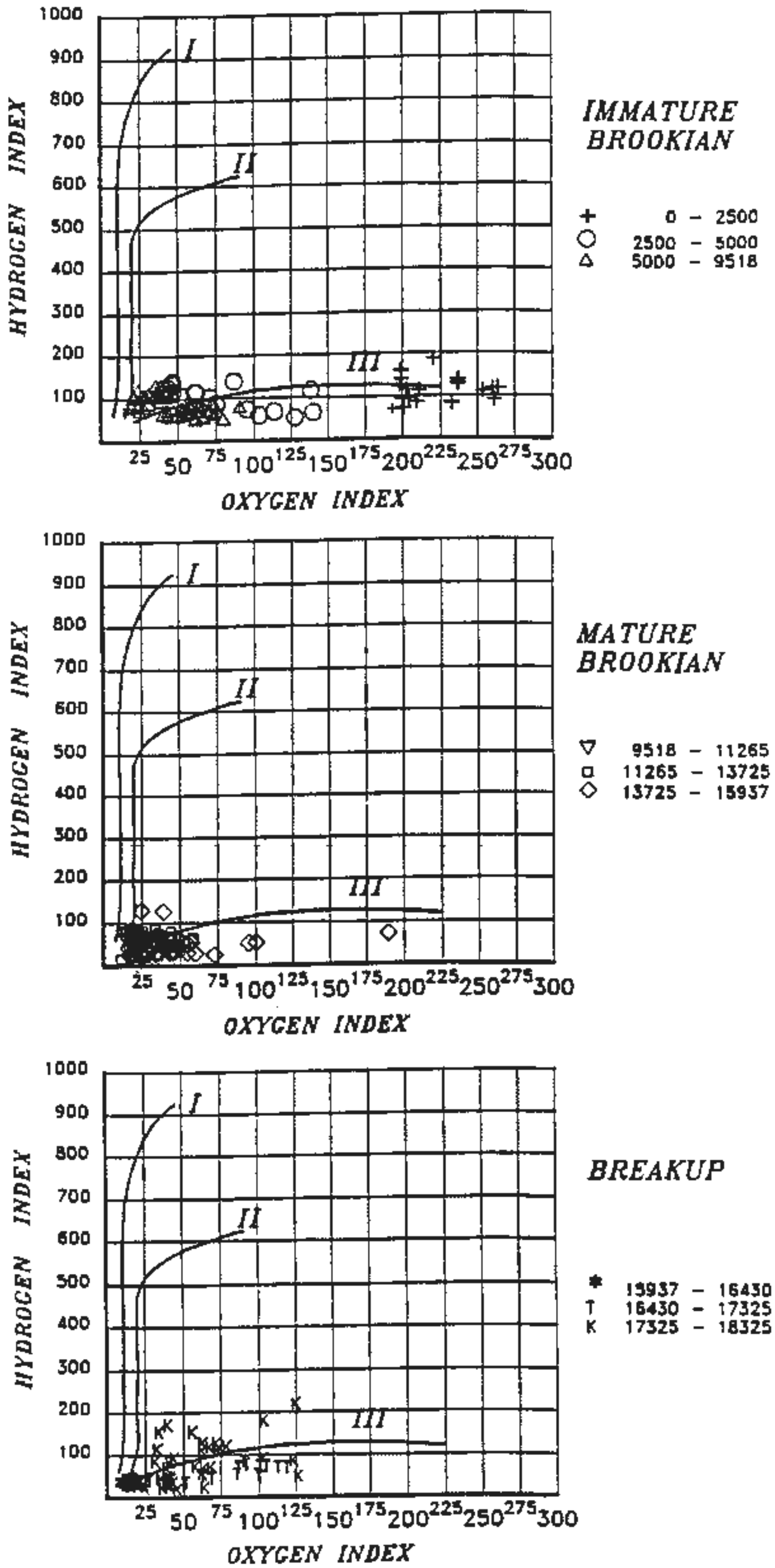


Figure 5
Modified van Krevien diagrams showing kerogens from the three major stratigraphic divisions at Aurora well

marine shelf, middle Brookian samples at Aurora. Thus, the dearth of Aurora samples with good source rock potential indicates that most of the Brookian rocks are unlikely candidates for consideration as prime oil generating source rocks at this location. This includes most of the high TOC, thermally mature samples near the base of the Brookian section. Furthermore, analysis of the middle Brookian section indicates that these rocks have very little gas generating capacity. The predominantly low values of the pyrolysis data (G.P., P.I. and O.I.) show that the kerogens are mostly recycled organic matter and are very similar to rocks that have already passed beyond the catagenetic phase.

By comparison, there are no identified, good, mature source rocks in the middle Brookian sequence of the Canadian Beaufort. Rather, the hydrocarbon source rocks are buried more deeply and more basinward than current exploration drilling (Issler and Snowdon 1990).

Kerogens

Despite the monotonous lithology, kerogen types appear to be more varied through the Brookian section than in the older rocks (Plate 3). Amorphous kerogen is the predominant species described. However, this probably means that most of the macerals were difficult to identify accurately and precisely, rather than being truly amorphous sapropelic kerogens. Pyrolyitc analyses (G.P., P. I. and H.I.) show far too little potential to generate hydrocarbons from this material than from average Amorphous kerogen macerals at these levels of thermal maturity. Tissot (1984) describes similar pyrolytic results from recycled or residual Type IV organic material that has almost no petroleum generating potential. Thus most of the amorphous material should more accurately be considered as Inertinite. (For comparison I use Amorphous as the correctly identified hydrogen-rich maceral and amorphous as the catch-all category describing the Aurora kerogens)

This amorphous kerogen constitutes some 40 - 80% of the total kerogens in the 930 to 5,000 section. It comprises approximately 80% to a depth of 9,000, and it varies from 5 - 95%, throughout the rest of the Brookian section. Alginite is a rare and unique maceral to the middle Brookian rocks at this location. This Alginite comprises a mere 5% ot the total kerogens at about 8,300 which is its only occurrence. Exinite accounts for some 20% of the kerogen at 930 but the content decreases continuously down-section. Exinite is totally absent by approximately 6,000 *(plate 3)*. Only one other sample recorded any Exinite; 5% at 14,900.

Vitrinite content ranges from 5 - 40% between 930 to 6,000. It averages 10 - 15% to about 8,300, and it varies widely between 0 - 60% downsection to about 15,900. Finally, Inertinite was identified in almost all of the samples. Between 930 about 8,500 it varied from 5 - 20%. Below about 8,500 the content varied greatly from 0 - 70%, and below 15,000, Inertinite content dropped below 5%. Kerogens from correlative onshore lithologies are mostly Herbaceous or Woody with only minor amounts of Inertinite or amorphous material (Banet, 1990). Kerogens anlayzed from in and around the 1002 area at comparable thermal maturities commonly have moderate to good potential to generate hydrocarbons, including liquids. Evidently organic facies, and preservation in the Upper and Middle Brookian sections change markedy with the changing sedimentation patterns. The kerogens which determine hydrocarbon source rock potential of the Brookian rocks apparently become leaner, across the 1002 area.

Alternatively, the middle Brookian rocks at Aurora lack the thick, gray, marine shales found to the west. At least part of the reason is that the middle Brookian interbedded silts, sands and shales at Aurora represent more shelf depositonal environments than the deepwater facies found to the west. These typically have predominantly terrigenous organic material rather than the sapropelic kerogen found in deep water shales of the middle Brookian, onshore.

Extractable Organic Matter

Bitumen extracts are available only for the Brookian sectionabove 15,830. Total organic extracts (Soxhlet extraction using methylene chloride) vary between 314 to 14,269 ppm, with an average value of 1,305 ppm. The C15+ hydrocarbons range in value between 195 and 11,644 ppm. Nonhydrocarbon asphaltenes and resins comprise a much smaller portion of the extractables. Asphaltenes range in value from 73 to 1,945 ppm (table 6). Plate 5 shows the total extract data, plotted log scale as bar graphs, superimosed atop the %Gas Wetness curve.

Overall, the C15+ extracts do not increase with depth and increasing thermal maturity. In fact, they mostly decrease with depth and increased thermal maturity. *Figure 6* shows this source rock determination data (extract vs. TOC) plotted with the thermally

