SHORT COURSE B

Petroleum Source Rocks and Coal, a Core Workshop:

David Houseknecht

PETROLEUM SOURCE ROCKS AND COAL IN THE NATIONAL PETROLEUM RESERVE IN ALASKA: A CORE WORKSHOP

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INTRODUCTION

(revised from Houseknecht, 2001)

The North Slope of Alaska has re-emerged as one of the most active exploration provinces in the United States. Recent exploration successes, economic benefits of applying innovative exploration and production technologies, evolving industry demographics, rising oil and natural gas prices, and the anticipation that North Slope natural gas resources may become economically viable and marketable through a planned pipeline have stimulated a renewed intensity in leasing and exploration activity. Until recently, this activity was focused mostly on State lands and waters, as well as the Federal offshore immediately adjacent to the State-Federal boundary.

The 1994 discovery of the Alpine field (>400 mmbo reserves) on the Colville River delta and the production performance of the nearby Tarn field (>70 mmbo reserves) stimulated exploration interest in the National Petroleum Reserve in Alaska (NPRA). Consequently, two lease sales were held in eastern NPRA in 1999 and 2002, the first onshore Federal lease sales on the North Slope in more 15 years. Exploration wells have been drilled on NPRA leases during each winter drilling season since 2000, a number of discoveries have been announced, and plans for development of some of those discoveries are under review.

Although most information from the newly drilled wells in NPRA remains proprietary, the focus of most drilling appears to be the same play that hosts the Alpine oil field — stratigraphic traps within the Jurassic to Early Cretaceous Kingak Shale. Additional plays thought to hold significant potential for oil and gas resources include both stratigraphic and structural objectives that span much of the stratigraphic column (Bird and Houseknecht, 2002a, b).

The purpose of the core workshop is to provide an opportunity to examine cores representing all major petroleum-source rocks and coal-bearing stratigraphic units in NPRA.

NPRA Cores

All NPRA cores available for examination in the public domain were collected during Federal Government exploration of the NPRA and adjacent areas. Federal exploration was conducted in two phases (1943-1953 and 1974-1982) (Reed, 1958; Gryc, 1988), and included extensive coring of strata considered to be primary reservoir and source-rock intervals. Cores from 57 wells in and adjacent to the NPRA have been consolidated, slabbed, archived, and digitally photographed at the U.S. Geological Survey (USGS) Core Research Center in Lakewood, Colorado.

Figure 1 shows wells for which there are cores in the USGS archive and table 1 summarizes the stratigraphic intervals cored in each well. Splits of most of these cores and cores from a few additional wells from the 1943-1953 Federal exploration program in NPRA are archived at the Alaska Geologic Materials Center at Eagle River, Alaska (John Reeder, Curator).

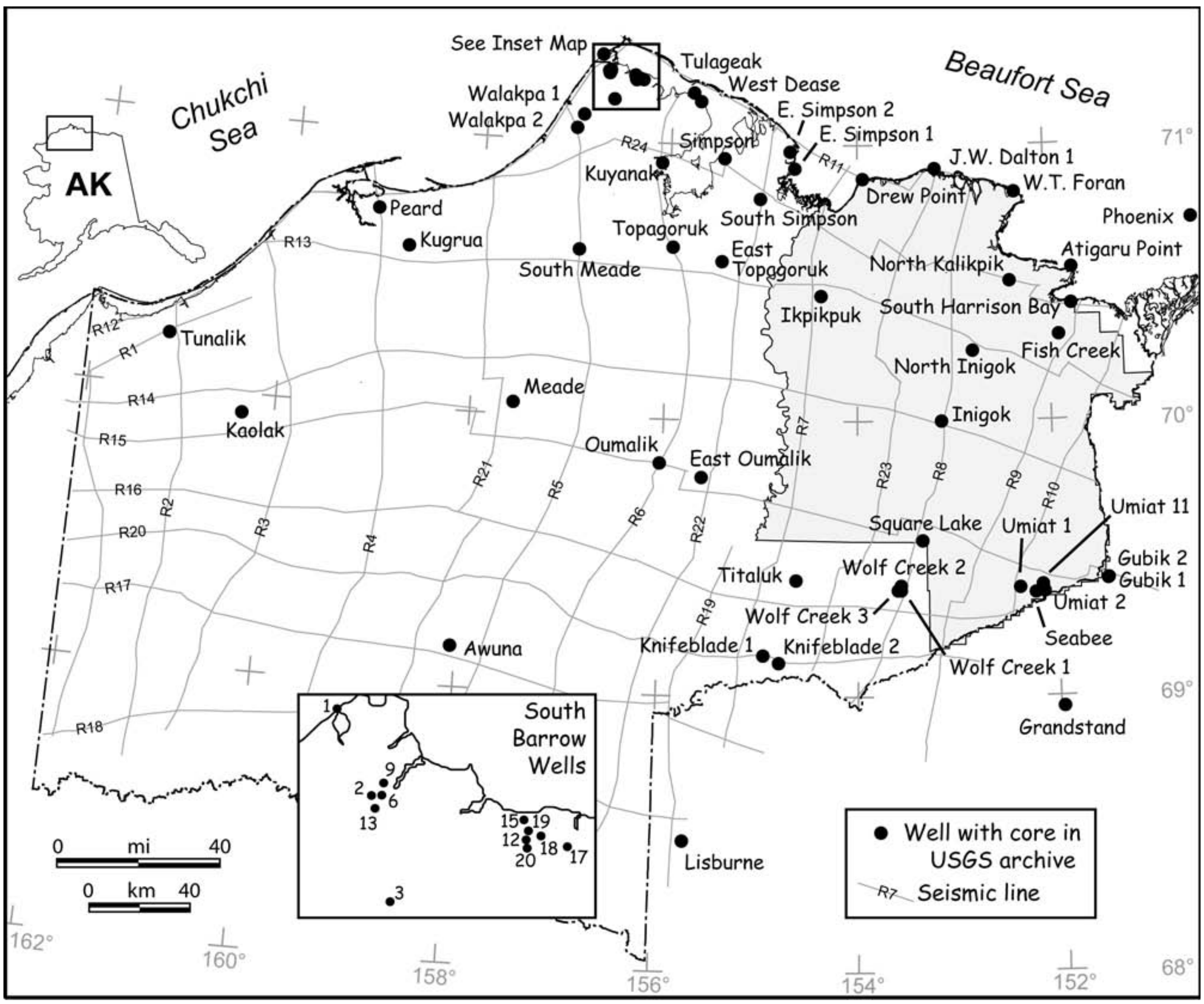


Figure 1. — Map of the Alaskan National Petroleum Reserve shows locations of wells with cores archived in the USGS Core Research Center and regional seismic lines used to place cores into regional context. Stippled area in eastern NPRA is planning area within which approximately 4 million acres were available for leasing in the 1999 Federal lease sale.

Table 1. — Wells with cores in the USGS archive showing stratigraphic units cored in each well.

	Well Name	Sagavanirktok	Colville	Nanushuk	Torok	Pebble Shale	Kingak	Sag River	Shublick	Sadlerochit	Lisburne	Endicott	Basement
1	Atigaru Point 1									X			X
2	Awuna 1				X								
3	Drew Point 1				X		X	X	X				X
4	East Oumalik 1			X	X								
5	East Simpson 1			X	X			X	X	X			X
6	East Simpson 2			X	X			X				X	X
7	East Topagoruk 1			X	X								
8	Fish Creek 1		X	X	X								
9	Grandstand 1			X	X								
10	Gubik 1	X	X	X	X								
11	Gubik 2		X	X	X								
12	Ikpikpuk 1			X	X	X	X		X	X	X	X	X
13	Inigok 1			X	X		X		X	X	X	X	
14	J. W. Dalton 1			X	X					X	X		X
15	Kaolak 1			X	X								
16	Knifeblade 1			X									
17	Knifeblade 2			X									
18	Kugrua 1					X	X			X			
19	Kuyanak 1					X	X	X					X
20	Lisburne 1										X		
21	Meade 1			X	X								
22	North Inigok 1				X	X	X		X				
23	North Kalikpik 1				X	X	X						
24	Oumalik 1			X	X	X	X						
25	Peard 1				X	X	X	X	X	X			X
26	Seabee 1				X		X						
27	Simpson 1					X	X	X	X				X
28	South Barrow 1					X							X
29	South Barrow 2				X		X						X
30	South Barrow 3				X		X	X	X				X
31	South Barrow 6						X						
32	South Barrow 9					X	X						
33	South Barrow 12						X	X					X
34	South Barrow 13					X	X						X
35	South Barrow 15				X	X	X						
36	South Barrow 17						X	X					X
37	South Barrow 18				X	X	X						
38	South Barrow 19				X		X	X					
39	South Barrow 20							X					X
40	South Harrison Bay 1				X						X		
41	South Meade 1				X		X	X	X	X			
42	South Simpson 1			X									
43	Square Lake 1	X	X	X	X								
44	Titaluk 1			X	X								
45	Topagoruk 1			X	X	X	X	X	X	X		X	X
46	Tulageak 1					X		X	X				X
47	Tunalik 1			X	X	X	X			X	X		
48	Umiat 1	X											
49	Umiat 2				X								
50	Umiat 11	X	X	X	X								
51	W. T. Foran 1								X		X		
52	Walakpa 1				X	X	X		X				X
53	Walakpa 2					X	X						
54	West Dease 1				X	X	X	X	X				X
55	Wolf Creek 1			X									
56	Wolf Creek 2			X									
57	Wolf Creek 3			X	X								

Data Resources

A digital summary of cored intervals in each well, including depths and formations cored, and digital photographs of all the slabbed cores are available in Houseknecht (2002b). Additional resources from recent core workshops include core workshop notes that address the entire stratigraphic column (Houseknecht, 2001) and core workshop notes that address the formations included in the most oil-prospective plays in NPRA (Houseknecht, 2002b).

The USGS has an ongoing effort to digitize and archive data collected during the 1974-1982 Federal exploration program in NPRA, and to release those digital data to the public. Reprocessed, regional seismic lines have been released on CD-ROM and the internet (Miller and others, 2000, 2001). Selected data from NPRA exploration wells, including digital versions of original core photographs, have been released in two CD-ROM publications (Zihlman and Oliver, 1999; Zihlman and others, 2000). Additional CD-ROMs that include thermal maturity (Johnsson and others, 1999) and organic geochemistry (Threlkeld and others, 2000) data from the NPRA also have been released. Most of these products also are available online from the USGS.

Complementary data from elsewhere on the North Slope also are available in digital format. These include the USGS 1998 assessment of oil and natural gas potential of the Arctic National Wildlife Refuge 1002 Area (USGS ANWR Assessment Team, 1999) and reprocessed seismic data from the Beaufort and Chukchi seas (Agena and others, 2000, 2001).

GEOLOGIC AND TECTONIC SETTING OF THE NPRA

(revised from Bird, 2001)

The NPRA occupies a central position in the north Alaska petroleum province (fig. 2). This province extends about 680 mi from the Canadian border westward to the maritime Russian border and from approximately 60 to 370 mi northward from the Brooks Range to the edge of the continental shelf. The province is characterized in the east by the relatively narrow, approximately 60 mi-wide Beaufort continental shelf and in the west by the broad, approximately 370 mi-wide Chukchi shelf. The province is bounded in the south by the Brooks Range — Herald Arch orogenic belt and offshore to the north by a passive continental margin.The offshore part of NPRA spans most of the province extending from the Brooks Range in the south across foothills and coastal plain to the Arctic Ocean in the north.

As summarized in figure 2, the NPRA includes many of the major tectonic features of northern Alaska. The Chukchi and Arctic platforms are remnants of a late Paleozoic to early Mesozoic south-facing continental margin. These features are separated by a north-trending structural sag, the Hanna trough, that is characterized by extensional normal faulting and thick sediment accumulations developed in Devonian(?) and Mississippian time and continuing on into the early part of the Mesozoic. Sherwood and others (1998) consider Hanna trough to be a failed rift. The Barrow arch and adjacent hinge-line fault zone are features developed during an episode

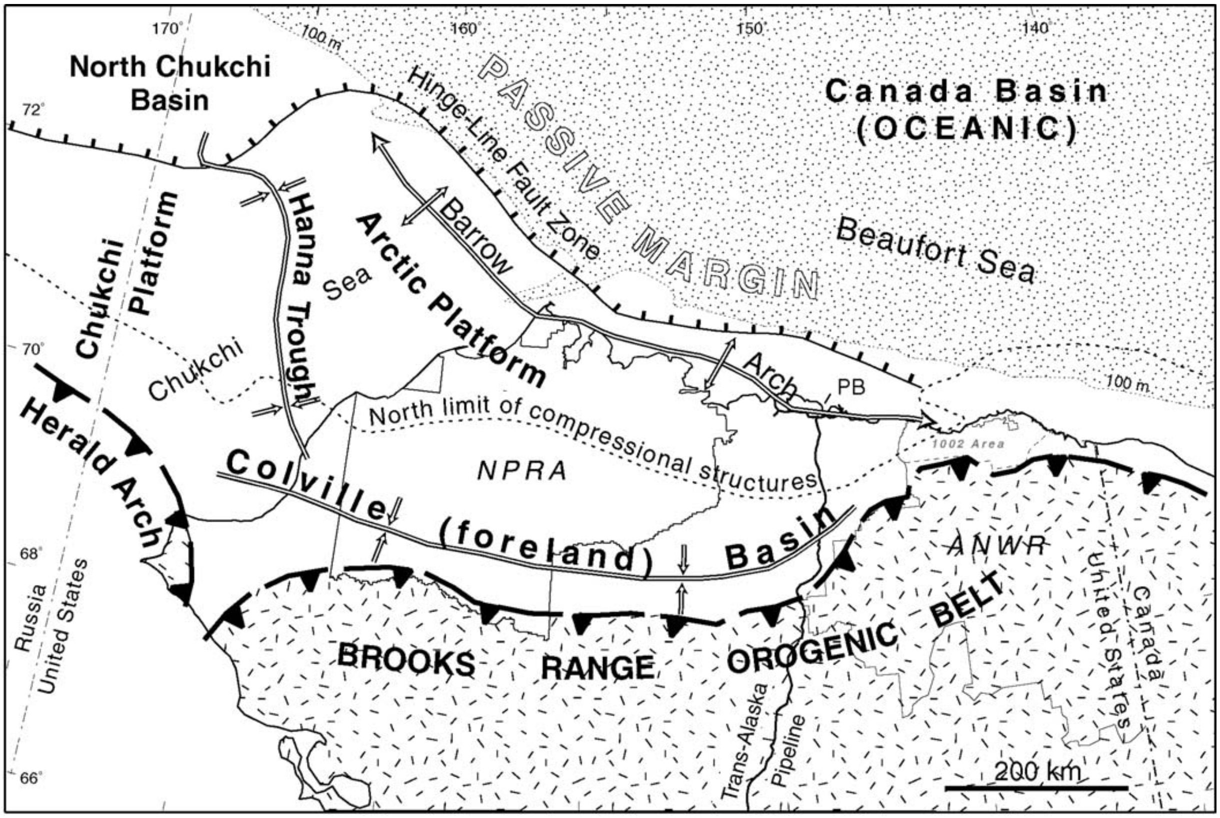


Figure 2. — Map showing the location of the NPRA relative to the major tectonic features of northern Alaska. [ANWR, Arctic National Wildlife Refuge; PB, Prudhoe Bay.]

of rifting that occurred in Jurassic and Early Cretaceous time. The oceanic Canada basin and the flanking passive margin owe their origin to this rifting event. At the southern margin of the Arctic and Chukchi platforms and overlapping in time with rifting to the north, an arc-continent collision produced the Brooks Range, the adjacent Colville foreland basin, and, presumably, the Herald arch orogenic belt. Compressional deformation in Tertiary time produced the fold- and thrust-belt that extends well north of the Brooks Range and crosses the entire southern part of the foreland basin. Additional details of the regional tectonic setting are provided by Hubbard and others (1987), Grantz and others (1990), and Moore and others (1994).

Stratigraphy

The stratigraphic record of the NPRA extends at least as far back as Ordovician (Carter and Laufeld, 1975) and possibly into the Precambrian, but rocks with petroleum and coal resources potential are Mississippian and younger (fig. 3). The traditional grouping of the rocks into tectono-stratigraphic sequences is followed here. This scheme, proposed by Lerand (1973) and modified by later investigators, emphasizes tectonic history, provenance, and genetic relations.

This section briefly describes the sequences and their stratigraphy in the NPRA north of the Brooks Range. Stratigraphy in the Brooks Range is somewhat different, consisting in large part of distal Ellesmerian and Beaufortian facies. It represents a relatively small part of the NPRA and is not considered here. Additional stratigraphic detail and references are provided in reports by Gryc (1988) and Moore and others (1994).

Franklinian Sequence

The Franklinian sequence in northern Alaska includes Devonian and older rocks representing diverse origins and a complex geologic history. In the NPRA, the Franklinian sequence forms the acoustic basement. It lies at depths of less than 4,000 ft subsea in the Barrow peninsula area and slopes southward, reaching depths of greater than 30,000 ft near the northern margin of the Brooks Range. Franklinian rocks in the NPRA, which are known only from widely scattered well penetrations located within 50 mi of the coast, consist mostly of steeply dipping fine-grained sedimentary rocks, apparently of deep marine origin, and, in one well, of gently dipping coarse-grained nonmarine deposits. Igneous and metamorphic rocks also are present locally. Franklinian sedimentary rocks have generally been buried and metamorphosed beyond the thermal stage for oil and are considered economic basement. Deformation of the Franklinian is attributed to the Devonian Ellesmerian orogeny.

Ellesmerian Sequence

Following the Ellesmerian orogeny and cutting of a regional unconformity, renewed

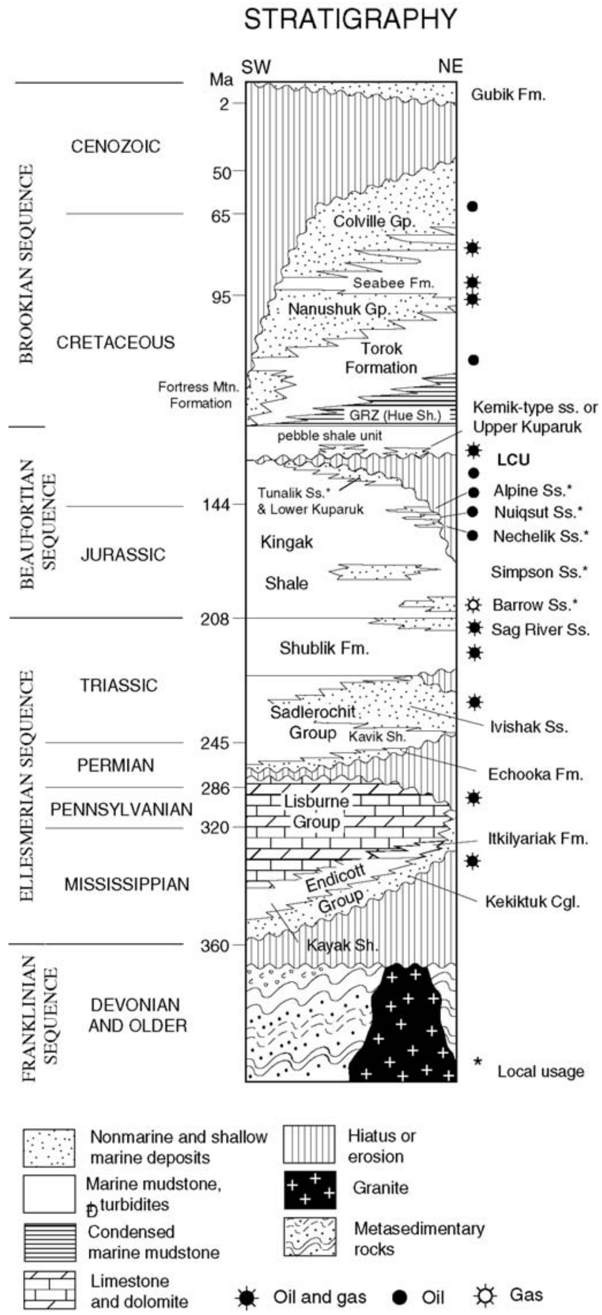


Figure 3. — Generalized stratigraphic column for the NPRA north of the Brooks Range showing tectono-stratigraphic sequence subdivisions and the stratigraphic position of hydrocarbon occurrences in northern Alaska. [GRZ, gamma-ray zone; LCU, Lower Cretaceous unconformity.]

subsidence and sedimentation developed on a south-facing continental margin, the Arctic platform. The Mississippian to Triassic Ellesmerian sequence consists of carbonate and clastic continental shelf deposits, typically less than 5,900 ft thick. In the northern part of the NPRA, these deposits show progressive northward onlap characteristic of a subsiding passive margin.

