

Sedimentology, stratigraphy, and reservoir properties of an unconventional, shallow, frozen petroleum reservoir in the Cretaceous Nanushuk Formation at Umiat field, North Slope, Alaska

Grant T. Shimer, Paul J. McCarthy, and Catherine L. Hanks

ABSTRACT

Numerous oil and gas accumulations exist in the Brooks Range foothills of the National Petroleum Reserve in Alaska (NPR). We use cores and well logs from 12 abandoned legacy wells at Umiat field, near the southeastern boundary of the NPR, to characterize the sedimentology and stratigraphy of unconventional shallow frozen reservoirs in sandstones of the Cretaceous (Albian–Cenomanian) Nanushuk Formation. The Nanushuk Formation at Umiat has five facies associations: offshore and prodelta, lower shoreface, upper shoreface, delta front, and delta plain.

Three stratigraphically distinct, regionally extensive Nanushuk Formation depositional systems at Umiat contain several potential petroleum reservoirs. The lower Nanushuk Formation, including a reservoir interval known informally as the lower Grandstand, primarily consists of marine mudstone and shoreface sandstones. The middle Nanushuk Formation is dominantly deltaic and contains a second major reservoir interval in the informal upper Grandstand sandstone. Both the upper Grandstand and lower Grandstand are regressive. The

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transgressive upper Nanushuk Formation contains an additional potential reservoir interval in shoreface sandstones of the informal Ninuluk interval. The primary reservoir intervals at Umiat field are upper shoreface and delta-front sandstones in the upper Grandstand and lower Grandstand, where increased sorting and decreased bioturbation in high-energy depositional environments affect overall permeability and permeability anisotropy.

INTRODUCTION

Umiat field is an undeveloped petroleum accumulation in the Brooks Range foothills of the National Petroleum Reserve in Alaska (NPRA) (Figure 1). The field consists of clastic deposits of the Albian–Cenomanian Nanushuk Formation deformed in a thrust-faulted anticline (Figure 2; Collins, 1958; Molenaar, 1982). Previous studies established the presence of two sandstone reservoir intervals with oil–water contacts at 450 and 640 ft (173 and 195 m) below sea level, almost entirely within deep permafrost found from 770 to 1055 ft (235 to 322 m) below ground surface (Molenaar, 1982). The shallow depth and presence of deep permafrost make Umiat unconventional. The field remains undeveloped, because of low reservoir pressures and the permeability-reducing effects of pore ice (Hanks et al., 2014). The site also lies at a distant location from existing pipeline infrastructure, approximately 100 mi (161 km) southwest of Prudhoe Bay and 80 mi (129 km) west of the Trans-Alaska Pipeline System. Although early estimates of recoverable oil ranged from 30 to 100 million bbl depending on recovery factors chosen (Molenaar, 1982), there may be as much as 1.4 billion bbl of oil in place (Levi-Johnson, 2010). Despite known engineering challenges, advances in horizontal drilling technology and high oil prices created renewed interest in Umiat field and justified a reassessment of potential reservoir intervals.

Several previous generations of research focused on the Nanushuk Formation at Umiat field. The field was discovered during the federal investigations of Naval Petroleum Reserve 4 (NPR-4) between 1944 and 1953, when 11 wells were drilled at the site to investigate oil seeps at the base of Umiat Mountain (Figure 2B; Collins, 1958). The Umiat wells are now considered legacy wells that are abandoned and shut-in. More than 4000 ft (1219 m) of core was recovered during initial investigations to better characterize the subsurface. The cores and cuttings are stored at the Alaska Geologic Materials Center

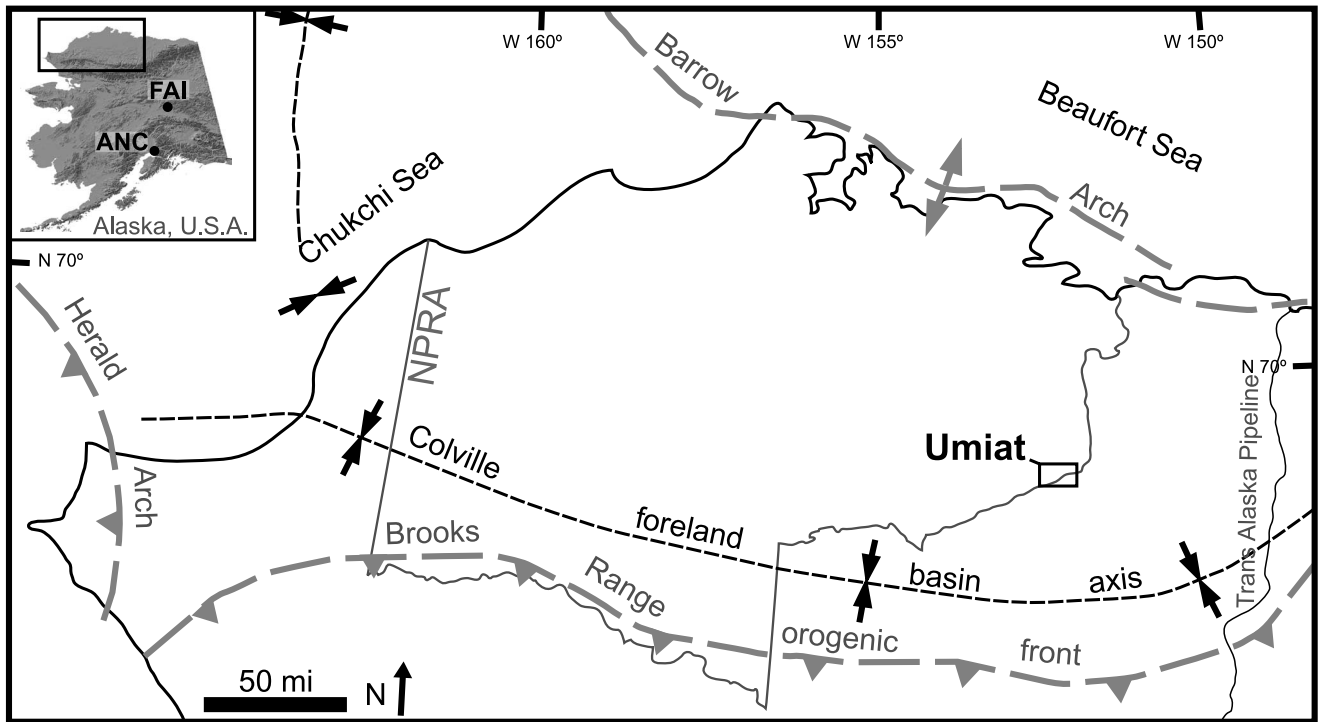


Figure 1. A map of northern Alaska shows the location of Umiat field (black rectangle) in relation to the axis of the Colville Basin, the thrust front of the Brooks Range, and the Herald and Barrow arches (modified from Decker, 2007). The Colville River forms the eastern boundary of the National Petroleum Reserve in Alaska (NPR-4). Inset (upper left): digital elevation model of Alaska with the study area outlined in black and with Fairbanks (FAI) and Anchorage (ANC) for reference.

(GMC) in Eagle River, Alaska, with additional samples at the U.S. Geological Survey Core Research Center in Lakewood, Colorado.

The original report on Umiat drilling operations (Collins, 1958) includes core and cuttings descriptions, microfaunal analyses, well logs (resistivity and spontaneous potential), and a summary of reservoir characteristics. Seven of the 11 Umiat wells produced oil from sandstones in the Nanushuk Formation (individual sandstone beds were not tested), although there was no recovery from an additional well (Umiat 2) because of interactions between the rock, permafrost, and freshwater drilling fluids (Collins, 1958). Although approximately 40,000 bbl of oil were recovered before 1953, the recovery factor estimates for this time ranged from 8% to 32.5% in the permafrost-affected reservoir (Molenaar, 1982). All 11 Umiat wells have not been studied in public literature in detail since the original drilling reports (Collins, 1958), and they represent a valuable resource for the evaluation of the Nanushuk Formation in the subsurface.

A federal reinvestigation of the petroleum resources of the NPR-4 began in 1974. In 1977, the National Petroleum Reserves Production Act transferred the NPR-4 from the U.S. Navy to the Department of the Interior, when it became the NPR-4 (Schindler, 1988). New reservoir-quality assessments of the Nanushuk Formation during this time included core description, biostratigraphy, petrographic analyses, and two-dimensional seismic interpretations (Ahlbrandt et al., 1979; Fox et al., 1979). In 1978, the Husky Seabee 1 well was also drilled at Umiat to sample deep strata below the Nanushuk Formation. Seabee 1 lies below the oil-water contact in the lower Grandstand based on geophysical well-log analysis and lacks any core samples from the Nanushuk Formation (Figure 2B). The well does have a modern suite of geophysical well logs through the Nanushuk Formation (Legg and Brockway, 1983) and a check-shot survey, which are both valuable for subsurface interpretations.

The second generation of summary reports and reviews of Umiat and the Nanushuk Formation

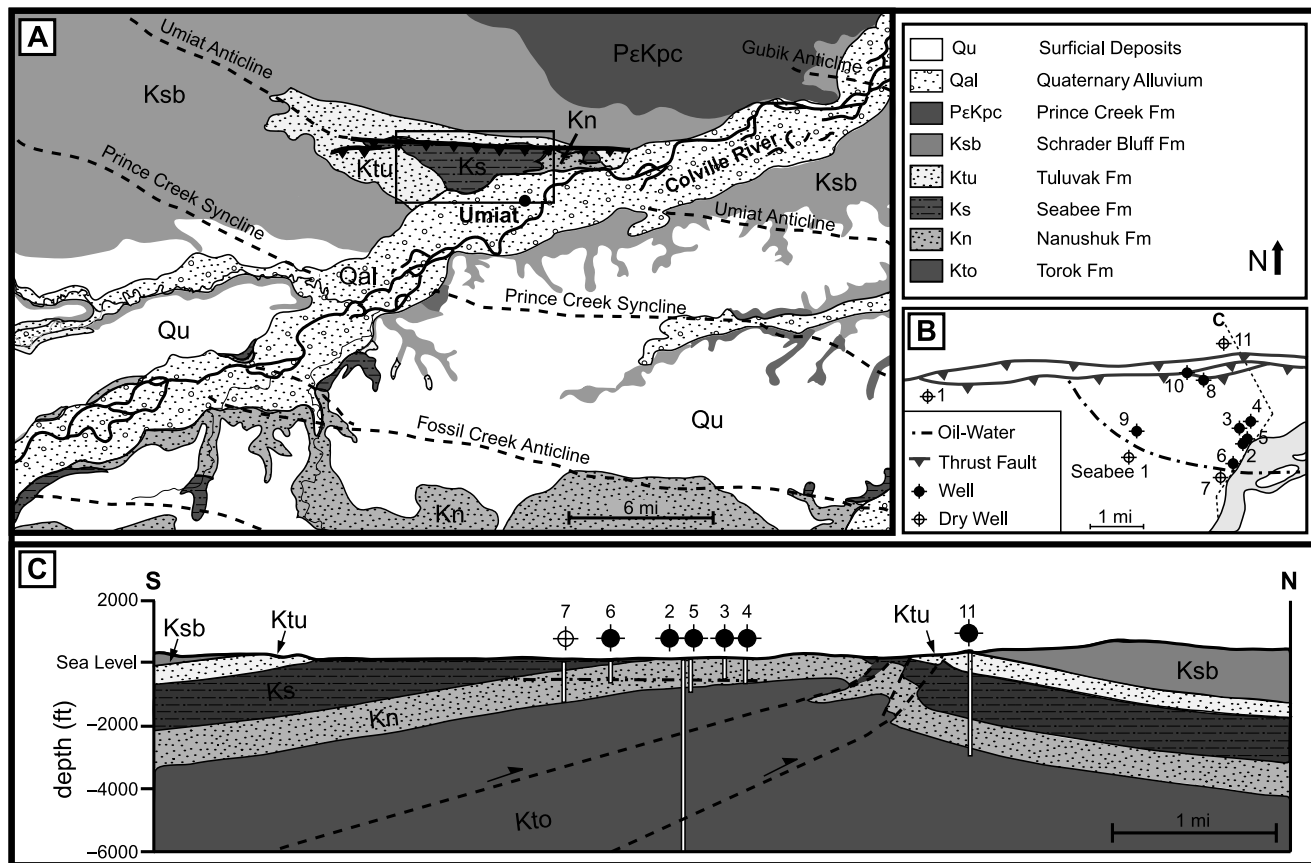


Figure 2. (A) Geologic map of the Umiat area (modified from Mull et al., 2004). Surface exposure of the Nanushuk Formation is limited. Note the orientation of major anticlines and synclines, indicative of the fold-and-thrust origin of the Brooks Range foothills. The black rectangle shows the location of (B). (B) Map showing locations of the 11 Umiat wells and the Seabee 1 well. The dash-dotted line indicates oil-water contact (OWC) on the south side of the Umiat anticline, whereas the dashed line marks the trace of the cross section in (C). (C) North-south cross section of Umiat anticline with basic stratigraphy, major thrust faults, and well locations (modified from Molenaar 1982). The dash-dotted line indicates the Nanushuk Formation OWC.

ended in the 1980s (Molenaar, 1982; Huffman, 1985; Gryc, 1988). Following years of inactivity, recent studies of the Nanushuk Formation at various locations on the North Slope used modern facies analysis (LePain and Kirkham, 2001; Houseknecht and Schenk, 2005; LePain et al., 2009) and sequence-stratigraphic interpretations (Houseknecht and Schenk, 2005; Decker, 2007) to establish the Nanushuk Formation as a spatially and chronostratigraphically variable mix of wave-, river-, and tide-influenced facies deposited in a mostly deltaic setting (LePain et al., 2009).

The purpose of this study is to assess facies variability within the Nanushuk Formation at Umiat field, characterize the reservoir-scale stratigraphic architecture, and investigate how facies variability affects potential reservoir distribution. Five facies

associations within three distinct depositional systems are defined based on cores and well logs from all 11 Umiat wells and the nearby Seabee 1 well (Figure 2B). Four broadly distributed reservoir intervals correspond to informal units of the Nanushuk Formation. Different sedimentary processes are responsible for each reservoir interval, but three of the intervals have similar characteristic permeability profiles and degrees of heterogeneity. The fourth interval is distinct in character but poorly represented in the subsurface. The results of this evaluation of the sedimentology and stratigraphy of the Nanushuk Formation at Umiat field are important for evolving production models and have implications for broader interpretations of Nanushuk Formation depositional environments on the east-central North Slope. Other potential permeable

intervals likely exist in upward-coarsening topset sandstones deposited in both wave- and river-dominated environments of the fold and thrust belt in the Brooks Range foothills.