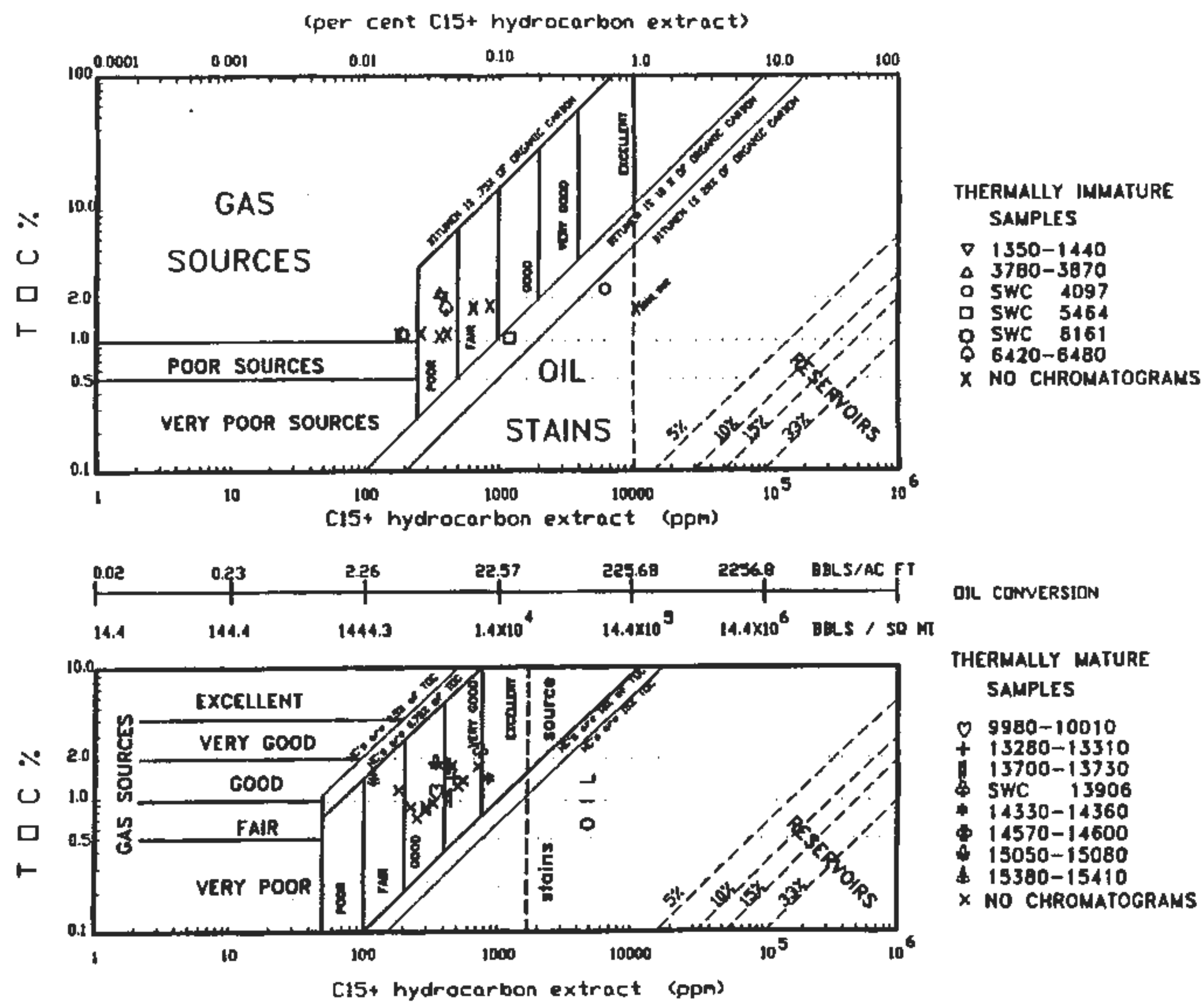


Figure 6
C15+ Hydrocarbon Source Potential determination and comparison between thermally mature and immature samples

immature samples at the top and the suite of thermally mature samples plotted beneath.

On initial inspection, most of the Aurora samples plot as poor to fair source potential for oil or as potential gas sources *(figure 6)*. The two highest C15+ extractable hydrocarbon values, 11,644 ppm at SWC 3592 and 6162 ppm at SWC 4097 are coincident to the highest pyrolysis data *(Plate 3)*. These high values show very good hydrocarbon potential and could be considered source rocks.

However, the C15+ hydrocarbon extracts comprise most of the samples' TOC (95.13 and 33.40%, respectively). Figure 6 shows that they plot well into the field of oil stained sediments. Also, because this portion of the well is thermally immature for the generation of hydrocarbon rich bitumen, these values reflect the presence of migrated hydrocarbons or contamination, and do not represent the potential of the indigenous hydrocarbons. Three additional samples representing the intervals 4,770 - 4,860, 5,400 - 5,490 and SWC 5,464 also have anomalously high extract values, high extract/TOC ratios and low thermal maturities, but do not have anomalously high pyrolysis data. These also probably represent migrated hydrocarbons. Thus, the remaining samples that are thermally immature have C15+ hydrocarbon values between 358 and 401 ppm with an average of 390 ppm. They have gas generating potential or poor-to-fair oil generating potential.

Other data from the extactable hydrocarbons shows that the pristane/phytane ratios are variable but overall increase, with depth, from approximately 1.00 to 1.71 through the thermally immmature Brookian section. Pristane/n-C17 data range in value between 0.57 and 1.53, showing no systematic changes with depth. CPI's are similarly variable and high, also suggesting immature bitumens. The saturates/aromatics ratios are between approximately 1.00 and 1.50 and total hydrocarbons are between 54 and 82% with no trends related to burial maturity. Since the lithologies, and likely the depositional environments, of the thermally immature samples are all similar, changes with depth should reflect increasing maturity effects. No such trends are apparent except that the anomalously high extract samples have C15+ hydrocarbon extract values more like bitumen from thermally mature samples. This supports interpretation that these anomalously high values represent migrated hydrocarbons, or contaminants.

Chromatograms of samples

from this section show that the samples with the greatest amounts of extractable hydrocarbons are severely degraded *(Plate 4)*. These chromatograms (SWC 4097 and SWC 3592) are devoid of resolveable n-alkanes due to severe weathering or biodegradation. They are distinctly similar to chromatograms of the oil-stained siltstones (Eocene) and Bentonitic shales (upper Cretaceous) found on the 1002 area coastal plain aproximately 18 miles south-southwest of Aurora (Banet, 1990). Samples from SWC 5464, the interval 5,400 - 5,490, and 4,770 - 4,860, also have high total C15+ extract values and high percentages of hydrocarbons. These appear to be marginally-mature marine-derived hydrocarbons (Plate 4). This observation also supports that they represent migrated bitumen. The remaining chromatograms have bimodal alkane distributions with high CPI's common to immature extracts, and most have a bimodal hump of nonresolveable compounds, reminsicient of terrigenous kerogens *(Plate 4)*. Note chromatogram similarities between the nonresolveable humps of the thermally immature samples from Aurora and the chromatograms of severely altered/weathered samples from Kavik Creek and along Katakturuk Creek of the 1002 area (Banet, 1990).

Analyses of hydrocarbon extracts, oil seeps and stains from onshore representing approximately coeval and nonmarine facies of the immature section at Aurora are all severely altered and weathered (Banet, 1990, Magoon and others 1986, Magoon and Claypool, 1981). By contrast, the Prudhoe suite oils generated from predominantly marine source rocks, have pristane/phytane ratios less than 1.5 and gas chromatograms which reflect a mature, and marine source rock derived crude oil.

The thermally mature Brookian C15+ hydrocarbon extract samples lack the anomalously high values of the migrated hydrocarbons that are conspicuous in the immature suite. These mature-sample hydrocarbon extracts range from 195 to 879 ppm with an average of 397 ppm These values are similar to the suite of immature samples and should be normal for their level of thermal maturity. Note also however, that there is no appreciable increase of extractables content with depth, even though thermal maturity reaches the mid-catagenetic range *(Plate 5)*.

These thermally mature sample extracts plot as having between fair to excellent potential oil generating sources *(figure 6)*. By contrast however, the pyrolysis data through the same interval shows source rock potential of the indigenous kerogens falls mostly into the no potential category. Pyrolysis data with Genetic Potential values in the moderate category are found only at about 9,500, 11,200, 13,600 and 14,300 *(Plate 3)*. Although the latter two intervals have coincident data, the extract data indicate far more source rock potential (very good to excellent, for oil) than do the kerogen data (fair, for gas). Accompanying Hydrogen and Oxygen indexes suggest Type III kerogens or Inertinite, mostly at advanced stages of thermal maturity rather than being fair to excellent potential source rocks *(figure 5)*.

Lithologic types are mostly uniform through the thermally mature Brookian section, and are generally similar to those in the overlying section. Consequently, whatever changes to the organic extracts that occur should reflect increasing thermal maturity, or presence of more migrated hydrocarbons.

Pristane/phytane ratios of the thermally mature Brookian section are markedly higher than through the immature section. They are mostly between about 2.25 and 2.75 except for the two deepest. Two extracts from Middle Brookian rocks in the 1002 area, a sandstone along Canning River and a conglomerate along Sabbath Creek, have similar pristane/phytane ratios (Banet, 1990). The pristane/n-C17 ratios are also higher than the in the immature samples but they also decrease through this interval. The CPI's are mostly greater than 1.30 and are not markedly different from the immature samples, except below about 15,000. Overall the total extract values and extract:TOC ratios are lower and show less variance than through the immature samples *(table 6)*. Again, there are no hydrocarbon-extract trends with depth and increasing thermal maturity. In fact, the CPI's and saturate:aromatic ratios are opposite what would be expected for comparing thermally immature and mature samples of such similar lithologies. The lack of normal thermal maturity trends, and the disparity beteween the C15+ hydrocarbon extract data and the pyrolytic kerogen analyses suggests the presence of migrated or contaminant hydrocarbons through this part of the thermally mature section.

Chromatograms of the thermally mature samples are generally similar for samples between the 8,940 - 9,000 and the 11,570 - 11,600 interval. However, these chromatograms appear to be more similar to extracts from rocks typically at the very beginning of catagenesis. Their accompanying