The lower part of the Ellesmerian sequence (Mississippian to Early Permian) was deposited during an episode of extensional (transtensional?) deformation, the locus of which was likely the Hanna trough beneath the Chukchi Sea (fig. 2). In the NPRA, this deformation resulted in the development of local basins, arches, and platforms and great variations in sediment thickness. For example, in the yoked Ikpikpuk and Umiat basins, 9,800 ft or more of coal-bearing sandstone and mudstone (Kekiktuk Conglomerate) were deposited whereas only a few hundred feet or less were deposited on adjacent arches and platforms. These deposits were succeeded by 500-1,000 ft of regionally extensive marine shelf and nearshore mudstones (Kayak Shale and Itkilyariak Formation) and as much as 3,000 ft of carbonate platform deposits (Lisburne Group).

A regional mid-Permian unconformity separates the lower from the upper (Late Permian to Triassic) part of the Ellesmerian sequence, except perhaps in local basins where sedimentation may have been continuous. Overlying this unconformity, the Sadlerochit Group consists in upward succession of transgressive marine sandstone (Echooka Formation), prodelta marine mudstone (Kavik Shale) and deltaic sandstone (Ivishak Sandstone). Overall thickness of the Sadlerochit is 2,000-3,000 ft. In mid– to late Triassic, reduced clastic input and relative sea level rise resulted in the deposition of about 300 ft of organic carbon-rich calcareous mudstone (Shublik Formation), a major petroleum source rock. The upper-most Ellesmerian is marked by deposition of 30-100 ft of regressive marine sandstone (Sag River Sandstone).

The Ellesmerian sequence includes both reservoir and source rocks. In the Prudhoe Bay area, the Kekiktuk, Lisburne, Ivishak, and Sag River are oil productive. Shublik source rocks, which lie near the top of the sequence, were not capable of petroleum generation until buried by Beaufortian and much thicker Brookian sequence deposits.

Beaufortian Sequence

The Jurassic and Early Cretaceous (Neocomian) Beaufortian sequence (Hubbard and others, 1987) consists of syn-rift deposits derived locally or from the north. This is a stratigraphically complex, marine mud-dominated succession with numerous, locally developed sandstones (fig. 3). Most of the sequence is represented by the Kingak Shale which may reach a thickness of more than 4,000 ft in the NPRA, while offshore in grabens, age-equivalent strata may be 4 times as thick (Hubbard and others, 1987; Grantz and others, 1988).

Beaufortian depositional architecture in the NPRA is characterized by stacked sequences of south-ward prograding clinoforms. Most sandstones are developed in topset facies and potential source rocks, in distal bottomset facies. Multiple unconformities are present, but most are not shown in figure 3. The youngest and most widespread of these is the Lower Cretaceous unconformity (LCU), interpreted by Grantz and others (1988) as the breakup unconformity. This unconformity progressively truncates the Beaufortian sequence northward onto the Barrow arch with a zero edge located along the northeast coastline. To the south, it passes into a correlative conformity that preserves the ultimate (Early Cretaceous) Beaufortian depositional profile of shelf, slope, and basin plain. The Barrow arch, first formed during rift-related uplift and subsequently accentuated by subsidence to the north and south, is a regional basement high and a key element in the formation of most north Alaskan oil fields. Subsidence of the rift-margin and the ensuing marine transgression resulted in deposition of a blanket-like marine mudstone (pebble shale unit) that marks the end of the Beaufortian sequence.

Regionally, the LCU truncates both reservoir and source rock intervals along the Barrow arch, and because of this, it plays an important role in the formation of many of the largest oil fields in northern Alaska. This role includes developing enhanced porosity in sub-unconformity reservoirs (Jameson, 1994; Shanmugam and Higgins, 1988) and providing a hydrocarbon migration pathway for charging multiple, sub-unconformity reservoirs. Cretaceous mudstone overlying the LCU may provide a seal, thus creating combination structural-stratigraphic traps in favorable circumstances.

Beaufortian reservoirs host gas accumulations on the Barrow peninsula (Walakpa, South and East Barrow, and Sikulik) and oil accumulations (Alpine and Fiord) at the eastern border of the NPRA.

Brookian Sequence

Cretaceous and Tertiary deposits derived from the Brooks Range orogen are assigned to the Brookian sequence. These voluminous clastic deposits reach thicknesses in excess of 25,000 ft in the Colville foreland basin, they overtop the rift shoulder (Barrow arch), and build the passive margin that forms the present-day continental terrace north of Alaska (Bird and Molenaar, 1992).

In the NPRA, subsidence analysis (Cole and others, 1997) suggests that the Colville basin formed in response to tectonic loading by the ancestral Brooks Range in the Early Cretaceous (Barremian), about 125 Ma. Seismic records show that Brookian deposition is characterized by clinoform progradation and that filling of the basin occurred from southwest to northeast (Molenaar, 1988). As a consequence, most of the Brookian in the NPRA is Aptian and Albian. Younger deposits, Upper Cretaceous and Paleocene, are relatively thin and are limited to the eastern part of the Reserve.

In the NPRA, the Brookian sequence consists of a complex assemblage of clastic strata (fig. 3). At its base, this assemblage includes a distal, condensed marine mudstone characterized by high gamma-ray readings, the gamma-ray zone (GRZ) of the Hue Shale (Molenaar and others, 1987). This is a source rock that typically occurs in a bottomset seismic facies. It interfingers with clinoform strata during transgressive episodes and, in extreme cases such as 93 Ma transgression responsible for the Upper Cretaceous Seabee Formation, it may even occur in a topset position. Overlying the distal facies are basin, slope and outer shelf mudstones and associated turbiditic sandstones of the Torok and Seabee Formations. Topset facies deltaic deposits (Nanushuk and Colville Groups) record complete filling of the basin. The most proximal facies is represented by the coarse-grained deposits of the Fortress Mountain Formation, an outcrop unit in the foothills of the Brooks Range (Molenaar and others, 1988).

Throughout northern Alaska, Brookian deposits provided the overburden necessary for the maturation of most petroleum source rocks in all sequences. Brookian depositional history suggests that hydrocarbon generation began in the southwestern part of the NPRA in Albian time and progressed northeastward in association with basin filling. Because structures in the NPRA fold-belt formed considerably later than hydrocarbon generation, it is likely that hydrocarbons accumulated first in stratigraphic traps. Structural disruption of these traps and remigration of hydrocarbons into structures or to the surface is postulated. Several gas accumulations of poorly determined size (Meade, Wolf Creek, Square Lake, and Gubik) and one oil accumulation (Umiat) are known in Brookian reservoirs in the fold belt, whereas two small oil accumulations (Fish Creek and Simpson) are known north of the fold belt.

COAL-BEARING FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS OF THE MISSISSIPPIAN ENDICOTT GROUP

(revised from Wilson and others, 2001)

The Endicott Group crops out in the Brooks Range from the Arctic National Wildlife Refuge (ANWR) (LePain and others, 1994; Bird and Molenaar, 1987; Nilsen, 1981) westward into the central and western Brooks Range (Brosgé and others, 1988). In the subsurface it has been described in the Prudhoe Bay area (Wicks and others, 1991; Melvin, 1993) and the NPRA (Bird, 1988; Kirschner and Rycerski, 1988; Moore and others, 1994). It consists of, in ascending order, the Kekiktuk Conglomerate, Kayak Shale, and Itkilyariak Formation (Bird and Jordan, 1977) (fig. 4). The Kekiktuk Conglomerate is the reservoir for the 400 MMSTB Endicott field (Wicks and others, 1991).

The Endicott Group has been penetrated by a number of wells drilled in the NPRA, but it is poorly represented in core. Cored wells include the East Simpson 2, Topagoruk 1, Ikpikpuk 1, and Inigok 1 (fig. 4). This section describes facies associations represented in four cores from the East Simpson 2. These cores generally are correlated to the Kekiktuk Conglomerate.

Endicott Depositional Setting

The Endicott Group forms the basal part of the northern-sourced transgressive-regressive middle Ellesmerian Megasequence defined by Hubbard and others (1987) and is overlain by shallow marine carbonate rocks of the Lisburne Group. Regionally, the Endicott Group is characterized by nonmarine and shallow marine clastic rocks (Moore and others, 1994) and comprises an overall transgressive sequence (Bird and Jordan, 1977). The Kekiktuk Formation at the base has been described as a fan delta system or braid delta produced by low-gradient, high-sand, braided streams (Bloch and others, 1990). Melvin (1993) divided the Kekiktuk of the Endicott field into three zones consisting of swamp, braided stream, and lower delta plain interdistributary bay fill to meandering stream deposits. The Kekiktuk overlies a regional angular unconformity developed on the Pre-Mississippian Franklinian sequence of Hubbard and others (1987).

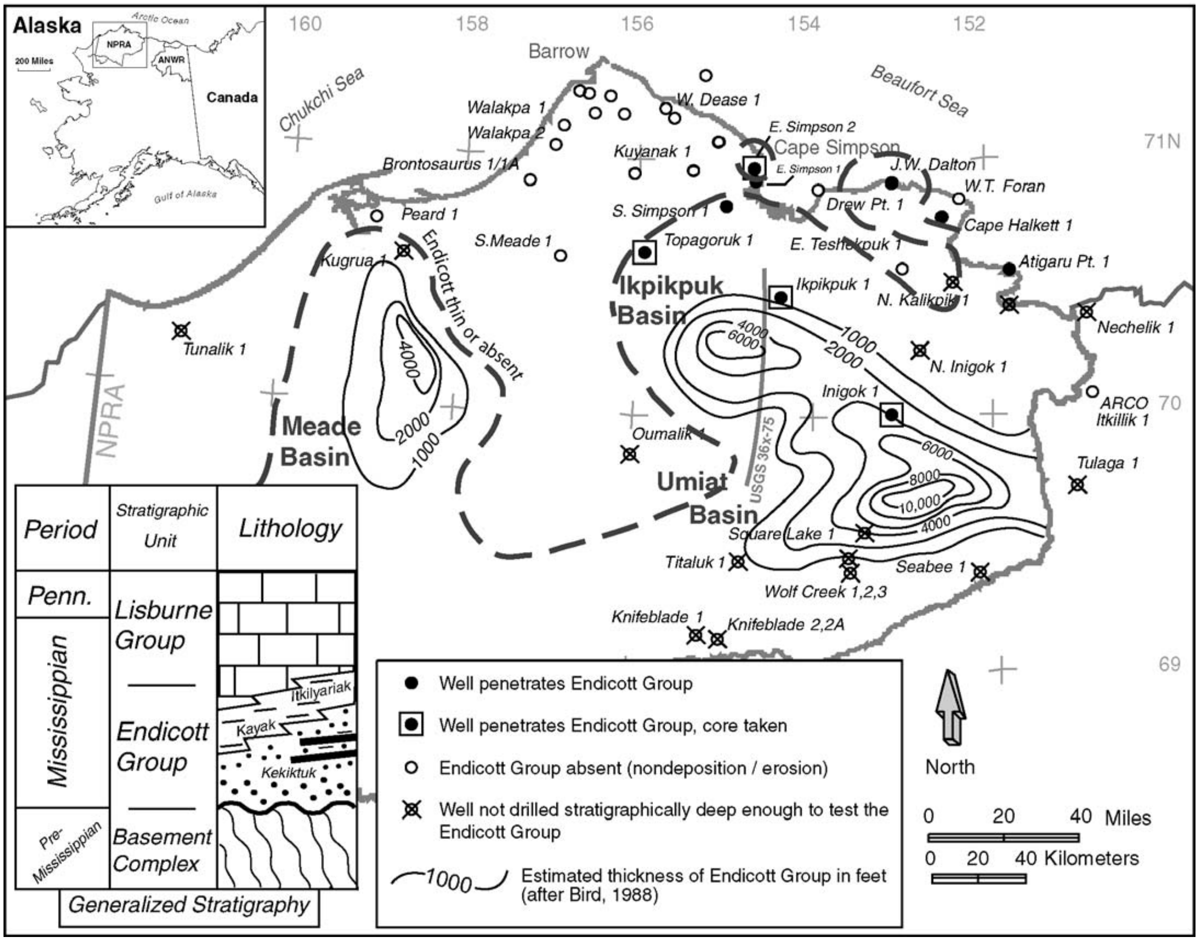


Figure 4. — Endicott Group thickness isopach in the NPRA, with generalized stratigraphy (inset) displayed in the lower left. Contours are adapted from Bird (1988), with permission.

Kirschner and Rycerski (1988) interpreted from seismic data a rift-like breakup of the central Arctic in the Late Devonian to Early Mississippian. In the NPRA, this breakup is manifested by the Meade, Ikpikpuk, and Umiat basins (fig. 4). A fourth basin is present in the Prudhoe Bay area (Wicks and others, 1991).

The Inigok 1, the deepest test of one of these basins in the NPRA, penetrates about 4,200 ft of the shallow marine limestone of the Lisburne Group and about 1,920 ft of Endicott Group non-marine clastic rocks. The well reached a total depth of 20,102 ft in the Endicott Group. Kirschner and Rycerski (1988) estimated as much as 17,700 ft of siliciclastic and carbonate basin fill in the NPRA. Because of the lack of well control in the deepest parts of these basins, assignment of these strata to rock units of known age is problematic. Consequently, regional correlation within these deep basins is speculative.

Hubbard and others (1987) suggested the age of the basal unconformity from well data is as old as earliest Mississippian (335 Ma) in the basins and as young as mid to late Mississippian over the basement highs. In the NPRA, this basal unconformity is an irregular surface and includes smaller sub-basins to those already mentioned. Examples include the thin sequence penetrated in East Simpson 2 (the interval is absent directly to the south in East Simpson 1) and the JW Dalton area (fig. 4).

Facies Associations and Interpretations
East Simpson 2 Cores 5, 6, 7, and 8

The most continuous set of cores for the Endicott Group in the NPRA is found in East Simpson 2 (fig. 5). These cores consist of coals, sandstone, and mudstone that appear to be consistent with shallow water lacustrine deposits and splays of a fan delta system into flood basins. Therefore, we correlate these rocks to the Kekiktuk Formation of the Endicott Group. Coals in this sequence are Mississippian in age (Mike Mickey, personal communication; ARCO Alaska internal reports), distinguishing these rocks from the Ivishak Sandstone of the Permo-Triassic Sadlerochit Group. A possible exception is the uppermost part of core 5. Overlying a thin pebble lag is fluvial sandstone that appears similar in character to the Triassic Ivishak Sandstone (fig. 5) present in East Simpson 1 cores. From the drill cuttings samples of East Simpson 2, Mickey (personal communication) interprets Norian down to a depth of at least 7,150 ft, only 15 ft from the top of core 5.

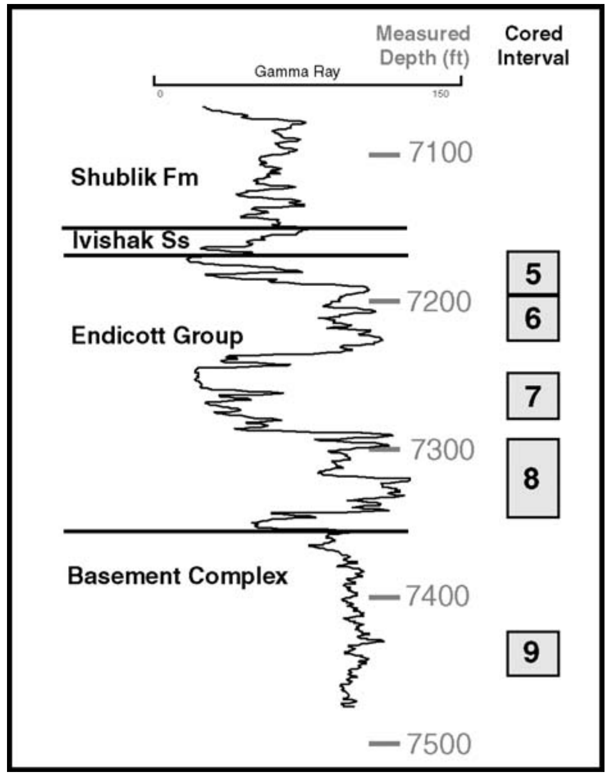


Figure 5. — Gamma ray log of Endicott Group (Kekiktuk Fm.) in East Simpson 2 showing cored intervals. See figure 6 for detailed lithofacies.

To summarize, the interpreted succession of lowermost strata in East Simpson 2 consists of Basement Complex unconformably overlain by the Endicott Group, in turn unconformably overlain by the Ivishak Sandstone. The Ivishak Sandstone thickens southward into the East Simpson 1 well, where it overlies Basement Complex in an angular unconformity, whereas the Kekiktuk Sandstone pinches out southward between East Simpson 2 and East Simpson 1 (fig. 4). South of the East Simpson 1 well the Endicott Group thickens rapidly into the Ikpikpuk Basin (fig. 4).

The following descriptions of core from East Simpson 2 each contain one or more lithofacies of the Kekiktuk Formation (KF) grouped together as genetic units.

Facies Association KF-1A (fig. 6): This facies consists of light gray to medium gray siltstone and very fine to coarse-grained sandstone with distorted mudstone drapes, in places interbedded with dark gray, highly organic mudstone. Sandstone is locally rich in dark gray mud clasts and carbonized plant debris. Primary sedimentary structures include massive beds, wavy beds, high angle cross beds, and parallel laminations. Some units are highly contorted and display as much as 1 ft of relief.

Interpretation — Splay into a flood basin, rapid deposition.

The probable cause of the convolutions in this facies was initial depositional relief, resulting in soft-sediment slumping and contorting. High angle cross beds probably represent trough-fill. Individual splay deposits are as thick as 9 ft , however composite thickness of multiple splay deposits are nearly 20 ft . These splays overlie flood basin deposits.

Facies Association KF-1B (fig. 6): This facies is medium gray to dark gray, sandy mudstone and siltstone with about 10-15 percent parallel to parallel inclined, laminated, light gray very fine-grained sandstone. In places this facies is contorted.

Interpretation — Splay into a flood basin, slower deposition than KS-1A.

Facies Association KF-2 (fig. 6): Coals and subordinate mud-stone, siltstone, and sandstone dominate this facies. Coals range in thickness from a few centimeters to about 13 ft. Commonly, a vertical succession consists of (1) a lower dark gray, massive, root mottled, clayey siltstone with abundant carbonized plant debris and local lenses of mud clast conglomerate; (2) a middle thin to thick coal; and (3) an upper unit consisting of alternating dark gray mudstone and siltstone with a few thin beds of light gray, moderately sorted, wavy laminated, very fine-grained sandstone.

Interpretation — Coal Swamp

Facies Association KF-3 (fig. 6): These deposits consist of alternating medium dark gray siltstone and grayish black carbonaceous mudstone. The mudstone is indistinctly wavy laminated. Siltstone occurs as thin beds, lentils, and pods within the mudstone. Sand-sized mud clasts are common in the siltstones.

Interpretation — Flood basin/lacustrine.