GEOLOGIC SETTING

Umiat field, Alaska (N69°22'12", W152°8'10") is located in the northern Brooks Range foothills along the southeastern boundary of the NPRA (Figure 1). Most of the infrastructure at Umiat, including some of the original well sites, sits on Quaternary sediments of the Colville River floodplain on the southern limb of an asymmetric, northward-vergent thrust-faulted anticline (Figure 2A–C). The anticline deforms Lower Cretaceous to Cenozoic sediments derived from the ancestral Brooks Range to the south (Mull et al., 2004). These Brookian strata are part of a thick package of clastic sediments that filled the Colville foreland basin starting in the Early Cretaceous (Figure 3; Mull et al., 2003). The four relevant Brookian formations at Umiat are the Albian–Cenomanian Torok and Nanushuk Formations and the overlying Cenomanian–Turonian Seabee and Tuluva Formations. These formation pairs make up two distinct depositional megasequences (Mull, 1985; Hubbard et al., 1987; Decker, 2007). Cenomanian–Turonian strata, including the upper part of the Nanushuk Formation, are exposed on the eastern limb of the Umiat anticline in bluffs at Umiat Mountain (Houseknecht and Schenk, 2005), but the upper Grandstand and lower Grandstand intervals of the Nanushuk Formation are not exposed at the surface.

The Nanushuk Formation prograded from west to east along the axis of the Colville Basin, with an additional south–north component in the area that now makes up the east-central Brooks Range foothills (Houseknecht and Schenk, 2005; Decker, 2007; Houseknecht et al., 2009; LePain et al., 2009). The formation has been described as fluvial, deltaic, and shallow marine, with major deltaic depocenters in the west and central North Slope (Ahlbrandt et al., 1979; Mull, 1985), but a considerable west–east variation exists in Nanushuk Formation depositional environments across the North

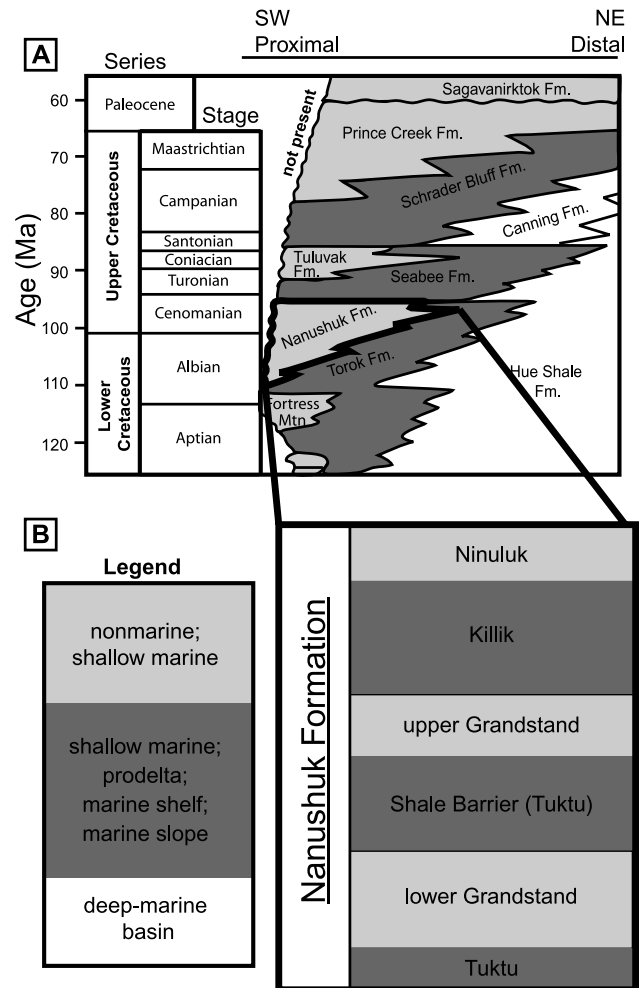


Figure 3. (A) Brookian stratigraphic units of the Colville Basin relevant to this study. The Nanushuk Formation is outlined in bold (modified from Mull et al., 2003). A color legend refers to the generalized depositional environments for each formation. (B) Informal subsurface stratigraphy of the Nanushuk Formation in common usage at Umiat field. Fm. = Formation; Tert. = Tertiary; Early C = Early Cretaceous.

Slope. In the Umiat area, the Nanushuk Formation is slightly younger and more sand rich than in the west, possibly because of sources from multiple shorter rivers draining the northern flank of the ancestral Brooks Range or because of greater wave influence and reworking (Molenaar, 1985; LePain and Kirkham, 2001; Houseknecht and Schenk, 2005; LePain et al., 2009).

Originally defined as the Nanushuk Group (Detterman, 1956), with numerous shallow-marine and nonmarine formations, the Nanushuk was lowered to formation status to comply with international guidelines (Mull et al., 2003). Although now

informal units, the formations of the former Nanushuk Group remain in common use in the subsurface (Figure 3B). At Umiat field, these units include the marine Tuktu, shallow-marine to deltaic Grandstand, marginal marine to nonmarine Killik tongue of the Chandler, and the shallow-marine Ninuluk units. Killik is used here instead of Chandler to emphasize the local character of the former formation. Furthermore, in the subsurface at Umiat, the Grandstand contains two distinct sand-rich intervals (upper Grandstand and lower Grandstand) separated by a tongue of marine mudstone of the Tuktu, commonly referred to as the shale barrier.

Umiat reservoir tests during the 1944 to 1953 drilling period produced oil primarily from the upper Grandstand, with minor production from the Ninuluk and oil shows in the other formations (Molenaar, 1982). In Umiat 11, the Grandstand and Killik have higher average porosity and permeability than the Ninuluk, probably because of the changes in depositional environment and possible changes in provenance (Fox et al., 1979). This relationship has been assumed to be consistent in the subsurface throughout the reservoir, but note that Umiat 11 was a dry well that lies in the footwall of the thrust structure and outside the limits of the known petroleum trap.

REGIONAL CONTEXT

The Colville Basin formed in flexural response to tectonic loading along the ancestral Brooks Range and Herald arch (Figure 1) (Nunn et al., 1987; Coakley and Watts, 1991; Moore et al., 1994). The earliest sedimentary evidence for initiation of the Brookian orogeny is Hauterivian in age (Bird and Molenaar, 1992), but the Albian–Cenomanian (113–100.5 Ma; Cohen et al., 2013) Torok and Nanushuk Formations were deposited during a period of extension and exhumation on the south side of the Brooks Range that started at approximately 113 Ma (Blythe et al., 1996; O’Sullivan et al., 1997). By the Late Albian, the Torok and Nanushuk Formations filled much of the Colville Basin and

overtopped the Barrow arch (Molenaar, 1985; LePain et al., 2009).

METHODS

Cores (4218 ft; 1286 m) were photographed, described, and logged from the 11 Umiat wells in collections at the GMC. Most of the available cores were from the Umiat 1, 2, 3, 9, 10, and 11 wells (Figure 4). The condition and size of the cores varies between wells. Wells 1 and 2 have 1.5-in. (4-cm)-diameter cores, whereas wells 9, 10, and 11 have 2.5-in. (6-cm)-diameter cores. Many of the cores were still coated in drilling mud, and Umiat 11 was the only well with significant slabbed intervals. With the permission of the GMC, we slabbed much of the core from Umiat 9.

New interpretations were cross-referenced with the original core and cuttings descriptions (Collins, 1958). The thicknesses of sandstone and mudstone intervals in all of the Umiat wells were quantified using core descriptions and published cuttings data (Collins, 1958), and a sandstone-to-mudstone ratio was calculated for the mudstone-dominated intervals in the subsurface. Where resistivity and spontaneous-potential well logs were available, we used the data to interpret gaps between cored intervals and to correlate between the Umiat wells. The Seabee 1 well also has a gamma-ray log, used for further correlation. Although the oil–water contacts are believed to be at 450 and 640 ft (137 and 195 m) below sea level, the contact was not directly observed in core. Bioturbation intensities, which are used to assess the degree of burrowing, were determined using a scale of 0 to 6 (Bann et al., 2004).

Air-permeability data were collected using a New England Research Tiny Perm II mini-permeameter. Horizontal permeability (K_h) was recorded at 1-ft (0.3-m) intervals from slabbed sandstone cores. The rough surfaces of unslabbed cores prevented the formation of an adequate seal for permeameter readings. Vertical permeability (K_v) measurements were made on relatively flat, unlaminate surfaces at more irregular intervals. For ease of

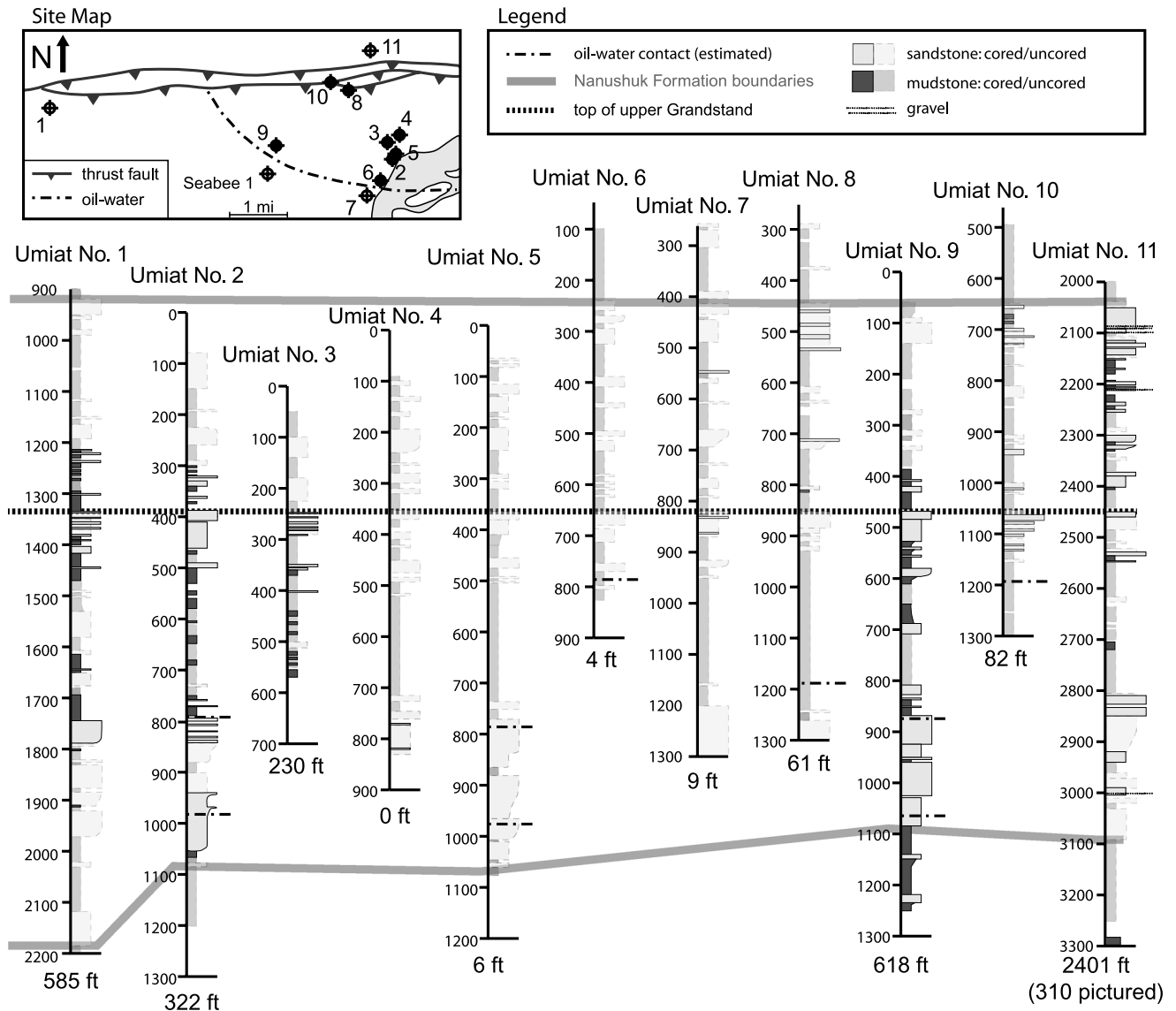


Figure 4. Stratigraphic sections from each of the 11 Umiat wells, illustrating the Nanushuk Formation. The inset map shows the location of each well. In the stratigraphic sections, cored intervals are darkened, whereas uncored intervals are lightly shaded. Totals at the bottom of each well indicate the amount of core described for each well. Not all of the described core is pictured; some is from outside of the Nanushuk Formation. Also pictured is the estimated position of the oil–water contact (OWC) in wells with oil shows that reached sufficient depth. The stratigraphic sections are hung on the top of the upper Grandstand sandstone.

interpretation, individual permeability values (K_h and K_v) underwent log transformation:

$$\log(K) = \log_{\text{permeability}} \quad (1)$$

Log-transformed values range from 0 ($\log 1$ md) to 3 ($\log 1000$ md). Ten millidarcys was used as the lower cutoff for defining reservoir sandstones. We also calculated permeability anisotropy (K_v/K_h) and present these data as averages for reservoir intervals.

Any ratio more than 2.0 was considered an outlier caused by instrumental or operator error and was not included in the average values.