Table 6
Data from eluted C15+ liquid chromatatographic fractions

INTERVAL/ DEPTH	SYMBOL	TOC (%)	*extract/ TOC (%)*	Pr/Ph ratio	*Pr/ nC-17*	CPI	total Extract	total HC's	%HC's	sat'd's	aro's	asph	[illegible]	total non HC's	bal ?
		ratios						HYDROCARBONS				NONHYDROCARBONS			
1350 – 1440	▽	2.01	*4.34*	1.13	*0.69*	2.38	737	396	54	237	159	131	172	303	38
3780 – 3870	△	2.17	*3.86*	0.76	*0.57*	1.20	852			157		280			
3308 SWC	×	1.50	*2.59*	0.58	*1.02*	1.71	401			87		122			
3592 SWC	×	1.56	*95.13*	---	--	---	14269	11644	82	5690	5954	400	1545	1945	680
4097 SWC	○	2.26	*33.40*	---	--	---	7783	6162	79	3081	3081	440	672	1112	509
4770 – 4860	×	1.67	*8.43*	1.03	*0.89*	1.16	1223	880	72	539	341	76	214	290	53
4962 SWC	□	1.55	*3.15*	0.74	*1.28*	1.47	485			117		108			
5400 – 5490	×	1.60	*5.70*	1.07	*1.10*	1.26	912	611	67	358	253	76	174	250	51
6420 – 6480	♤	1.56	*4.86*	1.03	*1.52*	1.36	608	401	66	200	201	83	108	191	16
5464 SWC	×	1.18	*11.19*	1.28	*1.14*	1.09	1410	1137	81	758	379	138	112	250	23
6161 SWC	○	1.22	*2.99*	1.28	*1.53*	1.83	353			84		117			
7800 – 7860	×	1.14	*4.33*	1.71	*1.42*	1.58	481	358	74	180	178	53	61	114	9
8940 – 9000	×	1.37	*4.03*	1.88	*1.27*	1.39	608	405	67	233	172	99	77	176	27
9980 – 10010	♡	1.02	*5.03*	*2.66*	*1.91*	1.40	519	339	66	117	222	95	78	173	7
10340 – 10370	×	1.30	*6.13*	*3.38*	*2.57*	1.63	815	549	67	222	327	111	136	247	19
10430 – 10460	×	0.92	*5.44*	*2.19*	*1.31*	1.38	495	333	67	132	201	77	77	154	8
11060 – 11090	×	0.87	*4.89*	*2.36*	*1.83*	1.37	422	316	75	134	182	55	49	104	2
11570 – 11600	×	0.68	*3.92*	*2.47*	*1.68*	1.34	353	261	74	110	151	50	39	89	3
11990 – 12020	×	0.96	*3.89*	*2.28*	*1.36*	1.30	362	232	64	72	160	72	53	125	5
12500 – 12530	×	1.15	*2.71*	*2.26*	*1.07*	1.50	314	195	62	96	99	60	56	116	3
13100 – 13130	×	1.72	*2.73*	2.28	*1.25*	1.36	728	469	67	214	275	131	104	235	4
13280 – 13310	+	1.34	*5.14*	2.66	*1.27*	1.23	684	492	72	224	268	101	60	161	31
13430 – 13460	×	1.18	*4.37*	2.49	*1.14*	1.46	581	433	74	209	224	94	49	143	5
13580 – 13610	×	1.79	*4.30*	2.35	*1.16*	2.35	1019	750	74	358	392	173	86	259	10
13700 – 13730	ℍ	1.11	*1.94*	2.54	*1.09*	1.58	616	448	73	215	233	91	74	165	3
14060 – 14090	×	1.40	*3.42*	2.78	*0.97*	1.21	673	520	77	229	291	78	66	144	9
13906 SWC	♧	2.10	*5.38*	2.59	*1.43*	1.39	1098	717	65	322	395	227	146	373	8
14330 – 14360	*	1.27	*8.41*	2.42	*0.95*	2.42	1043	879	84	625	254	66	92	158	6
14570 – 14600	[illegible]	1.68	*4.81*	2.20	*0.79*	2.39	808	462	57	247	215	197	138	335	11
15050 – 15080	[illegible]	1.68	*2.79*	2.22	*0.78*	1.19	430	334	78	187	147	50	40	90	6
15380 – 15410	×	1.36	*1.85*	1.63	*0.53*	1.16	332			105		85			
15800 – 15830	[illegible]	2.78	*1.26*	1.88	*0.51*	1.18	354	276	78	87	189	35	38	73	5

(bal ? = unrecovered fraction, i.e. non-eluted components and material lost during solvent evaporation) anomalously high CPI values and bimodal shapes of the nonresolveable fractions support this tenet. With %Ro's greater than about 0.70, chromatograms appear to have a mature, predominantly nonmarine/terrigenous kerogen derived hydrocarbon distribution. Only chromatograms of the deepest samples appear to be predominatly marine derived.

An unidentified peak eluting between n-C20 and n-C21 appears in the 12,500 - 12,530 chromatogram, prominently in the 13,100 - 13,730 (three different samples), and as the largest peak in the 14,570 - 14,600 samples. This may be a manmade contaminant or a naturally occurring substance. Comparing chromatograms of some crude oil alkane fractions, suggests that the unidentified peak may be a mono-methyl substituted n-C20 alkane, such as 9-Methyleicosane, or most likely a C-23 Regular isoprenoid, such as 2,6,10,14-Tetramethylnondecane (Ronov, 1987). Snowden (1978) reported possible methyl(?)-substituted diterpanes (possibly diesel contaminant) eluting with the alkane fraction of some crude oil extracts from Cretaceous to Tertiary age sediments from the Canadian Beaufort-Mackenzie Delta. This unidentified peak in the Aurora chromatograms could be a similar methyl-substituted polymerized isoprenoid like a diterpane. While this is possible, it is unlikely because it does not elute at the same time, between the same n-alkanes, nor does its shape resemble the broad diterpane elution.

The chromatograms where the unidentified peak appears, especially where it is most prominent, have some additonal unique features. These chromatograms show enrichment in the nC-25+ odd-numbered alkanes. Thus, the bitumen from these samples of thermally mature Brookian sediments appears more like bitumen indigenous to immature sediments. This would support that these extracts represent migrated hydrocarbons. However, migrating mostly immature hydrocarbons into mostly mature (with respect to the organic reactions) sediments requires a more complicated migration scheme(s). The chromatograms from the deepest samples appear as typical, mature, predominantly marine-derived extracts. Comparing chromatograms, there are minor similarities between the mature Brookian extracts and Middle Brookian extracts from along Katakturuk Creek in the 1002 area, which have similar high pristane/phytane values (Banet, 1990).

Breakup Sequence

Total Organic Carbon

TOC's from the Breakup Sequence at Aurora vary between about 0.5 and 3.5%, with most values falling between 1 and 2%. Unit III, 15,937 - 16,446 shows about a 1% difference between sidewall core values (SWC's) which are slightly less than 1% and cuttings samples which are 2% and greater. This shows that either the SWC's are not representative of this section or that some of the overlying, organic rich Bookian cuttings have mixed with Unit III cuttings. However, stuck pipe and drilling problems necessitated side tracking at about 15,503 and at 16,556. These problems resulted in poor sample recovery and the probable addition of lost-circulation materials warrant suspicion of the analyses from this part of the hole.

TOC's are mostly around 2% through the upper portions of the Tapkaurak Unit 16,446 - 17,000 coincident with the increased sand content. TOC's fall to about 1.25 - 1.50% towards the base of the unit at 17,325. TOC's through Unit I, the Kingak Formation, range between 1.12 and 2.77%, with an average of 1.55%. The TOC's from these three Breakup sequence units are comparable to the TOC measurements from stratigraphically equivalent onshore units. TOC's range between 0.4 - 5.1% for the HRZ and Pebble Shale units and from 0.6 - 3.4% through the Kingak Formation, where tested in and around the 1002 area (Banet, 1990, Magoon and others, 1986, and Lyle and others 1980).

Pyrolysis

Pyrolysis data for the Breakup sequence samples plot as predominantly gas-prone Type III kerogens. By comparison they appear to have more potential for generating hydrocarbons than any of the mature Brookian samples. Many samples from the Kingak and Tapkaurak Units also appear to be less thermally altered than the kerogens from the overlying, thermally mature Brookian samples *(figure 5)*. These observations reinforce the interpretation that much of the kerogen from the middle Brookian section is recycled, mostly inert, organic material rather than kerogens having hydrocarbon generating capacity. Additionally, these analyses may reflect contamination from drilling additives through the Breakup sequence.

Similar data from the onshore, show that the Pebble Shale unit, which is partly coeval and correlatable to the Tapkaurak Unit has Genetic Potentials generally less than 2,000 ppm and mostly low Hydrogen Indexes, 35 - 400 mg/g. However, the onshore data are from widely differing thermal maturities which affects the comparisons of much of this data. The Kingak Formation has Genetic Potentials mostly less than 5,000 ppm and slightly lower Hydrogen Indexes, 25 - 350 mg/g than the Pebble Shale Unit *(table 5)*

Thermal Maturity

The thermal maturity data, %Ro, TAI, Tmax and Gas Wetness show that the diagenetic zone is from the begining of data at 930 to 9,518. These data have a single trend through the diagenetic section. The %Ro, Gas Wetness and Tmax increase with depth at moderate, but approximately constant rates. However, the rate of increase and the onset of thermal maturity vary for the TAI determinations *(Plates 3 and 5, table 7, and appendix).*

The maturity indicators concur indicating that the catagenetic zone extends from 9,518 to about 17,500. The onset of catagenesis picked at the pronounced offsets of the %Ro and Gas Wetness data. These offsets coincide most closely with the log breaks which separate Unit IX from Unit X *(Plates 3 and 5).* Through the catagenetic zone the %Ro, varies from 0.55% to about 1.8%. The Gas Wetness curve abruptly increase from about 25% through the diagenetic zone to about 70%. Through the catagenetic zone Gas Wetness typically ranges between about 60% and 80% *(Plate 5).* Highest Gas Wetness values (greater than 80%) occur between 12,600 and 14,685. This interval includes the Oruktalik sand from which a minor gas show was recorded, but not tested. There is a Gas Wetness minimum at about the base of the middle Brookian sequence at 15,937. But, this minimum is not considered to be the base of the thermally mature section because wetness values steadily increase again to about 45%, down to about 17,200. Below 17,500 Gas Wetness declines abruptly.