These deposits possibly accumulated in a few feet of freshwater.

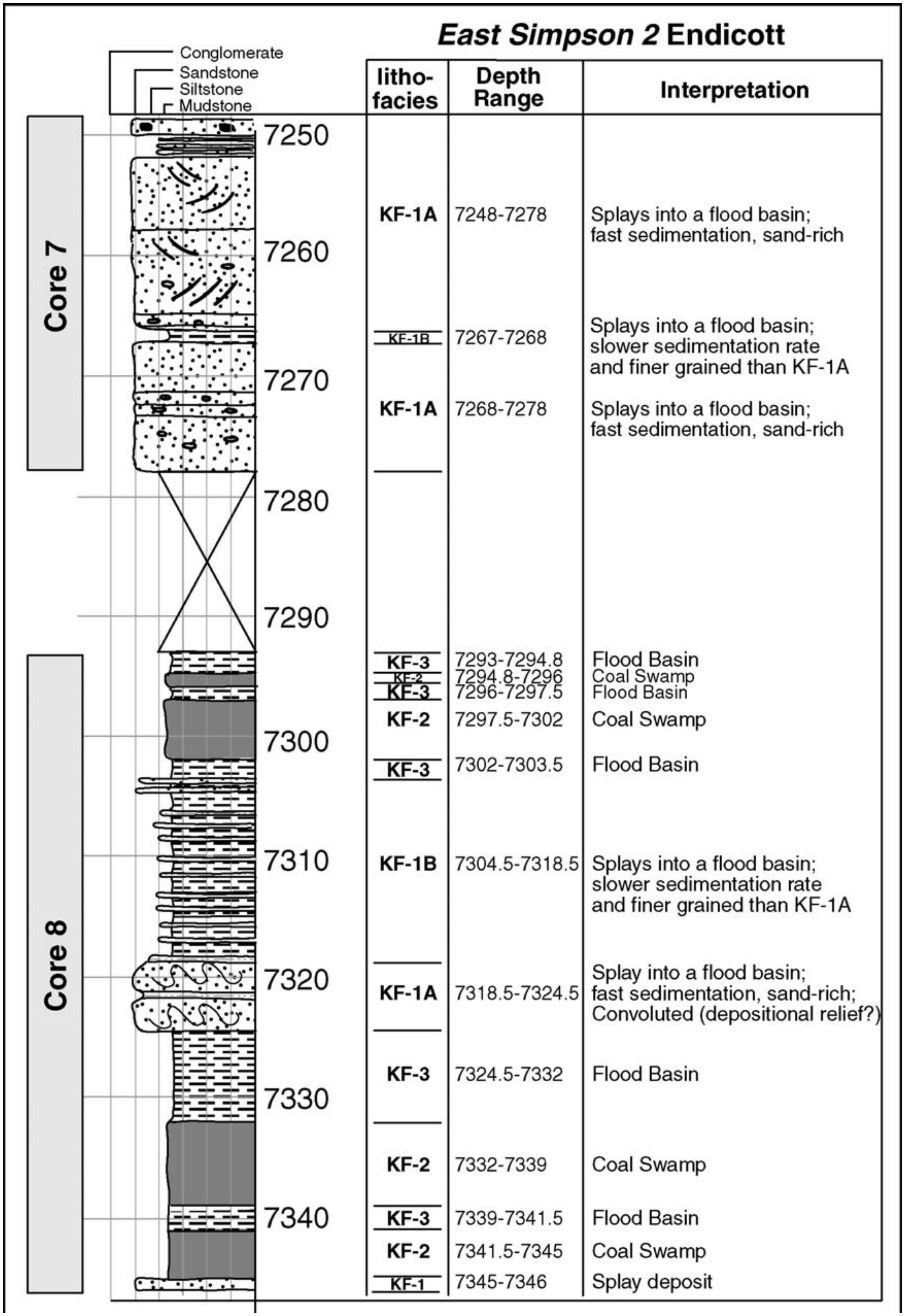


Figure 6A. — Lithology log, lithofacies, and interpretations for the Endicott Group rocks in cores 5, 6, 7, and 8 of East Simpson 2 (continued on next page).

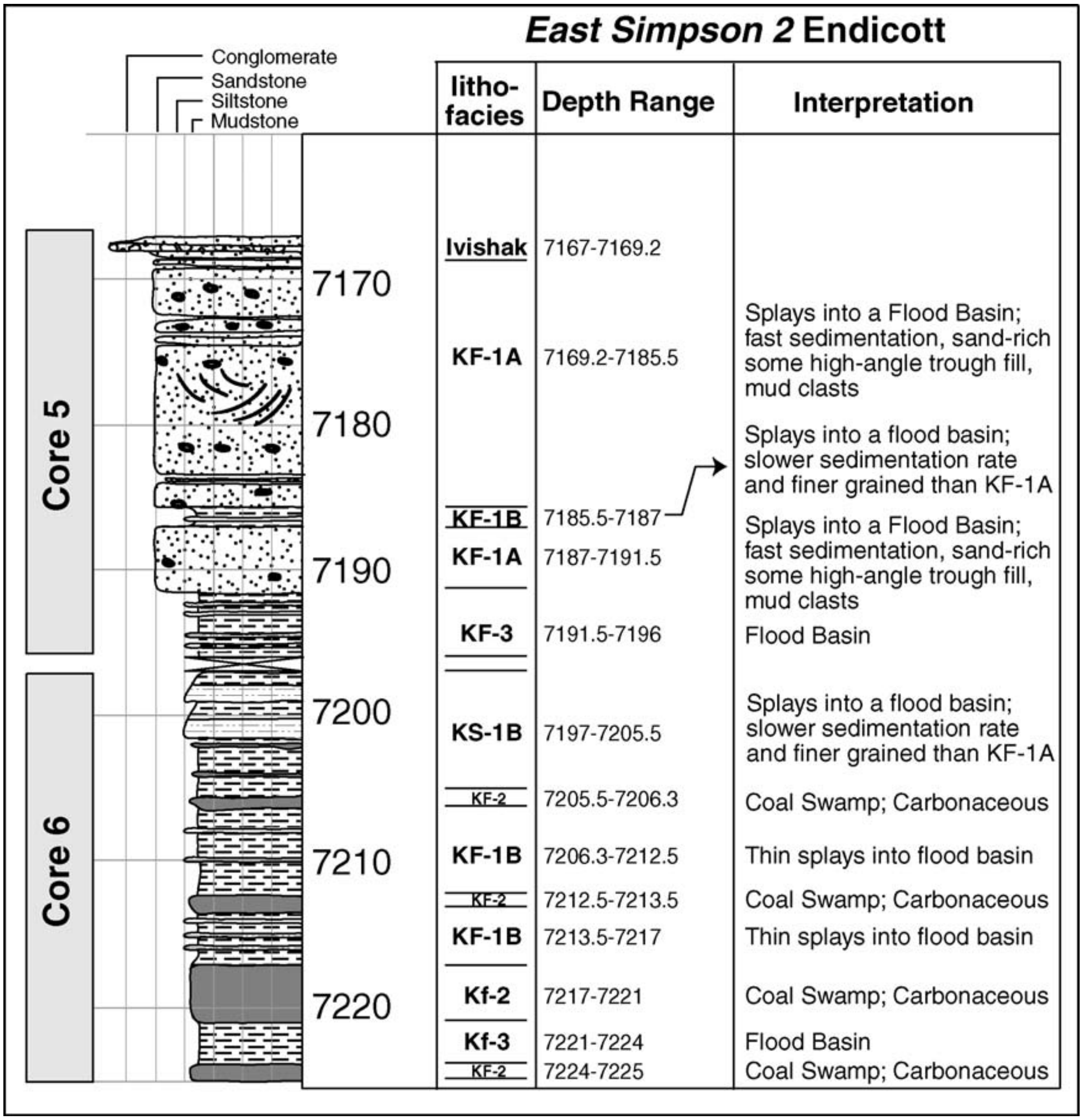


Figure 6B. — (continued from previous page).

Endicott Summary

Because of limited core from the Endicott Group in the NPRA, any meaningful regional interpretation of depositional setting is difficult.

Seismic and well data in the NPRA indicate that the Endicott Group was deposited in thick accumulations within narrowly defined basins (Meade, Ikpikpuk, and Umiat basins), but is largely absent or thin across the intervening highs due either to nondeposition or erosion. Deep burial within these basins suggests reservoir potential is low, as is indicated by the small amount of tight, quartz-cemented core in Inigok 1.

The Endicott Group in the NPRA overlies a highly irregular surface on the Basement Complex. Owing to this irregular surface, the Endicott occupies several relatively thin localized subbasins (East Simpson 2 and JW Dalton areas). Endicott in these subbasins has not been buried as deeply and might retain better reservoir potential.

The Kekiktuk Formation of East Simpson 2 appears to have been deposited on the lower delta plain. Cored intervals can be grouped into facies associations that consist largely of splay, flood basin, and coal swamp deposits.

SHUBLIK FORMATION LITHOFACIES AND PETROLEUM SOURCE ROCKS

(revised from Parrish and others, 2001)

The Triassic Shublik Formation of northern Alaska has a facies array that is typical of modern upwelling zones (Parrish, 1987). Well-developed modern upwelling zones have a distinctive, concentric array of sediment types, comprising a core of organic-rich sediment fringed by a zone of phosphatic sediment that, in turn, is fringed by a zone of glauconitic sediment (Bremner, 1983; Glenn and others, 1994; and many others). These facies are related to high primary productivity and to the oxygen depletion that results from high organic input to the sediment.

The Shublik Formation is of considerable economic interest because it consists of phosphatic rocks (Patton and Matzko, 1959; Detterman, 1970) and organic-rich rocks that probably are source beds for much of the Prudhoe Bay oil (Tailleur, 1964; Hughes and others, 1983; Magoon and Claypool, 1983; Magoon and Bird, 1988; Kupecz, 1995). It also contains glauconitic rocks. The distribution of these organic-rich, phosaphatic, and glauconitic rocks is consistent with that seen in well-developed modern upwelling zones (Bremner, 1983; Glenn and others, 1994; Parrish, 1987; and Parrish and others, 2001). Studyies of outcrops and cores in the ANWR and in the NPRA, concluded that the Shublik was deposited in such a setting (fig. 7; see also Dingus, 1984; Kupecz, 1995).

The Shublik Formation is identified in the subsurface by a distinctive signature of gamma ray and resistivity peaks (Jones and Speers, 1976; Dingus, 1984; Kupecz, 1995). The formation is thin: 0-585 ft thick in the subsurface (Bird, 1982) and 121-546 ft thick in outcrop sections measured by Parrish (1987) and Parrish and others (2001). Over the Barrow Arch, the Shublik thins to zero owing to depositional onlap. In the Prudhoe Bay region, the formation is truncated by a Cretaceous erosional unconformity (Bird, 1985). In general, the formation thickens to the south until it is truncated by thrust faulting in the Brooks Range.

Regional study of outcrops and cores from NPRA indicates the Shublik Formation is dominated by siliciclastic deposits in the northern parts of the region and by phosphatic or organic-rich limestone in the southern parts. The siliciclastics range from very fine sandstone to mudstone and are commonly bioturbated and glauconitic in NPRA cores (South Barrow 3, Tulageak 1, Walakpa 1, Simpson 1, West Dease 1; fig. 1). Phosphate is present in some of the NPRA cores that are dominated by siliciclastics (Peard 1, South Barrow 1) and is a major component in some

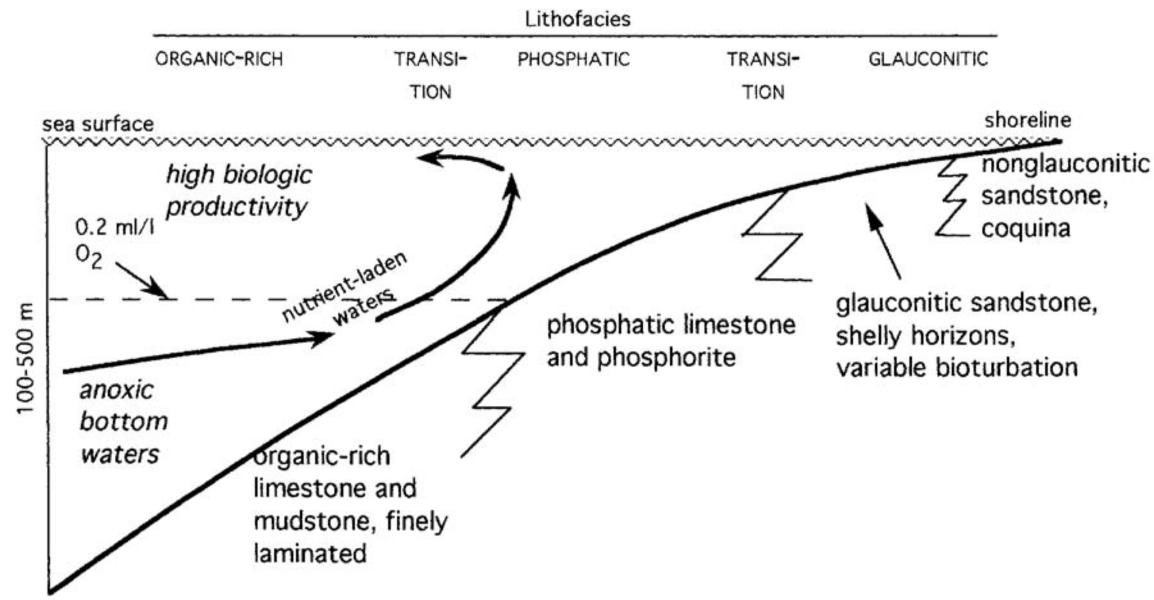


Figure 7. — Schematic reconstruction of the continental shelf and vertical shelf circulation perpendicular to the paleoshoreline during deposition of the Shublik Formation, showing the distribution of lithofacies (from Parrish, 1987), north to right. In modern upwelling zones, the highest biological productivity occurs just offshore from the site of upwelling (Barber, 1974) and the 0.2 ml/l oxygen isopleth defines the boundary of the anoxic zone (Burnett, 1980); the figure shows where these might have occurred at the time of Shublik deposition. Paleodepth at the seaward side would have depended on a number of factors, especially bottom topography (Parrish, 1982).

of the limestone cores (East Simpson 1, North Inigok 1, Ikpikpuk 1; fig. 1). The limestone is black and organic rich in the southernmost cores (South Meade 1, Ikpikpuk 1, North Inigok 1, and Inigok 1; fig. 1).

SHUBLIK PETROLEUM SOURCE ROCKS IN THE TENNECO PHOENIX 1

(revised from Robison and Dawson, 2001)

This section is based on an integrated sedimentological, petrological, petrophysical and organic geochemical study (Robison and others, 1996) of cored Permo-Triassic strata in the Tenneco Phoenix 1 well (OCS-Y-0338), located along the Barrow Arch in the Federal offshore northeast of NPRA (fig. 1). The Tenneco Phoenix 1 well recovered nearly continuous core (7,592 to 8,544 ft) from the Shublik Formation and the underlying Sadlerochit Group, including strata that are equivalent to the main source-rock intervals and reservoir in Prudhoe Bay field. Although the Phoenix 1 well encountered noncommercial hydrocarbons, these cores provide an exceptional opportunity to study and document stratigraphic variations within a known petroleum system.

Lithostratigraphy

Lithostratigraphic aspects of the Ivishak, Eileen, and Shublik Formations and the nature of the formational contacts described by Jones and Spears (1976), Van deKamp (1979), Parrish (1987), and Bird (1994) are consistent with our observations of cored intervals in the Phoenix 1 well. Cores recovered from the Phoenix 1 well range in depth from 7,592 to 8,544 ft; this interval represents complete coring of the Shublik Formation and the underlying Eileen and Ivishak Formations.

The lower Ivishak interval (8,132 to 8,544 ft) consists of sharp-based, stacked, fining-upward units (1 to 3 ft), composed of conglomerates and medium- to coarse-grained, nonfossiliferous, cross-stratified sandstones. Red and gray mottled siltstones and shales cap each conglomeratic sandstone unit. The upper part (8,115 to 8,132 ft) of the Ivishak Formation is composed mainly of horizontally laminated, medium- to fine-grained, well-sorted sandstones. Contoured laminae and conglomeratic sandstones are developed locally in upper Ivishak strata. Rarely, these laminations are disrupted by isolated mottles (probable burrows).

The Ivishak/Eileen contact is denoted in the core by a thin (8,114.5 to 8,115 ft) conglomerate. This distinctive contact is equivalent to the Member D-Member E transition in the Ivishak Formation discussed by Jones and Spears (1976). The Eileen Formation is thin (35 ft) and consists mostly of fine-grained, sparsely fossiliferous and glauconitic, intensely mottled argillaceous sandstones. The overlying Shublik Formation (Triassic) is nearly 300 ft thick in the Phoenix 1 well and consists predominantly of fossiliferous shales and siltstones. These shales are well laminated and exhibit minimal evidence of bioturbation. A mineralized (phosphate, glauconite, and pyrite) unit (7,898.9 to 7,901.9 ft) is present within the middle Shublik interval.

Jurassic-aged strata, present elsewhere along the North Slope, are absent (because of erosion) in the Tenneco Phoenix 1 well. Hence, the Sag River Sandstone (Triassic) is truncated by the regional LCU and is overlain by the Pebble Shale (Cretaceous). Most of the hydrocarbons in the Prudhoe Bay field and the surrounding area occur in reservoirs that are truncated by the LCU.

The studied cored interval (7,800 to 8,200 ft) in the Phoenix 1 well can be subdivided into major lithofacies, each having distinctive sedimentary structures, textures, and petrophysical properties. The Ivishak Formation (412 ft) consists of three interstratified sandstone lithofacies: 1) cross-stratified, medium- to coarse-grained sandstones; 2) conglomeratic sandstones; and 3) horizontally laminated, medium- to fine-grained sandstones. The medium- to coarse-grained sandstones exhibit well-developed planar cross stratification. Clasts of kaolinitic claystone are a conspicuous accessory component of this lithofacies. The average porosity of these cross-stratified units is 21.3 percent, and the average horizontal permeability is 2,272 md. Pyro-bitumens are present within the intergranular pores of the cross-stratified sandstones. The interstratified conglomeratic sandstones contain abundant shale and sideritic intraclasts. This lithofacies consists of sharp-based, fining-upward units that grade into cross-stratified medium-grained sandstones and are capped by finely laminated red and gray siltstones and shales. These poorly sorted conglomeratic units have an average porosity of 18.3 percent with an average horizontal permeability of 235 md. Relatively low average porosity (12.5 percent) and minimal permeability (0.14 md) characterize the interstratified siltstone and shale units. Hence, these fined-grained units are potential intra-reservoir baffles, which can induce reservoir compartmentalization.

Horizontally laminated, very fine- to medium-grained, upper Ivishak sandstones occur as thin fining-upward units that are capped by gray/red mottled siltstones and shales. Concentrations of carbonaceous debris accentuate the laminated fabric. Nodular siderite is an accessory feature of this lithofacies. Locally, mottles and soft-sediment deformation disrupt the well-developed laminar fabric. The basal (medium-grained) parts of these laminated units have an average porosity of 18.9 percent and an average horizontal permeability of 353 md. The interstratified, very fine- to fine-grained, laminated sandstones have a comparable average porosity (19.1 percent), but a considerably lower horizontal permeability (138 md). At 8,120.3 ft in the Tenneco Phoenix 1 core, coarse-grained, cross-stratified sandstones truncate laminated Ivishak sandstones. Ivishak sandstones are separated from the overlying Eileen Formation by a thin (8,114.5 to 8,155 ft) conglomeratic unit.