FACIES ASSOCIATIONS

Facies are distinguished on the basis of grain size, sedimentary structures, and biological features (Table 1; Figure 5). Individual facies are grouped

Table 1. Facies Defined from Core at Umiat Field*

Facies	Diagnostic Features	Process Interpretation
F-1: Silty shale	Laminated silty mudstone with color dependent on both grain size and organic-matter content. Laminations are parallel to subparallel. Grades up into F-3 in some settings. BI of 3 or less.	Suspension settling in low-energy settings. Well-preserved laminations may indicate low-oxygen (dysoxic) conditions that inhibit biogenic activity.
F-2: Mudstone	a. Dark-gray to black shale to sandy silt, with color dependent on both grain size and organic-matter content. Some red-orange staining is present. Either massive or with a BI of 4 or greater; individual traces are discernible, but bedding features are indistinct. Includes a wide range of trace fossils. Bivalve and gastropod shells are present. b. Carbonaceous mudstone, with common plant fossils and bivalve fossils.	Suspension settling in an environment that supports significant biogenic activity. Red-orange staining may indicate exposure to the atmosphere or diagenetic alteration. Accumulation of organic matter and mud in water-saturated and poorly oxygenated lake or bay environments.
F-3: Lenticular to wavy bedded mudstone	Dark-gray lenticular to wavy bedded mudstone. Very fine to fine-grained sand or silty laminations (1–5 cm [0.4–2.0 in.] thick) have internal ripple cross-laminations.	Suspension settling interrupted by rare unidirectional currents.
F-4: Apparently massive sandstone	Light-gray, well-sorted, very fine to fine-grained sandstone with rare beds of medium sandstone. No visible structures but rare carbonaceous partings.	Lack of visible structure caused by rapid deposition, high degree of sorting, dewatering, or cryptobioturbation.
F-5: Low-angle cross-laminated sandstone	Light-gray, well-sorted very fine to fine-grained sandstone. Low-angle laminations dip less than 15° and show changes in thickness. Beds 0.5–2 m (1.6–7 ft) thick. Associated features include mudstone rip-up clasts and shell lags.	Hummocky to swaley cross-stratification deposited by oscillatory currents (Dott and Bourgeois, 1982).
F-6: Ripple cross-laminated sandstone	a. Light-gray very fine to fine-grained asymmetrical ripple cross-laminated sandstone. Mudstone laminations are common. b. Light-gray very fine to fine-grained symmetrical ripple cross-laminated sandstone. Mudstone laminations are common.	Ripple migration under unidirectional currents as part of larger, subaqueous bar-forming processes. Ripple formation under oscillatory currents.
F-7: Mud-draped ripple cross-laminated sandstone	Light-gray to tan, fine- to medium-grained ripple cross-laminated sandstones with centimeter-thick oxidized mud drapes.	Mixed energy conditions, with suspension settling during low-energy slack-water conditions.
F-8: Parallel laminated sandstone	Light-gray, well-sorted very fine to medium-grained plane-parallel laminated sandstone. Larger laminations show normal grading. Lamination surfaces are commonly associated with carbonaceous partings.	Upper-flow-regime plane-bed conditions or swash-zone conditions (Paola et al., 1989).
F-9: Trough cross-laminated sandstone	Gray to tan very fine to medium-grained sandstone with high-angle (>15°) laminations.	Subaqueous dunes formed by unidirectional currents in the distributary system or by cross-shore and longshore currents along the coast.
F-10: Poorly sorted sandstone and gravelly sandstone	Gray to tan poorly sorted very fine to coarse-grained sand. Sand is always the dominant grain size, with pebble-size clasts that include mudstone rip-ups, coal fragments, and rare lithics. Pebbles occur as lag deposits or mixed into a poorly sorted matrix.	Channel lag and bar formed by unidirectional currents. Coal fragments point to terrestrial origin.

F-11: Coal	Black coal deposits from 5–10 cm (2–4 in.) thick, commonly found in association with F-12.	Accumulation of organic matter in low-lying, water-saturated, and poorly oxygenated terrestrial environments.
F-12: Bentonite	Yellow and light-gray beds of clay (montmorillonite; Anderson and Reynolds, 1966), some biotite rich. Occasionally with root traces. Commonly found with F-11.	Altered volcanic air-fall deposits preserved in low-energy terrestrial settings.
F-13: Lag deposits	Layers of mudstone rip-up or disarticulated bivalve shells. Typical layer only as thick as a single clast	Coarse-grained deposits associated with high-energy deposition of storm beds.

*Depositional facies are defined on the basis of grain size, sorting, sedimentary structures, fossils, trace fossils, and bioturbation intensity (BI). BI values are based on Bann et al. (2004).

into facies associations (Table 2) on the basis of bedding relationships observed in core, upward-coarsening or -fining trends from lithologic and well logs, and observed trace fossils (Figure 6). Five defined facies associations exist (Figures 7–9), with additional subdivision of facies associations to differentiate distinct elements (i.e., distal and proximal lower shoreface).

Facies Association 1

Description

Facies association 1 (FA-1; Figures 7, 8) (Table 2) comprises successions of silty shale (F-1), massive mudstone (F-2), and wavy or lenticular bedded mudstone (F-3). Highly bioturbated (bioturbation intensity [BI] 4–6) mudstones contain abundant *Phycosiphon* and *Schaubcylindrichnus freyi* (Figure 6). *Palaeophycus* and *Planolites* are associated with increasing sand content and the transition to FA-2a. Lenticular or wavy bedded mudstones (F-3) are less bioturbated (BI 0–3). Both F-2 and F-3 mudstones contain arenaceous and calcareous foraminifera of the Albian *Verneuilinoides borealis* faunal zone (Bergquist, 1958) and have the highest percentage of dinoflagellates in the Nanushuk Formation (May and Shane, 1985).

Interpretation: Offshore

Published faunal and palynological analyses establish the marine character of FA-1 mudstones. The *Verneuilinoides borealis* faunal zone consists of shallow-marine fauna (Bergquist, 1958), whereas the palynological assemblage of dinoflagellates, acritarchs, and spores is typical of a near-shore shallow-marine setting (May and Shane, 1985). Furthermore, the trace-fossil assemblage closely resembles the *Cruziana* ichnofacies, which is associated with both offshore marine and prodelta settings (MacEachern et al., 2005).

This article follows the convention of LePain et al. (2009) and groups prodelta and nondeltaic shelf mudstones of the Nanushuk Formation into a single offshore facies association deposited below storm-wave base (sensu Van Wagoner et al., 1990; Hampson and Storms, 2003). Thin sandy laminations or wavy and lenticular bedding found

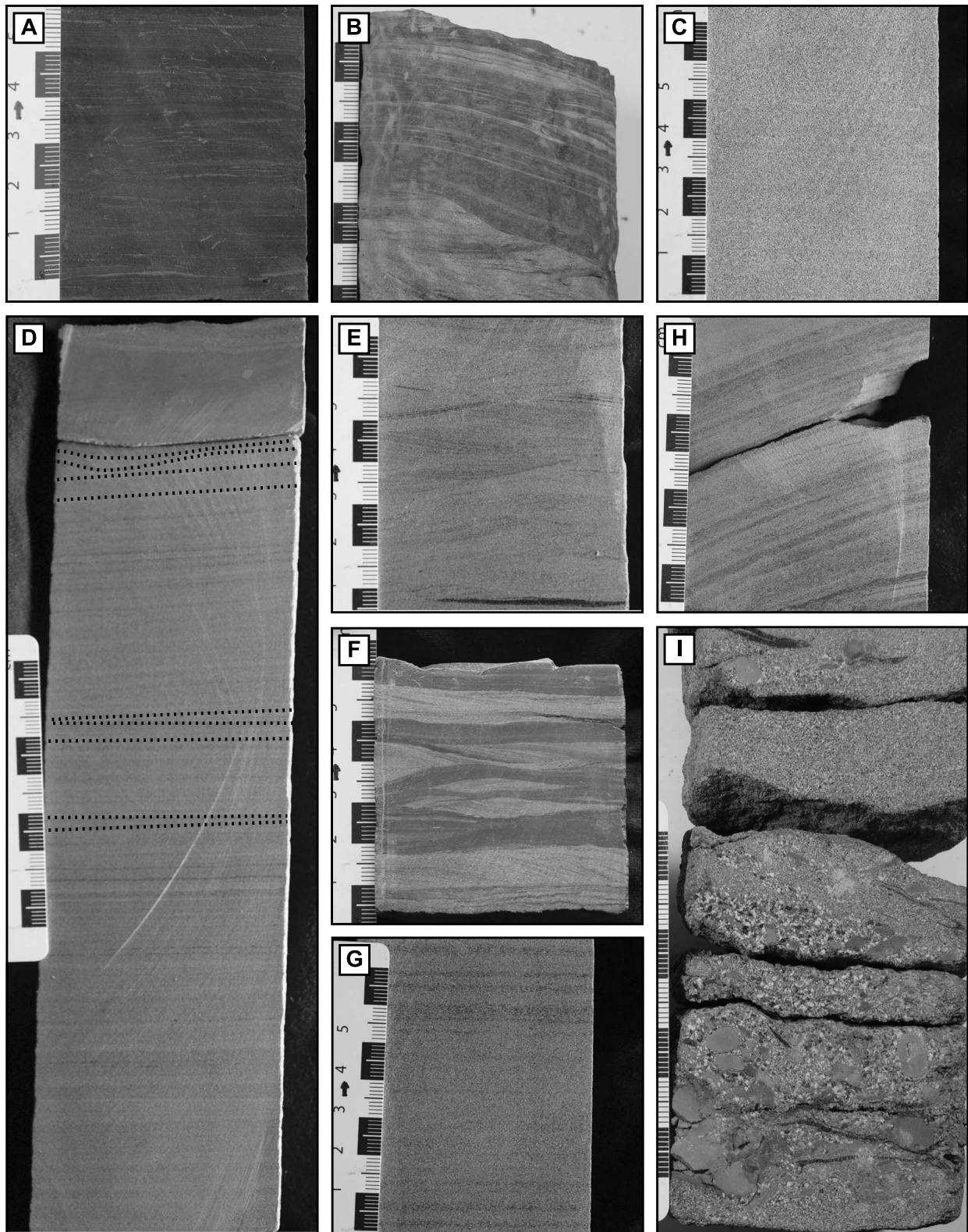


Figure 5. Core photographs from the Nanushuk Formation at Umiat field showing selected sedimentary facies described in the text. Scale bar in centimeters. (A) F-1, laminated mudstone; (B) F-3, wavy or lenticular bedded mudstone; (C) F-4, apparently massive sandstone, with possible faint parallel bedding; (D) F-5, low-angle cross-laminated sandstone, with dotted lines to highlight lamination surfaces; (E) F-6, ripple cross-laminated sandstone; (F) F-7, mud-draped ripple cross-laminated sandstone; (G) F-8, parallel laminated sandstone; (H) F-9, trough cross-bedded sandstone with foreset dips more than 15°; (I) F-10, poorly sorted sandstone and gravel. Not pictured: F-2 mudstone; F-11 coal; F-12 bentonite; F-13 lag deposits.

Table 2. Summary of Facies Associations at Umiat Field

Facies Association	Facies	Diagnostic Features	Environmental Interpretation	Depositional Processes
FA-1	F-1, F-2	Laminated shale or bioturbated mudstone (<i>Cruziana</i> ichnofacies).	Offshore or prodelta	Suspension settling in the prodelta or the marine shelf near storm-wave base.
FA-2	F-2, F-3, F-5, F-13	Interbedded bioturbated mudstone (<i>Cruziana</i> ichnofacies) and upward-coarsening hummocky and swaley cross-stratified sand (<i>Skolithos</i> ichnofacies). Some sand beds are obliterated by bioturbation (BI 5–6).	a. Distal lower shoreface	Mixed-energy shelf, above storm-wave base. Deposition by suspension settling and storm-wave redistribution of sand and silt originally delivered to the coast by deltaic systems.
	F-4, F-5	Amalgamated sand beds with hummocky and swaley cross-laminated very fine sandstone, with highly bioturbated beds (<i>Skolithos</i> ichnofacies).	b. Proximal lower shoreface	Storm-wave deposition and redistribution of sand between fair-weather and storm-wave base.
FA-3	F-4, F-5, F-9, F-13	Low-angle trough cross-stratified and plane-laminated fine-grained sandstone. Rare bioturbation (<i>Skolithos</i> ichnofacies).	Upper shoreface and foreshore	Subaqueous bar migration above fair-weather-wave base, with some swash zone deposits.
FA-4	F-3, F-6a, F-7, F-8, F9, F-10, F-13	Wavy and lenticular bedding with occasional soft-sediment deformation coarsens up into ripple cross-laminated and massive sand. Bioturbation intensity and diversity low.	Delta front	Progradation of distributary mouth bars into muddy prodelta. Rapid deposition associated with massive sand, soft-sediment deformation, low BI.
FA-5	F-1, F-2, F-3, F-6a, F-6b, F-7, F-11, F-12	Carbonaceous mudstone with brackish-water bivalve assemblage (<i>Corbula</i>), volcanic ash deposits, and plant fossils. Closely associated with the top FA-3 and FA-4. Thin ripple cross-laminated sandstone beds less than 10 ft (3 m) thick, heavily oxidized.	a. Delta plain	Suspension settling in protected interdistributary bays or lagoons, with some tidal influence (F-7), organic-matter accumulation in marshes or swamps.
	F-3; F-6a, F-7, F-8 (rare), F-13	Wavy bedding coarsens up into flaser bedding and ripple cross-laminated sandstone. Beds are 5–10 ft (1.5–3 m) thick. Mud drapes are common in some sandstone beds and are commonly sideritized, especially in Umiat 11. Rare mudstone rip-up clasts.	b. Crevasse sands	Crevasse-channel and -splay deposits that form during flood or avulsion into interdistributary bays or the delta plain. Some tidal influence indicated by mud drapes.