The %Ro (0.55%) for the beginning of catagenesis, at Aurora, is slightly lower than the more typically accepted value of 0.60%. However, there are at least three reasons for using this lower value for the onset of thermal maturity at Aurora. At the 9,518 log break, there is a distinct offset (at least 0.05% across the log-break) to the %Ro data. In addition, the kerogens from this section are markedly Hydrogen-deficient *(figure 5)*, and Hydrogen deficient kerogens, such as Type III, typically begin to yield hydrocarbons at lower thermal maturities

Table 7

Stratigraphic and thermal maturity date used in the burial history model

Formation Event/ Log Unit	Type	Begin Age (Ma)	Well top ft	Present section ft	Missing section ft	Lithology ss/slst/sh log %	Init por	Compact Factor km^{-1}	Average Density g/cm^3	Matrix Cond W/m^oC	Heat Cap kJ/m^3	TOC %
Gubik-ShallowBay	F	.125	0	50		50/30/10	0.54	2.13	2.62	2.11	2562	
trans-regs	H	2										
Gubik-Tuk	F	3	50	250		30/50/10	0.54	2.13	2.62	2.11	2562	
Tuk Unconformity	E	3.2			-2000							
prehia	H	4.5										
missing Mio-Plio	D	10			2000	25/25/47	0.56	2.22	2.6	1.86	2378	2.5
Miocene unc	E	12			-2000							
hiatus	H	14										
miss Olig-Mio	D	25			2000	25/25/47	0.56	2.22	2.6	1.86	2378	1.3
XIV U Brookian	F	35	300	2085		25/25/47	0.59	2.35	2.59	1.59	2174	1.5
hiatus	H	36										
U Brookian Unc	E	38			-2000							
hiatus	H	39										
XIII	F	40	2385	1050		05/08/89	0.59	2.37	2.6	1.56	2151	1.1
XII	F	41.5	3435	1243		07/08/85	0.59	2.35	2.6	1.59	2176	1.5
XI	F	43	4678	1307		10/10/79	0.58	2.33	2.6	1.64	2213	1.2
X	F	55	5985	3533		07/08/89	0.59	2.35	2.6	1.59	2176	1.0
IX	F	56	9518	972		05/05/89	0.59	2.37	2.6	1.56	2151	.8
VIII	F	58	10490	805		10/10/79	0.58	2.33	2.6	1.64	2213	.8
VII	F	58.5	11295	798		07/08/85	0.59	2.35	2.6	1.59	2176	1.0
VI	F	59.2	12093	1159		--/04/89	0.6	2.4	2.59	1.49	2110	1.0
V	F	59.3	13252	473		--/08/90	0.6	2.4	2.59	1.5	2129	1.5
IV Oruktalik	F	59.8	13725	2212		25/20/53	0.56	2.22	2.6	1.86	2362	2.0
LTU	E	60			-2500							
hiatus	H	62										
Colville Sh	D	85			1500	10/20/67	0.59	2.35	2.61	1.64	2266	3.0
Bentonitic Sh	D	97.5			500	--/11/80	0.63	2.52	2.51	1.27	2006	9.0
Mid Brookian U	E	100			-2000							
hiatus	H	102										
HRZ	D	111			500	05/20/70	.6	2.4	2.53	1.35	2010	5.0
III	F	122	15937	509		08/20/69	.6	2.41	2.58	1.47	2112	2.5
II Tapkaurak	F	125	16446	879		40/10/48	0.54	2.14	2.6	2.02	2412	2.0
hiatus	H	127										
LCU	E	144			-2000							
hiatus	H	150										
I Kingak	F	165	17325	2000		05/15/57	0.59	2.05	2.6	1.59	2200	1.5

F formation deposition
H depositional hiatus
E erosional event
D eroded unit

Table 7, continued

Geothermal Gradient Data

	section 1		section 2		section 3		section 4	
Time (Ma)	Depth 1 ft	Gradient (°F/1000 ft)	Depth ft	Gradient (°F/1000 ft)	Depth ft	Gradient (°F/1000 ft)	Depth ft	Gradient (°F/1000 ft)
0	0	10	9518	12.50	14000	14.0	18000	15.5
40	0	12	8000	14.0	15000	17		
63	0	12	5000	15				
100	0	15	5000	17				
135	0	12	3000	12.5				
140	0	12						

BoreHole Temperature Table

Depth (feet)	Temp (%F)	Factor
3040	62.1	2.0
9477	158.0	1.5
14928	203.0	1.2
15500	255.0	1.1
18325	325.0	1.0

Current Surface Temp = -10
Current Heat Flow = 2.00
Current Surface elevation= -60.1
Well Data
Longitude = 0.00000000
Latitude = 0.00000000
KB Elevation = 0.00

Time (Ma)	Heat Flow (HFU)	Subsurface Temp °F	Sea level/depth ft	ft
.05	1.0	30	0	0
.125	1.00	35.1	100	100
2.0	1.43	45.0	-500	100
3.0	1.55	60.1	200	100
4.0	1.5	60.0	-200	0
5.1	0.96	40	-200	300
10	0.96	40	-500	300
12	1.67	70.0	-500	0
20	1.19	40	300	300
30	1.70	40.0	100	100
38	1.55	50	-500	0
39	3.34	70.0	-100	200
41	1.79	40	500	300
59	2.75	40	400	300
60	4.06	70.0	-500	0
85	1.79	50.0	400	300
98	2.03	40	300	750
100	3.82	70.0	-300	0
125	2.15	40	200	200
128	3.0	55	0	0
144	4.00	40	0	0
165	2.8	40	100	300

Maturity =Ro
Current Elevation = -60.00
Thermal Conductivity = (Watts/m*%C)
Heat Flow = (HFU)
Gradient = (%F/1000 ft)
Arrhenius = (1/my)

Model Parameters
Compaction = Mechanical
Thermal Calculation = Gradient
Use BHT's = Smooth
TTI Reference Temp = 105.00
TTI Doubling Temp = 10.00
Maturity Calculation = Lopatin
Kinetics Calculation = Quick
Time Interval = 5.00
Depth Interval = 1000.00
Integrate Depth = Yes
Kerogen Mode = LLNL

Table 7, continued

Measured Maturity Table

Depth (feet)	%Ro	TAI	Tmax
1170	.30		428
1350	.34		428
1710	.35		426
2070	.36		427
2340	.36		424
2610	.36		423
2970	.37		421
3183	.39		416
3509	.36		417
3817	.39		427
4135	.37		426
4531	.37		422
4866	.37		423
5123	.42		424
5370	.41		425
5663	.44		422
5962	.36		422
6346	.41		426
6754	.29	2.0	423
7152	.41	2.0	423
7438	.47	2.0	424
7732	.41	2.0	426
8059	.43		428
9249	.49		426
9560	.56	2.0	437
9830	.55	2.0	435
10130	.61	2.0	436
10430	.58	2.0	438
10457	.60	2.0	435
10730	.60	2.0	437
11030	.60	2.0	439

Measured Maturity Table

Depth (feet)	%Ro	TAI	Tmax
11300	.62	2.0	439
11630	.63		439
11930	.63	2.2	440
12200	.65	2.0	438
12230	.63	2.0	439
12254	.62	2.2	441
12830	.74	2.2	440
13100	.71	2.2	444
13400	.78	2.6	429
13670	.79	2.8	446
13821	.89	2.6	445
14000	.86	2.5	451
14300	.91	3.0	451
14588	1.10	3.0	431
14900	1.17	3.0	460
14977	1.10		469
15200	1.15	3.2	453
15530	1.23	3.0	458
15762	1.51		490
15800	1.48	3.2	477
16100	1.47	3.2	472
16400	1.57	3.2	472
16700	1.69	3.8	472
16705	1.59	3.4	501
16950		3.6	470
17160	1.56	3.4	445
17310	1.72		448
17640	1.90		445
17820	2.05		451
17990		3.8	457
18000	2.11	4.0	458
18325	2.14		

(Tissot and Welte, 1984). Finally, the Gas Wetness curve calibrates very well to the onset of catagenesis at 9,518. Through this section TAI values increase irregularly, whereas Tmax data increases steadily.

Overall, the TAI's are variable and increase through the catagenesis interval. They show a pronounced shift to higher values in the deeper part of the section. These TAI data are not sensitive to lithological changes. In addition, there is a data gap in the interval between the high catagenetic values and the metagenetic values where data are available *(Plates 3 and 5)*.

The Tmax data show an overall steady increase through the catagenetic zone. However, there is noticeable disparity between SWC's and cuttings data Tmax values through approximately the 16,000 to 17,000 interval. This is through the lowest middle Brookian and upper Break up sequences. This disparity coincides with differences observed in TOC data between cuttings and SWC through the same interval *(Plates 3 and 5)*. An intial observation is that the hole problems encountered through this interval are suspect for resulting in probable/possible sloughing and mixing of samples.

Below about 17,000, Tmax data are uniform again. However, these data are offset by some 25 degrees to lower values. At a first approximation, this appears to be related to the lower TOC's and higher pyrolytic generated hydrocarbons through the interval 17,000 - TD *(Plates 3 and 5)*. Again, this offset may be because of the introduction of circulation materials to the drilling mud. There are some problems attendant to involking drilling mud contamination. One of these is that a typical lignosulfonate drilling mud additive would likely contaminate the mud with relatively high TOC readings. A lignite-derived mud additive should also reflect a thermal maturity of %Ro= 0.3 to 0.4 or a Tmax of about 400 degrees Celsius. Neither these low vitrinite reflectance values nor a bimodal distribution of data points are recorded in the data. Consequently, contamination by lignosulfonate drilling mud additives does not adequately explain the reversals in data trends below about 17,000.

Within the catagenetic zone, the Ro thermal maturity plots show three distinct sections; 9,518 - 12,600; 12,600 to 15,937 and from 15,937 to TD (18,325). Both the %Ro and % Gas Wetness show abrupt changes to distinctively higher values, which mark the top of thermal maturity. At 9,518 there is both a change in the steepness to the slope of the %Ro line and an offset in %Ro values. This offset could indicate that there is major change in thermal regime to more severe conditions or that there is an unconformity at about this level. Extrapolating upwards, the slope of the 9,518 - 12,600 segment suggests that about 3,000 or 4,000 feet of section may have been eroded (Dow, 1974). On first interpretation this could be an indication of the unconformity that separates the Middle from the Upper Brookian (Hubbard and others, 1987). However, analysis of the logs, particularly the sonic, show only minor variations at this level. These minor log variations are similar in scope and magnitude to those separating the other Brookian log units where there are no unconformities suspected. Thus, this offset to the %Ro at 9,518 is not considered to be coincident to a major unconformity.

The 12,600 - 15,937 section of the %Ro catagenetic maturity plot is considerably steeper than the overlying section. This steepness suggests a pronounced or punctuated increase in thermal regime. Through this section, both TAI and Tmax data reflect this level of thermal maturity by their values, but they are apparently less sensitive to variations than %Ro. Gas Wetness declines to a minimum at about 15,937.

Between 15,937 - 17,500 the %Ro data from both the cuttings and SWC's are uniform in value and reach the high end of catagenesis. Apparently any offset to the %Ro data from the LCU (which is at 17,325) has annealed sufficiently to be unnoticeable. The disparity seen between cuttings and SWC's in the TOC and Tmax data through this section is not apparent in %Ro data. *Plates 3 and 4* show similar %Ro cuttings and SWC values.