Overlying lower Eileen strata (8,105 to 8,114.5 ft) consist of faintly laminated, well-sorted, fine-grained sandstones. Lower Eileen sandstones have 19.5 percent average porosity and an average horizontal permeability of 14 md. These basal fine-grained sandstones grade upward into very fine- to fine-grained argillaceous and glauconitic sandstones that exhibit extensive mottling (8,081 to 8,105 ft). The average porosity of the mottled sandstones is 18.9 percent, and their average (horizontal) permeability is low (39 md). Distinctive coarse-grained sandstone beds are interstratified with the fine-grained Eileen sandstones; the coarse-grained beds have an average porosity of 24.3 percent and an average horizontal permeability of 1460 md. Coarse-grained Eileen sandstone beds lack evidence of mottling and have irregular basal contacts. A significant change in lithology occurs at 8,079.5 ft in the Tenneco Phoenix 1 core. That is, this contact marks a change from sandstone-dominated lithofacies to shale-dominated lithofacies. Also, this contact represents the Eileen/Shublik boundary.

Shublik strata (7,796 to 8,079.5 ft) consist dominantly of dark gray calcareous shales, which are interstratified with light gray, calcite-cemented, glauconitic quartzose siltstones. These shales and siltstones exhibit well-developed mm-scale to cm-scale laminar fabric; mottled (bioturbation) fabrics are absent. Fossils (molluscan shells) are abundant and commonly have been concentrated into discrete bioclastic (“shell hash”) layers. A prominent glauconitic and pyritic interval (7,898.9 to 7,901.9 ft) is present near the middle of the Shublik Formation. Triassic strata are separated from the overlying Cretaceous series by a thin (0.2 in) gravel lag that represents the LCU in the Phoenix 1 cores.

Sequence Stratigraphy and Sedimentology

A sequence stratigraphic interpretation of the Phoenix 1 well (Robison and others, 1996) is based on the interpretation of wire-line log signatures following the approach summarized by Mitchum and others (1993). As shown by figure 8, the Sadlerochit-Shublik interval in the Phoenix 1 well exhibits distinctive log patterns representative of the lithostratigraphy and depositional sequences. The upper Sadlerochit Group consists of conglomeratic and coarse-grained, cross-bedded sandstones (Ivishak Formation) characterized by blocky (aggradational) well log signatures. Ivishak sandstones record nonmarine deposition during a highstand. These sandstones

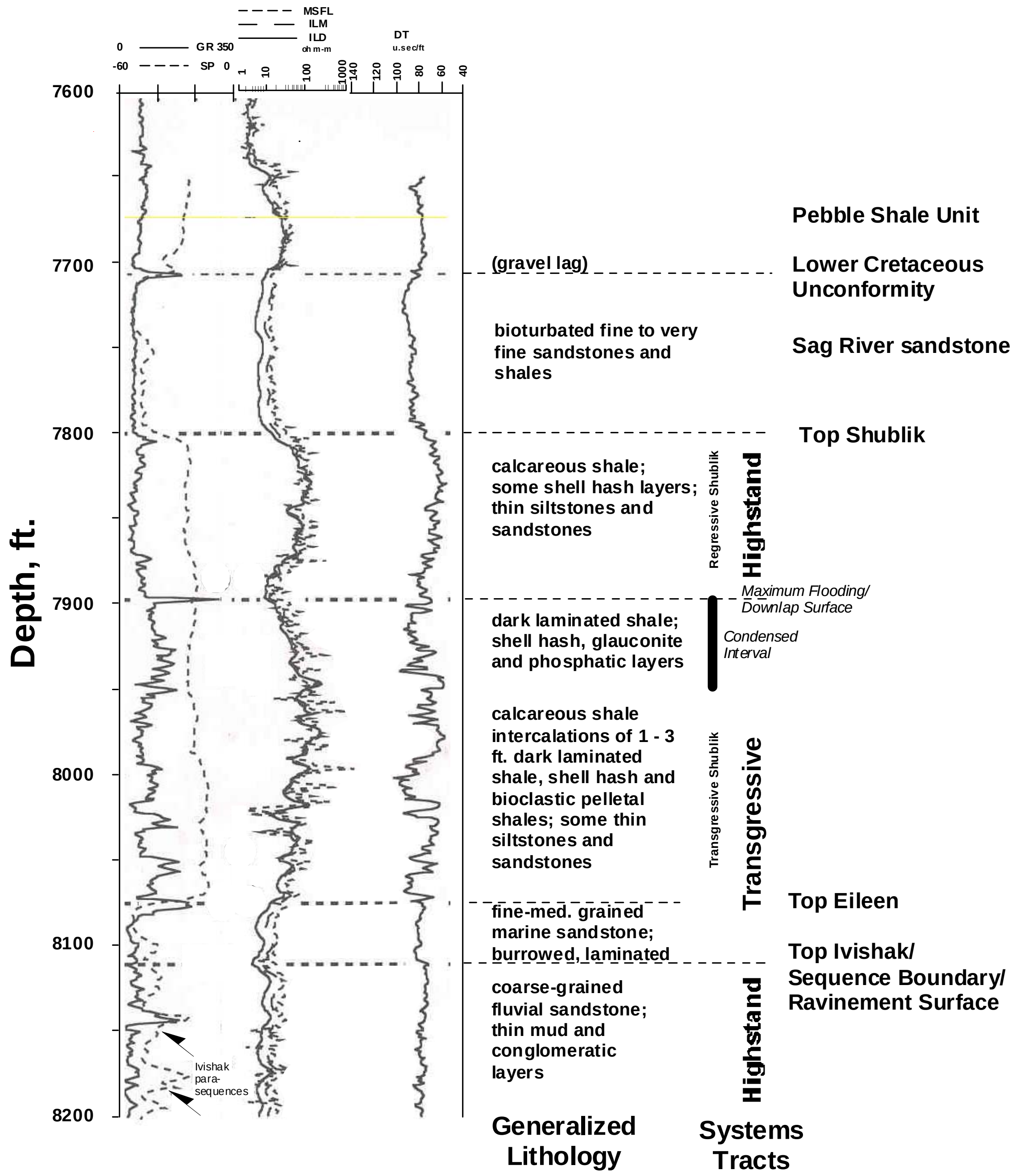


Figure 8. — Well log suite, generalized lithology and interpreted sequence stratigraphy through the Ivishak-Shublik Formations and overlying units in the Tenneco Phoenix 1 well, Alaska. [GR, total gamma ray; SP, spontaneous potential; MSFL, ILM, and ILD are resistivity logs; DT. sonic].

are multi-story, channelized units deposited regionally within a fluvial-deltaic setting (Jamison and others, 1980). Herein, Ivishak sandstones are interpreted as probable braid-plain delta deposits. The overlying fine-grained, burrowed, glauconitic sandstones (Eileen Formation) record deposition during the initial phase of a marine transgression. The transition from nonmarine (Ivishak) to marine (Eileen) strata is abrupt (occurring at 8,114.5 ft) and records a significant transgressive event (Jones and Spears, 1976). This nonmarine to marine transition is marked by a lag conglomerate that denotes a sequence boundary, associated with a relative drop of base level, which coincided with a transgressive surface. The conglomerate developed above this sequence boundary is interpreted as a transgressive lag deposit consistent with shoreface ravinement. This lag conglomerate is overlain by the Eileen Formation, which represents the initial establishment of widespread marine conditions. The extensively bioturbated fine-grained Eileen sandstones record deposition in a shallow marine (lower shoreface/below normal wave base) paleo-environment. Interstratified coarse-grained sandstones record high frequency (probable storm-induced) depositional events. The base of the Eileen Formation is practically indistinguishable from the underlying Ivishak Formation on the well log (fig. 8). However, based on examination of the Tenneco Phoenix 1 core, this Ivishak/Eileen boundary is interpreted as a coincident sequence boundary and transgressive surface (represented in the core as a thin conglomerate). This interpretation discrepancy illustrates the dilemma of recognizing some sequence boundaries using well log data without the benefit of lithologic information.

The Eileen/Shublik boundary is abrupt (fig. 8). This change from sandstone to shale-dominated lithofacies is indicated by a gamma-ray “kick” as well as marked changes in the resistivity, SP and sonic log responses. If only well log signatures are considered, this prominent change in wire-line log character could be misinterpreted as a sequence boundary. As noted above, core analysis reveals that the sequence boundary actually occurs approximately 35 ft below the prominent change in well log signatures. Overall, the Shublik Formation is characterized by fining-upward well log signatures. Shublik strata exhibit a series of high frequency gamma-ray log anomalies, coincident with increases in uranium content of the shales. These anomalies appear to record episodes of sediment starvation and/or changes in paleo-water chemistry consistent with precipitation of glauconite and phosphatic minerals. A pronounced gamma-ray anomaly at 7,900 ft (fig. 8) can be correlated to a distinctive glauconitic and pyritic interval in the cores. This thin interval (7,899 to 7,901 ft) near the middle of the Shublik Formation records an episode of maximum sediment starvation and is interpreted as a condensed interval (Loutit and others, 1988). The top of this interval is interpreted as the maximum flooding surface within the Shublik transgressive interval. The overlying uppermost part of the Shublik Formation has well log patterns typical of regressive deposition. Regionally, the Shublik Formation represents a major transgressive-regressive cycle (Fraser and Clarke, 1976).

Source Rock Character

Bird (1994) documented the Shublik Formation as a major source of hydrocarbons for the Ellesmerian (!) Petroleum System. The Shublik encountered in the Phoenix 1 well is proximal to the ancient shoreline compared to the Shublik Formation facies south of the Barrow Arch that are thought to have generated much of the discovered oil and gas reserves to date along the North Slope.

In the Phoenix 1 well, the Shublik Formation is organically enriched, displaying organic carbon values ranging from 0.5 to 13.1 percent (fig. 9). Potential hydrocarbon source rocks must not only have a minimum concentration of organic carbon to be effective, but must also be capable of generating hydrocarbons. Generation potentials as defined by Rock-Eval pyrolysis range from 1 to 91 mg HC/g rock (fig 9). TOC values of approximately 1 wt percent organic carbon and generation potentials of 6 mg HC/g rock are thought to be a minimum for an effective petroleum source rock (Bissada, 1982). Hydrogen indices, used as an indicator of the oil-proneness of the organic matter, indicate that the Shublik Formation ranges from a strongly oil-prone Type I kerogen to a more gas-prone Type III kerogen in the Phoenix 1 well (fig. 10). Several intervals also apparently contain inert organic matter, which is incapable of generating hydrocarbons.

The Shublik Formation in the Phoenix 1 well displays source rock characteristics that vary stratigraphically and can be related to the lithologic character and explained in terms of the sequence stratigraphic architecture. The lower part of the Shublik Formation is organically enriched, has higher generation potential, and contains more oil-prone kerogens compared with the upper part (Robison and others, 1996). The lower part of the Shublik Formation, below 7,900 ft, is interpreted as a transgressive systems tract TST. The organic facies in this interval are variable but this portion of the Shublik displays the most significant potential for generating liquid hydrocarbons (fig. 11). Notably, the highest hydrogen indices (>800) are recorded near the top of the TST. Throughout this lower portion (7,900-8,082 ft) of the Shublik Formation, fluorescent amorphinite, marine alginite, and other exinites are the most abundant kerogen macerals (Robison and others, 1996). Subtle variation in the concentration of the oil-prone organic debris is typical of this portion of the Shublik.

At the top of the TST, the organic content and quality, for example, the hydrogen index and percent oil-prone kerogen, decline significantly. This zone corresponds with the section interpreted to record the maximum sediment

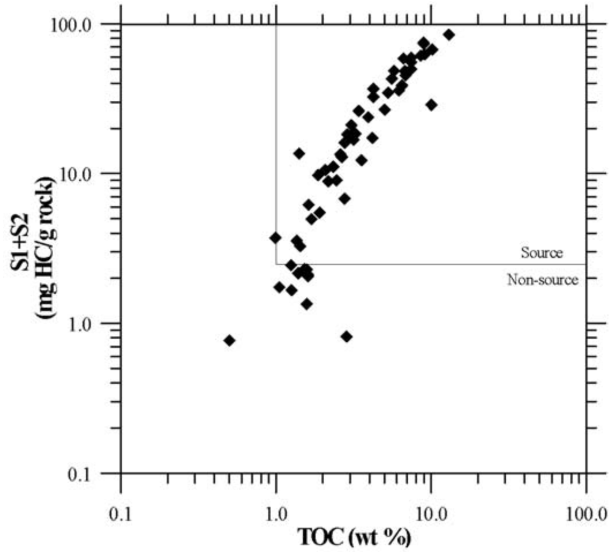


Figure 9. — Total organic carbon versus Rock-Eval S1+ S2 for samples from the Shublik Formation in the Tenneco Phoenix 1 well. Most samples contain well above the minimum organic enrichment and generation potential to be considered a potential hydrocarbon source rock.

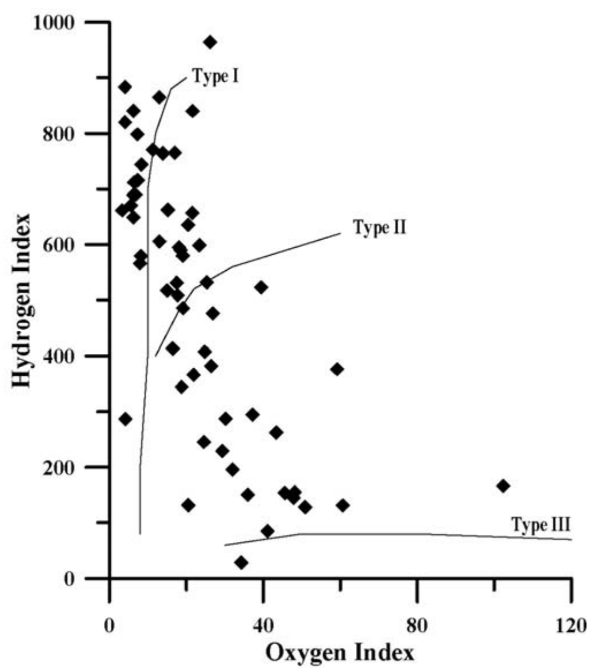


Figure 10. — Modified van Krevelen diagram illustrating the variability in organic matter type in the Shublik Formation in the Tenneco Phoenix 1 well. Samples contain kerogens ranging from strongly oil-prone, Type I, to gas-prone and non-source kerogens, Type III and inert.

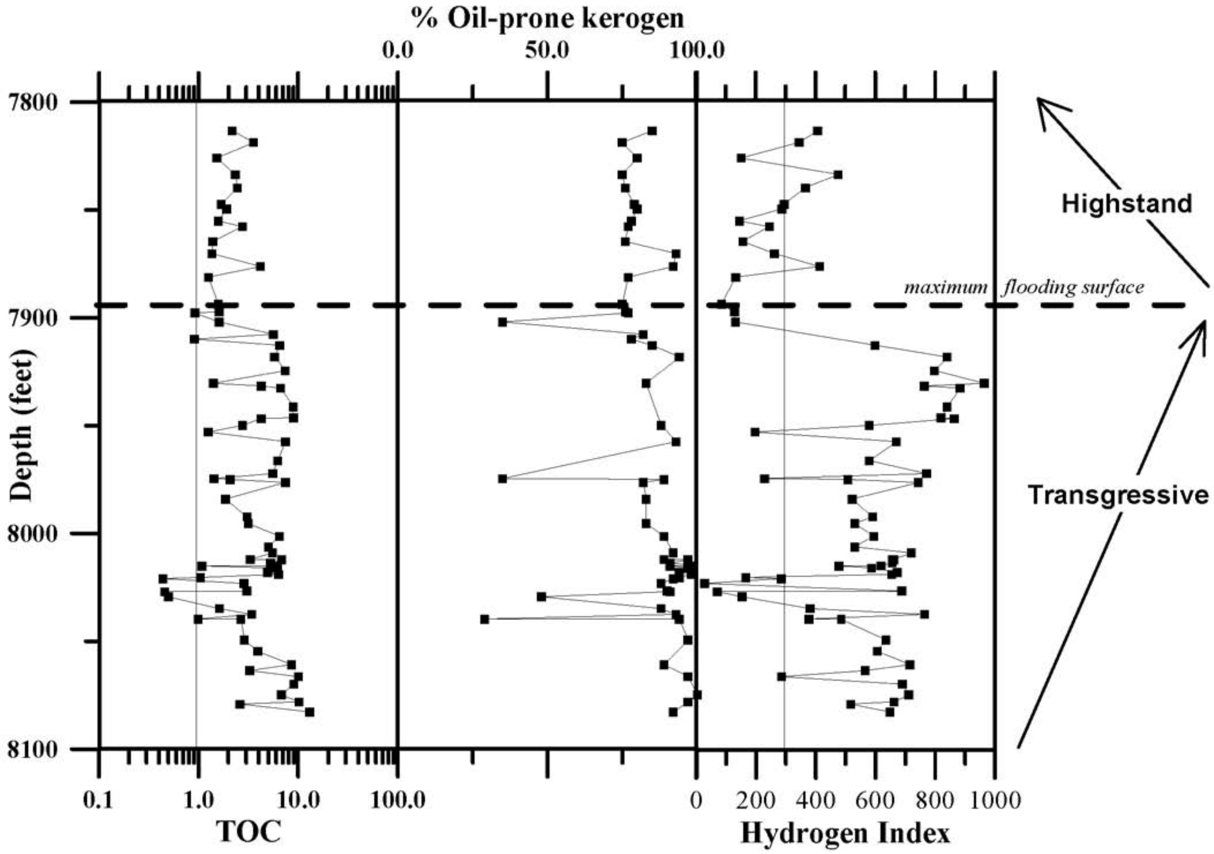


Figure 11. — Summary depth profiles illustrating the variations in total organic carbon content, percent oil-prone kerogen, and hydrogen indices for the Shublik Formation in the Tenneco Phoenix 1 well relative to the interpreted systems tracts.

starvation. The pronounced uranium anomaly and the occurrence of a glauconite and pyrite-rich interval also occur in this interval. Above this interpreted maximum flooding surface, siliciclastic content and the input of detrital organic material increase, marking the onset of a regressive depositional episode. Within the condensed section at the top of the transgressive sequence, there is a significant reduction in the amount of oil-prone kerogen in the rocks. This interval contains weakly fluorescent to non-fluorescent amorphinite as the dominant organic matter type.

These fluctuations in kerogen composition and associated source rock potential within the transgressive sequence reflect likely variations in those factors that controlled deposition and preservation of the organic matter incorporated into this part of the Shublik Formation. This situation may be seen in the sometimes disproportional relationship between the Hydrogen Index and the total oil-prone kerogen.

Most of the organic matter in the upper third of the core, in the interpreted highstand systems tract (HST), is either gas-prone or of non-source quality. Organic content in this portion of the Shublik core, while still typically above 1 wt percent TOC, is depressed compared to the lower TST. Associated with this decrease in organic matter content is a notable decrease in both generation potential and oil-proneness of the section as determined by hydrogen index and organic petrology. Fluctuations in kerogen composition are much less pronounced in the HST when compared with the transgressive sequence. Fluorescent amorphinite, of probable marine origin, is the dominant kerogen type, but there is also 10-15 percent vitrinite with comparable amounts of inertinite. The amount of vitrinite and inertinite in the shales of the HST of the Shublik Formation gradually increases upward. Thus, the source-rock potential within this interval is lower than the underlying transgressive sequence.

The thermal maturity of the Shublik Formation in the Phoenix 1 well, as expressed in terms of mean random vitrinite reflectance, is 0.76 percent at the top of the HST and 0.80 percent at the base of the TST. Other organic geochemical maturity parameters are consistent with this assessment. This places the Shublik Formation in the area of the Phoenix well within the early part of the main phase of hydrocarbon generation and expulsion.

