SHUBLIK FORMATION LITHOFACIES, ENVIRONMENTS, AND SEQUENCE STRATIGRAPHY, ARCTIC ALASKA, U.S.A.

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ABSTRACT

The Shublik Formation (Triassic, North Slope, Alaska) is an organic-, phosphate-, and glauconite-rich unit with abundant fossils of marine vertebrates and mollusks. Five lithofacies, generalized around significant chemical constituents or lack thereof, are identified in the Shublik Formation:

(1) nonglauconitic sandstone – thin- to medium-bedded, fine, quartzose, calcareous to noncalcareous sandstone or silty to muddy sandstone, fossiliferous in places;
(2) glauconitic – thin- to medium-bedded, fine, quartzose sandstone, muddy sandstone, or siltstone containing 10% to > 50% glauconite grains
(3) phosphatic – thin- to medium-bedded siltstone or sandstone or laminated, black silty limestone or limestone containing phosphate nodules; and
(4) organic-rich – laminated, black limestone, marl, and mudstone
(5) nonphosphatic, nonorganic-rich limestone – bioclastic wackestone, or argillaceous grainstone and packstone or graded grainstone and packstone.

Ichnofabrics provide evidence of fluctuating oxygen levels within the facies, especially the nonglauconitic sandstone and glauconitic facies. The organic-rich facies and, to a lesser extent, the phosphatic facies contain abundant, pristine, disarticulated shells of the clam *Halobia*. The lithofacies, ichnofabrics, and taphonomy are interpreted to be related to onshore-offshore gradients in biologic productivity and redox conditions. The Shublik Formation is interpreted as an upwelling-zone deposit formed on a shallow shelf.

The Shublik Formation in the Prudhoe Bay region is interpreted to comprise three sequences; these have been extended to outcrop but not to cores in the National Petroleum Reserve. Facies stacking patterns indicate that siliclastic facies are most common during lowstand and transgression, organic-rich facies are characteristic of transgression, and carbonate-rich facies are more prevalent during highstand. Phosphatic facies occur along transgressive and maximum flooding surfaces and are thus integral to subdividing sequences into systems tracts.

INTRODUCTION

Although the origin of marine organic-rich rock remains somewhat controversial (Parrish 1995; Calvert et al. 1996), some such units in the geologic record were almost certainly deposited under upwelling zones, that is, zones of high primary biologic productivity. Well-developed modern upwelling zones have a distinctive, concentric array of sediment types, consisting of 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 et al. 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 Triassic Shublik Formation of northern Alaska has a facies array that is typical of well-developed upwelling zones (Parrish 1987).

The Shublik Formation is lithologically heterogeneous (Parrish 1987; Parrish et al. 2001). The 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 et al. 1983; Magoon and Claypool 1983; Magoon and Bird 1988; Kupecz 1995). It also contains glauconitic rocks. The distribution of these organic-rich, phosphatic, and glauconitic rocks is consistent with that seen in well-developed modern upwelling zones (Bremner 1983; Glenn et al. 1994). Parrish (1987) and Parrish et al (2001), studying outcrops and cores in the Arctic National Wildlife Refuge (ANWR) and in the National Petroleum Reserve in Alaska (NPRA), concluded that the Shublik was deposited in such a setting (see also Dingus 1984; Kupecz 1995).

The purpose of this paper is to link information about the Shublik Formation in outcrops in and near the Arctic National Wildlife Refuge and cores from the National Petroleum Reserve in Alaska (NPRA) from Parrish et al. (2001) with an interpretation of the sequence stratigraphy based on cores and well logs from Prudhoe Bay by Hulm (1999). We provide measured sections and core descriptions from ANWR and NPRA, respectively (Parrish et al. 2001), including the Fire Creek section also measured by M.T. Whalen (unpublished), through which the two studies are connected. Variations in ichnofabrics and in the paleoecology of the bivalves that are abundant in this formation (Parrish et al.,2001), also are discussed. Parrish et al. (2001) also studied the organic and inorganic geochemistry of the Shublik; that information is not discussed here.

GEOLOGIC FRAMEWORK

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 Navy collected several cores of the Shublik Formation from NPRA. The formation is thin: 1-173 m (0-585 feet) thick in the subsurface (Bird 1982) and 36-161 m (121-546 feet) thick in outcrop sections measured for this study (Fig. 1). 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.

The Shublik Formation originally included cherty rocks of similar age in the north-central Brooks Range (e.g., Brosgé et al. 1960; Chapman et al. 1964). These rocks are now included in the Otuk Formation. The Otuk Formation is Lower Triassic to Middle Jurassic (Mull et al. 1982) and has been studied in detail by Bodnar (1984) and dated with radiolarians by Reed and Blome (1986) and Blome (1987). The three middle members, the informal chert and limestone members and the overlying formal Karen Creek Member, are correlative with the Shublik Formation (Blome 1986; Blome 1987). The chert member consists of rhythmically interbedded radiolarian chert, silicified mudstone, limestone, and shale (Bodnar 1984). The limestone member consists of rhythmically interbedded limestone, cherty limestone, and black or gray-green shale (Bodnar 1984). The Karen Creek Member consists of siltstone and is directly correlative with the Karen Creek Sandstone, which is the upper member of the Shublik Formation at Fire Creek (Detterman et al. 1975; Bodnar 1984).

In the subsurface at Prudhoe Bay, the Shublik Formation is underlain by the Eileen Sandstone (informally named uppermost member of the Ivishak Formation) and overlain by the Sag River Sandstone (Jones and Speers, 1976; Robison et al., 1996). In the northeastern Brooks Range, the Fire Creek Siltstone (Eileen equivalent) and the Karen Creek Sandstone (Sag River equivalent) underlie and overlie the Shublik, respectively (Detterman et al., 1975). The Fire Creek Siltstone is the upper member of the Ivishak Formation at Fire

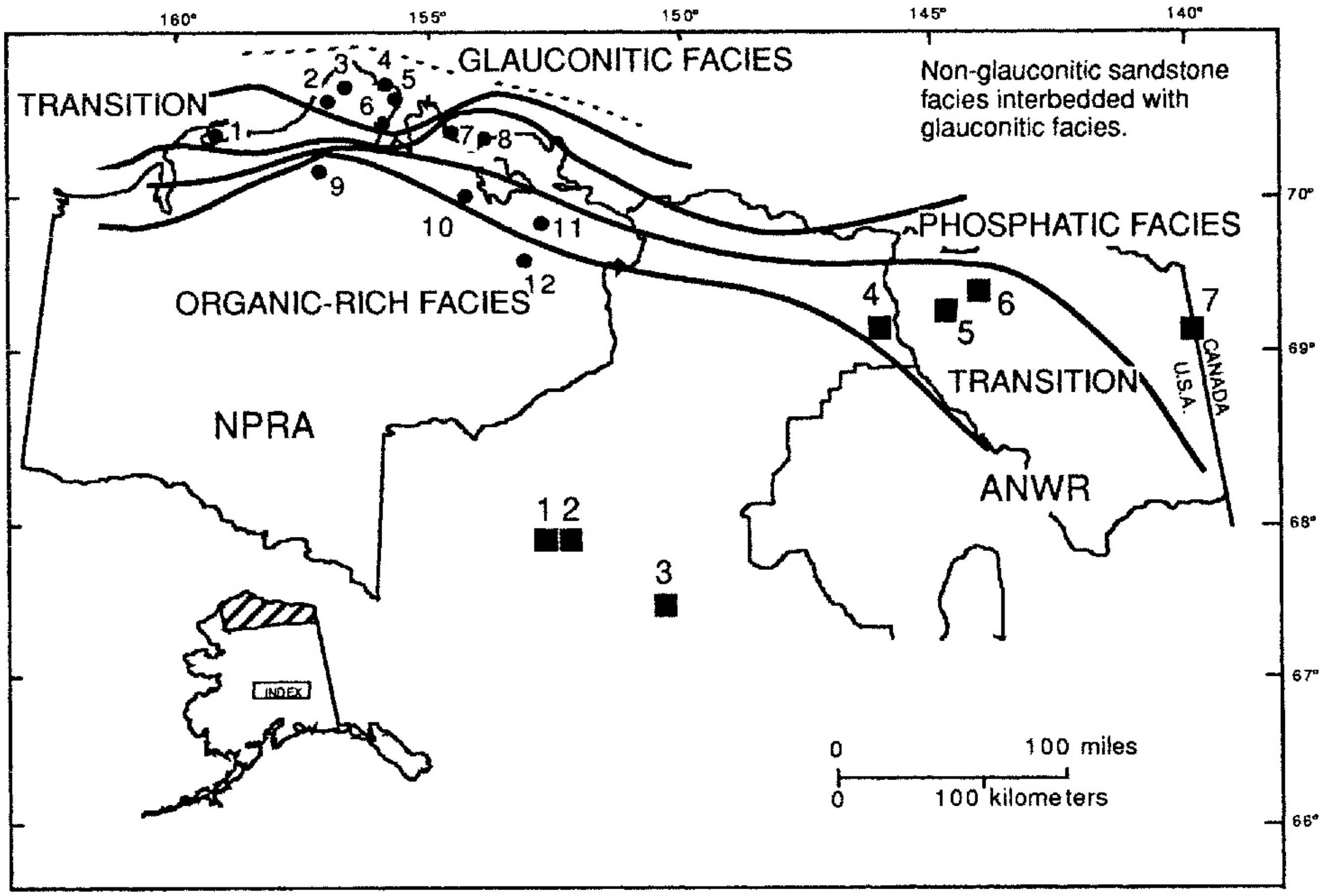


Figure 1. Index map of study area showing locations of cores and outcrops examined and lithofacies boundaries (heavy lines). Transitional zones are where adjacent facies are interbedded in core (see Figs. 2-4). Squares, outcrops: 1, Encampment Creek; 2, Tiglukpuk Creek; 3, Mt. Doonerak; 4, Kavik River; 5, Fire Creek; 6, Last Creek; 7, Loney Creek. Circles, wells: 1, Peard #1; 2, South Barrow #3; 3, Walakpa #1; 4, Tulageak #1; 5, West Dease #1; 6, Simpson #1; 7, East Simpson #1; 8, Drew Point #1; 9, South Meade #1; 10, Ikpikpuk #1; 11, North Inigok #1; 12, Inigok #1. Dashed line indicates the general trend of the axis of Barrow Arch (from Bird 1983). Modified from Parrish (1987).

Creek. The Eileen Sandstone and Fire Creek Siltstone were interpreted to be genetically related to the Shublik Formation, whereas the overlying Karen Creek and Sag River Sandstones appear to be part of a subsequent depositional sequence (Hulm, 1999; M.T. Whalen, unpublished data).