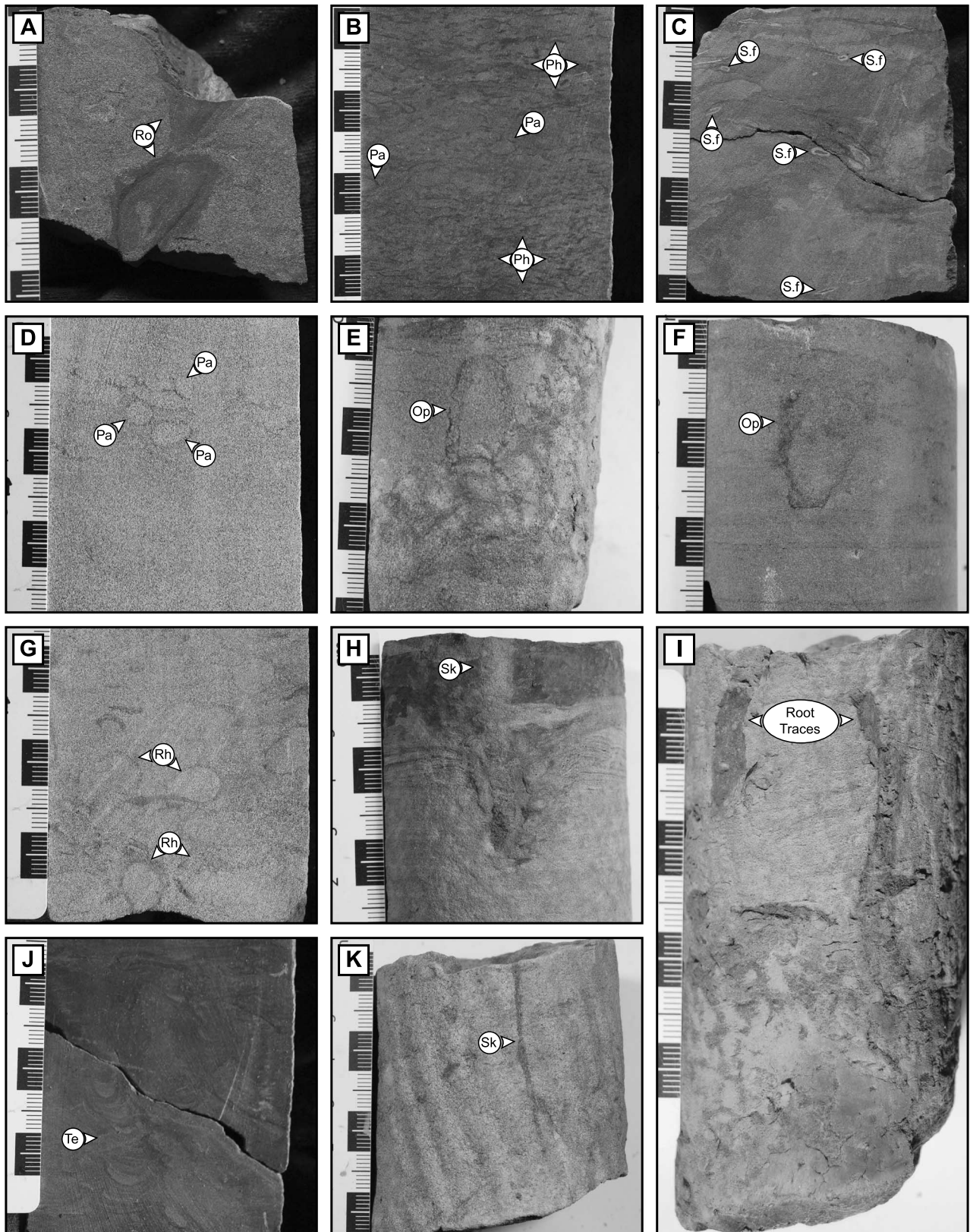


Figure 6. Examples of trace fossils observed in core. Scale bar in centimeters. (A) *Rosselia* (Ro), (B) *Phycosiphon* (Ph) and *Palaeophycus* (Pa), (C) *Schaubcylindrichnus freyi* (S.f), (D) *Palaeophycus*, (E) *Ophiomorpha* (Op), (F) *Ophiomorpha*, (G) *Rhizocorallium* (Rh), (H) *Skolithos* (Sk), (I) Root traces, (J) faint *Teichichnus* (Te), (K) *Skolithos*.

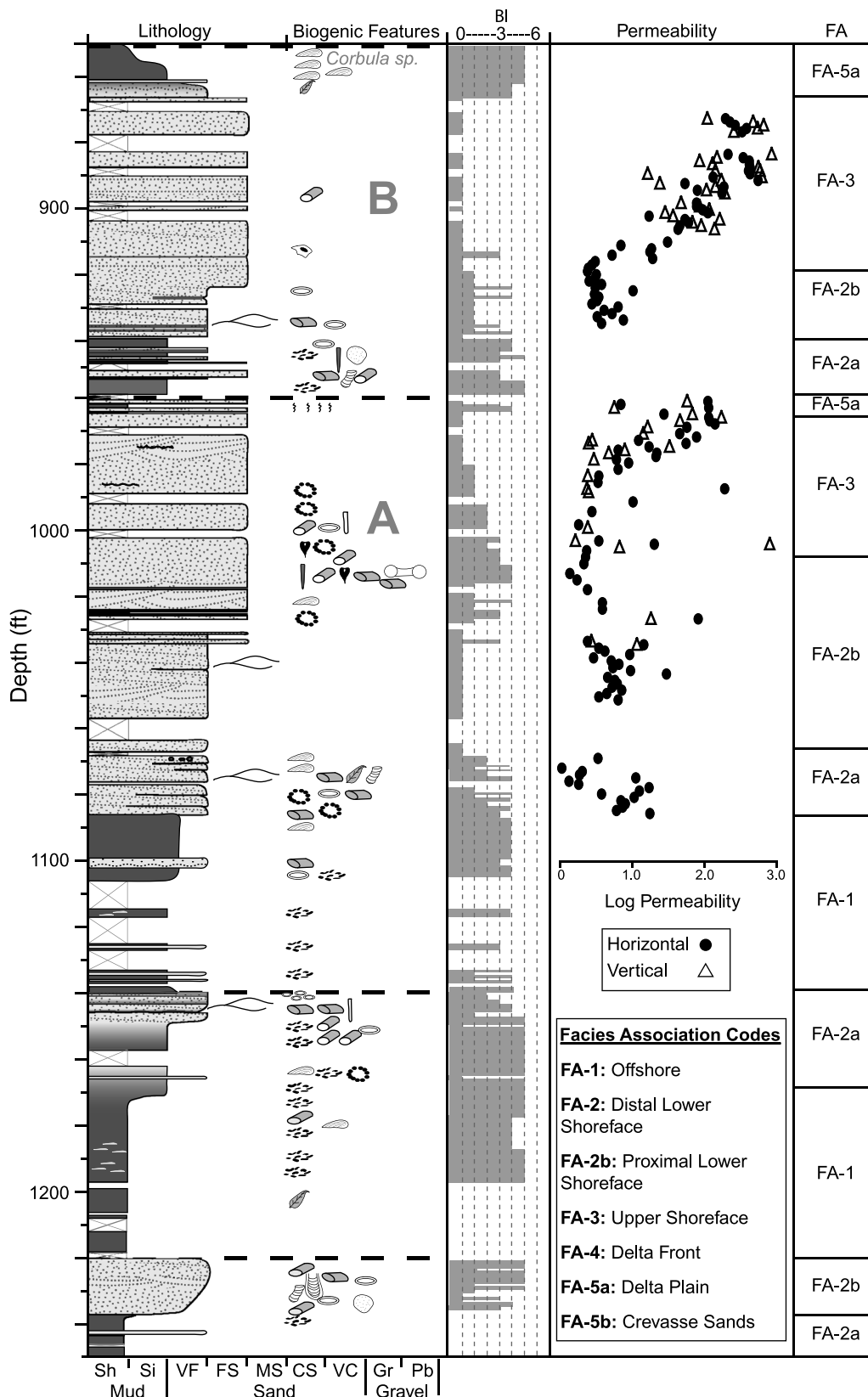
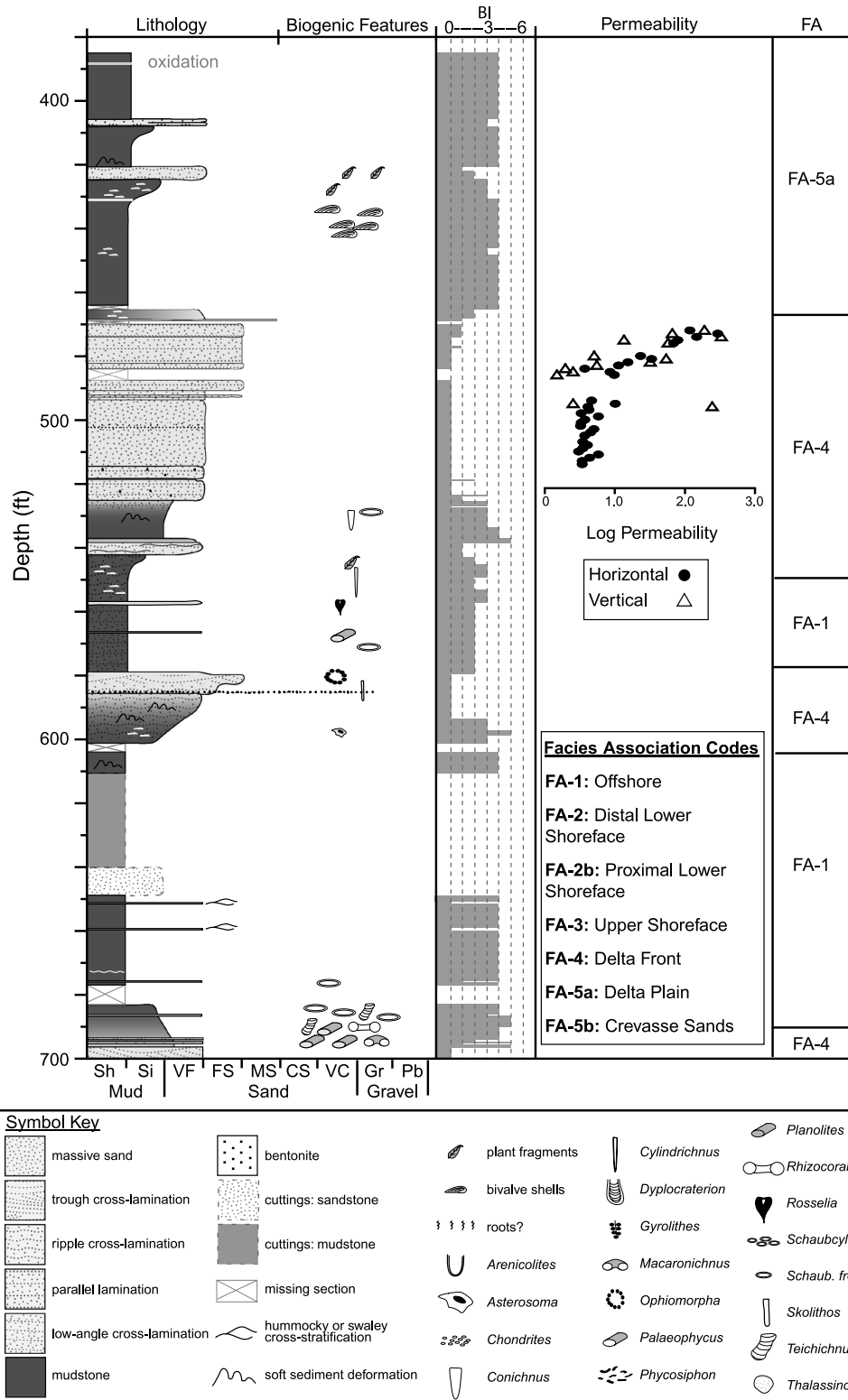


Figure 7. Four upward-coarsening successions (bound by dashed lines) consist of offshore (FA-1), distal lower shoreface (FA-2a), proximal lower shoreface (FA-2b), and upper shoreface (FA-3) deposits in Umiat 9. This multistory shoreface succession is typical of the lower Grandstand in the Umiat wells. Thin delta-plain (FA-5a) mudstones occur at the top of the two uppermost shoreface sandstones. Bioturbation intensity is highest in muddy or heterolithic deposits and decreases as sandstone beds become amalgamated from 1020 to 970 ft (311 to 296 m) and 920 to 870 ft (280 to 265 m). Permeability, in contrast, increases toward the top of shoreface successions (990–970 ft [302–296 m] and 930–870 ft [283–265 m]). A and B refer to reservoir units. Lighter shaded areas with dashed lines are interpretations based on original cuttings data (Collins, 1958). See Figure 8 for the complete symbol legend.

Figure 8. An upward-coarsening delta-front succession from 580 to 470 ft (177 to 143 m) in Umiat 9 consists of prodelta (FA-1), delta-front (FA-4), and delta-plain (FA-5) deposits. The single-story delta-front succession is typical of the upper Grandstand in the Umiat wells. Bioturbation intensity is low, even in prodelta or distal delta-front deposits (580–530 ft [177–162 m]). Permeability increases toward the top of the delta-front sands (490–470 ft [149–143 m]). Lighter shaded areas with dashed lines are interpretations based on original cuttings data (Collins, 1958).



in FA-1 may be the distal expression of storm-wave, surge, or river flood-derived turbidity flows that bring sand onto the inner shelf (Nelson, 1982; Myrow and Southard, 1996; Myrow et al., 2002;

Pattinson, 2005; Lamb et al., 2008). These features genetically link FA-1 with overlying shallow-marine and deltaic facies associations in progradational systems (Figures 7, 8).