Discussion and Conclusions

The integration of core lithofacies, wire-line log, and organic geochemical data in a sequence stratigraphic context yields a comprehensive interpretation of the source rock potential and reservoir character of Shublik and underlying Ivishak strata penetrated in the Phoenix 1 well. The studied Shublik-Eileen-Ivishak interval appears to comprise part of a third-order eustatic cycle. The lower part of the Shublik Formation is interpreted as a TST. These lower Shublik strata have the most significant potential for generating liquid hydrocarbons; the highest hydrogen indices (> 800) are recorded near the top of the Shublik TST. A condensed interval culminates this transgression. The condensed interval is readily identified by the abundance of authigenic minerals (glauconite, pyrite, and phosphates). Our data reveal that the organic content and source quality (hydrogen index and percent oil-prone kerogen) decline significantly in the condensed interval relative to underlying (i.e., transgressive) Shublik strata. Organic matter in the upper part of the Shublik Formation, interpreted as a HST, exhibits a marked decrease in both generation potential and oil proneness of the kerogens relative to transgressive Shublik strata. This regressive upper Shublik interval is interpreted as having gas-prone or non-source characteristics. In general, Shublik Formation in the Phoenix 1 well has good to excellent oil source-rock characteristics. Lower Shublik strata are not only organically enriched but are capable of generating significant quantities of oil.

The distribution of oil- and gas-prone organic facies seen within the Shublik Formation is consistent with the findings of other workers that have investigated differences in organic matter between transgressive and regressive depositional cycles (Curiale and others, 1992; Habib and Miller, 1989; Pasley and others, 1991; 1993). These studies have demonstrated that transgressive strata contain, consistently, more highly fluorescent amorphinite and considerably less terrestrially-derived organic material relative to regressive strata. The relative abundance of vitrinitic and inertinitic macerals in strata occurring above the maximum flooding surface represents an increased rate of land plant material input during regressive phases (Habib and Miller, 1989; Hart and others, 1994). Because of differences in the types of kerogens in transgressive and regressive systems tracts, major variations in organic enrichment and hydrogen enrichment should also expected (Jones, 1987).

SOURCE ROCKS AND STRATIGRAPHIC TRAPS IN THE KINGAK SHALE

(revised from Houseknecht, 2002a,b)

A primary focus of recent exploration on the Colville delta and in the NPRA is stratigraphic traps within the Kingak Shale of the Beaufortian Sequence, a Jurassic through Early Cretaceous (Neocomian) stratigraphic interval genetically linked to tectonic events that led to the opening of the Arctic Ocean (Hubbard and others, 1987). Renewed exploration in this area was stimulated by the 1994 discovery of the Alpine field, located on the Colville River delta immediately adjacent to the northeastern boundary of NPRA (fig. 1). Brought on line in November 2000, the Alpine field has been announced to contain 429 million barrels of recoverable, high gravity oil (ARCO press release, 1999 reservoired in Beaufortian strata (Hannon and others, 2000a,b).

Much of the previous work on Beaufortian strata in NPRA emphasized the source rock potential of the Kingak Shale, although the presence of sandstone tongues, locally displaying good reservoir quality — especially in the Barrow and Simpson areas where they are gas reservoirs, was documented by those studies (Bird, 1985, 1987, 1988, 1994; Magoon and Bird, 1988). The potential for sandstones such as these to contain oil within NPRA was recognized based on analogues from adjacent parts of the North Slope (Bird, 1995).

Outside NPRA, published work has focused on Beaufortian strata as important oil-reservoir intervals, primarily in the Kuparuk River field (Carman and Hardwick, 1983; Masterson and Paris, 1987; Werner, 1987; Masterson and Eggert, 1992). These studies not only documented the reservoir potential of Beaufortian sandstones, but revealed significant information regarding the complexities of regional and local stratigraphy, and of trap types and geometries within Beaufortian strata. Recent presentations on the Alpine field have revealed information regarding sequence stratigraphy, reservoir quality, and source-rock potential of Beaufortian strata in the area of the Colville River delta (Hannon and others, 2000a,b; Morris and others, 2000).

This section presents a regional sequence stratigraphic framework for the Kingak Shale in NPRA, summarizes the occurrence of petroleum source rocks and stratigraphic traps within that framework, and provides an overview of NPRA cores that illustrate various aspects of sequence stratigraphy applied to petroleum geology.

*Sequence Stratigraphy of the Kingak S*hale in NPRA

Four depositional sequence sets (K1 through K4) have been defined and mapped in this study (fig. 12). Overall, the four sequence sets define a generally southward offlapping succession in NPRA (fig. 12A). Age constraints based on paleontology data from NPRA wells (Mickey and Haga, 1987; Magoon and others, 1988; previously unpublished data) permit approximate chronostratigraphic relationships to be established for these sequences (fig. 12B). These relationships suggest that three of the four sequences are segregated by significant and widespread unconformities or disconformities that occur within the Beaufortian section, including one in the lowermost Jurassic (sub-K1), a second in the middle Jurassic (between

K1 and K2), and a third spanning the uppermost Jurassic-lowermost Cretaceous (between K2 and K3). The boundary between K3 and K4 appears to be erosional based on seismic evidence, although the resolution of public domain paleontology data is insufficient to suggest a

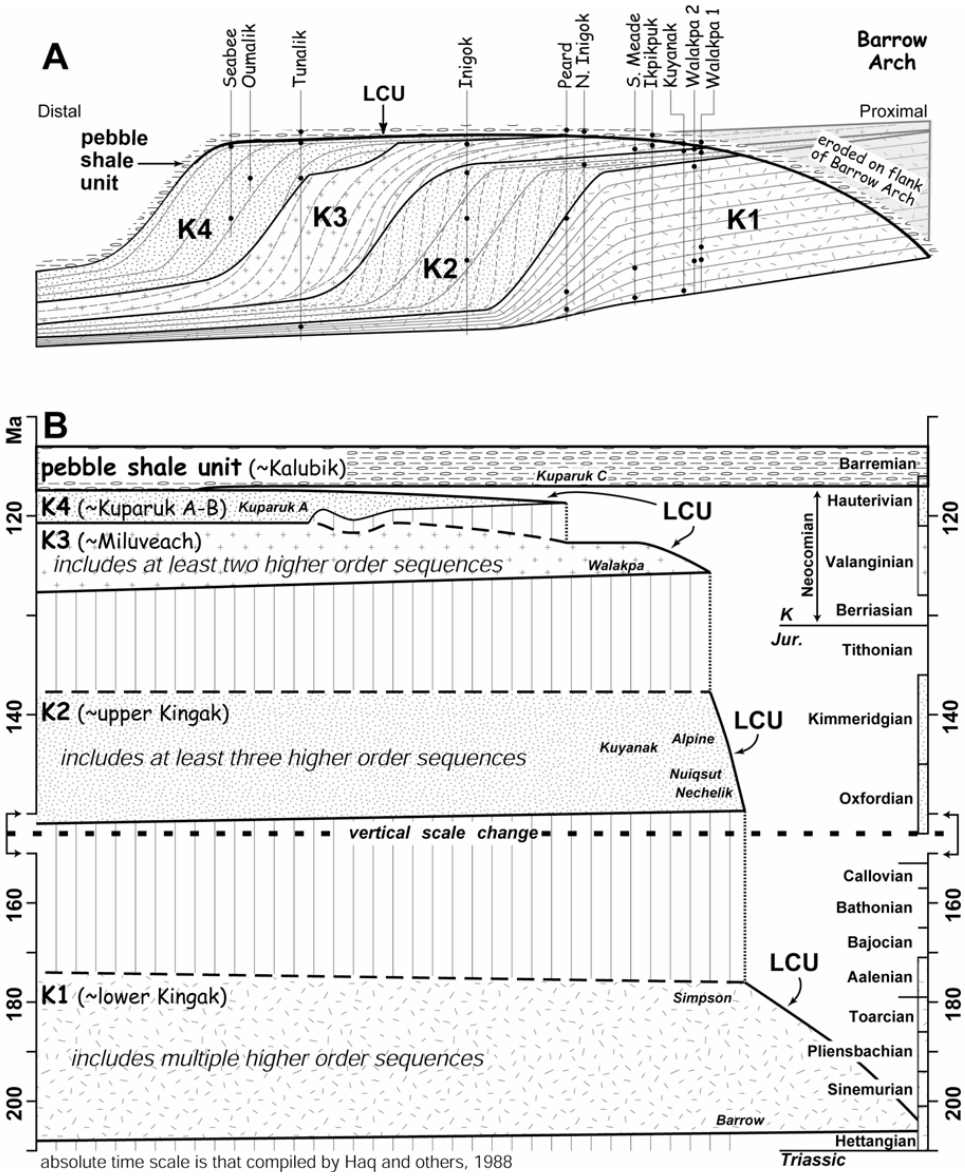


Figure 12. — Schematic summary of inferred depositional sequence sets in Kingak Shale of NPRA. **A**. Proximal (~north) to distal (~south) cross section of stratigraphic relationships among four Kingak depositional sequence sets, showing general aspects of internal stratal geometry. Note that the LCU bevels Kingak strata northward to a zero edge on the Barrow Arch. Selected wells are shown in positions relative to locations where they penetrate Kingak strata, and dots on wells represent approximate stratigraphic positions of cores in USGS archive. **B**. Chronostratigraphic depiction of Kingak sequence sets. Shown in parentheses are stratigraphic names widely applied to strata that are approximate age-equivalents of the four sequence sets. Names in italics show approximate positions of sandstones known to be reservoirs in some cases. Vertical lines denote time gaps between Kingak sequence sets. Note scale change near center of diagram. Time scale is that compiled by Haq and others (1988).

widespread unconformity at that horizon. In addition to the regionally extensive unconformities or disconformities that serve as boundaries between sequence sets, higher-order, sequence bounding unconformities occur within the sequence sets.

Sequence set K1 is a composite of numerous higher-order depositional sequences whose individual internal stratal geometries are too small to be resolved with public-domain seismic data. In northern NPRA, wire-line logs through K1 display at least six and perhaps as many as eight motifs that can be interpreted as individual depositional sequences. For example, near the base of K1 an interval that includes the “Barrow sandstone” displays a coarsening-upward section capped by sandstones interpreted as a progradational succession of shoreface deposits inferred to be a low-stand systems tract (fig. 13, Walakpa 1). This section is overlain by an abrupt fining from sandstone to siltstone that, in turn, is overlain by an abrupt fining from siltstone to shale with relatively high gamma-ray response (“warm shale”); together these are interpreted as a backstepping succession inferred to be a TST, with the shale corresponding to relatively condensed facies that include a maximum flooding surface. The condensed facies is typically imaged as a widespread seismic amplitude where it is in contact with underlying, higher velocity strata. The interval is capped by a section that coarsens upward from shale to siltstone, which is interpreted as a progradational succession of distal shoreface deposits inferred to be a HST. During the workshop, examples of this type of sequence will be examined in cores from Walakpa 1 and Walakpa 2.

Farther south in NPRA, wire-line logs through K1 display either subtle coarsening-upward sections capped with siltstone abruptly overlain by “warm shale,” or monotonous sections of silty mudstone abruptly punctuated by “warm shale” (fig. 13, Ikpikpuk). These intervals are interpreted as offshore to shelf successions that are the distal equivalents of the shoreface successions observed farther north. The “warm shales” are interpreted as condensed facies that include maximum flooding surfaces, and that are typically imaged as seismic amplitudes.

The most distal well penetrations of K1 occur near the toe of clinoforms that mark the K1 shelf margin in eastern NPRA, and beyond the toe of clinoforms. Wire-line logs through K1 at both locations display a “hot shale” (high gamma-ray response) within a thin interval of monotonous silty mudstone (fig. 13, Inigok). The “hot shale” thickens from North Inigok to Inigok and is interpreted as a basinal condensed section.

Within the context of the interpretations presented above, the laterally extensive, moderate to high amplitude reflections that characterize K1 generally represent low velocity, condensed facies deposited during times when the shelf was flooded by high relative sea level. On the shelf, these facies comprise “warm shales,” each of which includes a maximum flooding surface. At the shelf margin, the “warm shales” grade basinward into “hot shales” as they downlap and coalesce into a basinal condensed section. The basinward increase in gamma-ray response likely indicates increased organic content and represents coalescence of time lines in a basinward direction. Collectively, the condensed facies that were draped across the shelf margin and deposited in the deeper basin represent an important source rock interval that has long been recognized across the North Slope (Bird, 1985; Hubbard and others, 1987). The “Lower Kingak” has been mentioned in recent presentations (Hannon and others, 2000a,b) as the probable source of the high gravity

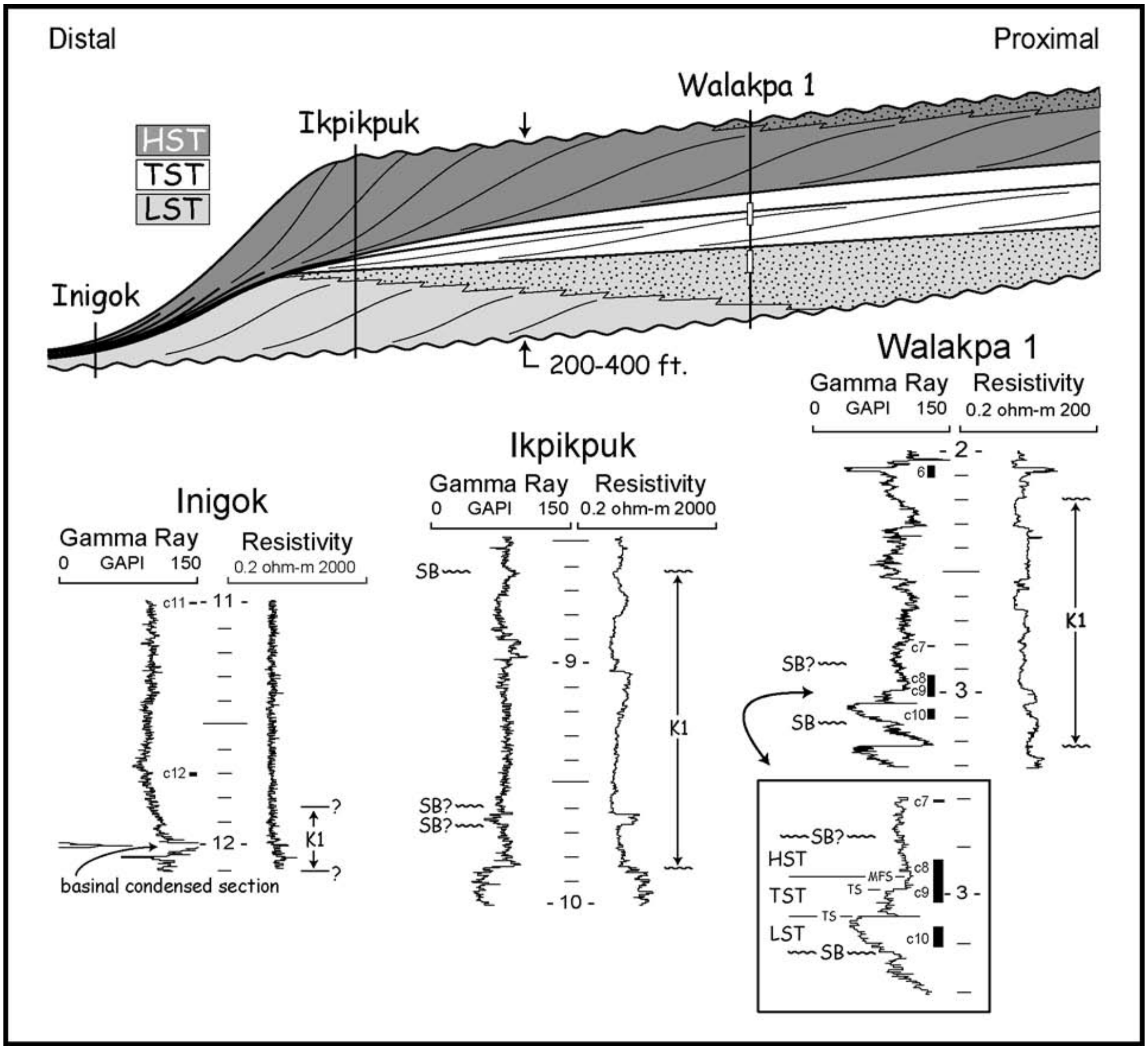


Figure 13. — Schematic illustration of an individual depositional sequence within K1 and wire-line logs from wells inferred to penetrate various locations within depositional sequence. Core intervals are shown schematically in upper figure (white rectangles on wells) and accurately in log plots (c-prefix numbers denote cores in each well). Total K1 interval is shown for each well. Although one inferred depositional sequence is delineated in the expanded view of the Walakpa 1 well log, no attempt is made to correlate higher-order depositional sequences between wells. [SB, sequence boundary; LST, lowstand systems tract; TST, transgressive systems tract; HST, highstand systems tract; TS, transgressive surface; MFS, maximum flooding surface. Wire-line log depth ticks are at 100 ft intervals and numbers are X1000 ft.]

oil in Alpine field, and these condensed facies are likely candidates for that source rock.

Sequence set K2 is interpreted as three or more higher-order depositional sequences, each including a lowstand systems tract (LST), a TST, and remnants of a HST (fig. 14). Each depositional sequence contains a well-defined package of offlapping clinoforms. A typical wire-line log response through the distal part of a clinoform package (fig. 14, Inigok) displays subtle patterns of coarsening upward (lower ~200 ft) from “warm shale” to silty sandstone, fining upward (middle ~300-400 ft) from silty sandstone to siltstone/mudstone, and siltstone/

mudstone (upper ~400-500 ft). The clinoform package is interpreted as a LST that represents rapid deposition of sediment on a marine slope during forced regression related to uplift and widespread erosion (probably subaerial) to form the unconformable sequence boundary to the north.