LITHOSTRATIGRAPHY, LITHOFACIES, AND LITHOFACIES ASSOCIATIONS

Shublik Formation in NPRA

Twelve cores of the Shublik Formation were examined by Parrish et al. (2001), and the core logs are presented in Figure 2. Coring was discontinuous in all wells. The tops and bottoms of the Shublik Formation in each well indicated on Figure 2 were determined from Bird (1982), unpublished sources, and the cores themselves. In addition to uncored intervals, the length of each cored interval commonly exceeded the length of the core available. For example, in South Barrow #3, the core boxes labeled 2732'-2752' contained only 7 feet (2.13 m) of core. No information was available that would locate this 7-foot core within the 20-foot core interval (including whether the missing core ever existed), so for the purposes of Figures 2 and 3, each core was arbitrarily placed at the top of the interval that it represents and the remainder labeled “missing”. The combination of uncored intervals and missing core

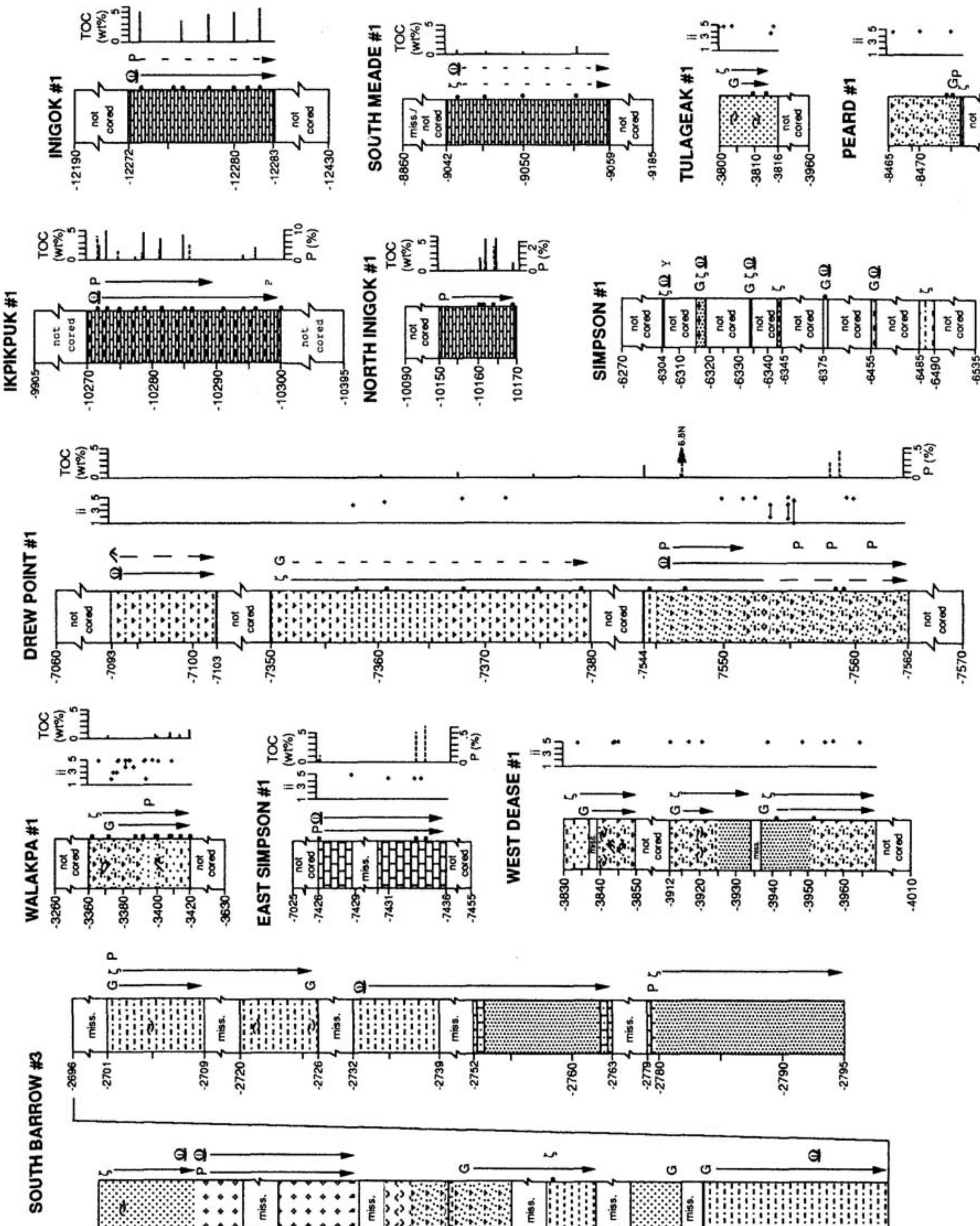


Figure 2. Graphical logs of cores of the Shublik Formation, National Petroleum Reserve in Alaska. The tops and bottoms are from well logs and were published by Bird (1982); cored intervals are from well reports. Intervals labeled "miss." represent gaps between the actual lengths of the cores and the depth ranges for those cores (see text). Units are feet; unlabeled depth marks represent 5 feet. Note that the scale is not the same for all the logs. Solid arrows: abundant and continuous; dashed arrows: scattered and discontinuous; dotted arrows: present but rare. For explanation of symbols and shading, see Figure 5.

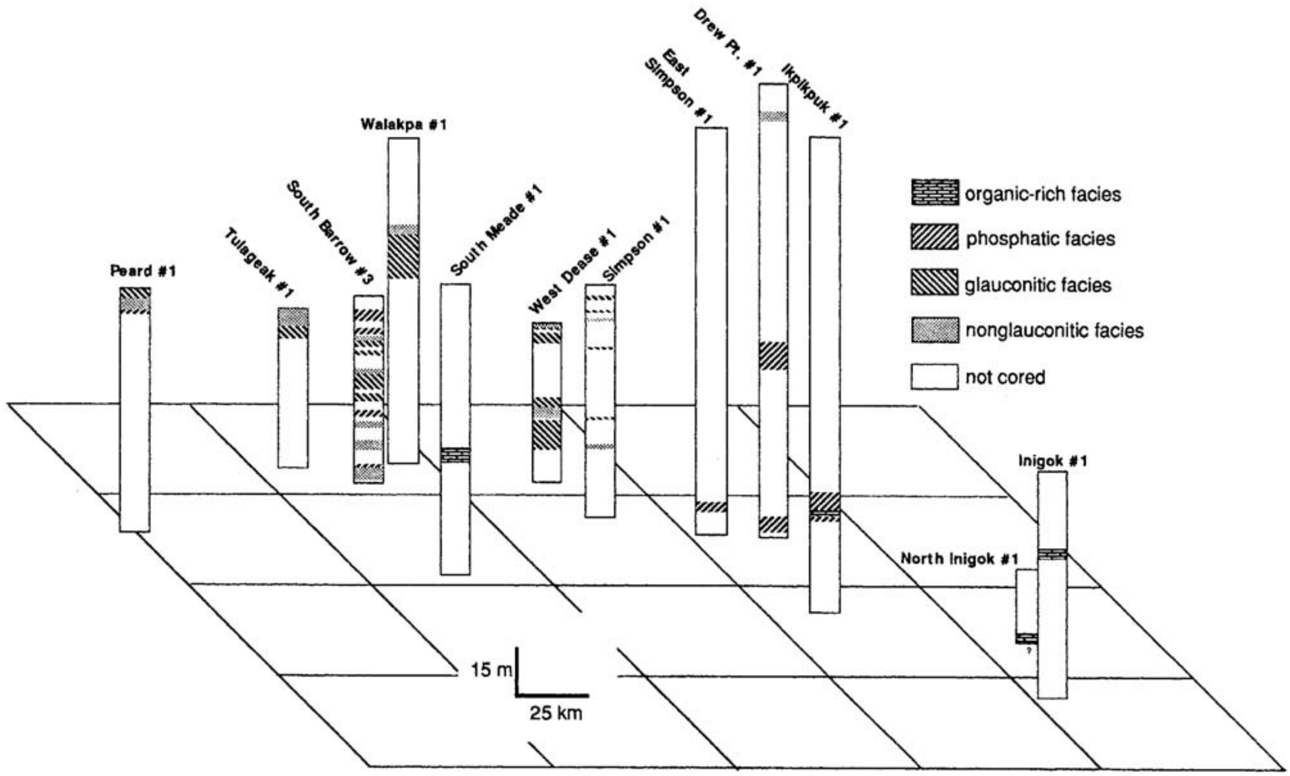


Figure 3. Three-dimensional diagram showing the relative positions of the sampled wells from NPRA. The height of each column represents the thickness of the Shublik Formation in each well as determined from well logs. Shading indicates the thicknesses and distribution of the cores in each well and the lithofacies represented by the cores.

resulted in an uneven and spotty record of the details of the subsurface stratigraphy.

The Shublik is dominated by siliciclastic deposits in the northern parts of the regions and by phosphatic or organic-rich limestone in the southern parts (Figs. 2, 3). The siliciclastics range from very fine sandstone to mudstone and are commonly bioturbated and glauconitic (South Barrow #3, Tulageak #1, Walakpa #1, Simpson #1, West Dease #1). Phosphate is present in some of the cores that are dominated by siliciclastics (Peard #1, South Barrow #1) and is a major component in some of the limestone cores (East Simpson #1, North Inigok #1, Ikpikpuk #1). The limestone is black and organic rich in the southernmost cores (South Meade #1, Ikpikpuk #1, North Inigok #1, and Inigok #1).

Figure 3 indicates the relative geographic positions of the wells, the thickness of the Shublik Formation in each well, and the vertical distribution and thicknesses of the cores in each well. The Shublik thickens to the south and east. This is also where the more phosphate- and organic-rich parts of the Shublik occur, but data are lacking for much of each section. Because the gaps are so large in the subsurface record, it is difficult to generalize beyond these observations. The most complete well is South Barrow #3. Importantly, Figure 3 shows that the lithofacies, described below, are interbedded but otherwise show no particular trend.

Shublik Formation in ANWR and Northwesternmost Canada

Sections of Shublik Formation were measured by J.T. Parrish (Parrish et al. 2001) along the Kavik River, at Last Creek and Fire Creek, Alaska, and at Loney Creek, Canada (Fig. 1). The sections are illustrated in Figure 4. The Fire Creek section also was measured by M.T. Whalen. All of these sections had been measured previously (Keller et al. 1961; Mountjoy 1966;

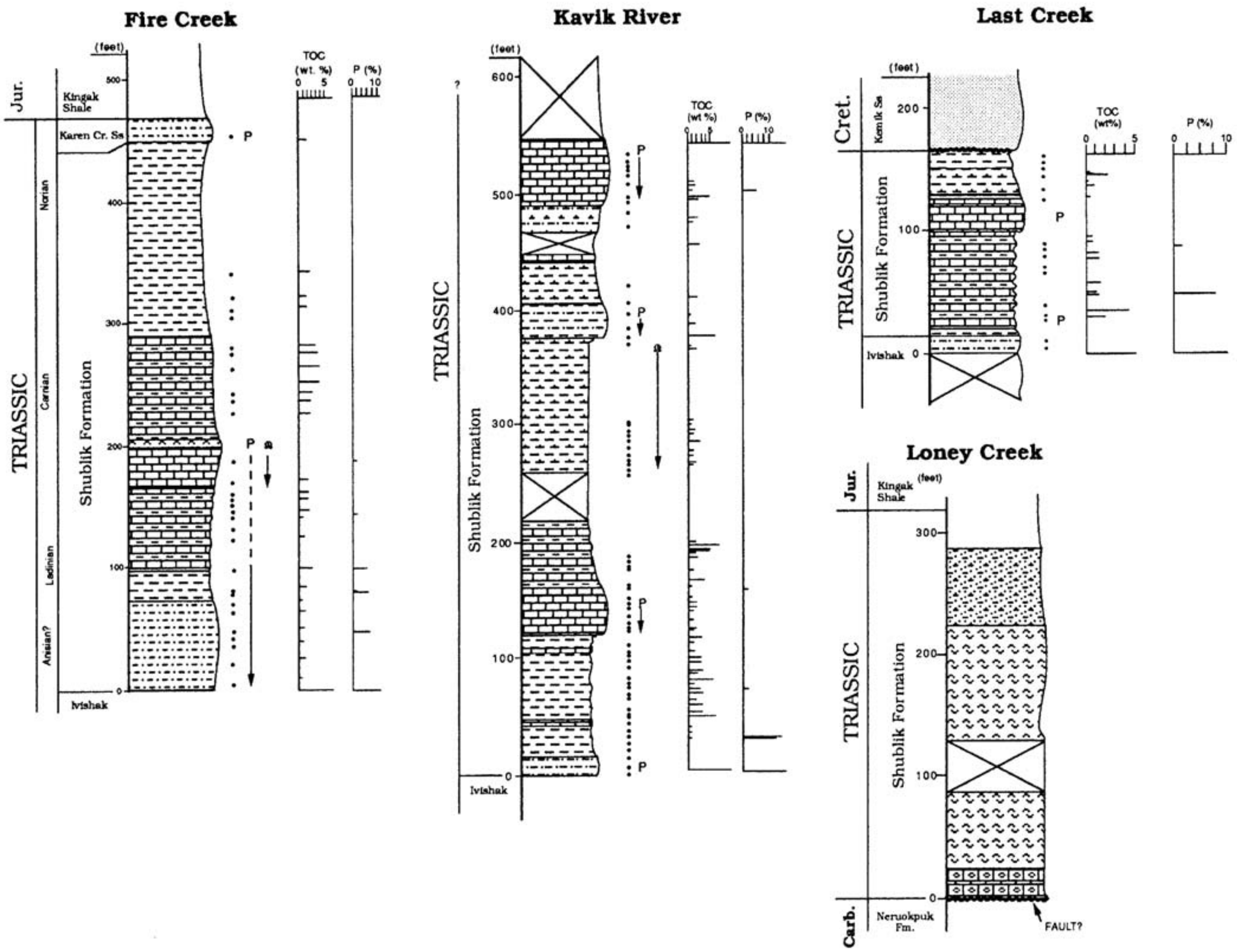


Figure 4. Measured sections of outcrops of the Shublik Formation, North Slope, Alaska (Kavik River, Last Creek, Fire Creek), and Northwest Territories, Canada (Loney Creek). The section at Loney Creek was measured by Mountjoy (1966), from which the figure was adapted. Units are feet; unlabeled depth marks represent 5 feet. Note that the scale is not the same for all the logs. Solid arrows: abundant and continuous; dashed arrows: scattered and discontinuous. For explanation of symbols and shading, see Figure 5.