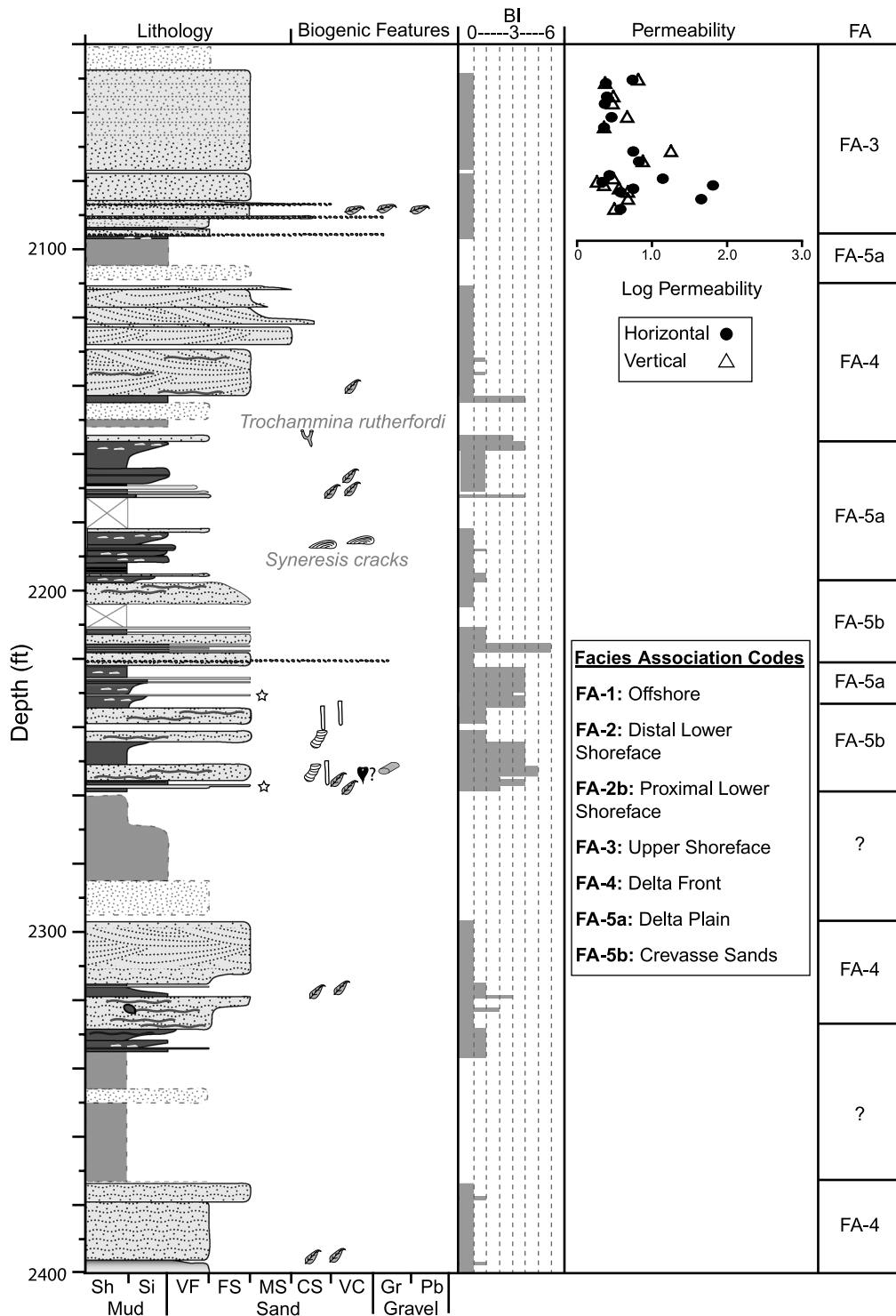


Figure 9. Umiat 11 is the only well with a complete succession of delta-plain deposits in core, including interdistributary bay (FA-5a) and crevasse-splay (FA-5b) facies associations. Thick sandstones at the top of the delta-plain succession (2095–2040 ft [639–622 m]) are transgressive in origin and show a reverse trend in permeability compared to lower sandstones (Figures 6, 7). Lighter shaded areas with dashed lines are interpretations based on original cuttings data (Collins, 1958). See Figure 8 for complete symbol legend.

Facies Association 2a

Description

Facies association 2a (FA-2a) is a heterolithic facies association composed of bioturbated mudstone (F-2) interbedded with thin beds (1–10 ft [0.3–

10 m]) of low-angle, cross-laminated very fine sandstone (F-5) or ripple cross-laminated very fine sandstone (F-6). Sandy beds typically coarsen upward and increase in number, thickness, and degree of amalgamation up core. Beds of mudstone may contain laminations or lenticular bedding disturbed

by bioturbation (BI 1–4). Mud drapes and thin (<1 ft; 0.3 m) beds of mudstone that occur between the sandy beds are heavily bioturbated (BI > 4). Some thin sandstone beds are heavily bioturbated (BI > 4), resulting in sand-rich mudstones associated with *Phycosiphon*, but most sandstone beds are not (BI < 3). The trace-fossil assemblage in sand-rich mudstones and sandstones also includes examples of *Schaubcylindrichnus freyi*, *Planolites*, and rarely, *Conichmus*, *Diplocraterion*, and *Ophiomorpha* (Figure 6).

Interpretation: Distal Lower Shoreface

Beds of very fine sandstone with low-angle cross-lamination (F-5) and ripple cross-lamination (F-6) interbedded with laminated or massive mudstone (F-2) beds are interpreted to represent hummocky cross-stratification formed by the oscillatory energy of storm waves in the distal lower shoreface (Dott and Bourgeois, 1982; Dumas and Arnott, 2006). The storm-wave–derived hummocky cross-strata in the distal lower shoreface represent discontinuities that punctuate periods of deposition dominated by suspension settling (sensu Hampson, 2000). These beds coarsen upward (Figure 7), suggesting a regressive character of the shoreface environment and a gradual transition to the proximal lower shoreface (FA-2b). Similar wave-derived facies successions have been described in shoreface settings from the Cretaceous Western Interior seaway (Pattinson, 1995; Hampson and Storms, 2003) and in modern and ancient asymmetric wave-dominated deltas, where wave energy concentrates sand on the updrift side of a river (Bhattacharya and Giosan, 2003; Li et al., 2011). The trace-fossil assemblage includes *Phycosiphon*, *Planolites*, and *Schaubcylindrichnus freyi*, components of the *Cruziana* ichnofacies found in both distal shoreface and wave-influenced deltaic environments (Buatois et al., 2008; Dafoe et al., 2010; Gingras et al., 2011).

Facies Association 2b

Description

Facies association 2b (FA-2b) consists of amalgamated beds of very fine to fine-grained sand-

stone. Sedimentary structures include low-angle (F-5), parallel (F-8), and ripple cross-laminated sandstones (F-6), which are occasionally lined with plant debris. Well-sorted, apparently massive sandstone (F-4) intervals increase in frequency upwell from more clearly laminated or bioturbated sandstones that have higher concentrations of organic matter. The trend of upward-coarsening, increasingly amalgamated sandstone beds continues upwell into FA-3. Isolated siderite rip-up clasts also increase in frequency upwell. Bioturbation is common, and trace fossils are more visible where organic matter is abundant. Traces include examples of *Palaeophycus*, *Ophiomorpha*, *Diplocraterion*, *Roselia*, and *Schaubcylindrichnus freyi* (Figure 6).

Interpretation: Proximal Lower Shoreface

The distinction between the distal lower shoreface (FA-2a) and proximal lower shoreface (FA-2b) is mostly based on the amalgamation of sandstone beds (Figure 7; sensu Van Wagoner et al., 1990; Hampson, 2000; Hampson and Storms, 2003). Outside of the Umiat 9 and 2 wells, core samples are sparse or of poor quality, and the boundary between distal and proximal lower shoreface is indistinct. Bioturbation intensity decreases in this facies association, but beds that seem well sorted and massive may contain extensive cryptobioturbation as in other storm- or wave-influenced environments (MacEachern et al., 2005).

Facies Association 3

Description

Trough cross-laminated (F-9), massive (F-4), and parallel-laminated fine-grained sandstones (F-8) are the most common facies in facies association 3 (FA-3). The vertical distribution of these facies is not systematic. Sets of amalgamated beds are 50 to 60 ft (15 to 18 m) thick. Bioturbation intensity and trace diversity are both low (Figure 7). Rare trace fossils include *Skolithos*.

Interpretation: Upper Shoreface

Amalgamated sandstones in FA-3 (Figure 7) are interpreted to reflect deposition at or above fair-weather-wave base where wave energy is constant

(sensu Hampson, 2000). Higher energy corresponds with an increase in grain size from very fine grained sandstone of the lower shoreface to fine-grained sandstone in the upper shoreface (Figure 7). In the upper shoreface, trough cross-lamination is interpreted as the result of subaqueous longshore dune migration (Flint, 1988; Hampson and Storms, 2003; Clifton, 2006). High-energy conditions in shoreface and foreshore settings prohibit bioturbation or inhibit preservation (Li et al., 2011) and are responsible for low bioturbation intensity and diversity.

Facies Association 4

Description

Facies association 4 (FA-4) consists of significant lenticular to wavy bedding (F-3) that transitions upwell to ripple cross-laminated (F-6a), parallel-laminated (F-8), and trough cross-laminated (F-9) sandstone. Sets of amalgamated beds are 60 to 70 ft (18 to 21 m) thick. Occasional beds of mud-draped ripple cross-laminated sandstones are also present (Figure 5). Gravel lag deposits (F-13) consisting of single pebble layers comprised of mudstone rip-up clasts are rare. Bioturbation intensity is low (BI 0–3) in sandstones and lenticular or wavy bedded mudstones (F-3), but soft-sediment deformation occurs in muddy facies and may obscure traces.

Interpretation: Delta Front

A delta front generally encompasses shoreline and seaward-dipping subaqueous topset and foreset beds of coarse sediment (Bhattacharya, 2006). Major depositional environments in a river-dominated delta front are derived from terminal distributary channels and include subaqueous levees, distributary mouth bars, and distributary channels themselves (Coleman and Gagliano, 1965). In the Umiat wells, parallel-laminated, ripple cross-laminated, and trough cross-laminated sandstones are attributed to distributary mouth bars or distributary channel bars that abruptly prograded out on top of distal delta-front mudstones, as indicated by soft-sediment deformation (Figure 8). Sparse bioturbation is also typical of delta-front deposits, where high water turbidity, high sedimentation rate, and salin-

ity fluctuations can inhibit burrowing organisms (MacEachern et al., 2005). The gravel lag deposits are interpreted as evidence for channelization. The lack of additional evidence for channels is not surprising, given the limited amount of core available, as well as the propensity for delta distributary channels to be actively filled by distributary mouth bars (Olariu and Bhattacharya, 2006). The rare occurrence of mud-draped ripples is interpreted as minimal evidence for tidal influence in the distributary system. Although commonly associated with fluctuations in energy in tidal systems (Bhattacharya, 2006), mud drapes are not always tidal in origin (Clifton, 2006).

Facies Association 5a

Description

Facies association 5a (FA-5a) includes dark-gray to black mudstones, typically carbonaceous, both laminated (F-1) and massive (F-2), with lenticular or wavy bedded mudstones (F-3) that have rare syneresis cracks. Other characteristic features are layers of oxidized siltstone or claystone, corbiculid bivalves, plant fossils, root traces, coal (F-11), and bentonites (F-12). Coal deposits are thin (<1 ft [0.3 m]). *Teichichnus* and *Skolithos* trace fossils are found in interbedded mudstone and sandstone intervals. *Teichichnus* is more common in FA-5a than in other facies associations. In the Umiat 1 and 11 wells, a mix of dinoflagellates and acritarchs, spores, and gymnosperm pollen was observed (May and Shane, 1985) in associated intervals.

Interpretation: Delta Plain

The mudstones of FA-5a are interpreted as marginal marine to nonmarine lagoon, interdistributary bay, and lake deposits on the basis of several factors. Corbiculid bivalve beds, abundant plant fragments, spores, gymnosperm pollen, and thin beds of coal distinguish FA-5 from marine mudstones of FA-1. Corbiculid bivalves are found in brackish or hypoxic water conditions (May and Shane, 1985; Holmes and Miller, 2006), and the palynological assemblage of dinoflagellates, acritarchs, spores, and gymnosperm pollen suggests brackish conditions as well (May and Shane, 1985). Syneresis cracks

also occur in settings with mixed salinity, such as brackish-water bays (Pratt, 1998). The trace-fossil assemblage also supports a brackish delta-plain interpretation. Although not exclusive to brackish conditions, *Teichichnus* is typically one of the dominant trace fossils in brackish interdistributary bays and is commonly found in association with syneresis cracks (Buatois et al., 2008). A similar set of facies occurs in brackish to nonmarine shallow-water deposits of the Dunvegan Formation in northwestern Alberta (Bhattacharya and Walker, 1991). These facies are typical of deltas comprised of numerous mud-dominated subenvironments, including swamps, marshes, tidal flats, lagoons, and interdistributary bays, which can be difficult to distinguish in ancient settings (Bhattacharya, 2006). Interdistributary bay or lagoon environments are also important downdrift components of asymmetric wave-dominated deltas (Bhattacharya and Giosan, 2003) and in wave-dominated shoreface successions (Flint, 1988). A delta-plain or coastal-plain interpretation is preferred based on the stratigraphic position of FA-5 above the upper shoreface (FA-3) or delta-front (FA-4) deposits (Figures 7, 8).

Facies Association 5b

Description

Wavy bedded mudstones (F-3) grade up into thin (5–10 ft [1.5–3 m]) flaser-bedded and asymmetrical ripple cross-laminated sandstone (F-6a) and mud-draped, ripple cross-laminated sandstone (F-7). Mud drapes are commonly sideritized, especially in Umiat 11. In isolated instances, a gravel lag of mudstone rip-up clasts, a thin sandstone, and a subsequent upward-fining succession interrupt upward-coarsening flaser bedding (F-7). Underlying interbedded mudstone intervals (FA-5a) com-

monly exhibit soft-sediment deformation (probably convolute bedding or ball-and-pillow structures, but core samples are too small to definitively determine the origin of soft-sediment deformation features). *Skolithos* and *Teichichnus* are common, and the palynological assemblage is the same as FA-5a. Plant fragments are preserved on lamination surfaces in ripple cross-laminated sandstones.

Interpretation: Crevasse Sands

Facies association 5b (FA-5b) represents sandstones and mudstone rip-up lag deposits found in association with mudstones and coals of FA-5a (Figure 9). These deposits are interpreted as overbank sandstones and mudstones or avulsion-derived influxes of sand into interdistributary bays and lagoons on the delta plain. Specific process interpretations vary based on grain-size trends observed in core or inferred from well logs and follow deltaic facies interpretations (Elliot, 1974; Bhattacharya and Walker, 1991). Where beds coarsen upward, a crevasse-splay or crevasse-delta interpretation is preferred. Rarer upward-fining successions with mudstone rip-up lags are interpreted as passively filled crevasse channels.

PERMEABILITY FACIES DISTRIBUTION

Permeability profiles for different facies associations illustrate the relationship between permeability and depositional processes in the Nanushuk Formation at Umiat (Figures 7–9). Although sandstone reservoir intervals reach as much as 120 ft (37 m) in total thickness, only a small percentage of each sandstone interval has air-permeability values greater than 10 md (log permeability > 1). Permeable zones are restricted to sandstones from

Table 3. Permeability Anisotropy

Well	Depth (ft)	Facies Association	Anisotropy (K_v/K_h)	Reservoir Unit*
Umiat 10	420–490	FA-4: delta front/ FA-3 shoreface	0.09	Ninuluk
Umiat 10	1066–1085	FA-4: delta front	0.05	upper Grandstand
Umiat 9	873–907	FA-3: upper shoreface	0.73	lower Grandstand B
Umiat 9	960–1003	FA-3: upper shoreface	0.59	lower Grandstand A

*See further discussion below and Figures 6–10.