Overlying the LST and overstepping the LST in a northward (proximal) direction is a relatively thin (200-300 ft or less) interval defined by a seismically transparent zone beneath a laterally extensive, medium to high amplitude reflection. Northward, this interval generally thins and

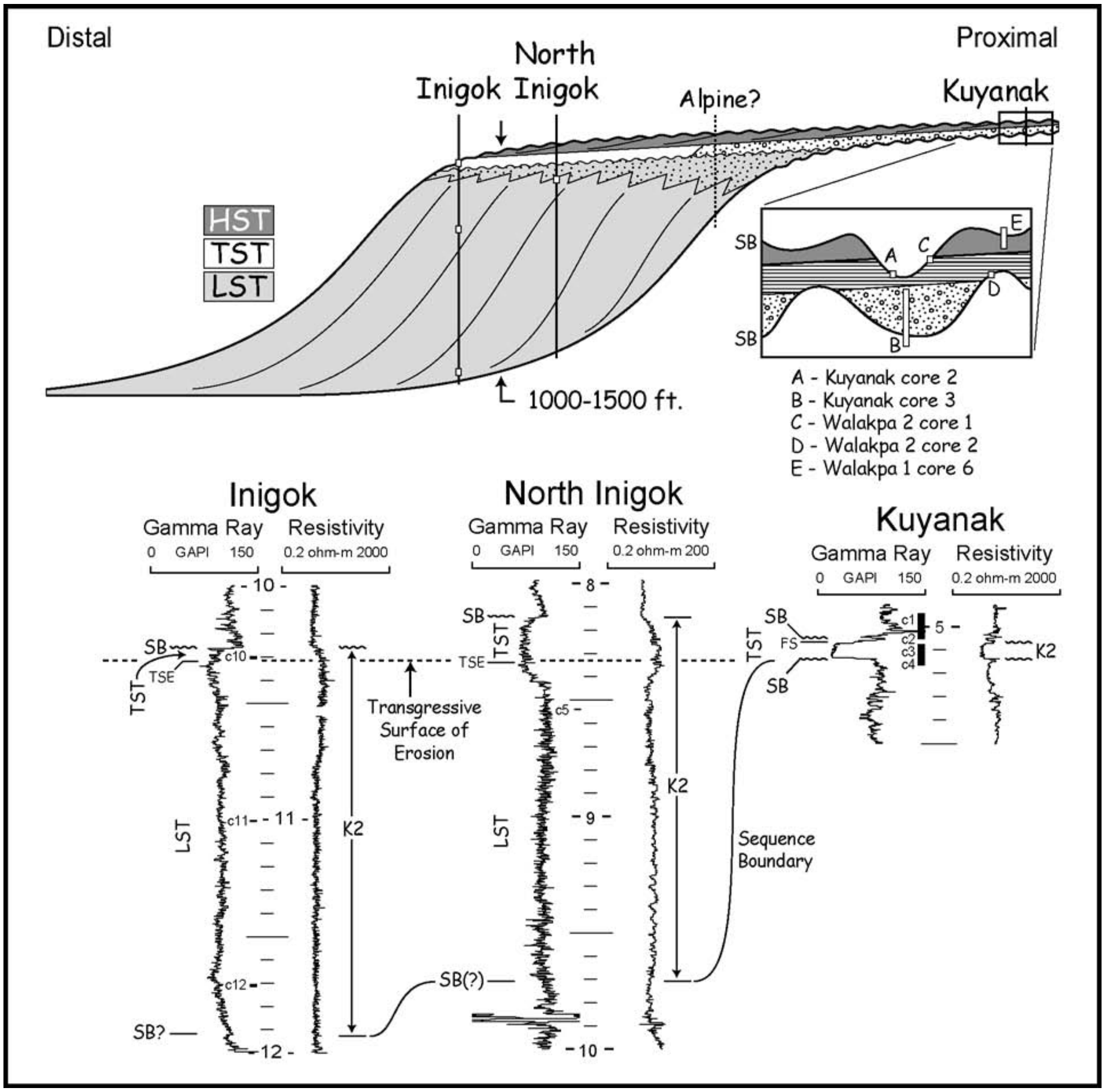


Figure 14. — Schematic illustration of individual depositional sequence within K2 and wire-line logs from wells inferred to penetrate various locations within depositional sequence. Dotted line labeled “Alpine” shows inferred position within depositional sequence of stratigraphic interval containing main reservoir in Alpine field. Core intervals are shown schematically in upper figure (white rectangles on wells) and accurately in log plots (numbers with c-prefix denote core numbers in each well). [Abbreviations same as in fig. 13, plus TSE, transgressive surface of erosion. Wire-line log depth ticks are at 100 ft intervals and numbers are X1000 ft.]

onlaps the underlying sequence boundary. Locally, the reflection that defines this interval may display relief, may truncate underlying reflections, or may be truncated by overlying reflections. One well penetration of this interval in northern NPRA reveals a blocky, shoreface sandstone resting directly on the sequence boundary (fig. 14, Kuyanak) whereas other penetrations reveal black, fissile shale resting directly on the sequence boundary (Walakpa 2); both cases will be examined in cores from Kuyanak and Walakpa 2 during the workshop. This interval is interpreted as a TST whose constituent facies succession varies locally depending the geometry and relief of the underlying sequence bounding unconformity, which also appears to be transgressive surface of erosion in northern NPRA (fig. 14).

At the base of the TST, shoreface sandstones displaying basal pebble lags and blocky log responses were deposited in topographically low areas. The porous, glauconitic sandstone in the Kuyanak well and the primary reservoir in the Alpine field (figs. 14 and 15) are interpreted as examples of shoreface sandstones deposited on transgressive surfaces of erosion (i.e., ravinements) within higher order depositional sequences of K2. As illustrated in figure 14, the "Kuyanak sand" likely was deposited in a proximal location where the transgressive surface of erosion and the basal sequence boundary are merged into a single surface, whereas the "Alpine sand" may have been deposited in a more distal, shelf-margin location where the transgressive surface of erosion caps a coarsening-upward parasequence of the LST, well above the basal sequence boundary.

The northward convergence of multiple sequence boundaries in K2 makes it difficult to correlate specific surfaces and sandstones, considering the limited resolution of public domain data. It is possible, therefore, that some sandstone bodies may be composites of shoreface sandstones deposited within different depositional sequences. In other words, sequence-bounding

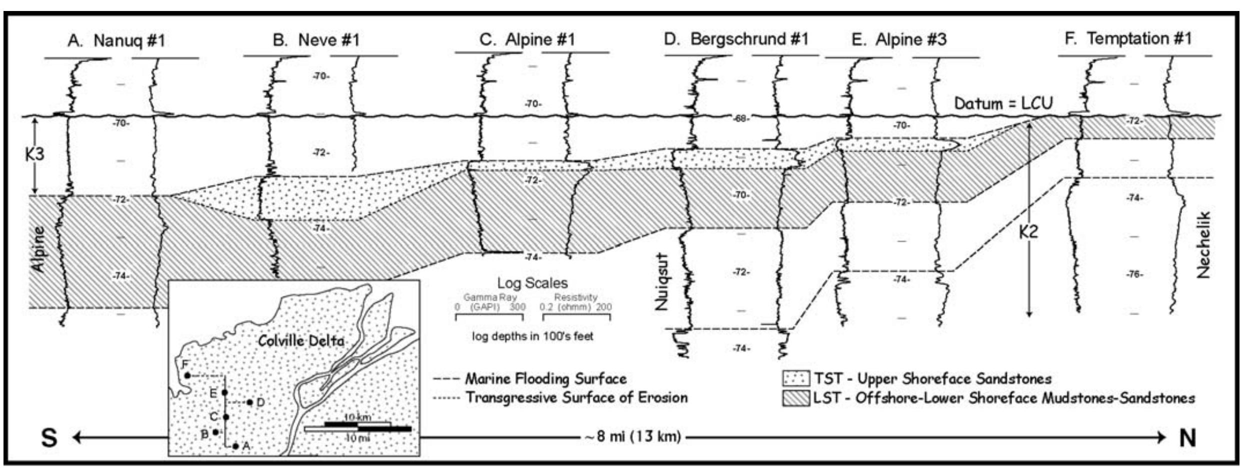


Figure 15. — South-north wire-line log cross section through Alpine field. Location of Alpine field shown in fig. 1. Stratigraphic intervals labeled Alpine, Nuiqsut, and Nechelik likely represent individual depositional sequences within sequence set K2. Inferred LST and TST are shown within Alpine interval. Marine flooding surfaces are also likely sequence boundaries. Main reservoir is inferred to be shoreface sandstone within TST. Datum is LCU.

unconformities may occur within the blocky sandstones.

As transgression proceeded to maximum flooding of the shelf, a condensed facies comprising dark grey to black, fissile shale was deposited. In areas of topographic lows on the ravinement/sequence boundary, this condensed facies caps shoreface sandstones and has excellent potential as a seal for any hydrocarbons in those sandstones (Alpine is a good example; fig. 15). In areas of topographic highs on the ravinement/sequence boundary, the condensed facies rests directly on the sequence bounding unconformity (Walakpa 2 core). A maximum flooding surface is inferred to be present within this condensed facies.

Incompletely preserved above the TST is a generally coarsening upward succession of mudstones through muddy and silty sandstones, all thoroughly bioturbated, that represent offshore through lower shoreface deposits. A good example of this succession will be examined in core from Walakpa 1, just beneath the "Walakpa sand." This succession is interpreted as a HST deposited during normal regression. Preservation of the HST is meager, particularly in northern NPRA, owing to widespread erosion of this succession during development of the succeeding sequence bounding unconformity(ies).

Sequence set K2 and its constituent higher-order sequences probably reflect repeated forced regressions (Posamentier and Allen, 1999) that caused widespread erosion across northcentral NPRA and accumulation of the derived sediment at the shelf margin in LSTs. The forced regressions likely were caused by episodic tectonic uplift along the Barrow Arch during the "failed rift" events described by Hubbard and others (1987). Each forced regression was followed by flooding of the shelf as the result of a rise in relative sea level and the deposition of a TST.

Sequence set K3 is interpreted as two or more higher-order sequences that display similar characteristics. Although not resolvable on seismic data, a thin TST is inferred to occur at the base of K3 in northern NPRA, based on wire-line log and core data. In the Walakpa wells (fig. 16), the gas reservoir is a sharp-based, blocky sandstone whose sedimentary structures and trace fossils indicate deposition in a shoreface environment. Micropaleontology data from core samples indicate that this sandstone is probably Valanginian in age, which suggests it is part of sequence K3. This shoreface sandstone likely represents a TST deposited during flooding of the shelf during a rise in relative sea level following a long interval of shelf exposure and erosion that formed the sequence bounding unconformity between K2 and K3. This TST and its basal, reservoir-quality sandstone will be examined in cores from Walakpa 1 and 2.

Wire-line logs elsewhere in northern NPRA display patterns that suggest the local presence of relatively sandy, proximal facies. For example, the Ikpikpuk well penetrated a sandstone-rich K3 section displaying log motifs that suggest complex facies within multiple depositional parasequences (fig. 16). Farther basinward, the Inigok log displays a sharp-topped, sandy succession at the top of the underlying K2, which is overlain by a "warm shale" (~100 ft thick) at the base of K3 (fig. 16). The abrupt K2-K3 contact is interpreted as both the sequence boundary at the base of K3 and a transgressive flooding surface. The sequence boundary may be either a subtle unconformity or a correlative conformity, as there is no seismic evidence for erosion. The "warm shale" at the base of K3 is interpreted as a thin TST that includes a maximum flooding

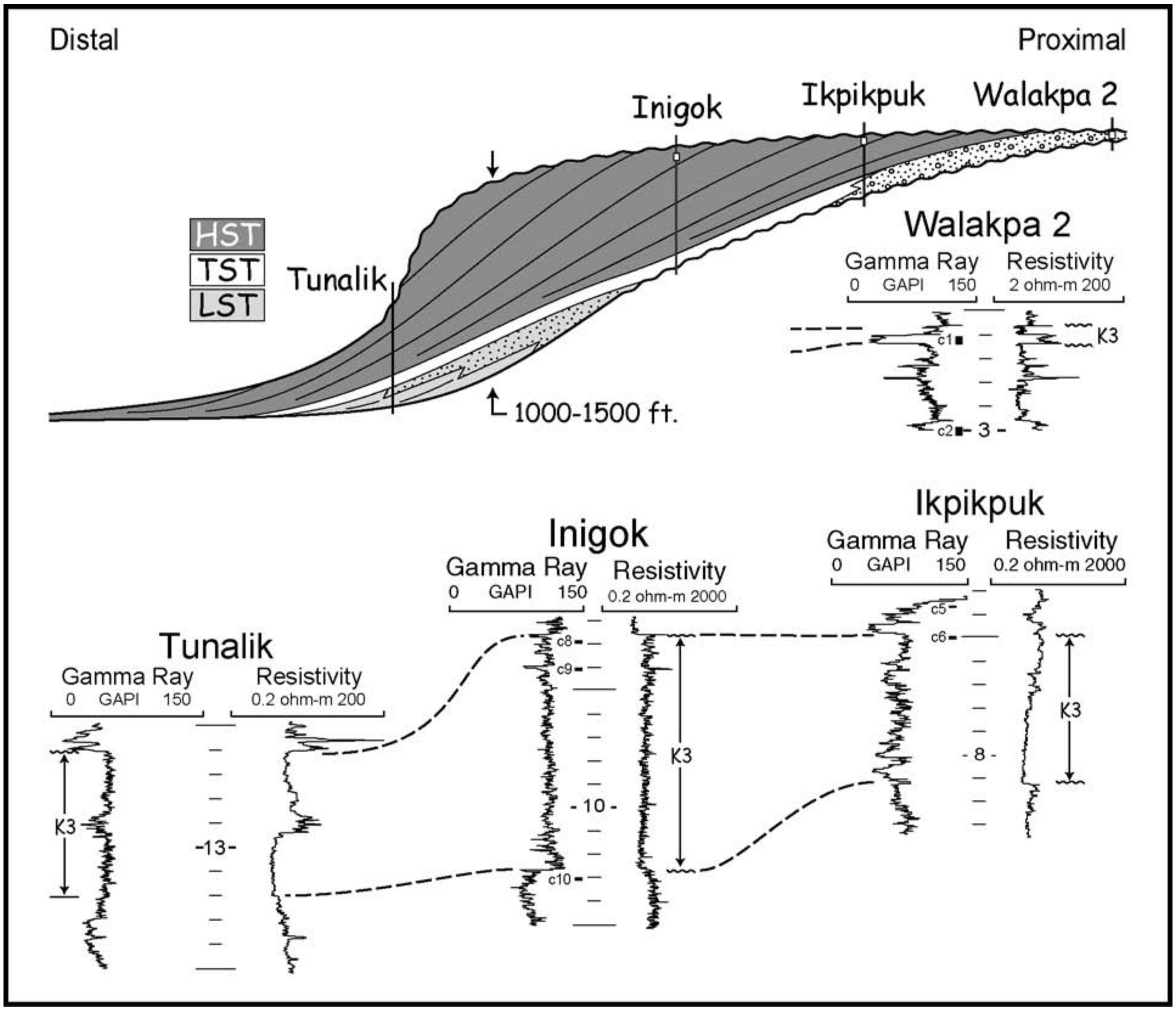


Figure 16. — Schematic illustration of individual depositional sequence within K3 and wire-line logs from wells inferred to penetrate various locations within depositional sequence. Core intervals are shown schematically in upper figure (white rectangles on wells) and accurately in log plots (numbers with c-prefix denote core numbers in each well). Although total K3 interval is shown for each well, no attempt is made to correlate higher-order depositional sequences between wells. [Wire-line log depth ticks are at 100 ft intervals; numbers are X1000 ft.]

surface at or near its top. This shale is interpreted as a relatively condensed facies deposited when the shelf was flooded by high relative sea level.

The overlying interval is a thick succession (up to 600 ft) of monotonous to subtly coarsening-upward shale and silty shale that locally includes an interval of thin sandstone interbeds near its base (fig. 16, Inigok). Sparse core control from the Inigok and South Meade wells indicate lithologies and trace fossils typical of offshore successions deposited well below maximum (storm) wave base. This is the interval that correlates to low-dip clinoforms observed in seismic data, and it is interpreted as a HST comprising a muddy and silty succession deposited on a gently dipping marine slope (ramp?). Seismic observations suggest that this facies is volumetrically predominant in K3 across much of NPRA.

Thin intervals of northward onlapping reflections in the lower part of each depositional sequence within K3 likely represent LSTs. Although there is little well control in the distal parts of K3 sequences, the Tunalik log displays a K3 section comprising monotonous silty mudstone with one coarsening upward, sandstone-rich interval (fig. 16). This succession may represent distal offshore and/or slope facies. The sandstone-rich interval may be a submarine fan lobe within a LST.

The overall pattern of sedimentation indicated by K3 suggests progradation of at least two lobes of sediment under conditions of normal regression. The relatively distal character of most facies further suggests that relative sea level was high and that the study area was mostly an offshore system (distal shelf?) with perhaps indications of lower shoreface conditions in the northernmost areas of K3 preservation.

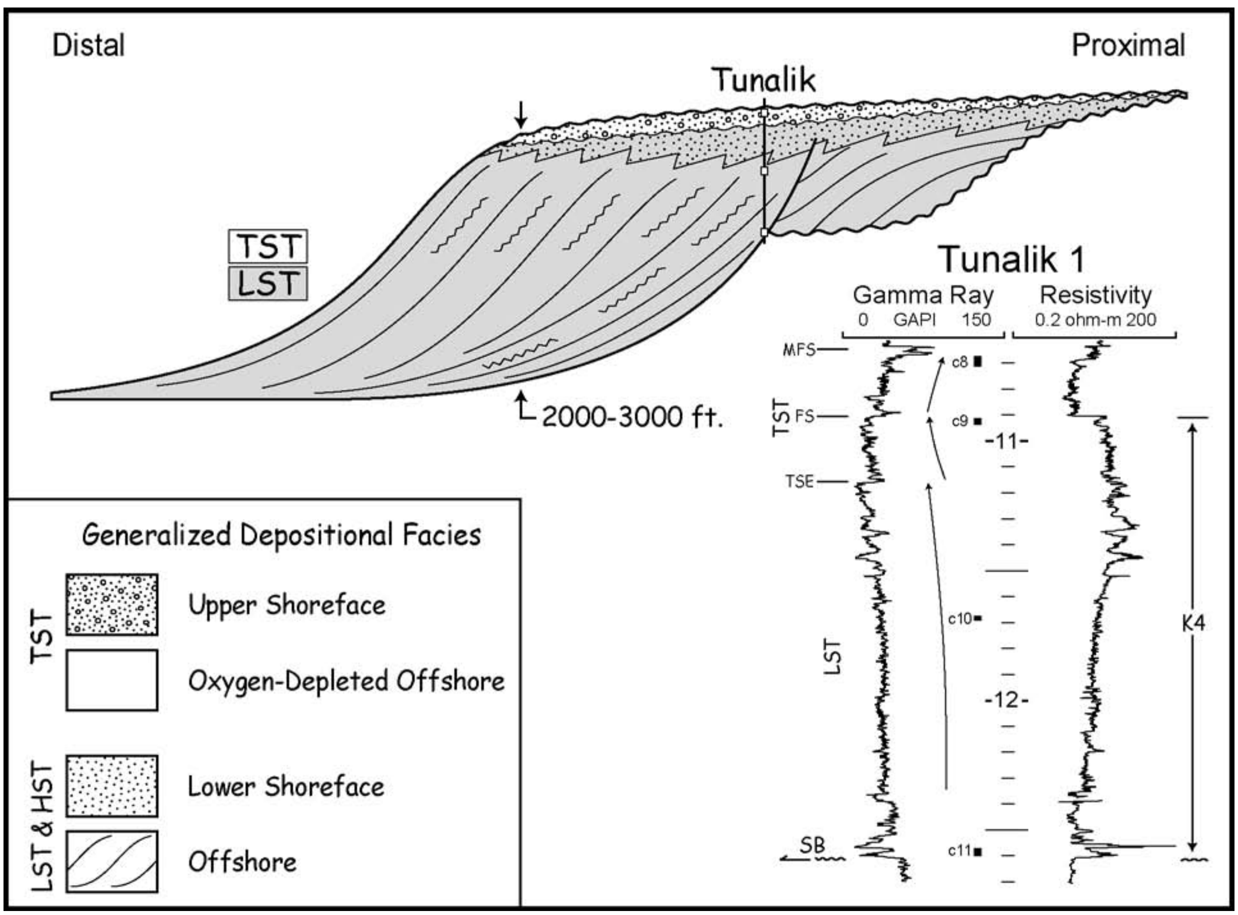


Figure 17. — Schematic illustration of depositional sequence set K4 and wire-line log from the Tunalik well. Core intervals are shown schematically in upper figure (white rectangles on wells) and accurately in log plot (numbers with c-prefix denote core numbers). [Wire-line log depth ticks are at 100 ft intervals and numbers are X1000 ft. Arrows on log highlight overall coarsening and fining upwards successions.]

Sequence set K4 interpretations rely heavily on information from the Tunalik well because a complete wire-line log suite and cores are available. Only two other wells have penetrated K4 in NPRA, and only partial wire-line logs are available from those wells.

Sequence set K4 is interpreted as a single depositional sequence, including a LST capped by a TST as illustrated schematically in figure 17. The sequence displays significant internal complexity inferred to be the result of repeated synsedimentary collapse of the shelf-margin.

The base of K4 is an erosion surface that, in the vicinity of the Tunalik well, cuts down into older Beaufortian sequences in two distinct steps (fig. 17). The more proximal step is filled with strata that include moderate amplitude reflections that onlap the basal unconformity in a proximal direction and downlap the basal sequence boundary basinward (fig. 17). These reflections are broadly convex upward and are interpreted as the early part of a LST.