Detterman 1970). Keller et al. (1961) considered the Kavik River section to be isoclinally folded as an explanation for the thickness of the Shublik Formation at this locality, which is greater than at any other place. However, careful examination of the section and thorough attempts to find overturned and repeated beds revealed no evidence for such folding, and all indications are that the beds are steeply dipping but upright and that the section is nearly complete.

Shublik Formation at Prudhoe Bay

Subsurface core from 10 wells and wireline logs from 97 wells were evaluated by Hulm (1999) in a sequence stratigraphic analysis of the Shublik and adjacent units. Five of the cored wells are in the Prudhoe Bay area and the other five occur along a roughly strike-parallel transect between Prudhoe Bay and Point Barrow, and thus overlap with the database of Parrish et

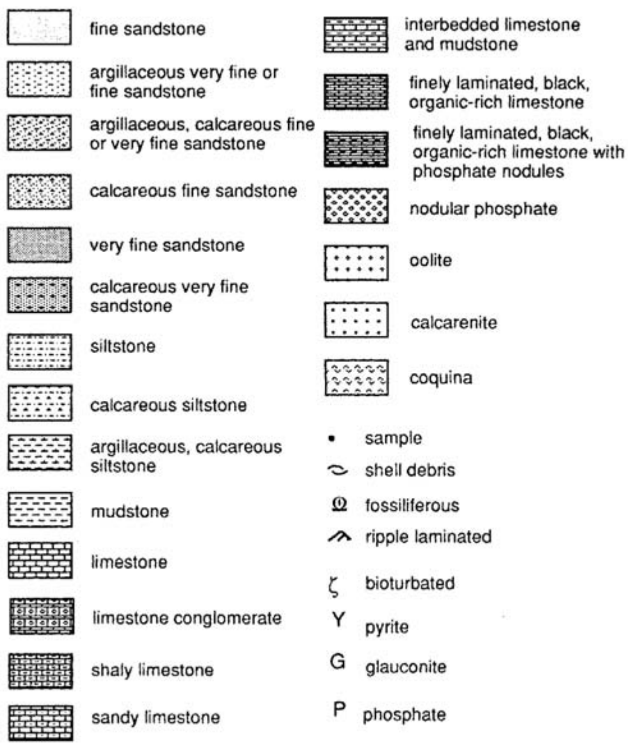


Figure 5. Explanation for Figures 2 and 4.

al. (2001). The majority of the wireline logs evaluated were also from the Prudhoe Bay area (Hulm, 1999). Overall, the unit thins depositionally from southwest to northeast.

Kupecz (1995) subdivided the Shublik Formation into 4 zones (D through A, bottom to top). Basal zone D is a massive, fine- to medium-grained phosphatic sandstone in the Prudhoe Bay area, outside of which it consists of calcareous shale, bioclastic limestone, siltstone, and sandstone with variable amounts of phosphatic components (Hulm, 1999). Zone C is composed predominantly of black shale and dark to light gray limestone with the latter dominating upwards. The shale is very organic rich and extremely fossiliferous, with abundant fossils of the bivalve *Halobia* (Dingus, 1984). Zone B is characterized by phosphorite and phosphatic carbonate and siliciclastic rocks. Zone A is lithologically similar to zone C. The base of zone A is comprised of black shale that grades upward into dark-gray limestone with abundant *Monotis* bivalve fossils (Dingus, 1984).

Lithofacies

Parrish et al. (2001) described four distinct lithofacies in the Shublik Formation: a nonglauconitic sandstone facies, a glauconitic facies, a phosphatic facies, and an organic-rich facies (Parrish 1987). They chose this approach, rather than the more conventional lithologic approach (e.g., trough crossbedded sandstone facies) because the chemical constituents, or their absence, are so distinctive in these rocks and key to understanding the chemical and biological environment of this shelf depositional system. The lithofacies are based on macroscopic descriptions of the rocks as observed in core and outcrop and on supplementary observations from thin sections.

Hulm (1999) took a more conventional and detailed approach to lithofacies description and subdivided the Eileen sandstone, Shublik Formation, and Sag River Formation into fifteen depositional facies (Table 1) that are interpreted to represent marginal marine and shelf depositional settings. These facies can be grouped into lithologically related facies assemblages similar to the four broadly defined lithofacies described by Parrish (1987) and Parrish et al. (2001), with the addition of a fifth group that includes nonphosphatic, nonorganic-rich limestone (Table 1). Parrish et al.'s (2001) lithofacies descriptions, which are mostly from NPRA cores, follow. Hulm's (1999) lithofacies are shown in Table 1.

Nonglauconitic Sandstone Facies – The nonglauconitic sandstone facies consists of thin- to medium-bedded, fine, quartzose, calcareous to noncalcareous sandstone or silty to muddy sandstone in most areas. With the exception of the outcrop at Loney Creek, Canada, this facies occurs only in the subsurface. The sandstone is very fossiliferous (mostly bivalves) in some horizons, and a few layers contain scattered granules or pebbles. Bioturbation is abundant to pervasive (ichnofabric indices 3 to 5, Droser and Bottjer 1989, see below). At Loney Creek, the facies consists entirely of quartzose, fine to medium sandstone and pebble conglomerate and contains abundant thick shells, some still articulated, of the bivalve *Monotis* (Mountjoy 1966). This is by far the coarsest occurrence of the Shublik.

In some horizons of the South Barrow #3 and Tulageak #1 cores, the sandstone is sideritic and/or hematitic. The South Barrow #3 core also contains noncalcareous pelletal hematite and blue-gray oolitic grains. Judging from the grain size and shape, the pelletal hematite probably is weathered glauconite. X-ray

Table 1. Facies descriptions and interpretations. Facies assemblages listed in the first column indicate the relationship between the generalized facies of Parrish et al. (2001; described in the text) and those of Hulm (1999). Facies numbers listed in the second column are referred to in the text. Facies descriptions in the third column include texture, mineralogy, grain size, sedimentary structures, and fossil content that were used to interpret the depositional setting (fourth column).

Facies Assemblage	No.	Facies	Description	Interpretation
	1	Conglomerate	Clast to matrix supported; subangular to well-rounded, quartz, chert, and lithic pebbles; med to coarse quartz sand and minor mud matrix; pyritic	Marginal Marine/ Shelf: Transgressive lag
Non-Glauconitic Sandstone	2	Cross-laminated sandstone	Tan; very fine- to fine-grained quartzose sandstone; ripple, parallel, tangential cross lamination into tabular and trough sets; lenticular and flaser bedding	Marginal Marine: Estuary
	3	Bioturbated sandstone	Very fine- to fine-grained quartzose sandstone with minor silt and clay; discontinuous and wavy clay laminae; bioturbated ; low diversity burrows; *Planolites*, *Diplocraterion*; pyritic	Marginal Marine: Estuary
Organic-Rich	4	Mudstone	Medium to dark gray-brown silty claystone and siltstone; wavy silt and sand laminae; rare bioturbation; pyritic	Marginal Marine: Estuary
	5	Parallel-laminated claystone	Dark gray/brown silty claystone; parallel, lensoidal, and pinstripe silt and sand laminae; rare graded and ripple cross laminated laminae; rare bivalves	Shelf: Restricted inner to open outer shelf
	6	Wavy-laminated, fossiliferous claystone and siltstone	Dark gray/brown silty claystone; calcareous and pyritic; wavy white fossiliferous laminae; bivalves very abundant	Shelf: Outer to inner shelf
Carbonate-Rich	7	Bioclastic wackestone	Dark to medium gray; quartz silt and lime mud, bivalve fragments common; parallel- to wavy-laminated; rare glauconite, phosphate nodules, and bioturbation	Shelf: Inner to mid shelf
	8	Bioclastic, argillaceous packstone and grainstone	Medium gray; composed of very fine- to fine-grained bioclastic microspar, and quartz sand and silt grains; massive; rare wavy laminae; bioturbated to burrowed; variable glauconite and phosphate	Shelf: Inner to mid shelf
	9	Graded grainstone and packstone	Light to medium gray; bioclastic grains predominate with minor phosphate and quartz grains; rare vertebrate fragments; grade upward into wackestone and claystone	Shelf: Transgressive lag
Glauconitic Sandstone	10	Bioturbated, calcareous sandstone	Light gray to tan; very fine-grained quartz sand with minor silt, clay, and bivalve fragments; extensively bioturbated; rare wavy laminae; rare glauconite and pyrite	Shelf: Lower shoreface to inner shelf
	11	Bioturbated, glauconitic sandstone and siltstone	Tan; very fine- to fine-grained quartz sand and silt grains; glauconite common; rare phosphate nodules, thick shelled bivalves, and wispy laminae; bioturbation and burrow common; *Cruziana* inchnofacies	Shelf: Lower shoreface to inner shelf
Phosphatic	12	Nodular phosphorite	> 30% in-situ, brown phosphate nodules; dark-gray matrix of clay, sandstone, wackestone, or packstone; displaced laminae is common; very pyritic; rare bioturbation and burrows	Shelf: Mid to outer shelf
	13	Pebbly phosphorite	Clast matrix supported; variable siliciclastic and carbonate matrix components; phosphate clasts are moderately to well sorted; randomly, oriented bivalve fragments are common	Shelf: Mid to outer shelf transgressive lag
	14	Phosphatic sandstone	Massive bedded, medium- to coarse-grained sandstone; composed of subangular quartz and phosphate grains; moderate to well sorting	Shelf: Inner shelf
	15	Oolite	Poorly sorted with variable amounts of ooids, mudstone; random oriented bivalve fragments; subtle upward fining; pyrite and siderite are common; rare bioturbation and burrows; locally phosphatic	Shelf: Offshore storm deposit

analysis of a red layer consisting of very large (1-2 mm) coated grains gave a composition similar to kao-linite (F.B. Van Houten, personal communication).

The nonglauconitic sandstone facies is interbedded with the glauconitic sandstone facies in South Barrow #3, Tulageak #1, Walakpa #1, Simpson #1, and West Dease #1.

Glauconitic Facies – The glauconitic facies consists of thin- to medium-bedded, fine, quartzose sandstone, muddy sandstone, or siltstone containing 10% to > 50% glauconite grains (glaucony of Odin and Létolle 1980; Dingus 1984 confirmed the mineralogy as glauconite) and scattered layers of bivalve shells. Bioturbation is sparse to abundant. Ripple lamination is present in rare instances in the sparsely bioturbated zones. In general, shell layers and abundant bioturbation occur together. The clay content is variable, ranging from zero to an estimated 15% to 25% of the rock.

This facies is observed only in core. In general, the glauconitic facies contains more clay and fewer shell layers than does the nonglauconitic sandstone but otherwise is similar except for the glauconite. The glauconitic facies is interbedded with nonglauconitic sandstone in several cores and is interbedded with phosphatic sandstone in Peard #1.

Phosphatic Facies – The phosphatic facies comprises thin- to medium-bedded siltstone or sandstone; laminated, black silty limestone; or limestone containing phosphate nodules ranging from one to several centimeters in size. Of these, siltstone and silty limestone form the most common matrix for the phosphate nodules in the subsurface. In contrast, much of the phosphate in outcrop consists of nodules in sandstone, although the dominant matrix is siltstone. The beds are generally massive, but in some instances, the rock consists of laminae disrupted by growth of phosphate nodules. Sedimentary structures are lacking and, in most beds, the nodules show no evidence of reworking. In some cores and in outcrop, the nodules are so dense as to constitute more than 75% of the rock. The nodules are spherical to highly irregular and usually brown, although some are black. Phosphate also occurs as pelletal, phosphatic sandstone that shows no evidence of current activity. A phosphate-cemented layer of sandstone and phosphate pebbles occurs at the base of the Shublik at Fire Creek. Parrish et al (2001) interpreted this layer as a hardground, although borings were not observed.