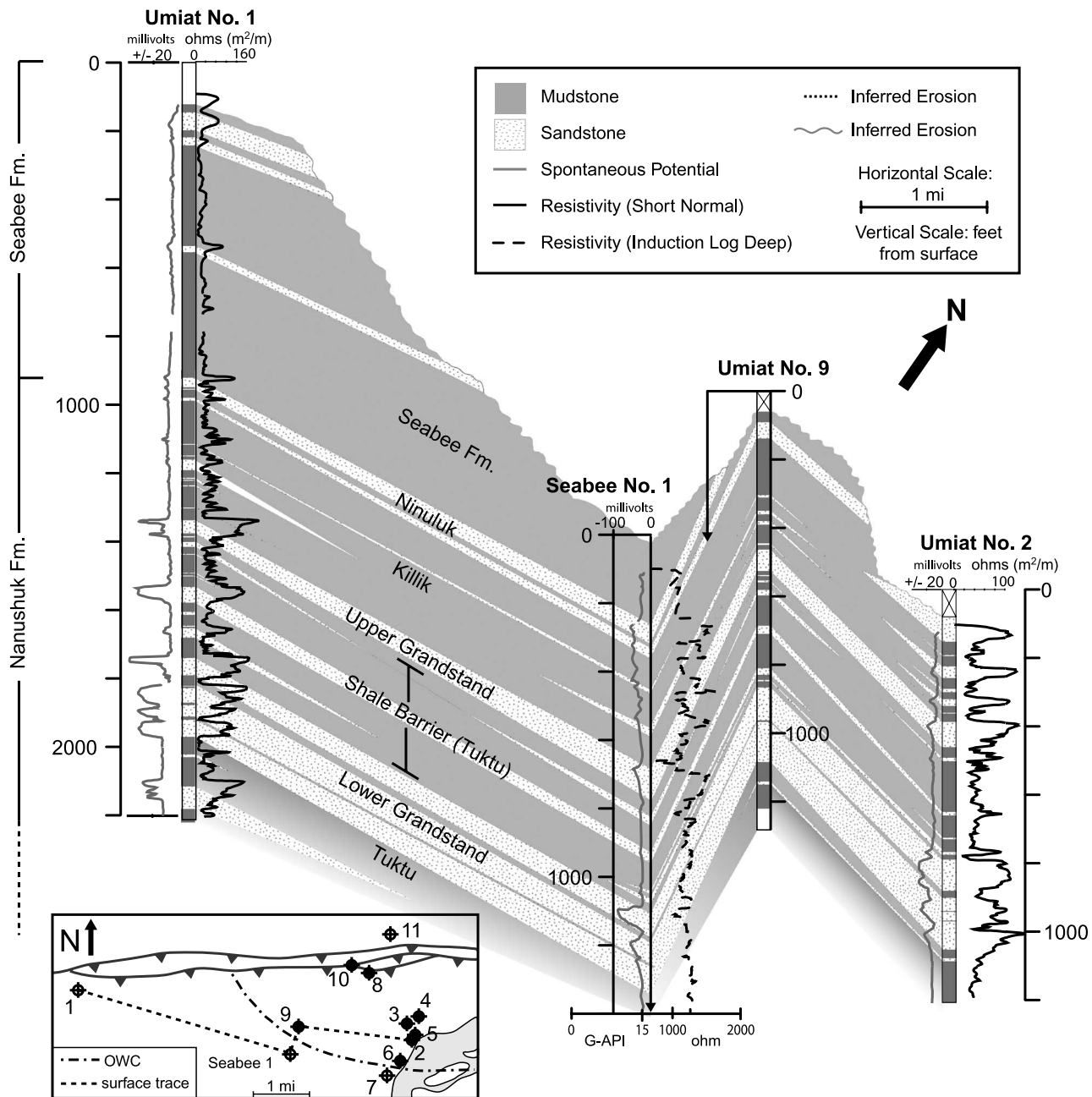
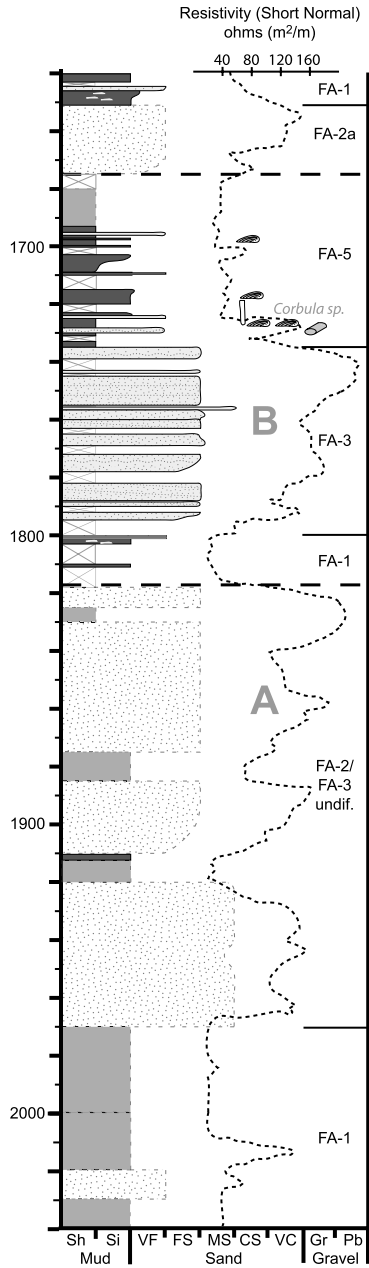


Figure 10. Fence diagram for Umiat field. Interpretations based on core description (this paper), cuttings (Collins, 1958), and well logs (Collins, 1958; Legg and Brockway, 1983). Umiat 9 is shifted slightly to the north in the diagram to distinguish it from the Seabee 1 well. The base of the Nanushuk Formation (Tuktu) is undetermined. The lower Grandstand (shoreface), upper Grandstand (delta front), and Ninuluk sandstone reservoir units are laterally extensive, although the Ninuluk is mostly eroded in the eastern part of Umiat field. It is difficult to correlate sandstones in the Killik and Shale Barrier (Tuktu) parts of the Nanushuk Formation, but some thin sands may represent the same surface. Inset map shows surface trace of fence diagram (dashed line). The oil-water contact (OWC) in the upper Grandstand passes between Umiat 9 and Seabee 1, as shown in the inset map (dash-dotted line).

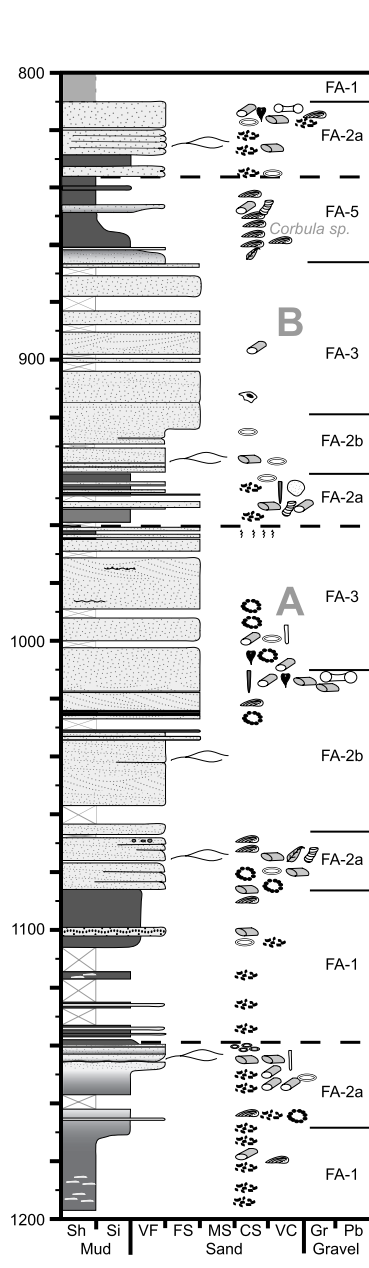
upper shoreface (FA-3) and delta-front (FA-4) facies associations (Figures 7, 8). Both K_h and K_v are associated with the coarsest and most well-sorted parts of upper shoreface and deltaic deposits. In most cases, these deposits coarsen upward (Figures 7, 8),

except near the top of the Nanushuk Formation (Figure 9).

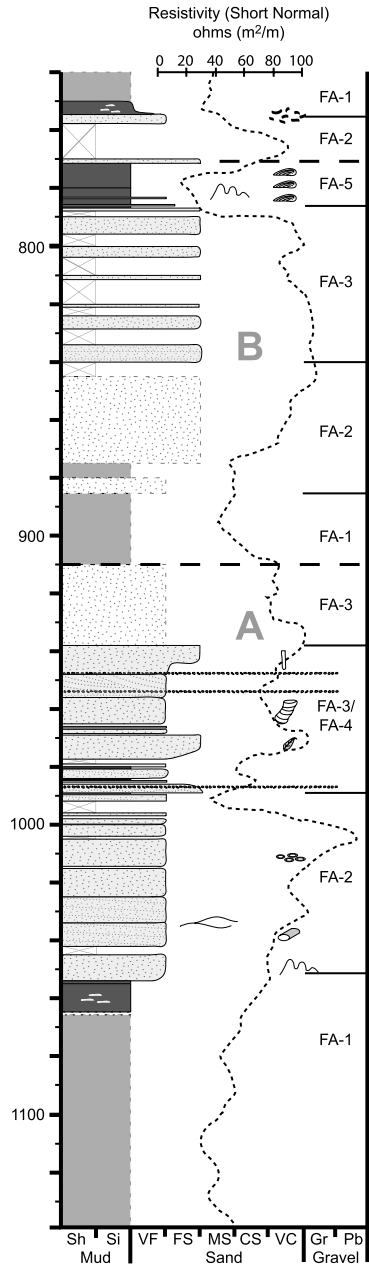
Permeability anisotropy varies depending on facies and facies association (Table 3). The lowest anisotropy (values near 1.0) occurs in upper shoreface



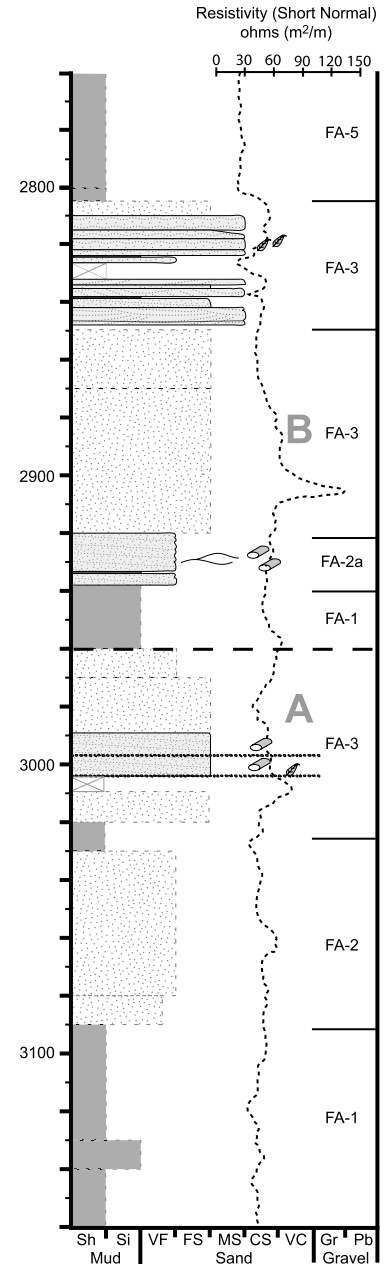
Umiat No. 1



Umiat No. 9



Umiat No. 2



Umiat No. 11

Figure 11 . Segments of measured sections from the Umiat 1, 9, 2, and 11 wells showing multistory shoreface deposits of the lower Grandstand. Wells are arranged in rough west-east order from left to right. A flooding surface separates reservoir units lower Grandstand A and B (thick dashed line). The top of the lower Grandstand includes delta-plain mudstones and is capped by a transgressive sandstone in each well except Umiat 11. Lighter shaded areas with dashed lines are interpretations based on original cuttings data (Collins, 1958). See Figure 8 for symbol legend.

deposits. This presumably occurs because of increased sorting and is associated with apparently massive sandstone (F-4) and a decrease in visible trace fossils ($BI < 2$) related to high energy, increased water turbidity, and substrate instability (MacEachern et al., 2005; Li et al., 2011). Anisotropy is higher in delta-front (FA-4) sandstones, which are comprised of ripple cross-laminated (F6), trough cross-laminated (F-9), and massive sandstone (F-4) and contain more frequent laminations defined by thin mudstone layers or carbonaceous debris. Bioturbation intensity is low ($BI < 2$), and mud deposition rates are high, in contrast to shoreface environments where wave energy transports suspended sediment offshore (MacEachern et al., 2005). Well-preserved mud drapes and carbonaceous laminations reduce vertical permeability and are the likely cause of higher anisotropy.

RESERVOIR-SCALE STRATIGRAPHIC ARCHITECTURE

The commonly used informal subsurface units of the Nanushuk Formation (Figure 3B) are effective for describing the stratigraphic architecture of shallow-marine and deltaic sandstones at Umiat field. Each of these informal units (Tuktu, lower Grandstand, shale barrier, upper Grandstand, Killik, Ninuluk) generally corresponds to a unique depositional environment that determines reservoir distribution and quality.

Tuktu

The Tuktu consists of marine mudstone (FA-1) that underlies and intertongues with shallow-marine (FA-2, FA-3) and deltaic (FA-4) sandstones of the lower Grandstand and upper Grandstand. Tongues of the Tuktu are present beneath the lower Grandstand, particularly in the west at Umiat 1 (Figures 10, 11). Elsewhere on the North Slope and below the depths studied in the Umiat wells, Tuktu mudstones at the base of the Nanushuk Formation transition downward into the Torok Formation, which consists of mudstones and turbidites deposited in marine slope and basin-floor

Table 4. Umiat Subsurface Unit Thicknesses by Well*

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	Mean/Median
Ninuluk**	35	–	–	–	–	15	20	95	50	10	60	41/35
	10					10	45			35	45	35/40
						30						
Killik	345	305	–	265 [†]	300	325	340	310	330	320	295	319/320
upper Grandstand	50	70	45	50	45	60	40	40	55	80	35	52/50
Shale Barrier (Tuktu)	290	330	280	305	325	–	290	335	310	–	325	310/310
lower Grandstand B	45	90	–	85	95	–	100	40 [†]	85	–	140	91/90
lower Grandstand A	150	155	–	–	160	–	–	–	120	–	130	143/150

*All thicknesses are in feet.

**In some wells, the Ninuluk consists of two or three sandstone units.

[†]Incomplete, not included in statistics.

settings (Mull et al., 2003). Another thick tongue of the Tuktu separates the lower Grandstand from the upper Grandstand (Figure 10). This tongue is known informally as the shale barrier at Umiat field and is best discussed with the upper Grandstand (see below).