The more distal (southern) step is filled with strata that display on seismic data an overall clinoform geometry complicated by a spectrum of synsedimentary deformation features. Some reflections appear to be offset by down-to-the-basin (south) normal faults and others are deformed into chaotic geometries. In fact, it is possible that a synsedimentary, listric normal fault forms the sequence boundary in part of this distal step. The Tunalik well penetrates this distal step and the wire-line log response displays a sandy section at the base of K4 overlain by a thick succession that generally coarsens upward from silty mudstones to sandstone (fig. 17). The sand-rich, upper part of this coarsening upward succession correlates to the lower half of a seismically transparent zone at the top of K4. A core through the basal, sand-rich section reveals intensely contorted shale and sandstone displaying megafauna and trace fossils that indicate shallow marine deposition (this core yielded foraminifera of "probable Valanginian" age). This section is interpreted as offshore to lower shoreface deposits of sequence K3 that slumped or collapsed into the base of sequence K4 as the shelf margin was deeply incised during formation of the K4 basal sequence boundary.

The thick, coarsening upward succession is interpreted as shoaling-upward deposits. Facies displayed in a core near the middle of the coarsening upward succession suggest more sand transport by unidirectional currents and less bioturbation than is commonly observed in shoreface deposits within the other Beaufortian sequences (K1-K3). Therefore, this succession is interpreted as prodelta through delta-front deposits. Collectively, these strata are interpreted as a LST deposited during forced regression, and they may represent a shelf-margin delta system.

The coarsening upward succession (LST) displays an abrupt top, which is overlain by a subtly coarsening upward interval more than 200 ft thick that correlates to the upper half of the seismically transparent zone that caps K4 (fig. 17). A core from this succession displays facies interpreted as the deposits of a wave-dominated shoreface. This succession is inferred to be a TST deposited as the shelf margin was flooded by a rise in relative sea level.

Although sequence K4 has been interpreted as a single depositional sequence comprising a LST and a TST, it also is possible to interpret the two distinct steps within the LST as separate sequences. In fact, the overall geometry of those steps resembles the multiple, higher-order sequence boundaries formed under conditions of episodic fall in relative sea level described by Posamentier and Allen (1999, p. 35).

Sequence K4 clearly represents a forced regression that caused widespread erosion across northern NPRA and accumulation of the derived sediment at the shelf margin in a LST. It is suggested that the forced regression was caused by tectonic uplift along the Barrow Arch during the "successful rift" events described by Hubbard and others (1987). The uppermost part of K4 is a TST that reflects flooding of the shelf as the result of a rise in relative sea level.

Summary – Kingak Shale

Beaufortian (Jurassic through Early Cretaceous) strata in the NPRA include four major depositional sequence sets that each display unique stratal geometries and thickness trends. Cores from NPRA wells provide the opportunity to examine many important attributes of these sequences, including key surfaces and depositional facies within a sequence stratigraphic framework.

Sequence set K1 (Lower-Middle Jurassic) is a composite of numerous depositional sequences whose progradation and aggradation through time constructed a clastic shelf in north-central NPRA. Cores from K1 illustrate the character of several key surfaces, and they display predominantly offshore through lower shoreface successions punctuated by evidence of exposure (fig. 18).

Sequence set K2 (Oxfordian-Kimmeridgian) is a composite of at least three depositional sequences that developed as the result of tectonic uplift along the Barrow Arch during "failed rift" events. Each higher-order sequence reflects a forced regression, which caused widespread erosion across northcentral NPRA and accumulation of sediment at the shelf margin in LSTS, followed by flooding of the shelf as the result of a rise in relative sea level, which resulted in deposition of a TST. Cores from K2 illustrate attributes of sequence boundaries, including exposure surfaces and transgressive surfaces of erosion, and they display facies indicative of oxygen-depleted offshore through upper shoreface deposition. Cores from K2 are particularly important in constraining the sequence stratigraphic framework of oil-prospective sandstone reservoirs such as Alpine.

Sequence set K3 (Valanginian) is a composite of at least two depositional sequences that display relatively distal facies characteristics, suggesting high relative sea level during most of the depositional history. An important exception is the presence of a TST at the base of K3 that contains shoreface sandstones that are gas reservoirs in the Walakpa field. Cores from K3 display a variety of sequence boundaries and depositional facies that range from oxygen-depleted offshore through upper shoreface.

Sequence K4 (Hauterivian) is a shelf-margin wedge that developed as the result of tectonic uplift along the Barrow Arch during the "successful rift" events related to opening of the Arctic Ocean basin. This sequence comprises LSTs-TSTs that display stratal geometries suggesting dynamic

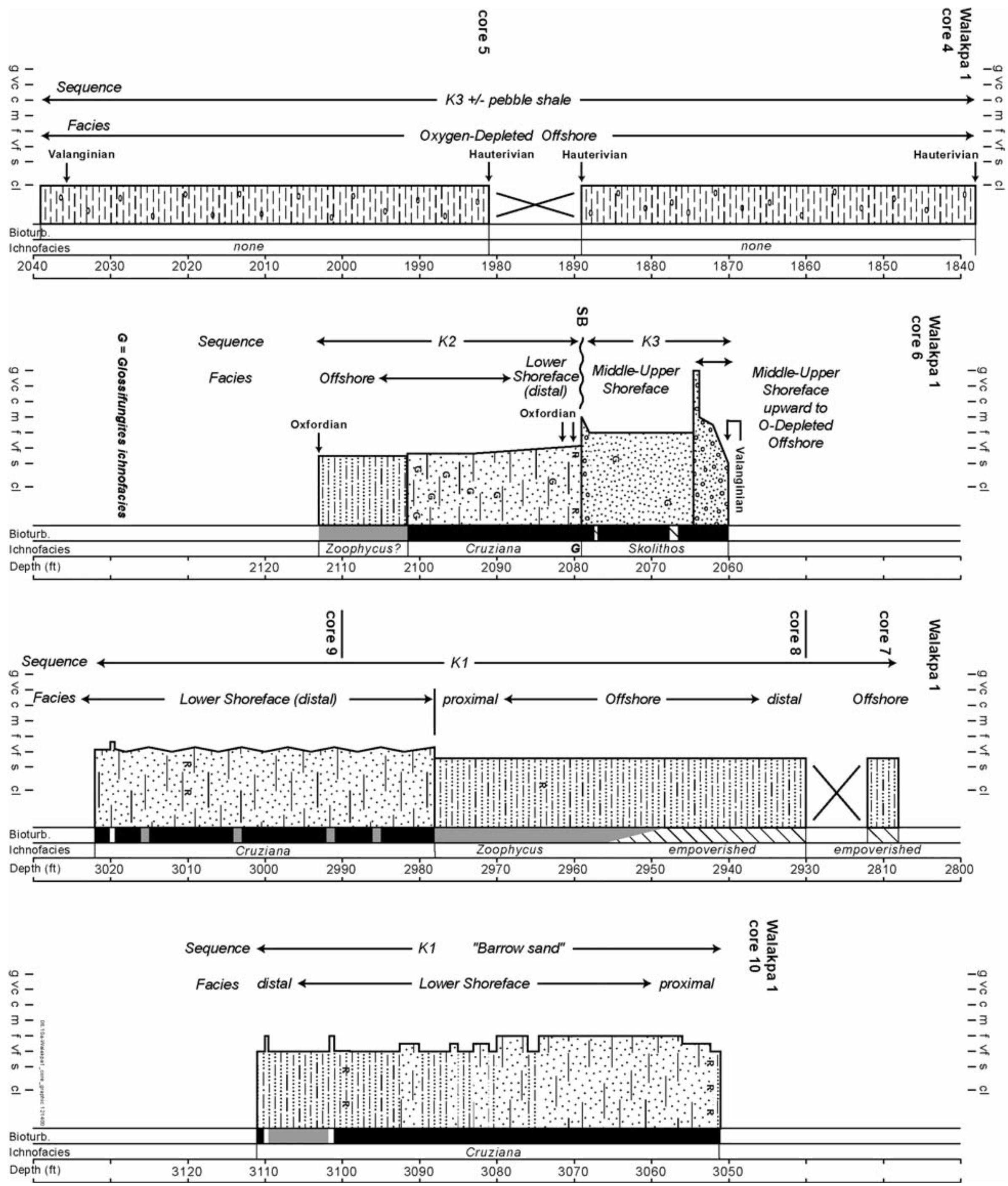


Figure 18. — Graphic measured sections of Beaufortian strata in NPRA cores. A: Walakpa 1.

incision and synsedimentary collapse of the shelf margin. Facies within K4 suggest higher energy depositional systems and/or higher rates of sedimentation as compared to sequence sets K1 through K3. Cores from K4 display attributes of sequence boundaries and depositional facies that range from oxygen-depleted offshore through upper shoreface.

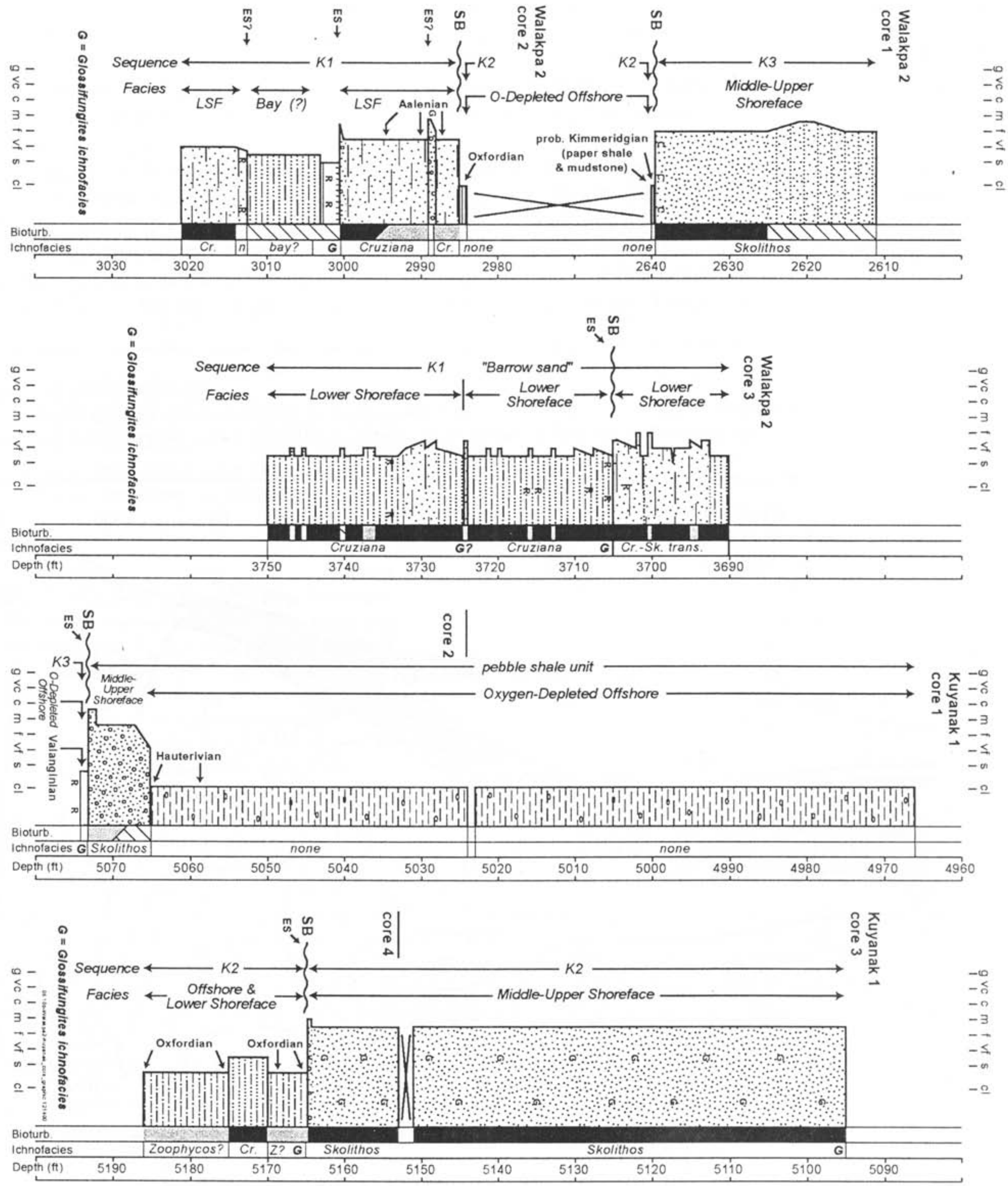


Figure 18. - Graphic measured sections of Beaufortian strata in NPRA cores - continued. B: Walakpa 2 and Kuyanak

Throughout the Beaufortian section, the best potential for stratigraphic traps occurs in TSTs containing high quality reservoir and seal facies. Well-winnowed, upper shoreface sand-stones deposited in topographic lows on transgressive surfaces of erosion commonly occur at the base of TSTs. These sandstones are typically capped by a condensed section deposited in oxygen-depleted offshore environments as the shelf was flooded during high relative sea levels.

SOURCE ROCK POTENTIAL OF THE PEBBLE SHALE UNIT AND GRZ

(revised from Keller and Macquaker, 2001)

The Lower Cretaceous, relatively condensed, mudstone succession of the North Slope of Alaska is thought to be an important petroleum source rock interval (fig. 3). This succession comprises the pebble shale unit and the gamma-ray zone (GRZ). In the eastern part of the North Slope and the 1002 area of the ANWR (fig. 2), the gamma-ray zone is assigned to the lower part of the Hue Shale, while in the western North Slope and the NPRA, the gamma-ray zone is placed between the pebble shale unit and the overlying, predominantly mudstone succession assigned to the Torok Formation.

The pebble shale unit has been variously described as comprising 1) “dark-gray to black, non-calcareous clayey to silty shale containing minor scattered, rounded and frosted, quartz grains” in addition to containing “common to rare matrix supported chert and quartzite pebbles...” and “ironstone concretions” (Bird and Molenaar, 1987), and 2) as being composed of “black anaerobic-dysaerobic shales, silty aerobic shales, pebbly mudstones and sandstones” (Blanchard and Tailleur, 1983). It is interpreted genetically to be the uppermost part of the northern sourced Beaufortian sequence, deposited on the continental slope in association with a northward-transgressing sea in a tectonically active region (Blanchard and Tailleur, 1983, Bird and Molenaar, 1987). The GRZ is considered to be the “distal condensed shale facies” of lowermost Brookian strata sourced from the south by uplift and erosion of the ancestral Brooks Range.

The pebble shale unit is considered oil prone in the central and western North Slope, and it is thought to be one of several sources for the large Prudhoe Bay accumulation, however, it is described as gas prone in the eastern North Slope and the 1002 area of the ANWR (Magoon and others, 1987). The RGZ is considered a good oil-prone source rock throughout the North Slope.

Cores of the pebble shale unit from the Kuyanak 1, Walakpa 1, and Tunalik 1 wells will be examined in the core workshop. The GRZ is discussed in the following section.

BROOKIAN DEPOSITIONAL SEQUENCES AND FACIES IN NPRA

(revised from Houseknecht and Schenk, 2001)

The Brookian “megasequence” of northern Alaska (fig. 3) includes Early Cretaceous through Tertiary strata comprising sediment derived from the ancestral Brooks Range and deposited in the Colville foreland basin (see regional summaries by Hubbard and others, 1987; and Bird and Molenaar, 1992). Filling of the Colville basin generally progressed from west to east through time as reflected by the eastward younging of Brookian strata across the North Slope. In NPRA, only Neocomian through Cenomanian strata are present within the Brookian sequence. This section focuses primarily on the Albian part of the Brookian section, and specifically the Torok and Nanushuk Formations (fig. 3).

Figure 19 schematically illustrates regional geometry of Brookian strata in eastern NPRA. Little deformation is evident beneath the coastal plain, although attitudes and thermal maturity patterns indicate this area was subjected to broad, regional uplift and erosion during Tertiary time (O'Sullivan and others, 1997). The foothills are the surficial expression of a fold-and-thrust belt that developed about 60 Ma and was further deformed by subsequent contractional tectonic events later in the Tertiary (O'Sullivan and others, 1997). Brookian strata beneath the foothills are characterized by detachment folds and tectonic thickening of the Torok, and these characteristics become more pronounced southward. The southern foothills are characterized by a tectonic wedge that displays greater structural complexity and exposes deeper stratigraphic horizons (Mull and others, 2000).

Subsurface patterns of thermal maturity, based on data compiled by Johnsson and others (1999) and new data from USGS fieldwork in the foothills, also are shown in figure 19. This illustration indicates that most of the Torok Formation in the subsurface of eastern NPRA is characterized by vitrinite reflectance values lower than those generally associated with thermal cracking of oil to gas (0.95 to 1.35 percent; Law, 1999). At greater depths beneath the foothills, vitrinite reflectance values are projected to be 1.5 to 2.5 percent in the lower Torok, and these levels of thermal maturity are commonly associated with prolific natural gas resources in other foreland basins (Houseknecht and Spötl, 1993). Figure 3 also shows the locations of the Tarn oil pool and heavily oil-stained, turbidite sandstones in Torok outcrops in the foothills. These observations collectively suggest the presence of a viable oil play in Torok turbidites across most of the north-south width of the Colville basin in NPRA, and the presence of a viable gas play in Torok turbidites in the foothills.

Seismic and Sequence Stratigraphy

Seismic data in NPRA display repetitive packages of strata that can be distinguished based on the recurrence of conspicuous, high amplitude, clinoform reflections. These broadly defined "sequences" can be dissected and analyzed using a motif of internal stratal geometries that is repeated from one sequence to another. This motif is inferred to represent four stages of sequence development, including regression, transgression, aggradation, and progradation (fig. 20). The characteristics and interpretation of this motif are discussed in the following sections.

Regression

The base of each sequence is defined by apparent truncation of older strata in the mid- to upper slope position and by subtle onlap of younger strata against that surface of truncation (fig. 20). These characteristics are inferred to indicate the presence of an erosional surface on the upper slope. At mid- to lower slope, a relatively thin and seismically transparent interval is commonly observed to pinch out via onlap against the inferred erosion surface. This transparent interval generally thickens basinward (although its thickness appears to be locally variable) as it downlaps and becomes interbedded with high amplitude reflections associated with the GRZ. Well penetrations show that this transparent interval is mostly sandstone and core examination indicates it is composed of turbidite facies.