The phosphatic facies is interbedded with the organic-rich facies in Ikpikpuk #1 and in the Kavik River, Fire Creek, and Last Creek sections. Cores from East Simpson #1 and Inigok #1 are limited to the phosphatic facies. In South Barrow #1, Drew Point #1, and Peard #1, the phosphatic facies is interbedded with the glauconitic and nonglauconitic sandstone facies.

Organic-Rich Facies – The organic-rich facies comprises laminated, locally massive, black limestone, marl, and mudstone. The laminae consist of very thin (< 0.5 mm) shells of the bivalves *Halobia* and *Monotis* (Tourtelot and Tailleur 1971; Dingus 1984; N.J. Silber-ling, unpublished data) alternating with black mudstone (see also Littke et al. 1991). The bivalve shells con-stitute more than 75% of the rock in some sections. In outcrop, this facies contained impressions of shells on almost every parting surface (see also Hulm 1999).

The organic-rich facies occurs in Inigok #1, South Meade #1, and North Inigok #1 and in the Last Creek, Kavik River, and Fire Creek sections. In parts of the Last Creek and Kavik River sections and in the cores from Inigok #1 and Ikpikpuk #1, the horizontally laminated, fossiliferous beds are interbedded with wavy-laminated beds or thin, massive calcarenite or calcilutite beds on scales of a few millimeters to a few centimeters. The massive calcarenite and calcilutite beds commonly have sharp bases, sharp or gradational tops, and evidence of erosion at the basal contacts. These beds are tentatively interpreted as microturbidites. Alternating light and dark gray pyritic siltstone with rare trace fossils composes the middle part of the Drew Point #1 core. The bottom 2.35 m of the South Meade #1 core is gray shale containing alternating slightly bioturbated and laminated beds 8-33 cm thick.

Facies Associations

Hulm (1999) identified four facies associations, based on facies stacking patterns, that include embayment fill, progradational shelf, retrogradational phosphatic shelf, and retrogradational silciclastic shelf facies associations (Table 2). These facies associations define packages that are interpreted to have resulted from fluctuations in relative sea-level and form the basis for the sequence stratigraphic and systems tract analysis.

SEQUENCE STRATIGRAPHY

Hulm (1999) analyzed subsurface data, from North Slope exploration and production wells, to develop a sequence stratigraphic model for the Shublik Formation and adjacent units. Available geochemical data (Kupecz 1995; Robison et al. 1996), petrographic

Table 2. Facies associations and stacking patterns of the Eileen Sandstone, Shublik Formation, and Sag River Sandstone. The first column indicates the facies association and the systems tract(s) and sequence(s) in which it occurs. The second column lists the facies stacking patterns for each facies association with facies listed from top to bottom. Numbers in parentheses refer to facies numbers from Table 1. The third column indicates the stratigraphic interval for each facies association.

Facies Association, Systems Tract, Sequence	Facies Stacking (Facies #) Top Bottom	Stratigraphic Interval
Embayment Fill TST Sequence 1	parallel laminated claystone (5) coarse-grained packstone and grainstone (8) pebbly phosphorite (13) mudstone and parallel laminated claystone (4&5) cross-laminated and bioturbated sandstone (2&3) conglomerate (1)	Eileen Standstone & Shublik Zone D
Progradational Shelf HST Seqences 1 and 2	bioturbated, calcareous sandstone (10) packstone and grainstone (8) bioclastic wackestone (7) wavy-laminated fossiliferous claystone (6) organic-rich, parallel-laminated claystone (5)	Shublik Zone C Shublik Zone A
Progradational Shelf LST sequence 3	fine-grained, bioturbated, glauconitic sandstone (11)	Sag River Zone C
Retrogradational Phosphatic Shelf TST sequence 2	oolite (facies 15) nodular and/or pebbly phosphorite (12&13) parallel laminated claystone (5) wackestone and packstone (7&8) graded packstone and grainstone (9) or and pebbly phosphorite (13)	Shublik Zone B
Retrogradational Silciclastic Shelf TST sequence 3	Glauconitic firmground with *Glossifungites* ichnofacies bioturbated, glauconitic sandstone/siltstone (11) wavy-laminated claystone (6)	Sag River Zones B and A

descriptions (Dingus 1984), and paleontologic reports (Micropaleo Consultants Inc., unpublished data) were also incorporated to further evaluate the depositional setting and chronostratigraphically constrain the interval. Detailed description of conventional core from 10 wells (Fig. 6) focused on the identification of lithologic components, sedimentary structures, bedding characteristics, ichnofabrics and ultimately facies architecture. Wireline logs from 97 wells were used to correlate and define the geometries and stratal relationships of sequences and systems tracts. Bounding surfaces and facies described in core were calibrated with the well logs to identify their log signature.

Preliminary work on the Shublik Formation and adjacent units at Fire Creek (M.T. Whalen, unpublished data) appears to support Hulm's (1999) sequence stratigraphic analysis. The overall cyclicity documented in Hulm's (1999) subsurface study can readily be identified in outcrop, although more detailed study is necessary to test the specifics of the model. In the discussion below, subsurface stratigraphic terminology from Prudhoe Bay will be used, but the discussion also applies to equivalent units in outcrop at Fire Creek. The sequence stratigraphic analysis has not been extended to the cores from NPRA nor to the other sections in Figure 1.

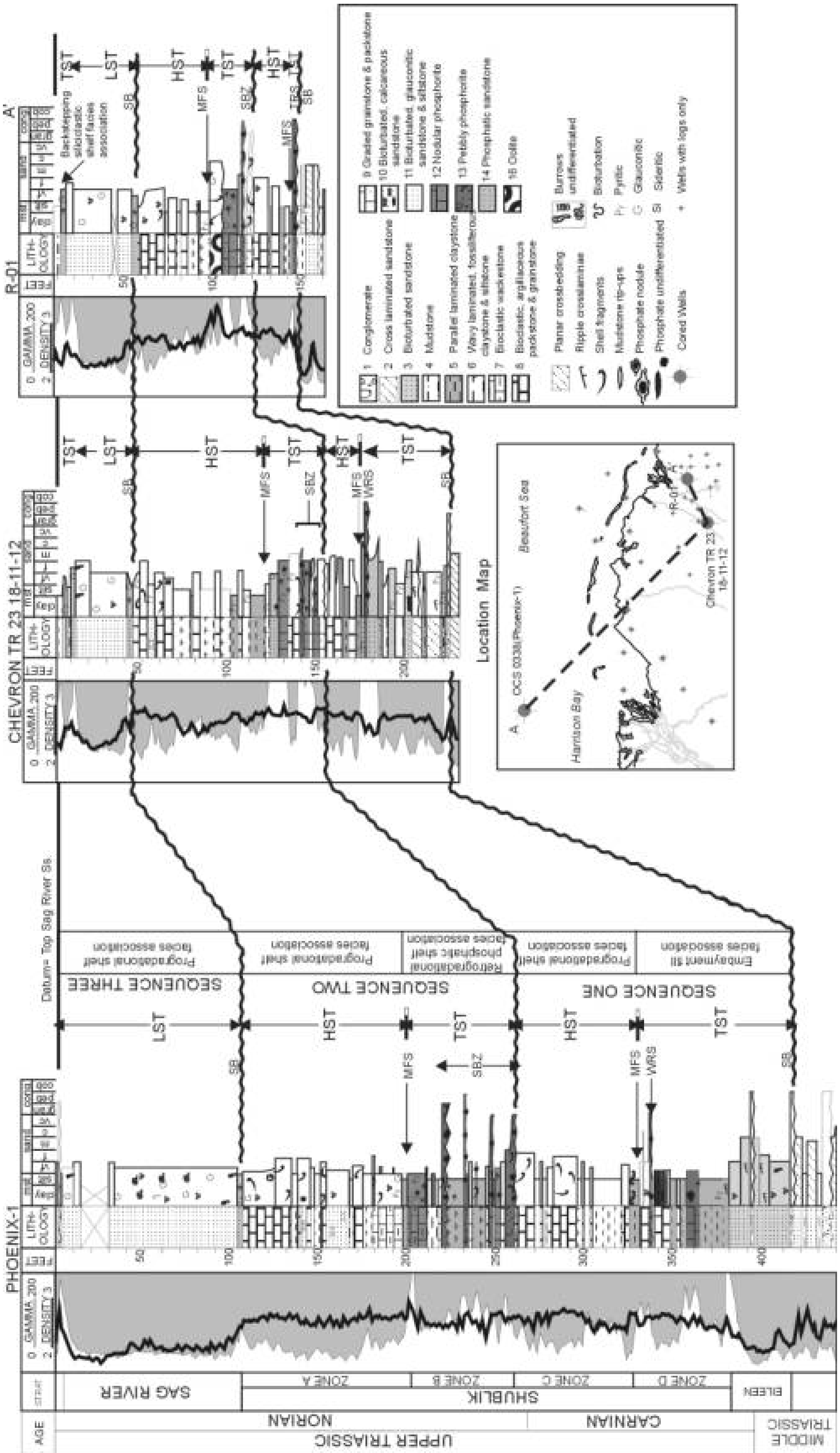


Figure 6. Sequence stratigraphic framework of the Eileen sandstone, Shublik Formation, and Sag River Sandstone on Alaska's North Slope, with a key to lithologic and stratigraphic symbols and an inset location map. The sequence stratigraphic interpretation is based predominantly on cored wells within the central North Slope. Black, wavy lines mark the sequence boundaries. LST, lowstand systems tract; TST, transgressive systems tract; HST, highstand systems tract; SB, sequence boundary; SBZ, sequence boundary zone; WRS, wave ravinement surface; MFS, maximum flooding surface; TRS, transgressive ravinement surface.

The Eileen through the Sag River interval has been subdivided into two complete sequences (Eileen through Shublik zone C and Shublik zones B and A) and a third partial sequence (Sag River Formation). Each sequence is interpreted to have been deposited during a third-order relative sea level cycle (duration 1-10 million years) based on available stage-level foraminiferal and palynological biostratigraphic data (Micropaleo Consultants Inc., unpublished). Cyclicity within the facies associations defined a number of marine-flooding surface bounded parasequences (Van Wagoner et al. 1988). The relationship between the bounding surfaces and the intervening facies associations, as well as the parasequence stacking patterns within the facies associations, has permitted the sequences to be subdivided into systems tracts (Brown and Fisher 1977).

Sequence One – Middle Triassic through Early Norian – Sequence one (Eileen sandstone and Shublik zones D and C; Figs. 6 and 7) is present throughout the study area except near Point Barrow, where it laps out depositionally against basement argillites. The majority of sequence one was deposited in a broad, low-lying embayment in the Harrison Bay area (Figs. 7 and 8) between the Barrow and Mikkelsen highs (Gryc 1988; Moore et al. 1994). The sequence boundary with the underlying Ivishak Formation is erosional and within the embayment underlies conglomerates (facies 1) at the base of the Eileen Sandstone. Outside the embayment, on the Mikkelsen high, the sequence boundary is below a similar basal Shublik Formation conglomerate. The embayment fill facies association (Eileen Sandstone and Shublik Zone D) defines the transgressive systems tract (TST) of sequence one (Table 2, Fig. 6). The facies composition of the lower half of the association consists of marginal marine siliciclastic facies dominated by cross-laminated and bioturbated sandstone facies (facies 2 and 3). The basal conglomerate facies are interpreted as a transgressive lag and indicate reworking of the underlying Ivishak and any lowstand deposits that might have been present prior to transgression. The marginal marine sandstones are overlain by thinning upward, retrogradational, restricted marine parasequences (facies 5, 8, and 12) that record progressive deepening (Fig. 6). Pebbly phosphorite (facies 13) and relatively coarse-grained packstone and grainstone (facies 8) abruptly overlying the restricted marine parasequences are interpreted to represent the development of a wave ravinement surface (WRS) as transgression continued (Fig. 6). Phosphorites are interpreted to indicate marine upwelling processes (Parrish 1982, Parrish et al. 2001). The facies association is interpreted to have been deposited in response to transgression based on upward fining in grain size and a shift from marginal marine to restricted marine facies. Outside the embayment, the thin conglomerate at the base of the Shublik Formation is the only vestige of TST deposition.