Lower Grandstand

In previous studies, the lower Grandstand was considered a single reservoir interval (Watt et al., 2010). Core interpretation and permeability profiles show that the lower Grandstand actually consists of at least two upward-coarsening sandstone bodies separated by a regionally extensive flooding surface (Figures 7, 10). Resistivity and spontaneous-potential logs are funnel shaped or blocky in character (Figure 11). The flooding surface and associated impermeable mudstones and sandstones represent a major flow barrier within the lower Grandstand. The widespread distribution of the flooding surface allows us to divide the lower Grandstand into a basal reservoir interval (lower Grandstand A) and upper reservoir interval (lower Grandstand B; Figure 11). The median thickness of

lower Grandstand A is 150 ft (46 m) (Table 4). Positive kicks in spontaneous-potential logs and drops in resistivity indicate further compartmentalization of lower Grandstand A in Umiat 1, Umiat 2, and Seabee 1 (Figures 10, 11). Lower Grandstand B is typically much thinner (~90 ft [27 m] thick in the central reservoir). More between-well variation is observed in lower Grandstand B, which is very thin in Umiat 1 (50 ft [15 m]) and much thicker in Umiat 11 (140 ft [43 m]), but the well-log character is more uniform (Figure 10).

The top of lower Grandstand B occurs at an abrupt transition from a fine-grained upper shoreface sandstone (FA-3) to a carbonaceous mudstone (FA-5a) deposited in interdistributary bays or lagoons. In most wells, the carbonaceous mudstone layer is approximately 20 to 50 ft (6 to 15 m) thick and is part of a regressive succession associated with lower Grandstand B. In Umiat 1, mudstones of FA-5 are 70 ft (21 m) thick, suggesting increased back-barrier accommodation to the west. In most of the wells, a thin (10–20-ft [3–6-m]-thick) sandstone truncates the carbonaceous mudstone (Figure 11). The sandstone is interpreted as a transgressive lag deposit at the base of the shale barrier.

Table 5. Sandstone-to-Mudstone Ratios of Mud-Dominated Reservoir Units

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11
Killik	0.19	0.85	–	0.71	0.88	0.33	0.33	0.17	0.14	0.28	0.40
Shale Barrier	0.76	0.10	0.10	0.21	0.10	–	0.09	0.05	0.29	–	0.10

Shale Barrier (Tuktu) and Upper Grandstand

The shale barrier is 290 to 335 ft (88 to 102 m) thick with an average thickness of 310 ft (94 m) (Table 4). The interval consists of marine mudstone (FA-1) and distal shoreface sandstones (FA-2a). Sandstones are typically very fine grained, with sandstone-to-mudstone ratios from 0.05 to 0.76 (Table 5). The maximum sandstone-to-mudstone estimate comes from Umiat 1, where the shale barrier is approximately 43% sand. However, Umiat 1 is located approximately 5 mi (8 km) west of centrally located wells, which have a relatively consistent sandstone:mudstone ratio of 0.10 to 0.30. A thick sandstone body in the middle of the shale barrier in Umiat 1 illustrates the reduction in sandstone content from west to east. The sandstone thins from 50 ft (15 m) in Umiat 1 in the west to 20 ft (6 m) in Umiat 9, and it is nearly absent in Umiat 2 (Figure 10).

The upper Grandstand is a regionally extensive, river-dominated deltaic sandstone (FA-4) found in all of the Umiat wells. The interval ranges from 35 to 80 ft (11 to 24 m) thick, with an average thickness of 52 ft (16 m). Well logs are funnel shaped or serrated (Figure 12). The upper Grandstand lacks correlating internal flooding surfaces, but it does thin toward the northeast, where it becomes more heterolithic (Table 4). The top of the upper Grandstand is an abrupt, easily distinguished boundary between fine- or medium-grained sandstone of the upper Grandstand and carbonaceous mudstone of the overlying Killik (Figure 12).

Killik

The Killik is a marginal marine to nonmarine delta plain (FA-5) genetically related to the underlying upper Grandstand. It is difficult to correlate sandstone layers within the Killik between wells (Figure 9), and the sandstone:mudstone ratio varies considerably in each well (Table 5). It is also difficult to correlate thin coal layers, which are interpreted as localized accumulations of organic matter in swamps or marshes on the delta plain.

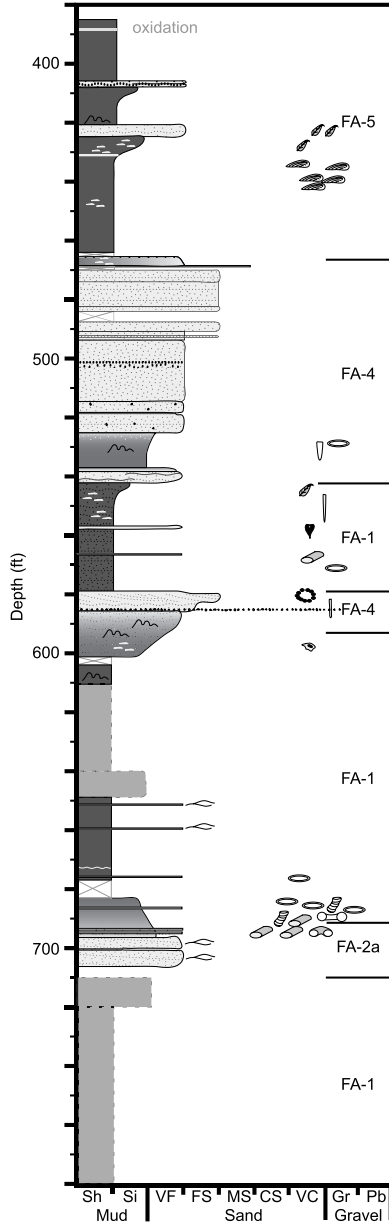
The sandstone layers within the Killik are crevasse-channel and crevasse-splay deposits on the delta plain (FA-5b). Crevasse-channel and -splay deposits are found elsewhere in the Nanushuk Formation (LePain et al., 2009) and are a typical component of the delta-plain environment (Elliot, 1974; Bhattacharya and Walker, 1991). The geometry and extent of the crevasse-splay sands, which can be tenuously correlated between Umiat wells in some instances (Figure 10), is similar to modern crevasse splays that cover as much as 7.5 to 9.5 mi² (12 to 15 km²) in deltaic environments (Coleman, 1988).

Ninuluk

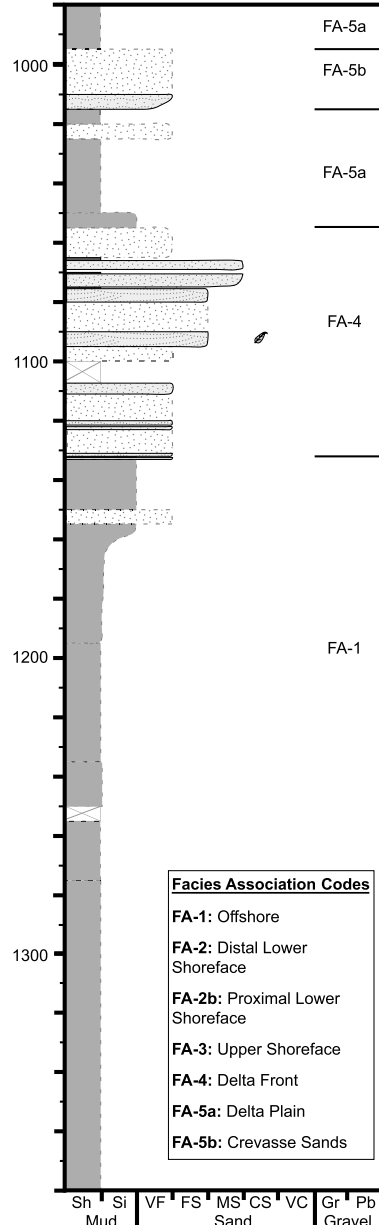
The Ninuluk is poorly represented in the Umiat wells because of erosion on the southern limb of the Umiat anticline. Facies variability within the Ninuluk is difficult to interpret because the primary data source for interpretation is the original cuttings descriptions (Collins, 1958). The best core data are from Umiat 11, in which two thick sandstone intervals are observed defined as Ninuluk A and Ninuluk B. Ninuluk A is the lower interval and is approximately 35 ft (11 m) thick (Table 4). A similarly thick sandstone interval can be found in wells 6, 7, and 10. The upper interval, Ninuluk B, averages 40 ft (12 m) thick (Table 4), although it is much thicker in wells 9 and 11. In Umiat 8, the Ninuluk is an apparently amalgamated sandstone nearly 100 ft (30 m) thick. Unfortunately, these sandstone intervals are missing in much of the field because of erosion.

NANUSHUK FORMATION DEPOSITIONAL SYSTEMS

In the Umiat area, the informal units of the Nanushuk Formation can be grouped together to describe two distinct deltaic systems: an upward-coarsening, progradational wave-dominated deltaic system comprised of the Tuktu and lower Grandstand and an upward-coarsening, progradational river-dominated deltaic system comprised of the



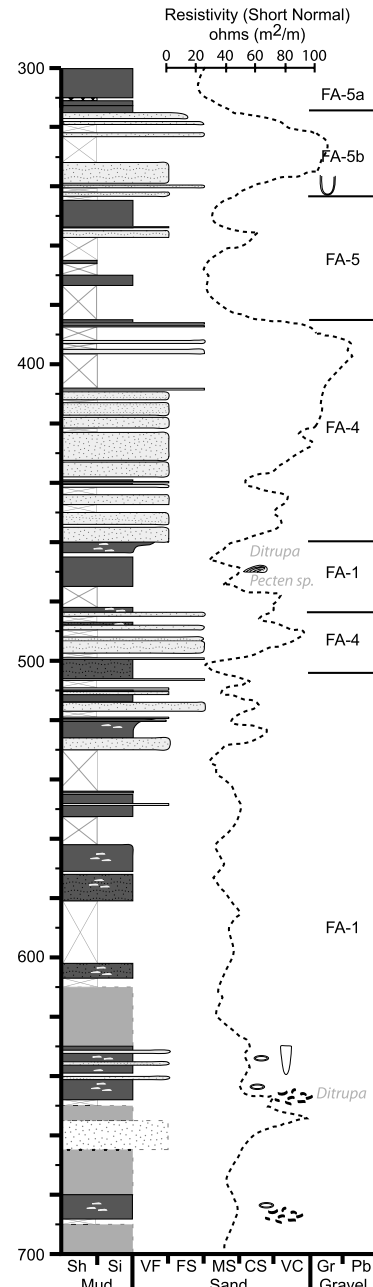
Umiat No. 9



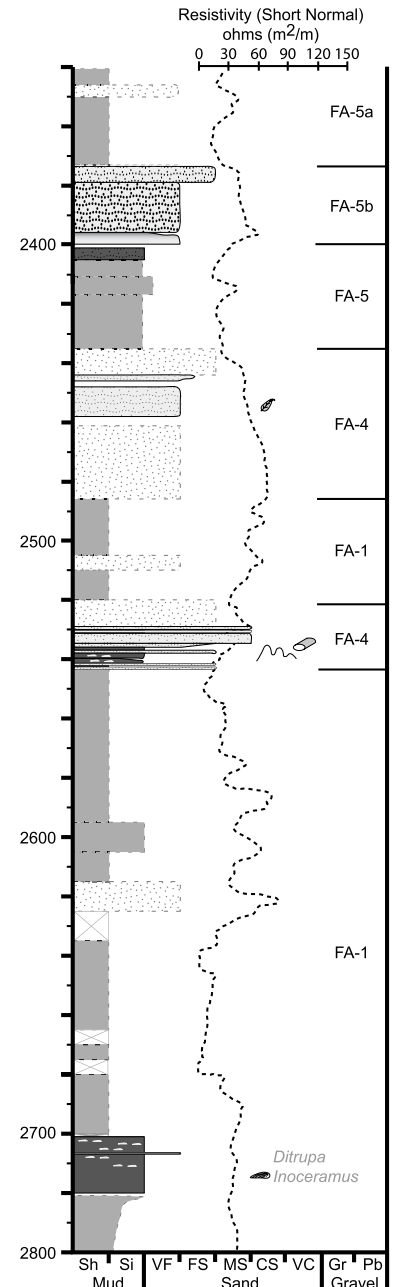
Facies Association Codes

- FA-1: Offshore
- FA-2: Distal Lower Shoreface
- FA-2b: Proximal Lower Shoreface
- FA-3: Upper Shoreface
- FA-4: Delta Front
- FA-5a: Delta Plain
- FA-5b: Crevasse Sands

Umiat No. 10



Umiat No. 2



Umiat No. 11

Figure 12. Segments of measured sections from the Umiat 9, 10, 2, and 11 wells showing approximately 60- to 70-ft (18- to 21 m)-thick upper Grandstand of the Nanushuk Formation wells arranged in rough west-east order from left to right. The upper Grandstand is interpreted as distributary mouth-bar deposits of a river-dominated delta. Lighter shaded areas with dashed lines are interpretations based on original cuttings data (Collins, 1958). See Figure 8 for symbol legend.

shale barrier, upper Grandstand, and Killik. These two major upward-coarsening regressive systems are capped by the Ninuluk, which is interpreted as a backstepping transgressive system.