Below approximately 16,000 and to TD, the %Ro slope is still about the same as in the overlying section, but there is an offset to lower %Ro values. In addition, Tmax data are offset to lower values below 17,000 which also suggests less thermal maturity through the deepest part of the well.

As stated earlier, drilling contaminants (both chemical additives and sloughed cuttings) are immediately suspect for this anomaly. However, similar data relationships would exist if more thermally mature rocks were reverse-faulted over a section of less thermally mature rocks. Along this part of the Hinge Line (Craig and others, 1985) and upsection of the down-to-basement normal faulting, reverse faulting like this could be a distinct possibility.

However, analysis of the logs

and the limited publicly available seismic data (Bird and Magoon, 1987) indicates that this thrust-fault interpretation does not readily seem to be the case. Alternatively, the entire section between 12,600 and TD may have the same thermal history and only the %Ro and Tmax data have large variance. Until more data are available, the interpretation of the data below 17,000 remains somewhat of an enigma.

Geothermal Gradient

The Aurora well penetrated some 3000 ft more of sedimentary section than any of the nearest wells. Aurora well also has the highest recorded bottom hole temperature (BHT) and the highest geothermal gradient *(figure 7)*. Where data are available, corrected BHT's (by graphical extrapolations) are shown. Otherwise, BHT's shown represent the temperatures taken after the maximum amounts of circulation.

Most wells in this region have an average geothermal gradient approximately 12 degrees Fahrenheit/1000 ft, especially for the section above approximately 14,000 ft *(figure 7)*. These wells represent input from four distinct but locally overlapping subsurface environments. The deeper offshore, represents areas where the pre-Brookian part of the section has been influenced by the Breakup or Rifting events. These wells have high geothermal gradients in the deeper part of the section because of the high heat flow associated with the rifting events. In addition, along the hinge line there are areas of higher geothermal gradient associated with the ductile movement of the mobile shales (Craig and others, 1985).

West of the 1002 area, most coastal plain and shallow offshore wells commonly test a relatively undisturbed section by compressional tectonics. Northward prograding Brookian clastic rocks comprise most of units tested. Finally the mountain front suite represents areas uplifted by the compressional tectonics of northeast Alaska. Geothermal gradients through the sedimentary section on the hanging wall of thrust faults are typically high because of their previous deeper burial. Sedimentary sections on the overthrust footwall are also high owing to their deep burial and relatively rapid thermal equilibration (Furlong and Edman, 1984).

In general, geothermal gradients are lower through the Brookian rocks than through the Breakup or Ellesmerian sequences. Wells from all four tectonic environments have

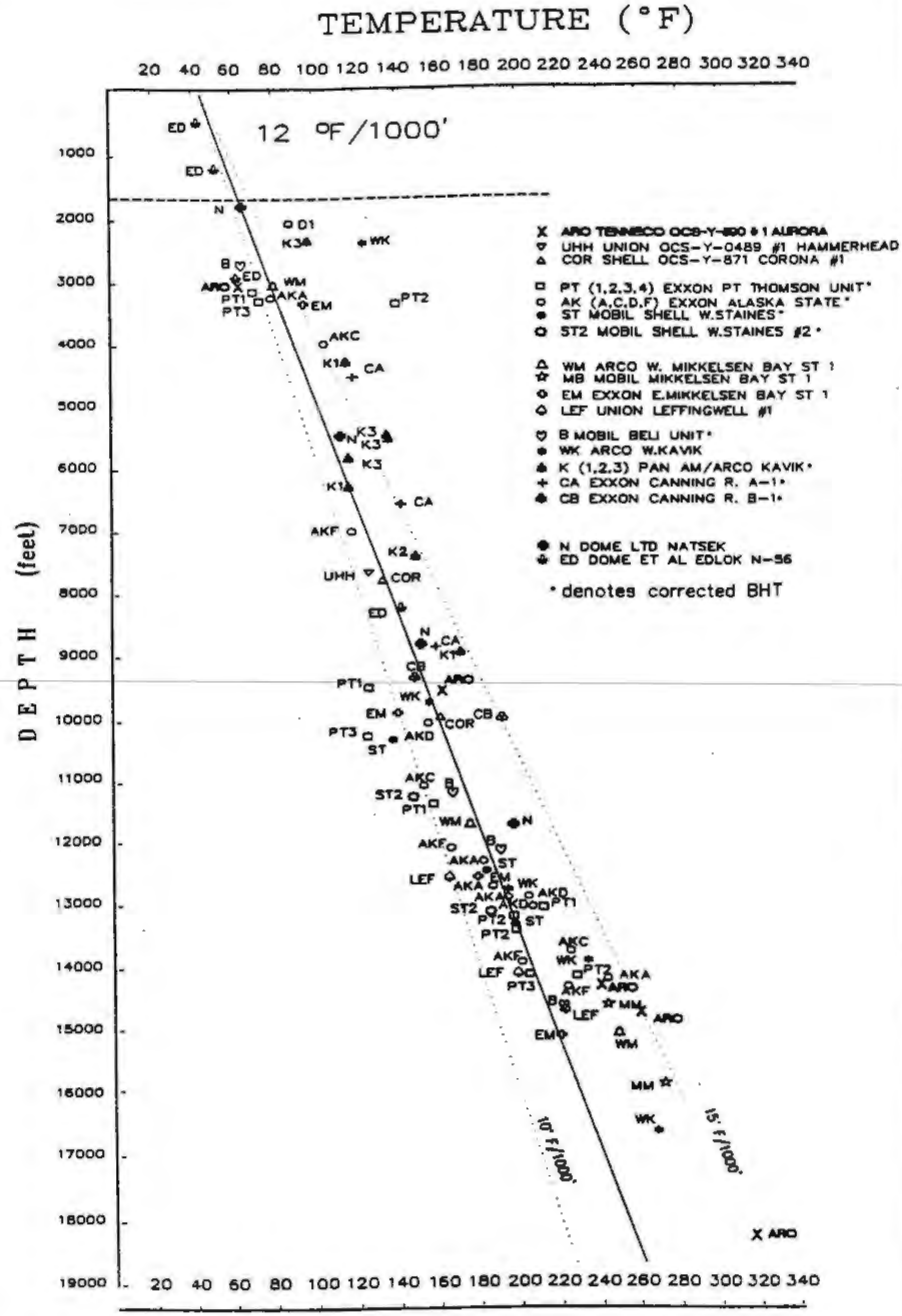


Figure 7
Temperature gradients from Aurora and nearby wells

higher geothermal gradients for stratigraphic sections buried deeper than about 14,000 ft regardless of the depositional sequence tested. These deep-section wells typically have geothermal gradients of 14 to 15 degrees (Fahrenheit)/1000 ft.

At Aurora, the geothermal gradient of approximately 12 degrees/1000 ft through the upper part of the well. This is similar to most wells which tested a predominantly Brookian section *(figure 7)*. The lower part of the well shows a higher geothermal gradient of about 15 degrees/1000 ft. Aurora had the highest recorded BHT of the nearby wells. This may reflect thermal influences from rifting events, proximity to fault-cored diapiric movements of shales along the Hinge line, or possibly influences from both phenomena. (Note that data for BHT corrections were available for only wells immediately west of the 1002 area. Aurora is not corrected.)

4. Burial History

Geochemical modelling estimates the amount and kinds of hydrocarbons that have been generated from source rocks in a basin. First order, or psuedo-first order reaction mechanics best describe the naturally occurring transformation of kerogens into hydrocarbons (Lopatin, 1971, Conan, 1974; Waples, 1980). Analyses of well and outcrop geochemical data provide information describing the present geologic conditions, whereas successful modelling incorporates age data, stratigraphy, various petrophysical properties and thermal maturity data to determine when, in basin history, hydrocarbon generation began and reached its zenith.

Consequently, an accurate determination of burial history from age data and sedimentation rates is neccessary to constructing a usable model. Waples and others (1992) elaborate that even under the best of conditions, combining the thermal maturity data, tectonics, sedimentology, petrology and paleontology data, with their inherent uncertainties is tantamount to an art form. Thus, as with dealing with uncertainties in data, there are a range of values or multiple possible scenarios which illustrate plausible burial histories that honor the data. Changing the timing and duration of the various geologic events is a veritable juggling act which interplays in a complex manner to change the results.

Commercially available software facilitates generating multiple burial history scenarios which test the various hypotheses. This Aurora well analysis used BASINMOD version 2.37 from Platte River Associates, Inc. (Any use of trade, product or firm names in this publication is for descriptive purposes only and does not imply endorsement by the Bureau of Land Management or the U.S. Government). Several input parameters (such as initial porosities, compaction coefficients, heat flow data, etc.) are "hard wired" into this program. These values are based on lithologies interpreted from the logs and cuttings descriptions *(table 7)*. Waples and others (1992) also provides useful data on modifying the thermal history and rock property input parameters. In general, these represent average values for similar sediments and they are useful towards determining the thermal maturity model. But note that their values probably exceed the precision of the the inferred age and estimated burial rate data *(table 7)*.

Since the Paleontogical data was not released with the logs and geochemical data, burial history reconstructions are modeled from publicly available North Slope information. Periods of depostional hiatus accompany the modeled unconformities to reflect some of the inherent uncertainity in timing. Also, it serves to visually underscore these events *(figure 8 and table 7)*.

In addition to well data, the burial history reconstructions emphasize that regional trends in the geology, such as unit thicknesses, ages of the units and events and thermal histories, from along the axis of the Barrow Arch feature are more representative of what likely occurs at Aurora rather than the geology from the Colville trough or the foothills.

Currently, there are few published burial history reconstructions and Lopatin thermal maturity determinations for northeast Alaska. Magoon and others (1987) model the Tertiary section for the Point Thomson Unit No.1 well from an area about 80 miles to the west (figure 2 well; designated U1). Their model shows rapid burial during upper Cretaceous and most of the Paleocene (Graphically estimated at 700 feet/million years). This is followed by a constant burial rate of about 200 feet/million years since the upper Paleocene. It also represents a constant rate of lowering of geothermal gradient with time. Banet's model (1990) for the West Staines No. 2 well *(figure 2)* is similar except that it lowers the geothermal gradient through all the Tertiary and does not project permafrost back to the Paleocene.