The stratigraphic relationships outlined above have many similarities with an incised-valley system. The embayment fill association is similar to an incised valley fill (Zaitlin et al. 1994) in that the conglomerate at the base of the unit represents erosional downcutting and basal Shublik conglomeratic facies onlap the edge of the embayment. The juxtaposition of distal over more proximal facies and the lack of identifiable truncated markers at the base of the package are key differences between the embayment fill association and an incised valley fill. The succession is interpretated to indicate a broad, relatively shallow, brackish-water embayment along the shoreline between Prudhoe Bay and Point Barrow based on thickness trends of the facies association (Figs. 7 and 8).

The highstand systems tract (HST) is represented by several coarsening upward parasequences of the progradational shelf facies association (Shublik Zone C; Table 2). Parasequences thin upward but internally carbonate facies (facies 7 and 8) thicken upward. Facies stacking and isopach patterns indicates progradation toward the south-southwest with a shoreline located towards the northeast (Figs. 6 and 7). The HST is erosionally truncated and overlain by transgressive facies of sequence two.

Sequence Two – Early to Mid-Norian? – Deposition of sequence two is represented by the retrogradational phosphatic shelf and progradational shelf facies associations (Shublik zones B and A; Fig. 6, Table 2). The sequence exhibits drastic lithologic and thickness heterogeneities (Figs. 6 and 7). In contrast to traditional sequence stratigraphic nomenclature, the basal sequence boundary is not a discrete, laterally-traceable surface but rather a 'sequence boundary zone' (Montanez and Osleger 1993; Elrick 1996). Such zones are interpreted to form on low-angle shelf or ramp environments on which fluctuations of relative sea level are more subtle and the boundaries between transgressive and regressive depositional patterns would be transitional and protracted (Elrick 1996).

The retrogradational phosphatic shelf facies association (Shublik upper zone C and zone B) characterizes the TST of sequence two (Fig. 6, Table 2). The lower boundary zone consists of a series of fining upward successions that begin with sharp-based, graded packstone and grainstone (facies 9) in proximal settings and pebbly phosphorite (facies 13) in more distal reaches. The fining upward successions mark the onset of transgression and the sharp bases are interpreted to represent a series of stacked transgressive surfaces (Fig. 6). The TST has a sheet-like geometry that thins toward the northeast and exhibits an overall fining-upward pattern associated with increasing phosphatic components (Fig. 6). Transgression marks the return to upwelling of nutrient-rich, anoxic basinal waters and precipitation of phosphorites. Overlying parallel-laminated claystone (facies 5; Shublik basal Zone A) imply the deepest water conditions and was deposited during maximum transgression. The TST depositionally onlaps against basement argillites on the Barrow high and phosphatic facies are replaced by glauconitic facies atop the submerged high (Figs. 7 and 8).

The progradational facies association (Shublik zone A; Table 2) represents the HST of sequence two (Table 2; Fig. 6). Coarsening and thinning upward parasequences generally become more carbonate-rich toward the top (Fig. 6). The HST becomes increasingly coarser and clastic-rich in proximal settings and thickens toward the southeast (Fig. 7). These patterns are interpreted to result from decreasing accommodation space associated with basinward shoreline progradation. The HST is sharply overlain by facies of the Sag River Formation and the contact is interpreted as a sequence boundary.

Sequence Three – Late Norian to Lower Jurassic – Facies of the Sag River Formation are interpreted as a lowstand systems tract (LST) and the lower portion of a TST (Figs. 6 and 8) to form part of sequence 3. To the south and west the underlying sequence boundary consists of a glauconitic, phosphatic hardground surface representing a depositional hiatus. Toward the northeast, the surface is an erosional unconformity containing reworked shell material and phosphate nodules derived from the underlying Shublik Formation. In both settings, the boundary juxtaposes shallower water Sag River sandstone facies over Shublik carbonate facies.

The LST of sequence three consists of the progradational facies association (Sag River Zone C). It is a laterally persistent wedge of non-cyclic, fine-grained, bioturbated, glauconitic lower shoreface and shelf sand that coarsens upward. The LST is interpreted to have been deposited in response to a forced regression (Posamentier et al. 1992) based on the wedge shaped geometry and abrupt juxtaposition of relatively proximal facies over distal carbonate facies (Figs. 6 and 7). Overlying the LST is the retrogradational siliciclastic shelf facies association (Sag River Zones A and B; Table 2) that characterizes the lower portion of a TST (Fig. 6). Like the retrogradational phosphatic shelf facies association, this facies association was deposited in response to transgression, but differs dramatically in terms of its facies architecture. In proximal settings towards the northeast, this association consists of two coarsening-upward parasequences dominated by bioturbated, glauconitic sandstone and siltstone (facies 11). Each cycle is bounded by thin, glauconite-rich surfaces that overlie *Glossifungites* ichnofacies assemblages. These surfaces are interpreted to have formed in response to sediment starvation during an episode of marine flooding (Pemberton et al. 1992). Biostratigraphic data in the vicinity of Prudhoe Bay identify the lower parasequence as late Norian and the upper parasequence as Jurassic (Pliensbachian), suggesting there is a pronounced depositional hiatus between the two. Maximum flooding is likely recorded in the overlying Kingak Formation but was not observed during this study.

The Barrow and Mikkelsen highs continued to influence depositional patterns with the greatest thicknesses of sequence three being along the flanks of the highs (Figs. 7 and 8). The sequence thins both on top of the highs and distally into the basin (Fig. 7). Though the highs were positive features during deposition of sequence three, they are interpreted as submergent based on the lack of coarse-grained facies and the presence of bioturbated, fine-grained, glauconitic facies that are characteristic of low sedimentation rates (Loutit et al. 1988). Limited core and well coverage hinder the identification of the sequence three TST in NPRA.

Ichnofabrics

A variety of typical Mesozoic shelf ichnofabrics occur within the cores of the Shublik Formation (Parrish et al. 2001). In general, bioturbation is most intense in the nonglauconitic sandstone and glauconitic facies, less intense in the phosphatic facies, and very rare in the organic-rich facies. Parrish et al. (2001) described four ichnofabric types: *Phycosiphon* ichnofabric, *Palaeophycus* ichnofabric, *Teichichnus* ichnofabric, and the Phosphate – *Palaeophycus* ichnofabric. The most common ichnofabric type is the *Phycosiphon* ichnofabric and is typical of upper offshore to lower shoreface siliciclastic environments of post-Paleozoic age (Goldring et al. 1991) and consistently has an ichnofabric index of ii5. This ichnofabric is characteristic of the nonglau-

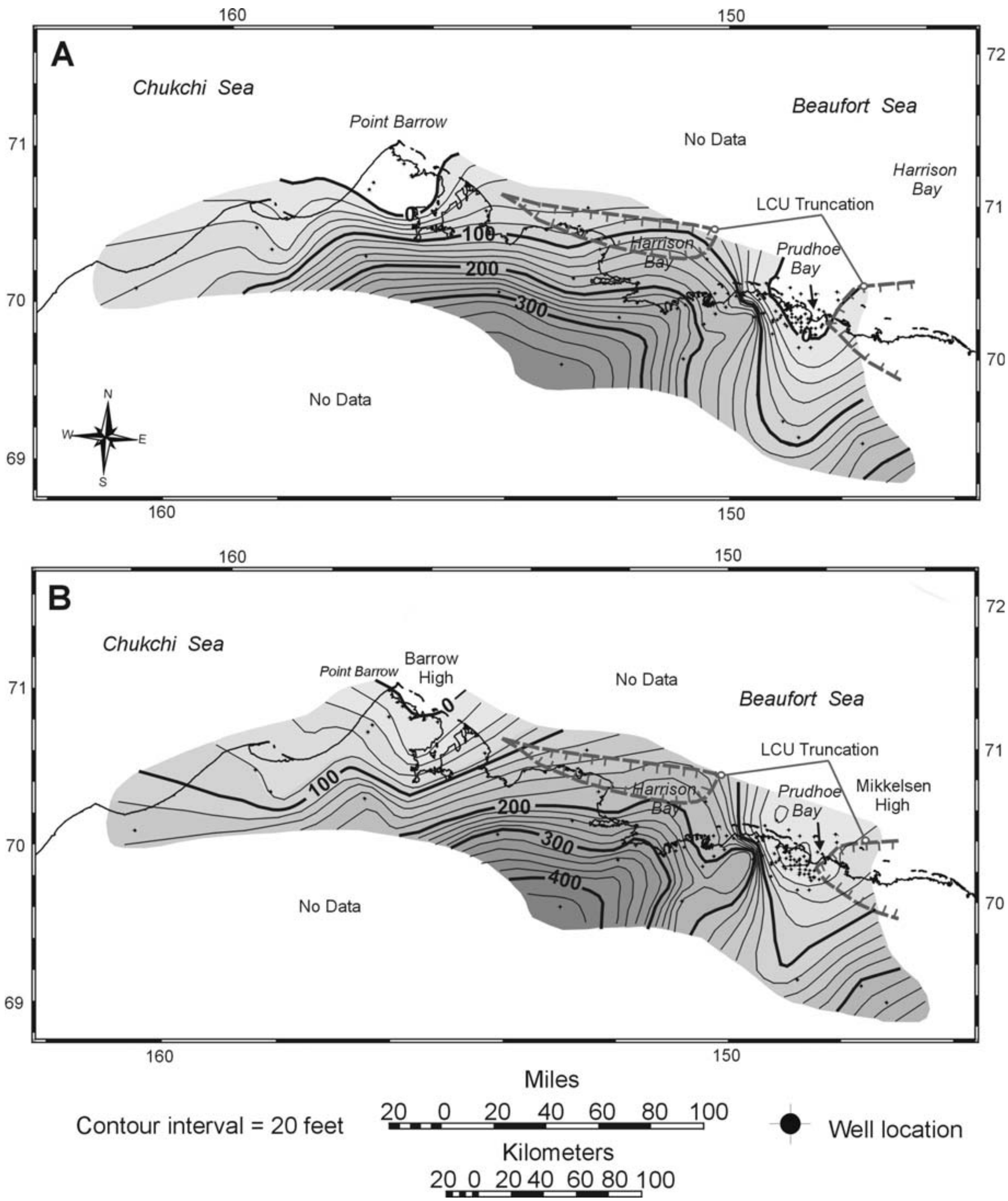
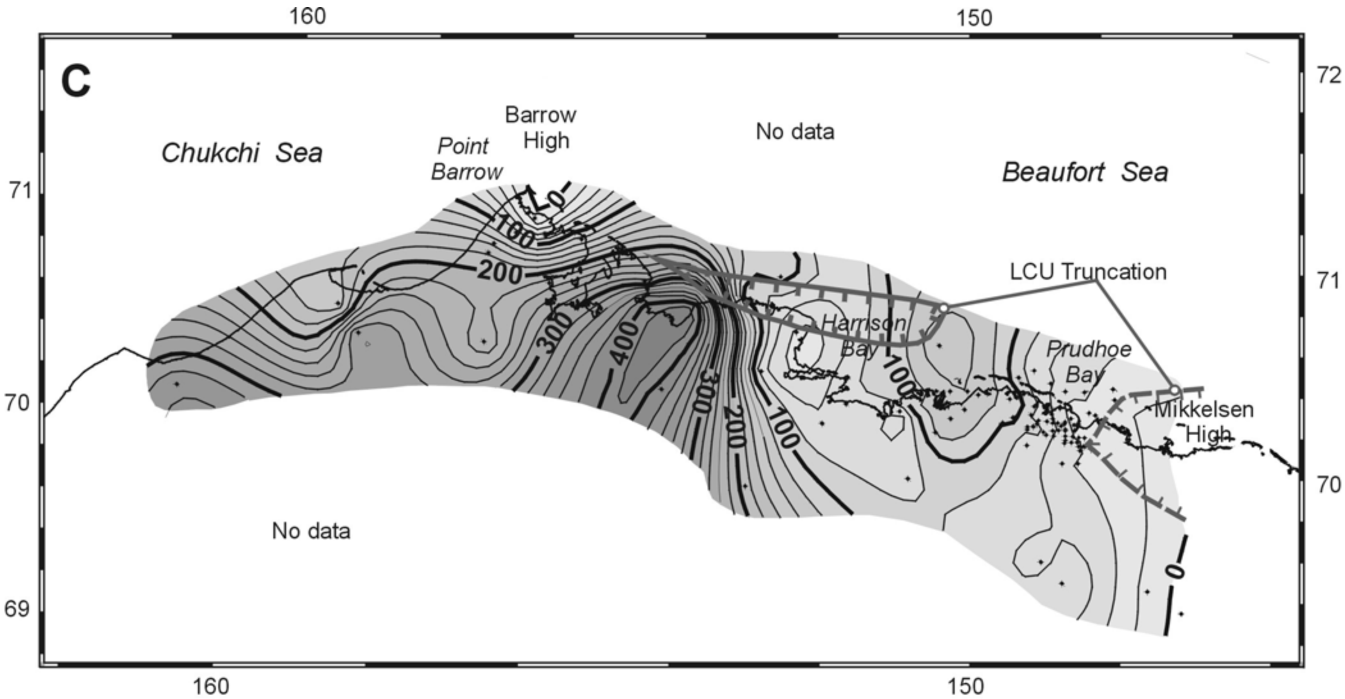