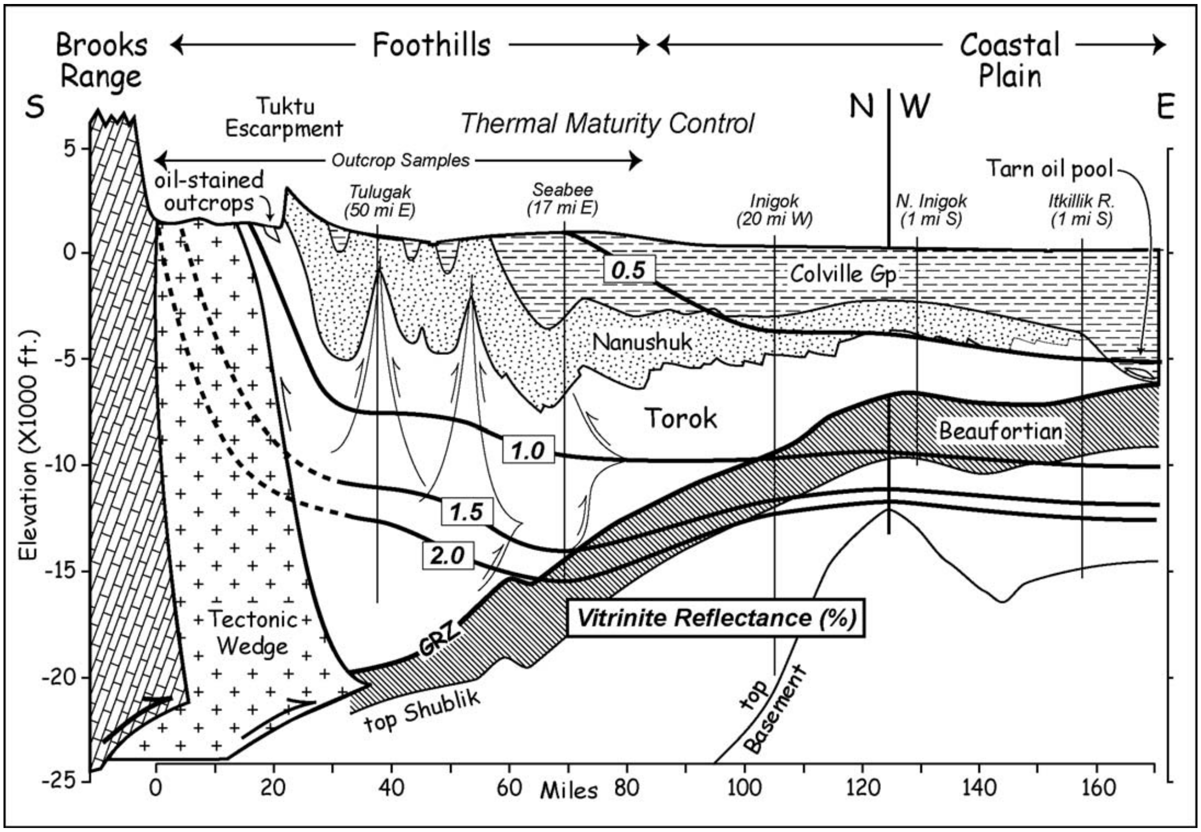
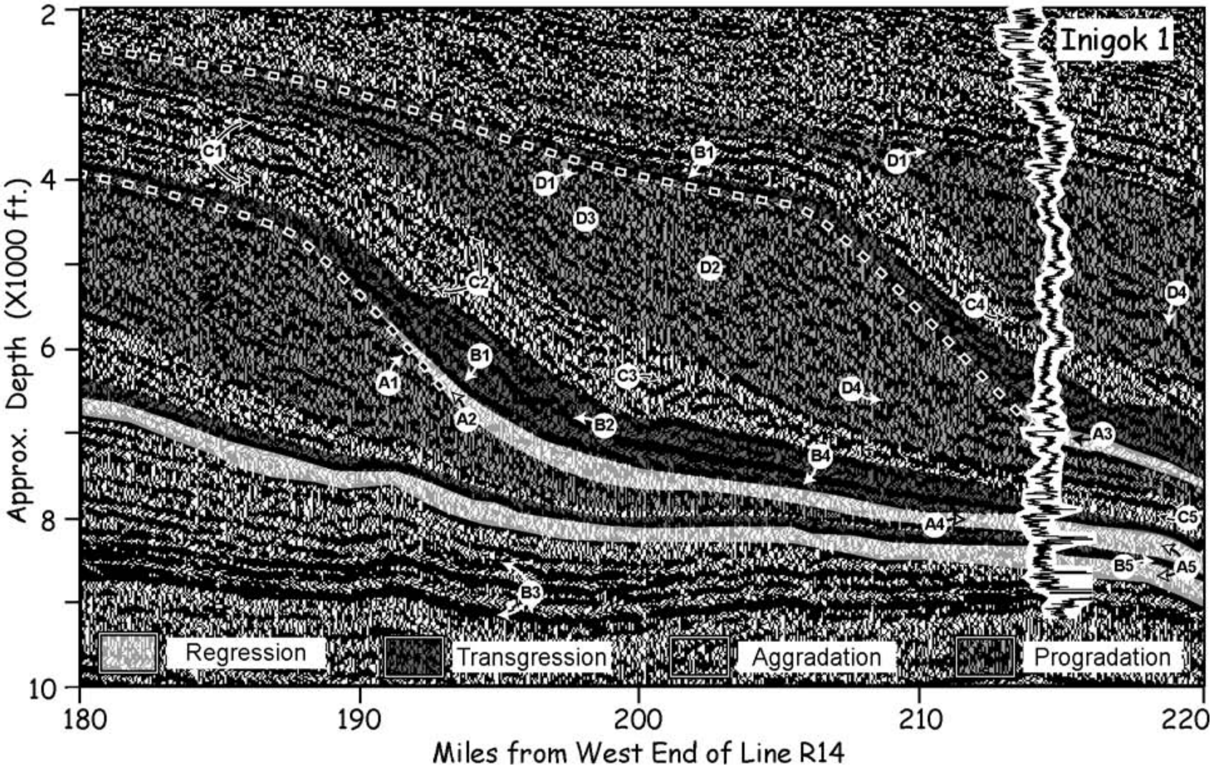


Figure 19. — Generalized cross-section, based on regional seismic lines, showing geology of Brookian strata in eastern NPRA and adjacent areas. Subsurface thermal maturity control projected onto cross-section from wells shown; surface thermal maturity control based on analysis of outcrop samples.

The erosional surface is interpreted as a sequence boundary (a high order unconformity) and the associated strata as a LST. At the base of the slope the LST is clearly composed of widespread, sandstone-rich turbidite facies as indicated by wire-line logs and core observations (Inigok cores 6 and 7 and Oumalik cores 82-88; fig. 21). At mid- to lower slope, where it pinches out via onlap against the sequence boundary, the LST likely includes incised turbidite channel facies as inferred from seismic reflection geometries and studies of Torok successions in outcrop and core. Thus, we infer this part of the Torok seismic motif to represent the product of a lowstand in relative sea level. It is likely equivalent to the LSTs recognized by McMillen (1991).

Transgression

The LST is overlain by a relatively thin interval characterized by one or more, high amplitude reflections that downlap basinward and coalesce with the GRZ (fig. 20). Up dip, the lower part of this interval typically onlaps the sequence bounding erosional surface on the upper slope. In some sequences, the upper part of this interval rolls over into topsets on the shelf margin. In other sequences, the interval containing high amplitude reflections appears to be slumped off the upper slope and occurs as a moderately deformed package of reflections on the mid- to lower



REGRESSION	TRANSGRESSION	AGGRADATION	PROGRADATION
A1-Truncation of older slope facies	B1-Condensed facies draped on shelf margin & slope	C1-Aggradational topsets & shelf margin	D1-Progradational topsets & shelf margin
A2-Seismically subtle onlap of LST	B2-Condensed facies commonly sole of slope failure	C2-Unstable upper slope prone to mass wasting	D2-Large volume of mud-dominated slope facies
A3-Deposition of incised turbidites on lower slope	B3-Distal CF's downlap onto & coalesce with GRZ	C3-Common evidence of mass-wasting (s-m scale)	D3-Unstable upper slope prone to mass wasting
A4-Deposition of LST, sand-rich fan facies at base of slope	B4-CF's cap/downlap LST within sequence	C4-Slope facies removed by mass wasting during progradation	D4-Abundant evidence of mass wasting (m-l scale)
A5-Multiple LSTs coalesce to form sand-rich interval in lower Torok	B5-Distal CF's define sequences & segregate LST's	C5-Submarine fan lobes possible	

Figure 20. — Segment of seismic line R14 illustrating seismic expression of four phases of Torok-Nanushuk depositional sequence motif.

slope. In those cases, high amplitude reflections also are present in the equivalent topsets, but they terminate abruptly at the shelf margin. The high amplitude reflections that occur on the shelf margin typically grade into medium and then low amplitude reflections over about 20 to 30 mi landward within topset strata.

The seismic interval containing high amplitude reflections is interpreted as a drape of condensed facies deposited during transgression, when marine waters flooded the shelf during a rise in relative sea level. The high amplitude reflections appear to represent relatively low velocity shales, likely higher in organic content than other slope facies (discussed below), deposited during times when most sediment was being deposited in more landward parts of the depositional system. These deposits represent a TST. The common deformation displayed by this

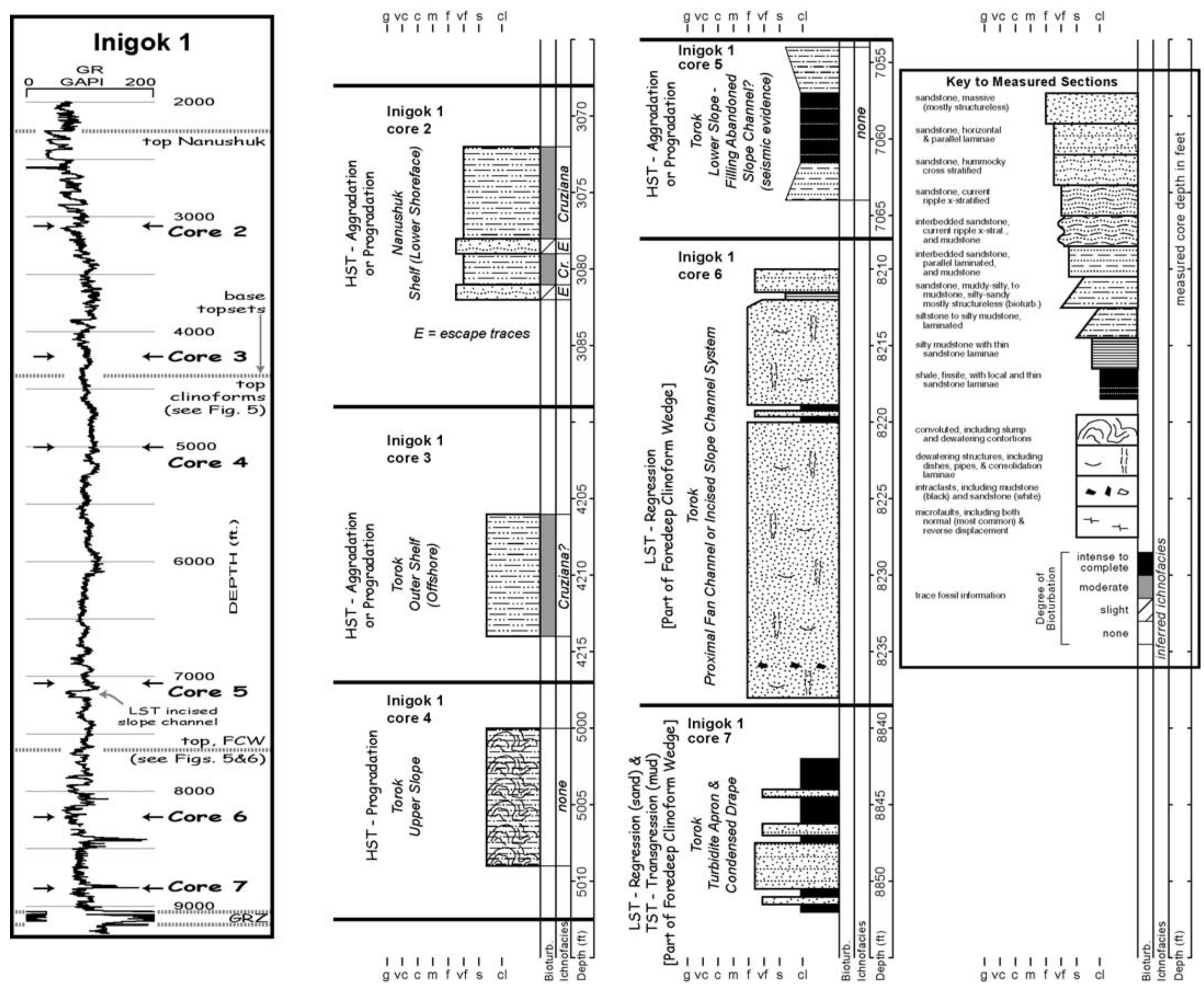


Figure 21A. — Wire-line logs and graphic measured sections of Torok and related strata in NPRA cores. Key to all measured sections included in A. [In wire-line log boxes, FCW, foredeep clinoform wedge; A. Inigok No. 1 and key.]

transgressive facies suggests that it commonly served as the sole of slope failure, as discussed below.

Aggradation

Transgressive facies are overlain by an interval characterized by thick topset strata that display

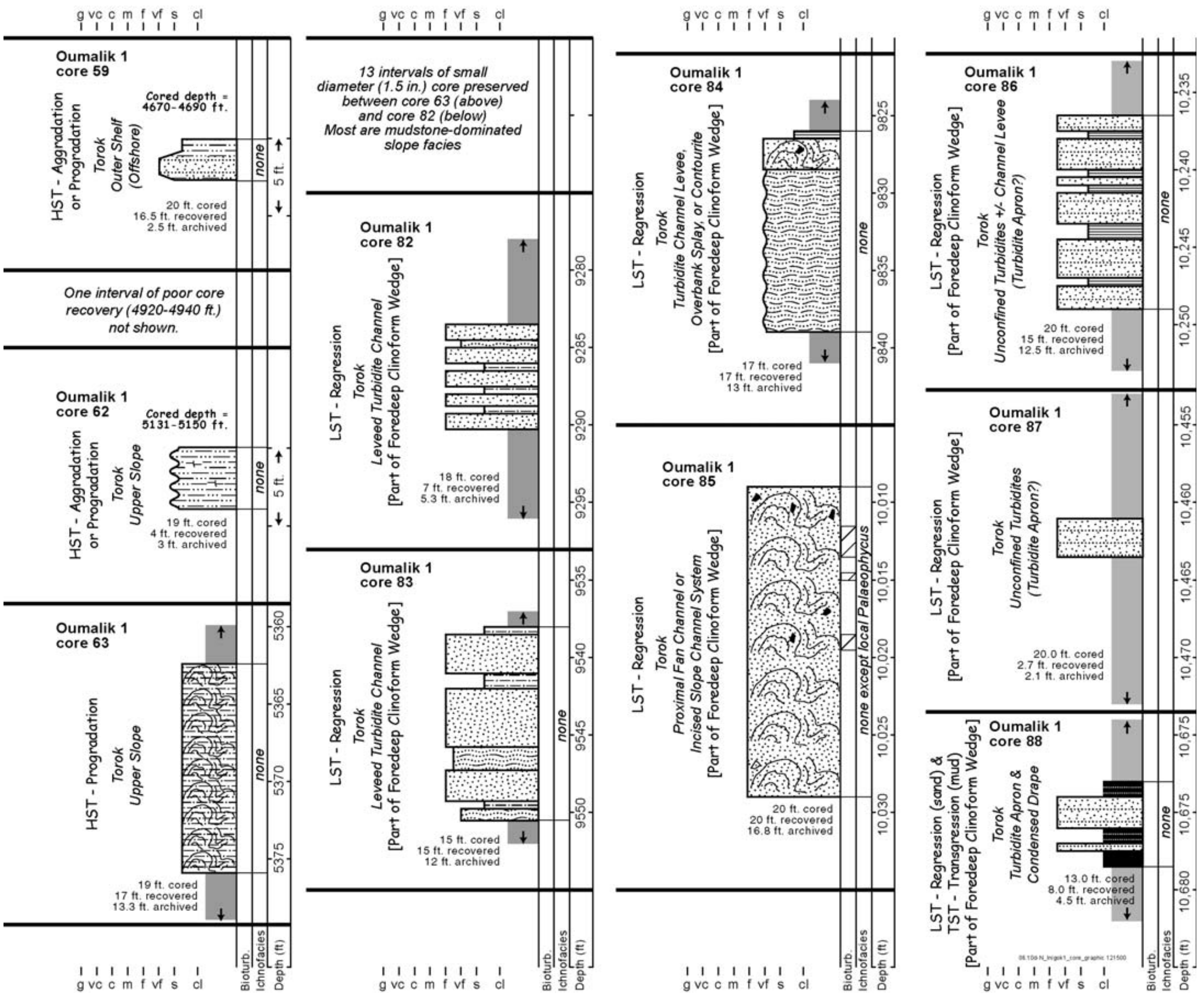


Figure 21B. — Wire-line logs and graphic measured sections of Torok and related strata in NPRA cores. Key to all measured sections included in A. [In wire-line log boxes, FCW, foredeep clinoform wedge—continued. B. Oumalik No. 1] continued.

evidence of significant vertical aggradation and little basinward progradation of the shelf margin. It is common to see seismic geometries that indicate more than 1,000 ft of vertical aggradation of topset reflections at the shelf margin with less than a few mi of shelf-margin progradation (fig. 20). The topset seismic facies are defined by moderate to high amplitude reflections that terminate or roll over abruptly into slope facies. In some sequences, the topset reflections display basinward-thickening, wedge-shaped geometries near the shelf margin. Basinward from the aggradational shelf margin, laterally adjacent seismic facies display a poorly defined clinoform geometry comprising low to medium amplitude reflections that commonly display contorted geometries. At the toe of the slope, broadly mounded seismic facies are commonly present within this seismic interval.

This interval is interpreted as marine shelf and slope deposition during times of high relative sea level and near equilibrium between sediment-influx volume and accommodation. These strata represent one part of a HST. The stratal geometry suggests that a large volume of sediment accumulated on the shelf and a relatively modest volume accumulated on the slope. Slope facies are predominantly mudstones and display seismic evidence of mass wasting at small to medium scale, especially on the upper slope where it is likely that slope failure was common. Mounded seismic faces at the base of the slope may indicate the presence of submarine fan lobes, which likely would consist of muddy to mixed sand/mud facies.

Progradation

Aggradational facies are overlain by an interval characterized by thin topset strata that display evidence of significant progradation and little aggradation of the shelf margin. It is common to see seismic geometries that indicate 20 mi or more of shelf margin progradation with only a few hundred feet of topset aggradation (fig. 20). The topset seismic faces are defined by moderate to high amplitude reflections that step basinward across the top of a large volume of slope facies that crudely define clinoforms. Internally, the slope facies display low to medium amplitude reflections that subtly toplap the overlying topsets and that display contorted geometries. Slope facies commonly thin abruptly at the toe of the slope, although that geometry may be influenced by erosion at the base of the overlying sequence (fig. 20).

This interval is interpreted as marine shelf and slope deposition during times of high relative sea level when sediment-influx volume exceeded accommo-dation. These strata represent the second part of a high-stand systems tract (HST). The stratal geometry suggests that a modest volume of sediment accumulated on the shelf and a large volume accumulated on the slope. Slope facies are mostly mudstones and display seismic evidence of mass wasting at medium to large scales. The large volume of mud deposited on the slope appears to have been highly prone to slope failure, ranging from relatively ductile creep and slumping that produced large masses of coherent reflections that display folded internal geometries to relatively fluidized failure that produced mounds of sediment with chaotic internal geometries.

Petroleum Potential

The depositional sequences delineated in this study provide a general framework for consideration of petroleum potential of Torok turbidites. As illustrated on the seismic example in figure 20, the base of an ideal sequence includes a concentration of sandstone on the basin plain and lower slope deposited during regression (LST). Basinward, the LST downlaps onto and interfingers with the condensed facies (GRZ) deposited on the basin plain. As the result of fluctuations in relative sea level, the sandstone-rich LST is capped by mudstone deposited during transgression (condensed facies of the TST). Condensed facies of the TST commonly overstep the LST sandstone in an up-slope direction and onlap the sequence-bounding erosion surface on the upper slope. This LST-TST combination not only places sandstone-rich facies (LST) into direct contact with oil-prone source rocks (GRZ), but it also forms a potential reservoir-seal couplet and is likely the geometry of stratigraphic traps such as Tarn oil field (Morris and others, 2000). These, in turn, are overlain by a thick succession of mudstone deposited during aggradation and progradation (together representing the HST), which also may contribute to the overall seal potential within the ideal sequence.

Although the stratal geometry described above forms an ideal stratigraphic trap, the LST sandstones penetrated by many wells and exposed in Torok outcrops in the foothills commonly are not sufficiently porous to be viable reservoirs. The widespread, sand-rich sandstones deposited on the lowermost slope and basin plain typically display attributes that suggest deposition as unconfined turbidites on basin-floor fans or aprons. These sandstones are typically very fine to fine grained and thin-bedded, and they display low porosity. In contrast, sandstones deposited higher on the slope typically display attributes that suggest deposition as confined turbidites in channels incised into the slope or developed on the proximal apex of a fan system. These sandstones are typically fine to medium grained and amalgamated, and they locally display higher porosity. Thus, the best potential for good reservoir and seal combinations occurs at mid-slope where the LST pinches out and is overstepped by the TST.

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