Data from both these wells show the onset of thermal maturity at depths of approximately 12,000 to

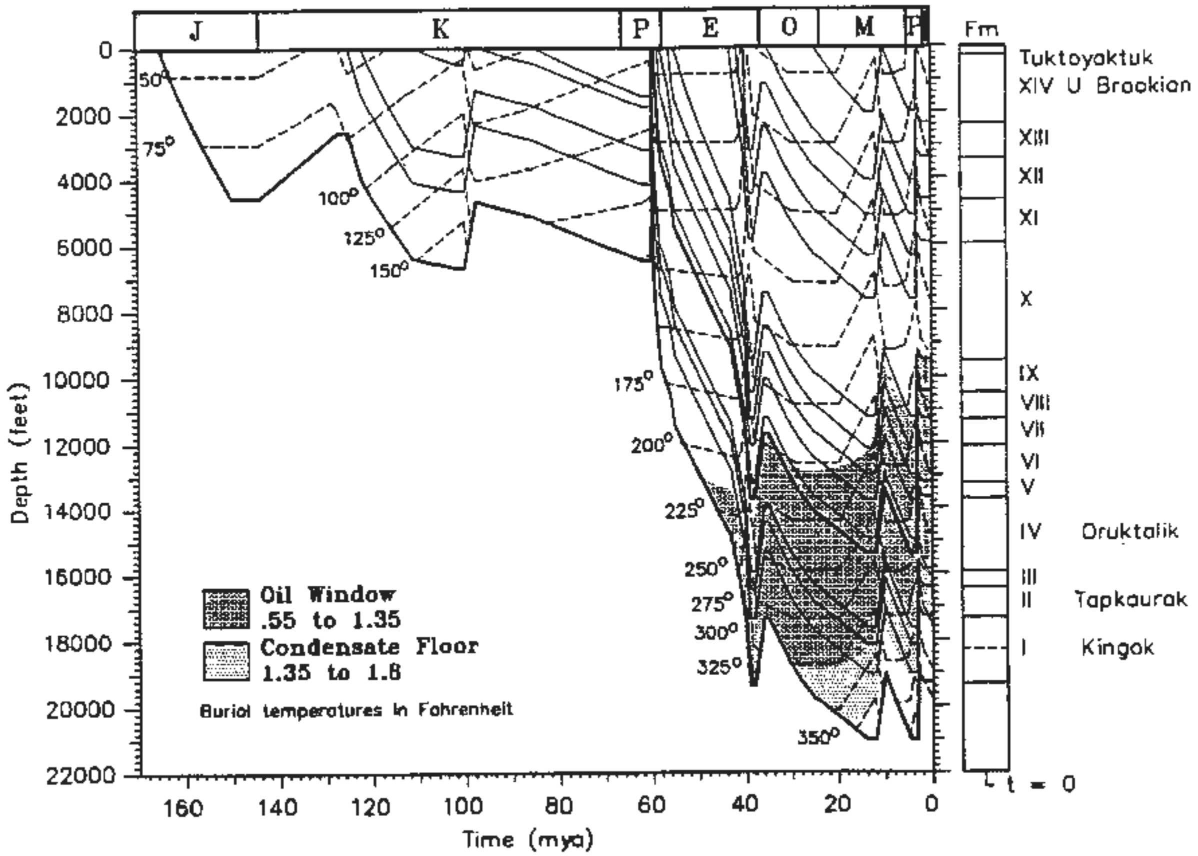


Figure 8A
Burial history for Aurora well

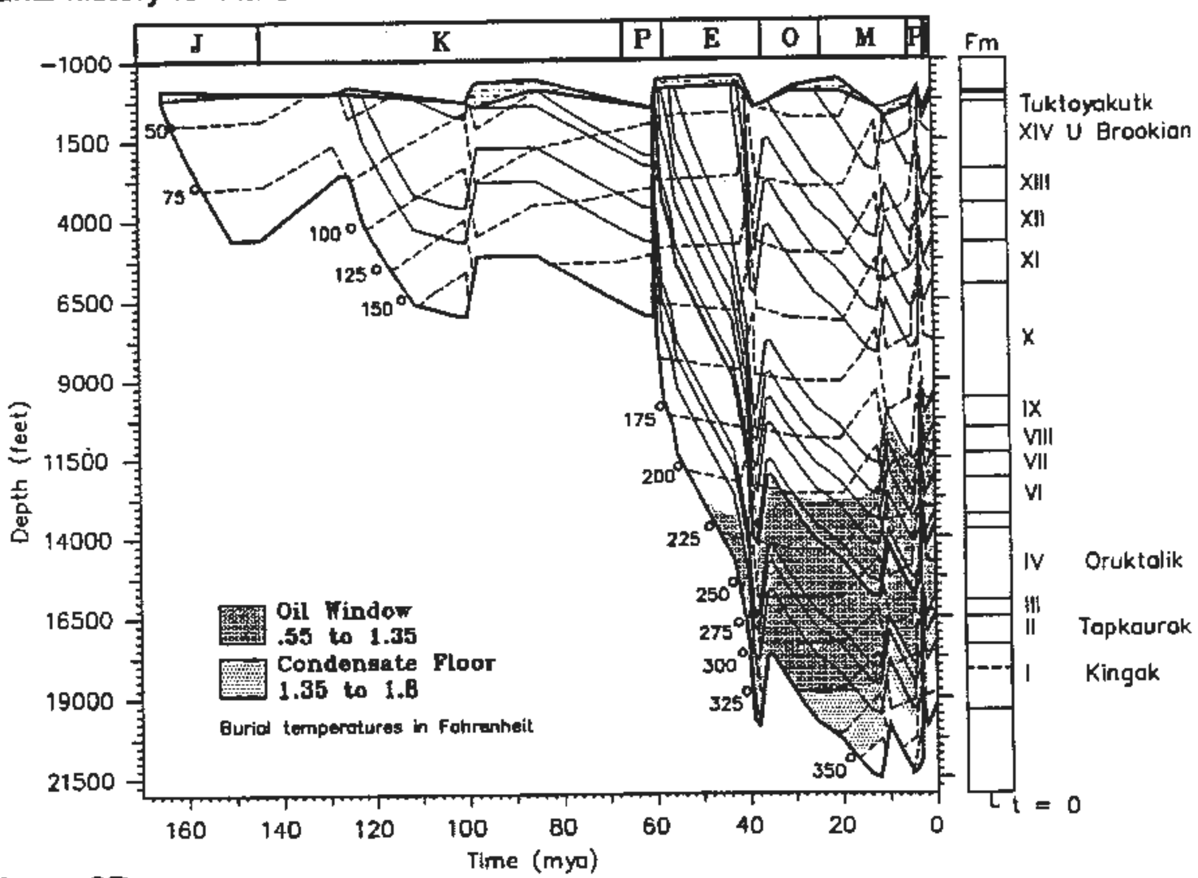


Figure 8B
Burial history adjusted for sea level and depths

13,000 ft. This depth to maturity agrees with most of the other coastal plain wells northwest of the 1002 area. (For comparison, the onset of thermal maturity around Prudhoe Bay is 8000 to 9000 feet.) Maximum burial depths were reached during the Pliocene and subsequent uplift has been less than about 500 ft. Both models suggest that catagenesis in the Pebble Shale Unit and the upper Cretaceous Bentonitic shale began some 5 million years ago in this area.

However, these burial history models are simplifications of the Pt. Thomson area. Both seismic and field geologic data from the ANWR 1002 area show that the Pt. Thomson area has a substantially less complicated tectonic and sedimentologic history than at Aurora. A stratigraphically simplisitic burial history model using similar assumptions for Aurora does not generate the maturity or temperatures encountered in the well data.

Issler and Snowdon (1990) model burial histories of wells from the Canadian Beaufort and test hydrocarbon-generation experimental kinetics from laboratory experiments. These models reflect input accommodating the changing heat flows and depositional episodes related to both rifting events and subsequent rapid burial events. The available seismic data from the 1002 area and the near offshore (Bird and Magoon, 1987; Craig and others, 1985; Grantz and May, 1983) indicates that the burial history at Aurora is more similar to some of the Canadian Beaufort wells than the Pt. Thomson area models (Banet, 1990 & 1992).

Table 7 shows Aurora burial history reconstruction data. Experimenting with models shows that burial effects of more recent episodes far outweigh those of older events. This is particularly true of erosional events and missing sections at Aurora.

I have estimated the amounts of erosion and missing section at approximately 2,000 ft for the Tertiary events. For the nature of this initial approximation and the amount and kind of data available (seismic and paleontological) at this time, I feel that this is sufficient for the initial burial history modelling.

Regional data suggest that different parts of northeast Alaska may have undergone considerably more numerous and/or extensive uplifts and erosional episodes. In fact the Tuktoyaktuk unconformity can be modeled as removing only 500 ft of section from an equally thick upper Brookian section and they still closely approximate the data.

However, I choose uniformity for this initial comparative effort in which the thicknesses can neither be confirmed nor denied, except perhaps arguably. Most importantly, these burial history estimates best fit the thermal maturity data derived from the well samples *(table 7 and appendix)*.

Aurora well is located in an area where considerably less data is available than for the previous modelling attempts. It is likely that there are several additional unconformities of limited areal extent and/or depositional hiatuses that exist but are not resolved on the available data. However, note that substantially greater sections, result in models that do not honor the present thermal maturity data and profile.

Both Aurora well data and regional analogies comprise thickness and age estimates for this burial history. This Aurora model has Kingak shale no younger than Oxfordian as Carman and Hardwick (1983) report from the Kuparuk River area. The current Kingak thickness for this location is estimated to be approximately 2000 ft with another 2000 ft of the uppermost Jurassic and lowest Cretaceous eroded at the LCU.