Figure 7. Regional sequence stratigraphic isopach maps. Thickness illustrated by contours and shading with darker colors indicating thicker intervals. The extent of LCU truncation is shown inside the hachured dashed lines. To characterize the package geometry prior to LCU truncation and where well control is sparse, the contours were extended through these areas based on thickness trends from surrounding wells. *A*. Map illustrating the distribution and thickness of the embayment fill facies association (TST sequence 1). The thickest interval is in the Harrison Bay area and defines a broad embayment that was the focus of Eileen Sandstone and Shublik Formation zone D deposition. *B*. Map illustrating the distribution and thickness of sequence one. The sequence is thickest in the vicinity of Harrison Bay and thins over the Barrow and Mikkelsen highs.



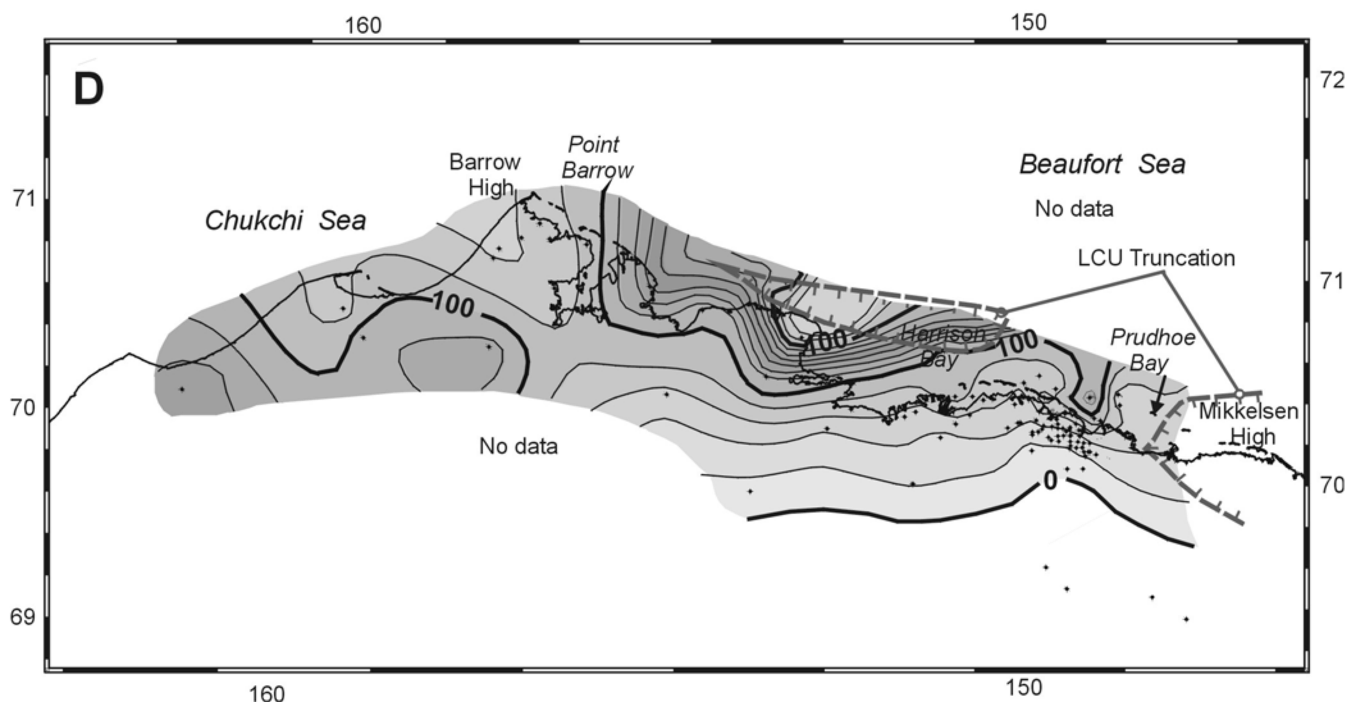


Figure 7. Regional sequence stratigraphic isopach maps—*Continued*. *C*. Map illustrating the distribution and thickness of sequence two. Sequence is thickest between the Fish Creek platform and Barrow and between the Fish Creek platform and Mikkelsen high and thins between these paleotopographic highs. *D*. Map illustrating the distribution and thickness of the LST and TST of sequence three. The sequence is thickest along the flanks of the Barrow and Mikkelsen highs and the Fish Creek platform.

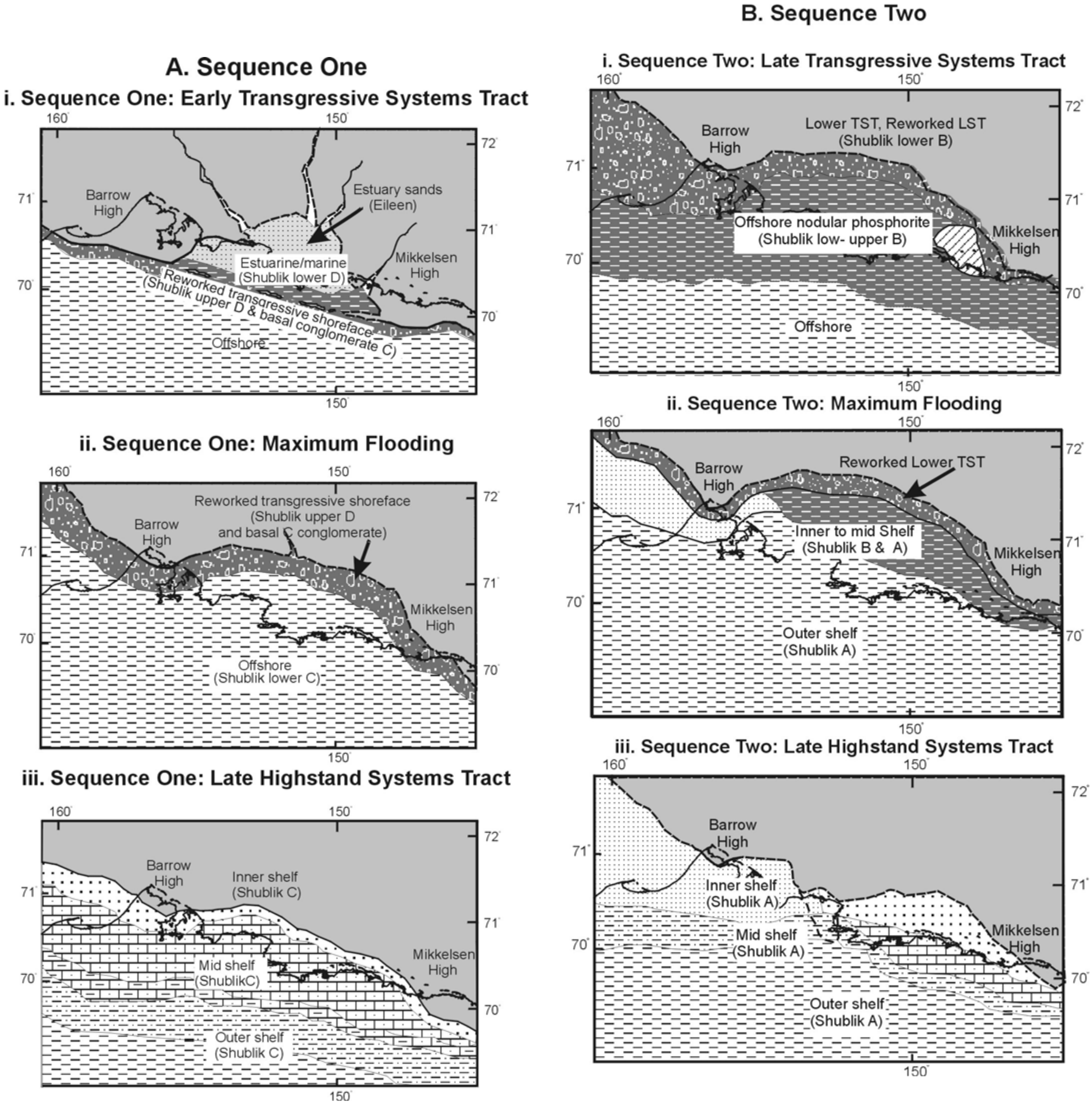


Figure 8. Schematic maps of sequences and systems tracts in the Prudhoe Bay area illustrating the paleogeography and facies distribution at various stages of deposition. Maps are based on facies relationships described in core, log correlations, and isopach maps. *A*. Schematic maps of sequence one. i) Early TST: deposition was concentrated in an embayment between the Barrow and Mikkelsen highs. ii) Late TST: shoreline steps landward and lower Shublik zone C claystones were deposited during maximum flooding. iii) HST: progradation of inner shelf sands and mid-shelf carbonates over outer shelf facies. *B*. Schematic maps of sequence two. i) Early TST: retrogradational onlap of phosphatic facies with deposition focused between Barrow and Mikkelsen highs. ii) Late TST: lower Shublik zone A claystones were deposited across the North Slope during maximum flooding. iii) HST: deposition of progradational shelf facies association.