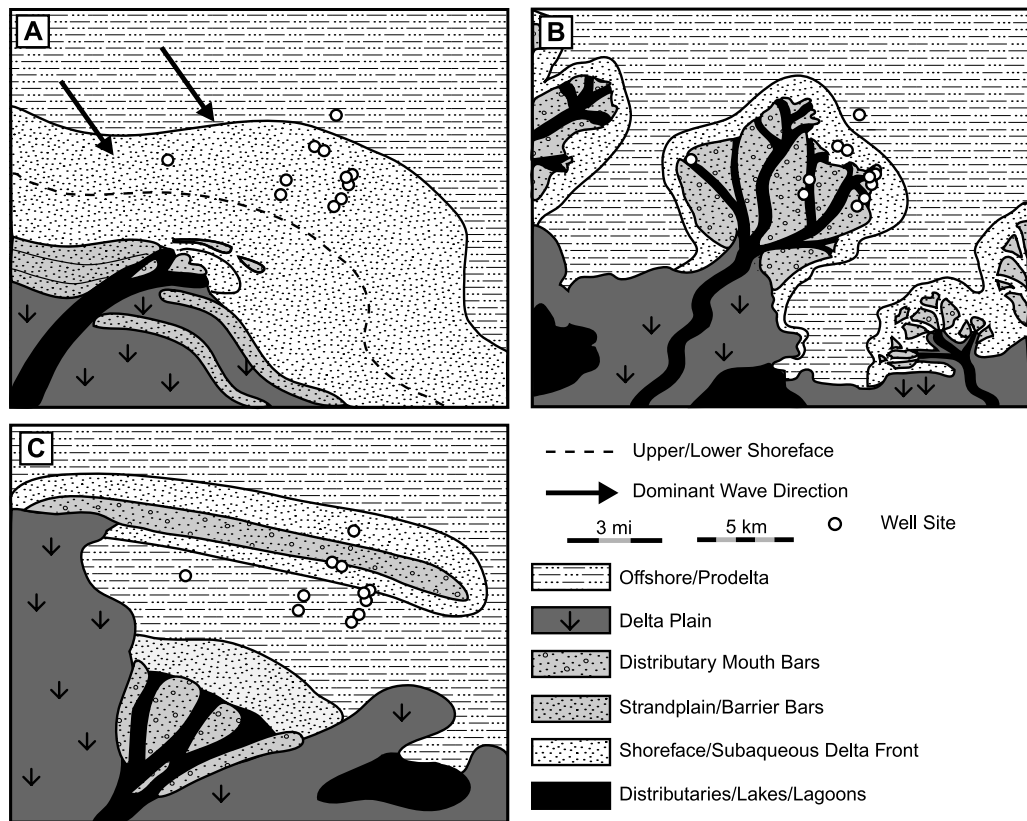
The Tuktu and Lower Grandstand: Wave-Dominated Deltaic System

The facies successions described in the Tuktu and lower Grandstand resemble the deposits of regressive wave-dominated shorefaces and wave-influenced deltas, where wave energy disperses sediment brought to the coast by distributary systems (Bhattacharya and Giosan, 2003; Hampson and Storms, 2003; Hampson and Howell, 2005; Figure 13A). The wave-dominated shoreface successions coarsen upward from offshore mudstones (FA-1) of the Tuktu into lower shoreface (FA-2) and upper shoreface (FA-3) sandstones of the lower Grandstand (Figure 11). The type examples for the shoreface succession are from Umiat 9 (860–940 ft [262–287 m], 965–1085 ft [294–331 m]; Figure 7), which closely resembles the characteristic profile of a wave-dominated shoreface (Van Wagoner et al., 1990; Bhattacharya and Walker, 1991; Hampson, 2000; Hampson and Storms, 2003). The trace-fossil assemblage of both *Cruziana* and *Skolithos* ichnofacies further supports a shoreface interpretation (Frey, 1990; Pemberton and MacEachern, 1995).

In the lower Grandstand A at both Umiat 2 (910–1050 ft [277–320 m]) and 11 (2960–3090 ft [902–942 m]; Figure 11), thin lags marked by rip-up clasts interrupt hummocky cross-strata. These features can be found in both shoreface and wave-influenced deltaic environments (Bhattacharya and Walker, 1991; Hampson and Howell, 2005). Although it is possible to distinguish nondeltaic shoreface deposits from wave-influenced deltas in core using physical and biogenic indicators of fluvial discharge (Dafoe et al., 2010), no characteristic features would permit this distinction in the Umiat wells.

The upper part of lower Grandstand A shows limited evidence for subaerial exposure beneath a minor flooding surface. Root traces exist at the top of lower Grandstand A in Umiat 9 (Figure 7).

Figure 13. Schematic cartoons illustrating interpretations for lower Grandstand (A), upper Grandstand and Killik tongue (B), and Killik and Ninuluk (C) depositional environments, with the locations of the Umiat wells for reference. The lower Grandstand consists of shoreface sandstones, interpreted as being deposited in a wave-influenced deltaic setting. The inferred wave direction is based on modern shoreline currents. The upper Grandstand and Killik were deposited in a river-dominated deltaic setting by delta-front (upper Grandstand) and delta-plain (Killik) processes. The Ninuluk includes both tidally influenced delta-front sandstones and overlying transgressive shoreface sandstones.



Immediately above this layer are mudstones of FA-1 with trace fossils of the *Cruziana* ichnofacies including *Phycosiphon*, *Palaeophycus*, and *Planolites* (Figure 6). The abrupt deepening of facies above lower Grandstand A marks the beginning of a second wave-dominated shoreface facies succession in all of the Umiat wells (Figure 11). This second succession, which is capped by brackish-water facies of the delta-plain or coastal-plain environments (FA-5a), makes up lower Grandstand B.

The top of lower Grandstand B lies beneath an approximately 20-ft (6-m)-thick sandstone in multiple wells (Figure 11). The base of this sandstone, which consists of distal lower shoreface deposits (FA-2a) with trace fossils of the *Cruziana* ichnofacies, is interpreted to be a transgressive surface of erosion. Transgressive surfaces of erosion cap progradational parasequences and displace changes in bioturbation intensity and character (Gani et al., 2008). The approximately 20-ft (6-m)-thick sandstone represents wave reworking of the shelf during a slow rise in relative sea level associated with a

backstepping shoreline trajectory. The overlying offshore mudstones (FA-1) are part of the shale barrier and represent a major flooding surface at the top of the lower Grandstand.

The Shale Barrier, Upper Grandstand, and Killik: River-Dominated Delta

The shale barrier consists of offshore marine mudstone (FA-1) with thin beds of distal lower shoreface sandstone (FA-2a). The abrupt deepening of facies from the lower Grandstand into the shale barrier is interpreted as a maximum flooding surface that represents a rise in relative sea level and an increase in accommodation. In this interpretation, the shale barrier, upper Grandstand, and Killik are genetically linked marine shelf or prodelta (FA-1), delta-front (FA-4), and delta-plain (FA-5) components of a prograding deltaic system (Figure 13B) that advanced out on top of the lower Grandstand. Unlike the lower Grandstand, the upper Grandstand sandstone is a single-story interval and has a

facies succession (Figure 12) consistent with a river-dominated delta interpretation (*sensu* Bhattacharya and Walker, 1991) with no evidence of wave influence. The overlying delta-plain mudstones of the Killik are more than 300 ft (91 m) thick, suggesting significant accommodation landward of the delta front. The dominance of brackish-water conditions throughout the Killik (May and Shane, 1985) favors a broad low-angle delta plain subject to influxes of marine water. Improved well control could be used to interpret minor transgressions within the Killik preceding the major transgression described below.

The Ninuluk: Backstepping Delta

The Ninuluk–Killik boundary is defined by a shift from mud-dominated delta-plain deposits with nonmarine microfossil assemblages to sandstones with marine microfossils similar to those found in the lower Grandstand and upper Grandstand (Collins, 1958). In Umiat 11, the Ninuluk consists of two thick sandstone intervals separated by a thin mudstone (Fig 9). The two intervals bear many similarities to a pair of sandstone intervals described in outcrop at Umiat Mountain (Houseknecht and Schenk, 2005), although the Ninuluk intervals in the Umiat wells are nearly twice as thick as those described in outcrop. In Umiat 11, the approximately 30-ft (9-m)-thick lower Ninuluk sandstone is interpreted as coalesced, tidally influenced tributary mouth-bar deposits (FA-4; Figure 13C). This interval is similar to the lower Ninuluk sandstone in outcrop that Houseknecht and Schenk (2005) interpreted as an estuary or flood-tidal inlet in a transgressive setting. The basis of their interpretation was the presence of possible herringbone cross-bedding. The decreasing frequency of spores and gymnosperm pollen and increasing frequency of dinoflagellates and acritarchs in the Ninuluk also support the transgressive interpretation (May and Shane, 1985). The lower Ninuluk in Umiat 11 has trough cross-stratification, with sideritized mud drapes, although no evidence exists for herringbone cross-bedding in the cores. It is also relatively coarse grained compared to the rest of the Nanushuk Formation. Consequently, the proximal dis-

tributary mouth-bar deposits in the lower Ninuluk sandstone at Umiat field are interpreted as part of a backstepping delta system (Figure 13C).

The upper Ninuluk sandstone interval in the Umiat 11 well is 50 ft (15 m) thick (Figure 9), with massive, trough cross-laminated, and parallel laminated sandstones (Figure 13C). A similar wave-influenced upper interval is exposed at Umiat Mountain (Houseknecht and Schenk, 2005). The facies succession in the upper Ninuluk sandstone is most similar to upper shoreface (FA-3) deposits but may also be deltaic in origin. Unlike the other Nanushuk Formation sandstones, the upper Ninuluk contains detrital and authigenic calcite (Collins, 1958; Fox et al., 1979), a possible sign of its transgressive shoreface origin. Calcareous cement can be associated with marine-flooding surfaces and transgressive events at the top of highstand systems tracts (Taylor et al., 1995; Ketzer et al., 2002). The upper Ninuluk is a transgressive upper shoreface sandstone with lag deposits at the base, capped by a flooding surface. The thickness of the Ninuluk supports a relatively slow relative sea level rise and a corresponding transgressive event, where significant accommodation developed in pace with sediment supply. This contrasts with thinner (<20 ft [6 m]) transgressive sandstones at the top of the lower Grandstand.

RESERVOIR POTENTIAL OF INFORMAL UNITS

The major reservoir intervals at Umiat are the lower Grandstand and upper Grandstand sandstones, with additional potential petroleum accumulations in the sandstones of the Killik and Ninuluk. Both the upper Grandstand and lower Grandstand are regionally extensive in the subsurface (Figure 10). The Ninuluk is also extensive but is eroded from the top of the Umiat anticline structure and is only found on the northern flank and in the footwall (Figure 2). In contrast, sandstones in the Killik are not laterally extensive and are difficult to correlate between wells. Consequently, the upper Grandstand and lower Grandstand are considered the primary reservoirs at Umiat.

Because of the regional extent of the upper Grandstand and lower Grandstand (Figure 10) and the similar thickness for the intervals within the predicted trap limits, it is likely that permeability trends are consistent across the site within each reservoir interval. The upward increase in permeability toward the top of reservoir intervals is apparent in both vertical and horizontal air-permeability results. These trends suggest that permeabilities greater than 10 md are limited to the upper 20 to 40 ft (6–12 m) of the upper Grandstand and lower Grandstand reservoir intervals (Figures 7, 8).

Permeability trends in both intervals of the lower Grandstand and in the upper Grandstand sandstone are consistent with increasing porosity related to improved sorting in increasingly high-energy deposits of regressive, upward-coarsening shoreface and deltaic sandstones (Figures 7, 8). Previous authors hypothesized that winnowing of ductile phyllitic grains by high-energy shoreface deposits was responsible for an increase in porosity at the top of Grandstand sandstones (Fox et al., 1979; Bartsch-Winkler, 1985; Huffman et al., 1985). This increase in permeability may also be related to a decrease in bioturbation intensity in upper shoreface settings (Figure 7) and the lack of bioturbation in deltaic settings (Figure 8). A similar relationship between energy and bioturbation intensity was observed in sandy deposits of the Cretaceous Ferron delta in southern Utah (Li et al., 2011). The trends in the upper Grandstand and lower Grandstand contrast directly with the Ninuluk, a transgressive interval with upward-decreasing permeability (Figure 9).

Most of the oil produced from the Nanushuk Formation at Umiat during the 1944 to 1953 drilling period came from the upper Grandstand (Molenaar, 1982), but recent studies have revised reservoir estimates for Umiat field because of an improved understanding of the lower Grandstand. Several of the wells crucial to original estimates did not reach the lower Grandstand, including the discovery well (Umiat 3; Figure 4). Ice formation and hole caving also prevented drillers from reaching the lower Grandstand in Umiat 6 (Collins, 1958), which is important because the interpreted oil–water contact in the upper Grandstand lies at 450 ft (137 m) below

sea level between Umiat 6 and Umiat 7 (Molenaar, 1982; Figure 2B). New estimates that include the reservoir potential of the lower Grandstand should increase the amount of producible oil from 70 - million bbl (Molenaar, 1982) to 12% to 15% of the more than 1.2 billion bbl original oil in place reported in recent assessments of the Umiat field (Levi-Johnson, 2010; Watt et al., 2010; Hanks et al., 2014). This is a range of 180 to 225 million bbl. Furthermore, the separation of the lower Grandstand into two intervals adds to the complexity of the reservoir, although both lower Grandstand A and B can be found in all the wells within the oil–water contact boundaries.

The Ninuluk is a low-priority reservoir target because of its absence by erosion over most of the field and postulated biodegraded oil in the areas where it is present. Contrary to the Grandstand sandstones, the upper Ninuluk has an upward-decreasing permeability profile (Figure 9), interpreted as an upward-deepening succession of less-winnowed shoreface sandstone. The presence of calcite cement is a likely inhibitor of porosity, further reducing the reservoir quality of the Ninuluk sandstones.

CONCLUSIONS

Umiat, first discovered in 1946, remains undeveloped because of engineering challenges present in a remotely located, shallow frozen light-oil field. Renewed interest in Umiat exists, however, because of higher oil prices, improvements in technology, and recent gas discoveries in the region. Although the 11 Umiat wells lack modern suites of geophysical well logs, the thousands of feet of core from the wells that are available for examination at the Alaska Geologic Materials Center make it possible to reinterpret Umiat field using modern facies analysis and stratigraphic concepts. New interpretations of the sedimentology, stratigraphy, and permeability characteristics of the Nanushuk Formation at Umiat field present a field characterized by laterally extensive shoreface and deltaic sandstones. Four primary potential reservoir intervals exist at Umiat: two in the vertically

compartmentalized, multistory shoreface sandstones of the lower Grandstand, one in a river-dominated deltaic reservoir in the upper Grandstand, and one in a limited transgressive deltaic and shoreface reservoir in the Ninuluk.

The results of this study have several implications for the development of Umiat field. Facies-controlled permeability characteristics allowed for improved reservoir simulations, and newly quantified reservoir-interval geometries were used to revise and increase estimates of original oil in place. Despite differences in depositional environments, the lower Grandstand and upper Grandstand reservoir intervals both have similar air-permeability profiles, and the laterally continuous nature of the intervals make them good targets for horizontal drilling techniques. As the field undergoes a new wave of exploration and further testing of production methods in the coming years, modern subsurface studies should shed further light on the nature of the Nanushuk Formation reservoirs at Umiat.

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