The Tapkaurak Unit and the overlying Unit III are also constrained by ages of the Breakup sequence at Kuparuk River. They are considered approximately Hauterivian-Barremian and Barremian-Aptian, respectively. Thicknesses are from the well data. In keeping with the regional geology, approximately 500 ft of HRZ is modeled as having been deposited and subsequently eroded by the basal Middle Brookian unconformity.

The missing Bentonitic Shale unit and overlying Colville Group shale of the Middle Brookian sequence are modeled after available well and outcrop data. Thicknesses, ages and erosion are best estimates from comparison to the Pt. Thomson area and the 1002 area *(figure 7, Banet, 1992)*. Only relative minor changes to the thermal maturity occur when these Cretaceous age units are modeled as being twice as thick as shown on table 7 or as not being deposited instead of being eroded *(Appendix 1)*. I model erosion of 2,500 feet at the lower Tertiary unconformity. This is comparable to extent of erosion at the LCU.

The middle Brookian sequence, 15,937 - 2,385 has two separate but related depositional regimes. Units IV - IX (15,937 - 9,518) have higher depositional rates than Units X - XIII (9,518 - 2,385). These changes coincide with pronounced offsets observed in the thermal maturity indicators *(Plate 5)* observed at 9,518. The sedimentation rates within each depositional regime are similar for the contained units. This pulse of middle Brookian clastic sedimentation initiates the beginning of major catagenesis in the Breakup sequence rocks at approximately 40 - 45 ma *(figure 8)*.

As per the well data, the middle Brookian sequence is 13,552 feet thick. The upper Eocene unconformity at 2,385 removes an estimated 2,000 feet of section. Adding this amount of erosion and restoring the 2000 feet of section removed by the LTU yields a total thickness of 17,552 ft. This total thickness is near the approximate midpoint of various regional middle Brookian thickness estimates for the eastern part of the Beaufort shelf (Dixon and others, 1992; Craig and others, 1985 and Deitrich and others, 1985). The timing of the erosional event which separates the Middle from the Upper Brookian sequence is picked at approximately 38 ma. Laramide deformation was most intense in the eastern Beaufort at this time (Hubbard and others, 1987). In addition, it approximately coincides with the sudden and major expansion of the Antarctic ice shelf which also may have contributed the regression of sea levels, world wide (Emiliani, 1987).

The upper Brookian section, above 2,385, is Oligocene through upper Miocene or lower Pliocene age *(Plates 1 and 2)*. The regional geology suggests that this shallowest section of this well has undergone several substantial episodes of uplift with subsequent burial and sediment input from the south and east. At least two major unconformities probably exist within this section (Craig and others, 1985; Banet, 1990; Dixon and others, 1992).

The log character indicates that these lithologies have very slow interval transit times above 2,385 to where the geophysical logging ended at 930 ft. Typically uncompacted sediments like these do not readily indicate any sonic discontinuites. So, log evidences of these unconformities may be overlooked in the analysis (Banet, 1992).

The unconformities may occur within the uppermost 900 ft which was not logged, or perhaps even the uppermost 300 ft, as the mudlog shows no significant lithological changes through this section. However, note that there is no evidence on the logs of the regional Miocene unconformity (or unconformities) within the upper Brookian section, which is/(are) so prominent in the offshore subsurface. Also, the lithologies across the angular, basal Tuktoyaktuk unconformity are similar enough, especially from cuttings descriptions, to pass undetected to the casual observer.

Regionally, the Upper Brookian sequence may be as much as 15,000 to 20,000 feet thick in the Barter and Demarcation subbasins juxtaposed to Aurora (Craig and others, 1985), or even thicker in the Canadian Beaufort (Issler and Snowdon, 1990). *Table 7* shows Unit XIV is estimated to be 2,085 feet thick. *Table 7* also shows that approximately 2,000 feet of section were removed by the upper Miocene unconformity.

Greater thicknesses do not fit the data, nor are they compatible with regional reconstructions. The upper Miocene age is compatible with reconstruction of uplifts in the Bulge, but it also coincides with the Antarctic ice sheet reaching the ocean (Emiliani, 1987). The basal Tuktoyaktuk sequence unconformity removes another 2,000 ft of Upper Brookian section *(table 7)*. Onshore, at the Marsh Creek anticline in the 1002 area, and offshore in the Beaufort this unconformity has an angular geometry. I reconstruct total Upper Brookian deposition at Aurora as 6,085 ft. Craig and others (1985) and Banet (1990) suggest similar thicknesses for this section along the Hinge Line where it overlies deformed Middle Brookian rocks. Burial reconstructions with thicker upper Brookian or Tuktoyaktuk sequence sections depress the onset of catagenesis. However, this is considerably below that which is observed in the well data.

As with the Upper Brookian unconformities, I suggest that the basal Tuktoyaktuk unconformity is probably coincident to both the tectonic uplifts marking the culmination of the Camden orogeny (Hubbard and others, 1987) of the Bulge and the approximate onset of North American glaciation (Emiliani, 1987). Initial Gubik deposition is about 3 ma *(table 7)*. This age agrees with surficial indications of faulting through the Quaternary, and it approximately coincides with the earlier stages of extensive North American glaciation.

The complex nature of glaciations, particularly the relatively recent Pliocene-Plesitocene glaciations, can only be approximated with the best of available modelling efforts. Multiple pulses of sedimentation and repeated regressions (Carter, 1987; Dinter, 1987) are combined and dated most closely to the time of the respective sedimentation or erosional maximum. In addition, the graphical representation is not easily shown in the less than 5% of the time-record available for showing the Pliocene and

Pleistocene *(figure 8)*.

The episodic Plio-Pleistocene glaciations and accompanying permafrost present particular problems. Regressions result in dramatic sea level lowerings and changes to sedimentation patterns. Alteration of the subsurface temperature regime is equally dramatic. For example, permafrost is a current phenomena, but a geologically ephemeral event. On the North Slope it may reach approximately 2,000 feet thickness and thins dramatically offshore due to the oceans' thermal mass. An initial result is that the permafrost mostly affects the shallow BHT measurements *(figure 7)*. I model these factors (successfully, I hope) as part of the most recent uplift event at Aurora. Additional subsurface temperature effects and corrections suggested by Lachenbruch and others (1982) exceed this current burial history modelling effort.

Table 7 lists the various time-value inputs. Heat flow data are mostly from comparison to existing burial history data and from Waples and others (1992). Surface temperatures are also estimates. The heat flow data are higher for rifting related events than for the Brookian deposition. Sea level data are largely after Vail and others (1977) and water depth are estimates from the sedimentology. Like the erosional modelling, where pertinent data are also limited, these are simplistic reconstructions and are likely conservative. The addition of sea level to the modelling effort mostly affects the temperatures and, to a lesser extent, the depths to which the units have been buried. The geothermal gradient data also reflect higher temperature regimes for rifting events and lower gradients for rapid deposition.

Even with these caveats, the observed data shows good agreement to calculated thermal maturity values from the burial history model *(appendix)*. Vitrinite reflectance maturity data (%Ro) is only slightly higher than the burial history model calculates through the catagenetic zone. I rely primarily on the %Ro data for comparing the burial history model to the thermal maturity data. In addition to the good fit of the burial history model to the %Ro data, the %Ro data is considerably more consistent than the either TAI or Tmax data which show a lot of scatter with depth *(appendix)*. Overall, this thermal maturity reconstruction fits the available data and this burial history reconstruction, remarkably well, given the initial estimates of erosion and uplifts in this area *(figure 8, table 7)*.

The episodic Plio-Pleistocene glaciations and accompanying permafrost present particular problems. Regressions result in dramatic sea level lowerings and changes to sedimentation patterns. Alteration of the subsurface temperature regime is equally dramatic. For example, permafrost is a current phenomena, but a geologically ephemeral event. On the North Slope it may reach approximately 2,000 feet thickness and thins dramatically offshore due to the oceans' thermal mass. An initial result is that the permafrost mostly affects the shallow BHT measurements *(figure 7)*. I model these factors (successfully, I hope) as part of the most recent uplift event at Aurora. Additional subsurface temperature effects and corrections suggested by Lachenbruch and others (1982) exceed this current burial history modelling effort.

Table 7 lists the various time-value inputs. Heat flow data are mostly from comparison to existing burial history data and from Waples and others (1992). Surface temperatures are also estimates. The heat flow data are higher for rifting related events than for the Brookian deposition. Sea level data are largely after Vail and others (1977) and water depth are estimates from the sedimentology. Like the erosional modelling, where pertinent data are also limited, these are simplistic reconstructions and are likely conservative. The addition of sea level to the modelling effort mostly affects the temperatures and, to a lesser extent, the depths to which the units have been buried. The geothermal gradient data also reflect higher temperature regimes for rifting events and lower gradients for rapid deposition.

Even with these caveats, the observed data shows good agreement to calculated thermal maturity values from the burial history model *(appendix)*. Vitrinite reflectance maturity data (%Ro) is only slightly higher than the burial history model calculates through the catagenetic zone. I rely primarily on the %Ro data for comparing the burial history model to the thermal maturity data. In addition to the good fit of the burial history model to the %Ro data, the %Ro data is considerably more consistent than the either TAI or Tmax data which show a lot of scatter with depth *(appendix)*. Overall, this thermal maturity reconstruction fits the available data and this burial history reconstruction, remarkably well, given the initial estimates of erosion and uplifts in this area *(figure 8, table 7)*.

5. Summary

Aurora well drilled and sampled 18,325 ft of clastic sediments from the Breakup, Middle Brookian, Upper Brookian and probably Tuktoyaktuk depositional sequences. These data fill a major gap between exploration efforts on Alaska's North Slope, the Beaufort shelf and the Canadian Beaufort-Mackenzie delta. The erosional and depositional history has several similarities to both the Pt. Thomson area to the west and the Canadian Beaufort to the east.

This geochemical profile shows that the Upper Brookian rocks have 1 to 2% TOC, are thermally immature and have kerogens that are prone to generate gas. The Middle Brookian rocks typically have 1% or less TOC and have kerogens that are likely Type IV, comprised predominantly of recycled organic material. The middle Brookian sequence at this location has limited capacity to generate hydrocarbons irrespective of thermal maturity. The basal Middle Brookian section has TOC values to about 5% but also has marginal capacity to yield hydrocarbons like the rest of the Brookian rocks. This is a classic example of rocks containing relatively high concentrations of TOC having marginal capacity to generate hydrocarbons: one of the most basic caveats of source rock analyses!