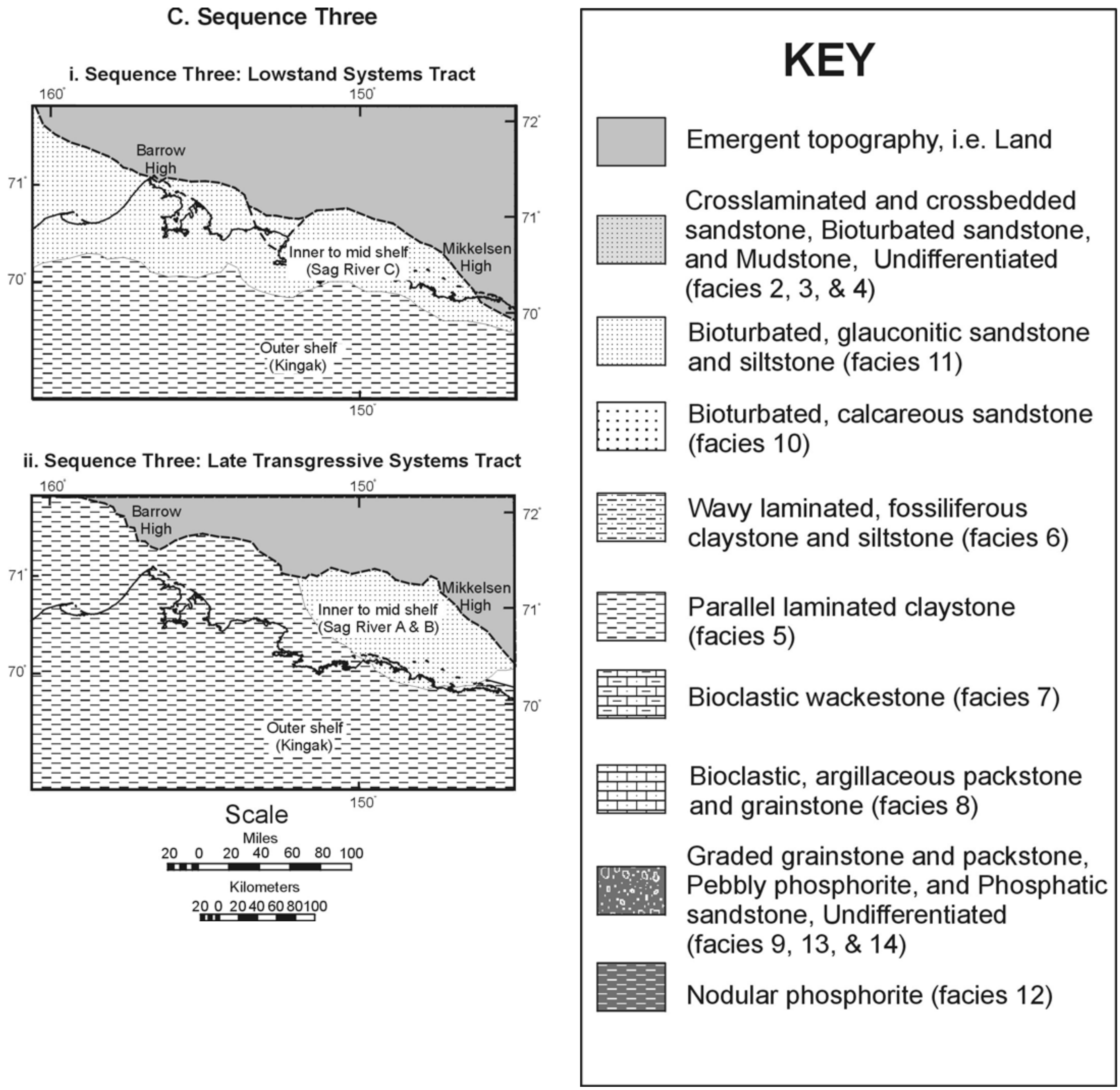


Figure 8. Schematic maps of sequences and systems tracts in the Prudhoe Bay area illustrating the paleogeography and facies distribution at various stages of deposition–*Continued*. *C*. Schematic maps of sequence three. i) LST: deposition and progradation of Sag River Zone C sands. ii) TST: deposition of backstepping parasequences of the Progradational shelf facies association of Sag River Zones A and B.

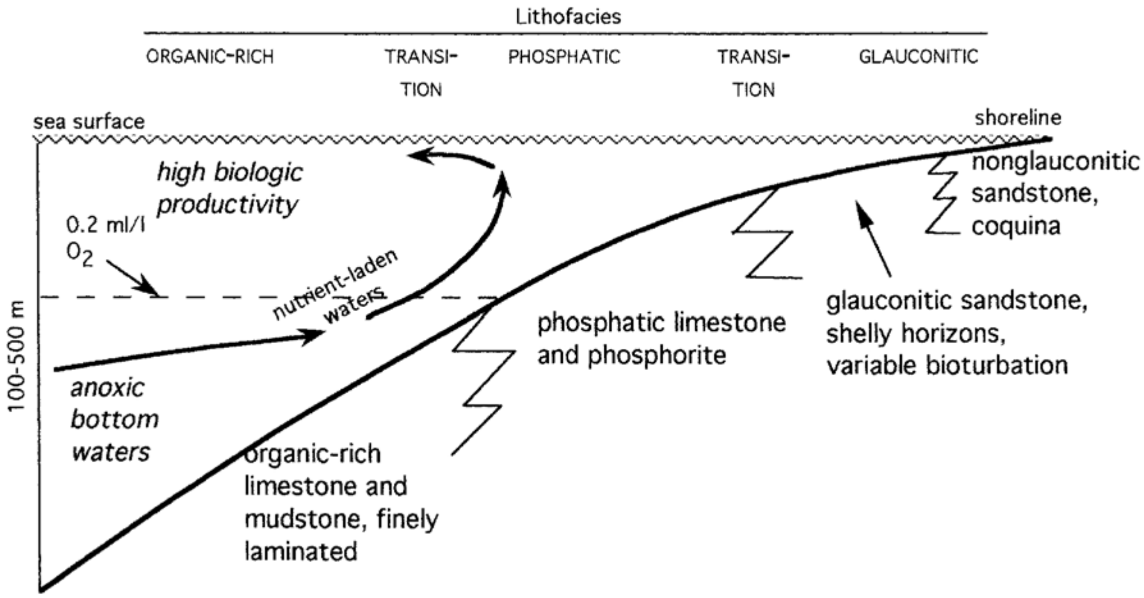


Figure 9. Schematic reconstruction of the continental shelf and vertical shelf circulation perpendicular to the paleoshoreline during deposition of the Shublik Formation, showing the distribution of lithofacies (from Parrish 1987), north to right. In modern upwelling zones, the highest biologic productivity 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).

conitic sandstone lithofacies. The *Palaeophycus* ichnofabric is similar to that described by Bockelie (1991) from the Jurassic siliciclastic facies of the North Sea region. Bockelie (1991) interpreted this ichnofabric as grading into the *Phycosiphon* ichnofabric but representing deposition in a generally deeper-water environment. This ichnofabric consistently has an ichnofabric index of ii5 and occurs in both the glauconitic and nonglauconitic sandstone lithofacies. The *Teichichnus* ichnofabric includes the trace fossils *Teichichnus*, *Phycosiphon*, and *Palaeophycus*. While ii5 is most commonly recorded from this ichnofabric, laminae and thin beds are locally preserved, producing ichnofabric indices ranging from ii2 to ii4. *Teichichnus* typically has a recorded depth of bioturbation of less than 3 cm. The ichnofabric is typical of the glauconitic lithofacies and grades into the *Palaeophycus* ichnofabric. Finally, the Phosphate – *Palaeophycus* ichnofabric, containing phosphate nodules from 1 cm to several centimeters in size, has the trace fossil *Palaeophycus* as a shallow tier with no deep tiers. The degree of bioturbation is difficult to assess because of the presence of phosphate nodules. However, it is clear that bioturbation is not significant and only one burrow type, a shallow-tier *Palaeophycus*, is present.

Taphonomy of *Halobia*

One of the most striking characteristics of the organic-rich facies is the abundance of impressions and shells of *Halobia*. In many cores and in outcrop, every parting in the shale is covered with overlapping shells of this bivalve mollusk. In thin section, the shells show no evidence of corrosion such as might occur with prolonged exposure at the sediment-water interface if sedimentation rates were low. In hand sample, shells and impressions show excellent preservation of the fine detail of the valves, supporting the observation of no corrosion. No articulated specimens were observed in the hand samples or in thin section. No specimens were observed in which the opposing valves were disarticulated but in close proximity. Shells are not imbricated but, rather, randomly overlapping. No evidence for convex-up or convex-down preference is present although the shells are so flat that such preference would not be expected, regardless of the mechanism of deposition.

DISCUSSION

Previous third-order sequence stratigraphic interpretations of the Eileen, Shublik, Sag River interval have focused mainly on the Shublik Formation and were limited in geographic scope (Kupecz 1995; Robison et al. 1996). Both studies determined the Shublik to represent deposition within one third-order sequence. Kupecz (1995) restricted her third-order sequence to the Shublik Formation, concluding that the basal conglomerate represents a thin transgressive lag deposit followed by a HST consisting of two shoaling upward parasequences. Nodular phosphorites of zone B are identified as the shallowest water deposits and represent the surface of maximum progradation. Robison et al. (1996) included the Eileen sandstone in a TST which continued through zone B, culminating in maximum flooding directly above the nodular phosphorites, followed by a HST in zone A. Neither study included the Sag River Formation in their analysis. Hulm's (1999) sequence stratigraphic subdivision has more similarities with the Robison et al. (1996) model, but differs from both in determining the Eileen through Shublik interval to represent two third-order sequences as opposed to one. Hulm’s (1999) interpretation hinges on the depositional implications of phosphorite intervals. Zones D and B of the Shublik Formation are both characterized by phosphorites and are interpreted to represent transgressive events based on their retrogradational facies architecture and relationship with overlying and underlying facies. Phosphatic lags were probably deposited along wave ravinement surfaces and are commonly overlain by laminated claystones interpreted as having been deposited in low oxygen environments during maximum flooding. These stratigraphic relationships necessitate the subdivision of the Eileen-Shublik interval into at least two stratigraphic sequences.

Detterman (1970) commented that "the waters must have been highly nutrient [rich] to support the quantity of marine invertebrate life." Consistent with, but expanding on, these interpretations, Parrish (1987) and Parrish et al (2001) interpreted the Shublik Formation as an upwelling-zone, high-productivity deposit. The phosphatic facies lies between the more proximal glauconitic facies and the more distal organic-rich facies (Fig. 9). Facies belts of (1) nonglauconitic sandstone, (2) glauconitic sandstone or siltstone, (3) phosphatic siltstone and limestone, and (3) organic-rich black limestone and mudstone probably were deposited successively farther offshore, as indicated by their positions relative to each other and by decreases in grain size and current-induced sedimentary structures. The nonphosphatic, nonorganic-rich limestones may be equivalent to the nonglauconitic sandstone in this geographic distribution but representing the shallowest deposits of an embayment isolated from sand influx from land, The distribution of lithofacies in the Shublik Formation both relative to each other (Figs. 1, 9) and in overall lateral extent (Fig. 1) is typical of that in well-developed modern upwelling zones (Bremner 1983; Parrish 1983; Bremner and Rogers 1990; Glenn et al. 1994). The trace fossils and ichnofabric are consistent with an upwelling interpretation. The *Phycosiphon*, *Palaeophycus*, and *Teichichnus* ichnofabrics are all characteristic of Mesozoic shelf environments. The *Teichichnus* ichnofabric likely represents a deeper-water environment, as indicated by preserved laminae. These laminae are likely preserved because low-oxygen conditions precluded burrowing organisms. The major difference between the *Phycosiphon* and the *Palaeophycus* ichnofabrics is the presence of *Phycosiphon*. This trace fossil does not occur in the glauconitic facies. The Phosphate – *Palaeophycus* ichnofabric most likely represents the deepest water of these four ichnofabrics, as indicated by the presence of only one type of burrow and the presence of phosphate. This is consistent with the lithological and geochemical data (see Parrish et al. 2001) that suggest a dysoxic environment.

The high-density assemblages of *Halobia* in the Shublik Formation can be explained only by very slow sedimentation rates or by rapid accumulation of organisms (Parrish et al. 2001). Preservation of the shells is excellent both macroscopically and microscopically, with no evidence of corrosion, as might be expected if sedimentation rates were low and shells sat at the sediment-water interface for extended periods. In addition, the bivalves are unlikely to have been living on the seafloor in such high densities for relatively long durations because of the typically very low oxygen concentrations of bottom waters. Thus, a pelagic habit and rapid transport of shells to the sea floor from the water column as the animals die is the most likely explanation for the dense accumulations of *Halobia* shells. Further support for a pelagic habit is the lack of articulated specimens. That all the observed specimens are preserved as disarticulated, whole valves, with no closely situated opposing valves, suggests that the animals lived in the water column and, upon death, disarticulated as they settled to the seafloor.

CONCLUSIONS

The lithology, geochemistry (Parrish et al. 2001), and fauna of the Shublik Formation are all consistent with deposition in a marine system with high biologic productivity, a condition found most commonly in upwelling zones. High organic input results in organic-carbon-rich sediment under the highest-productivity part of the upwelling current and creates the redox conditions required for the formation of glauconite and phosphate. The resulting lithofacies array observed in modern upwelling systems is identical in kind and scale to that observed in the Shublik Formation. The rapid supply of nutrients benefits not only the plankton that contribute nearly all of the organic matter to the sediment but to organisms higher on the food chain as well, including mollusks and vertebrates, which are abundant in the Shublik Formation.