The Breakup sequence rocks have TOC's between 1.5 and 2.0%. These rocks are thermally mature and have kerogens mostly prone to generate gas during pyrolysis. Their capacity to generate liquid hydrocarbons is mostly spent.

The presence of extractable hydrocarbons from the organically lean and thermally immature Brookian section indicates that some migrated hydrocarbons are present at this location. At present, the source or sources of these anomalous hydrocarbons are unknown. However, the richest samples are severely weathered and bear minor resemblance to weathered seeps from the 1002 area. Other samples' chromatograms and alkane distribution suggest a penchant or disposition for a predominantly nonmarine source rock.

Vitrininte reflectance and gas wetness show that the onset of thermal maturity is at 9,518 and that there are multiple thermal maturity regimes. The higher thermal maturity and rate of increase with burial suggests that the thermal maturity regime was more intense for the section below 9,518. TAI and Tmax are less sensitive to these changes.

The burial history reconstruction for this well is the most complex of any published for northern Alaska. However this approximation is still simplistic and conservative owing to the tectonic complexity of area and the amount of available data, especially for those parts affected by various glacial episodes. This burial history combines observed data with regional correlations and incorporates the limited available offshore seismic data suggesting that there have been multiple periods of uplift and erosion. Still, this initial approximation good agreement between the observed data and calculated values.

Burial history modelling indicates that hydrocarbon generation in the basal Breakup sequence rocks began approximately 45 ma with the deposition of the Middle Brookian section. Further burial resulted in the breakdown of petroleum to condensate at about 35 ma and the transformation to gas at about 16 ma. Maximum burial for the Breakup sequence was probably about 23,000 ft and subsequent uplifts have been greater than about 3,500 ft. The current beginning of thermal maturity in the Brookian section is at 9,518.

The burial history, the relatively organicly-lean nature of the kerogens and thermal maturity of the sediments suggest that petroleum generating capacity of the Middle Brookian section at this location is substantially less than that onshore. However, there are anomalous, migrated hydrocarbons present in this section. This indicates the presence of a successfully operating petroleum system somewhere in the vicinity. In addition, regional geologic considerations and correlations to the Pt. Thomson area suggest that more petroleum potential may exist south of this location, towards the culminations of the large seismically mapped structures of the ANWR 1002 area, where the two major sands, the Tapkaurak and Oruktalik, are not as deeply buried.

Bibliography

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

Banet, Arthur, C., Jr., 1992, Log analysis of Aurora 890-#1 OCS-Y-0943 well offshore of the Arctic National Wildlife Refuge 1002 area, northeast Alaska BLM-Alaska Technical Report 15

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

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

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

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

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

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

Connan, J., 1974 Time temperature relation in oil genesis: American Association of Petroleum Geologists Bulletin, v. 58, # 12, pp 2516-2524.

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

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

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

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

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

Dixon, J., J.R. Deitrich, L.R. Snowdon, G. Morrell, and D.H. McNeil, 1992, Geology and petroleum potentialof Upper Cretaceous and Tertiary strata, Beaufort-Mackenzie area, northwest Canada, American Association of Petroleum Geologists Bulletin v. 76, No. 6.

Dow, W. D., 1977 Kerogen studies and geological interpretations; Journal of Geology, v. 7, pp 79 - 99.

Emiliani, C., 1987, Dictionary of the Physical Sciences, Oxford University Press, New York.

Furlong, K. P. and Edman, J. D. 1984, Graphic approach to determination of hydrocarbons maturation in overthrust terrains; American Association of Petroleum Geologists Bulletin v. 68 # 11.

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

Grantz, Arthur, S.D. May and E.P. Hart, 1990, Geology of the Arctic Contintental Margin of Alaska, The Geology of North America Vol. 1, The Arctic Ocean Region, pps. 257-288 + plates The Geological Society of America.

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

Issler, D., R., and Snowdon, L., R. 1990 Hydrocarbon generation kinetics and thermal modelling, Beaufort-Mackenzie Basin ; Bulletin of Canadian Petroleum Geology v. 38. no. 1, p. 1-16.

Kelley, John and Detterman, R. L. 1989 Distribution of Mesozoic strata under lower Cretaceous unconformity in Sadlerochit Mountains and adjacent Coastal Plain, northeastern Alaska. abs. *in* American Association of Petroleum Geologists Bulletin, v. 73, #4, p. 543.

Lachenbruch, A. H., Sags, J. H., Lawyer, L. A., Brewer, M. C., and Mose, T. H., Jr. 1982, Depth and temperature of permafrost on the Alaskan Arctic Slope. USGS Open File Report # 82-1039.

Lopatin, N. V., 1971, Time and temperature as factors of coalification, Akad Naur SSSR Izv. Ser Geol., no. 3, pp 95-106.

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

Magoon, L.B. and Claypool, G.E. 1981 Two types of oil on North Slope, implications for exploration; American Association of Petroleum Geologists Bulletin, v. 65 pp 644-652.

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

Molenaar, C. M., 1983, Depositional relations of Cretaceous and Tertiary rocks, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 67, no. 7, p. 1066-1080.

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

Mowatt, Thomas C.., and Banet, Arthur C., Jr., and Reeder, John, W., 1992 Petrographic analyse of selected orizons, Aurora 089 No. 1 OCS-Y-0943 well, offshore northeast Alaska. Part 1: depth intervals 14,680 to 14,860 and 16,445 to 16,630 ft.

Ronov, A. A., 1987 Petroleum hydrocarbons, Springer Verlag, New York.

Scherr, James, S. M. Banet and B. J. Bascle, 1991. Correllation study of selected exploration wells from the North Slope and Beaufort Sea, Alaska; Minerals Management Service OCS Report MMS 91-0076.

Snowdon, L. R., and Powell, T. G., 1979, Families of crude oils and condensates in the Beaufort-Mackenzie basin; Bulletin of Canadian Petroleum Geology, v. 27, no. 2, p. 139-162.

Tissot, B.P. 1984 Recent advances in Petroleum Geochemistryapplied to hydrocarbon exploration: American Association of Petroleum Geologists Bulletin, v.68, No. 5. p. 545-563.

Tissot, B.P. and Welte, D.H., 1984, Petroleum Formation and Occurrence, 2nd edition, Springer-Verlag, New York.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubb, J.N., and Hatelid, W.G., 1977 Seismic stratigraphy and global changes in sea level, in seismic stratigraphy, in Payton, C.E., ed., American Association of Petroleum Geologists Memoir 26, p. 49-212.

Waples, D.W., 1980 Time and temperature in petroleum formation: application of Lopatin's method to petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 64, p.916-926.

Waples, D.W., Suizo, M. and Kamata, H. 1992 a. The art of maturity modeling. Part 1: Finding a satisfactory geologic model. American Association of Petroleum Geologists Bulletin v. 78, no 1. p. 31-45.

—— 1992 b. The art of maturity modeling. Part 2. Alternative models and sensitivity analysis. American Association of Petroleum Geologists Bulletin v. 76, no.1 p.47-66.

Appendix

The determination of appropriate age and burial-depth parameters is necessary in estimating the timing and extents of hydrocarbon generation. However, these kinetic parameters are critically interrelated and changing one depth or age necessitates adjusting others. Even where data are abundant, the accurate burial histories are composed of geological and geochemical assumptions and compromises. Thus, iterative methods facilitate comparing and determining the most logical and plausible assumptions.

These figures illustrate the fit of the Aurora analysis assumptions with the thermal maturity data. *Figure A* compares the %Ro, TAI and Tmax data to the Aurora burial history model. The %Ro data fit the burial model most closely at the high and low ends of thermal maturity. The data suggest a somewhat more severe thermal history, by about 0.1%Ro through the middle of the catagenetic zone. This is due, to perhaps, higher temperatures during the deposition of Units V and VI.

The %Ro data also reflect the distinct thermal maturity segments (the doglegs, discontinuous or kinky vitrinite reflectance profiles) described in the main portion of the text. As an important aside, a regression of the %Ro is run on the data. This regression actually honors little of the data, with wide discrepancies on both ends. (The regression is substanstially less severe than the data through the catagenetic zone, but suggests a much more severe regime through the condensate field.) The analysis of the accompanying logs supports that there are sedimentological changes that accompany these offsets to the %Ro data. The change and offset at 9,518 does not coincide with an unconformity, but the change and offset at approximately 16,000 *(Plate 4)* coincide well with the LTU pick at 15,937.

The TAI data are widely scattered. In a gross way, TAI data also reflect a more severe thermal maturity regime through the middle of the catagenetic zone than through the more deeply buried lithologies.

The Tmax data are more abundant than either %Ro and TAI and are more widely scattered than both. This variation in the data is similar to that reported from 1002 area outcrops. The Tmax data from Aurora change abruptly from representing a thermal regime less severe than the model through the diagenetic region, to a regime that was much more severe through diagenesis. Oddly, the Tmax data from the most deeply buried section shows thermal maturity equal or less than that from the catagenetic zone *(Figure A)*.

Changes to the burial history input parametars illustrate that the most recent changes have the most effect in determining the onset of hydrocarbon generation *(Figures B, C and D)*. By modelling that the upper Cretaceous shales were not deposited, rather than eroded, imparts only small changes to the generation of hydrocarbons. The depth to the onset of catagenesis at the base of the Kingak is unchanged. However, the timing of hydrocarbon generation is altered from approximately 50 ma with deposition and subsequent erosion to about 32 ma.

Figures C and D also illustrate what happens if the basal upper Brookian unconformity occurs at 9,518 and coincident to changes in the thermal maturity (%Ro and Gas Wetness). This assumption represents an influx of approximately 13,500 ft of upper Brookian sediment; over twice that shown in *figure 8*. The result is that the depth of catagenesis is lowered to about 13,500. Concommitantly, the onset of hydrocarbon generation is approximately 34 ma for the base of the Kingak.