Within the sequence stratigraphic framework, siliciclastic-rich facies were deposited during lowstand but were reworked by subsequent transgression in the Prudhoe Bay area. Carbonate-rich facies were deposited mainly during highstand. Phosphatic and organic rich-facies were deposited as part of the transgressive systems tracts of the first two sequences. Juxtaposition of deeper-water, low-oxygen environments over a broad shelf facilitated the development of laterally extensive phosphorites and petroleum source rocks. Phosphatic facies commonly occur as transgressive lag or wave ravinement deposits in proximal settings but grade into nodular phosphorites with no evidence of reworking in more distal settings. These units are key sequence stratigraphic idicators of initial and maximum transgression and help to demarcate different systems tracts.

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REFERENCES CITED

BARBER, R.T., 1974, The relationship between circulation and productivity in upwelling ecosystems: Tethys, v. 69(1-2), p. 319.

BIRD, K.J., 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska, U.S. Geological Survey Open-File Report 82-278, p. 105.

BIRD, K.J., 1983, Oil and gas resources of the North Slope, Alaska, U.S. Geological Survey Polar Research Symposium – Abstracts with Program. U.S. Geological Survey Circular 911, p. 27-30

BIRD, K.J., 1985, The framework geology of the North Slope of Alaska as related to oil-source rock correlations, *in* Magoon, L.B., and Claypool, G.E., eds., Alaska North Slope Oil/Rock Correlation Study: American Association of Petroleum Geologists Studies in Geology, p. 3-29.

BLOME, C.D., 1986, Paleogeographic significance of Upper Triassic and Lower Jurassic Radiolaria from Cordillearn terranes: Abstracts, Fourth North American Paleontological Convention, August 12-15, 1986, p. A5.

BLOME, C.D., 1987, Paleogeographic significance of lower Mesozoic radiolarians from the Brooks Range, Alaska, *in* Tailleur, I., and Weimer, P., eds., Alaskan North Slope Geology: Anchorage, Pacific Section, Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, p. 371-380.

BOCKELIE, J.F., 1991, Ichnofabric mapping and interpretation of Jurassic reservoir rocks of the Norwegian North Sea: Palaios, v. 6, p. 206-215.

BODNAR, D.A., 1984, Stratigraphy, age, depositional environments, and hydrocarbon source rock evaluation of the Otuk Formation, north-central Brooks Range, Alaska [unpublished MS thesis]: University of Alaska, Fairbanks, 231 p.

BREMNER, J.M., 1983, Biogenic sediments on the South West African (Namibian) continental margin, *in* Thiede, J., and Suess, E., eds., Coastal Upwelling: Its Sediment Record, Part B: New York, Plenum Publishing, p. 73-104.

BREMNER, J.M., and ROGERS, J., 1990, Phosphorite deposits on the Namibian continental shelf, *in* Burnett, W.C., and Riggs, S.R., eds., Phosphate Deposits of the World, Vol. 3, Neogene to Modern Phosphorites: Cambridge, Cambridge University Press, p. 143-152.

BROSGÉ, W.P., REISER, H.N., PATTON, W.W., JR., and MANGUS, M.D., 1960, Geologic map of the Killik-Anaktuvuk Rivers region, Brooks Range, Alaska, U.S. Geological Survey Open-File Report 60-21.

BROWN, L.F., and FISHER, W.L., 1977, Seismic-stratigraphic interpretation of depositional systems: examples from Brazil rift and pull-apart basins, *in* Payton, C.E., ed., Seismic Stratigraphy: Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26, p. 213-248.

BURNETT, W.C., 1980, Apatite-glauconite associations off Peru and Chile: palaeo-oceanographic implications: Journal of the Geological Society of London, v. 137, p. 757-764.

CALVERT, S.E., BUSTIN, R.M., and INGALL, E.D., 1996, Influence of water column anoxia and sediment supply on the burial and preservation of organic carbon in marine shales: Geochimica et Cosmochimica Acta, v. 60, p. 1577-1593.

CHAPMAN, R.M., DETTERMAN, R.L., and MANGUS, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska, U.S. Geological Survey Professional Paper 303-F, p. 325-407.

DETTERMAN, R.L., 1970, Sedimentary history of the Sadlerochit and Shublik Formations in northeastern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the Geological Seminar on the North Slope of Alaska:, Pacific Section, American Association of Petroleum Geologists, p. O1-O13.

DETTERMAN, R.L., REISER, H.N., BROSGE, W.P., and DUTRO, J.T., JR., 1975, Post-Carboniferous stratigraphy, northeastern Alaska, U.S. Geological Survey Professional Paper 886, 46 p.

DINGUS, A.S., 1984, Paleoenvironmental reconstruction of the Shublik Formation on the North Slope of Alaska [unpublished MS thesis]: University of California, Berkeley, 108 p.

DROSER, M.L., and BOTTJER, D.J., 1989, Ichnofabric of sandstones deposited in high-energy nearshore environments: measurement and utilization: Palaios, v. 4, p. 598-604.

ELRICK, M., 1996, Sequence stratigraphy and platform evolution of Lower-Middle Devonian carbonates, eastern Great Basin: Geological Society of America Bulletin, v. 108, p. 392-416.

GLENN, C.R., FÖLLMI, K.B., RIGGS, S.R., BATURIN, G.N., GRIMM, K.A., TRAPPE, J., ABED, A.M., GALLI-OLIVIER, C., GARRISON, R.E., ILYIN, A.V., JEHL, C., ROHRLICH, V., SADAQAH, R.M.Y., SCHIDLOWSKI, M., SHELDON, R.E., and SIEGMUND, H., 1994, Phosphorus and phosphorites: Sedimentology and environments of formation: Eclogae Geologicae Helvetiae, v. 87, p. 747-788.

GOLDRING, R., POLLARD, J.E., and TAYLOR, A.M., 1991, *Anconichnus horizontalis*: A pervasive ichnofabric-forming trace fossil in post-Paleozoic offshore siliciclastic facies: Palaios, v. 6, p. 250-263.

GRYC, G., 1988, Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, 940 p.

HUGHES, W.B., MIILLER, D.E., and HOLBA, A.G., 1983, North Slope, Alaska, oil-rock correlation study, *in* Magoon, L.B., and Claypool, G.E., eds., Alaska North Slope Oil-Rock Correlation Study—a Compilation of Abstracts: American Association of Petroleum Geologists Short Course: Dallas, TX, April 17, 1983, p. 379-402.

HULM, E.J., 1999, Subsurface facies architecture and sequence stratigraphy of the Eileen sandstone, Shublik Formation, and Sag River sandstone, Arctic Alaska [unpublished MS thesis]: University of Alaska Fairbanks, 105 p.

JONES, H.P., and SPEERS, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay Field, North Slope, Alaska, *in* Braunstein, J., ed., North American Oil and Gas Fields: American Association of Petroleum Geologists Memoir, p. 23-50.

KELLER, A.S., MORRIS, R.H., and DETTERMAN, R.L., 1961, Geology of the Shaviovik and Sagavanirktok Rivers region, Alaska: United States Geological Survey Professional Paper 303-D, p. 169-222.

KUPECZ, J.A., 1995, Depositional setting, sequence stratigraphy, diagenesis, and reservoir potential of a mixed-lithology, upwelling deposit: The Upper Triassic Shublik Formation, Prudhoe Bay, Alaska: American Association of Petroleum Geologists Bulletin, v. 79, p. 1301-1319.

LITTKE, R., BAKER, D.R., LEYTHAEUSER, D., and RULLKÖTTER, J., 1991, Keys to the depositional history of the Posidonia Shale (Toarcian) in the Hils Syncline, northern Germany, *in* Tyson, R.V., and Pearson, T.H., eds., Modern and Ancient Continental Shelf Anoxia: Geological Society of London Special Publication 58, p. 311-333.

LOUTIT, T.S., HARDENBOL, J., VAIL, P.R., and BAUM, G.R., 1988, Condensed sections: The key to age dating and correlation of continental margin sequences, *in* Wilgus, C.K., Posamentier, H., Ross, C.A., and Kendall, C.G.S.C., eds., Sea-Level Changes: An Integrated Approach: American Association of Petroleum Geologists Memoir 42, p. 183-213.

MAGOON, L.B., and BIRD, K.J., 1988, Evaluation of petroleum source rocks in the National Petroleum Reserve in Alaska using organic carbon content, hydrocarbon content, visual kerogen, and vitrinite reflectance data, *in* Gryc, G., ed., Geology and Exploration of National Petroleum Reserve in Alaska 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 381-450.

MAGOON, L.B., and CLAYPOOL, G.E., 1983, Petroleum source rock richness, type and maturity for four rock units on the Alaskan North Slope – are they sources for the two oil types?, U.S. Geological Survey Polar Research Symposium – Abstracts with Program. U.S. Geological Survey Circular 911, p. 30-31.

MONTANEZ, I.P., and Osleger, D.A., 1993, Parasequences stacking patterns, third-order accommodation events, and sequence stratigraphy of Middle to Upper Cambrian platform carbonates, Bonanza King Formation, southern Great Basin, *in* Loucks, B., and Sarg, J.F., eds., Recent Advances and Applications of Carbonate Sequence Stratigraphy: American Association of Petroleum Geologists Memoir 57, p. 305-326.

MOORE, T.E., WALLACE, W.K., BIRD, K.J., KARL, S.M., MULL, C.G., and DILLON, J.T., 1994, Geology of northern Alaska, *in* Plafker, G., and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, p. 49-140.

MOUNTJOY, E.W., 1966, Triassic stratigraphy of northern Yukon Territory, Geological Survey of Canada Paper 66-19 p. 348-362.

MULL, C.G., TAILLEUR, I.L., MAYFIELD, C.F., ELLERSIECK, I., and CURTIS, S., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists, v. 66, p. 348-362.

ODIN, G.S., and LÉTOLLE, R., 1980, Glauconitization and phosphatization environments: a tentative comparison, *in* Bentor, Y.K., ed., Marine Phosphorites: Geochemistry, Occurrence, Genesis: Society of Economic Paleontologists and Mineralologists, Special Publication 29, p. 227-238.

PARRISH, J.T., 1982, Upwelling and petroleum source beds, with reference to the Paleozoic: American Association of Petroleum Geologists Bulletin, v. 66, p. 750-774.

PARRISH, J.T., 1983, Upwelling deposits: nature of association of organic-rich rocks, chert, chalk, phosphorite, and glauconite (abs.): American Association of Petroleum Geologists Bulletin, v. 67, p. 529.

PARRISH, J.T., 1987, Lithology, geochemistry, and depositional environment of the Shublik Formation (Triassic), northern Alaska, *in* Tailleur, I.L., and Weimer, P., eds., Alaskan North Slope Geology: Anchorage, Pacific Section, Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, p. 391-396.

PARRISH, J.T., 1995, Paleogeography of organic-rich rocks and the preservation versus production controversy, *in* Huc, A.-Y., ed., Paleogeography, Paleoclimate, and Source Rocks: American Association of Petroleum Geologists Studies in Geology, p. 1-20.

PARRISH, J.T., DROSER, M.L., and BOTTJER, D.J., 2001, A Triassic upwelling zone: the Shublik Formation, Arctic Alaska: Journal of Sedimentary Research, v. 71, p. 272-285.

PATTON, W.W., JR., and MATZKO, J.J., 1959, Phosphate deposits in northern Alaska, U.S. Geological Survey Professional Paper 302A, 17 p.

PEMBERTON, S.G., MACEACHERN, J.A., and FREY, R.W., 1992, Trace fossil facies models: environmental and allostratigraphic significance, *in* Walker, R., and James, N., eds., Facies models: response to sea level change: Stittsville, Ontario, Geological Association of Canada, p. 47-72.

POSAMENTIER, H.W., ALLEN, G.P., JAMES, D.P. and TESSON, M., 1992, Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance: American Association of Petroleum Geologists Bulletin, v. 76, p. 1687-1709.

REED, K.M., and BLOME, C.D., 1986, Use of radiolarian biostratigraphy in stratigraphic problems in the Otuk Formation, Geologic Studies in Alaska by the U.S. Geological Survey during 1985: U.S. Geological Survey Circular 978, p. 16-19.

ROBISON, V.D., LIRO, L.M., ROBISON, C.R., DAWSON, W.C., and RUSSO, J.W., 1996, Integrated geochemistry, organic petrology, and sequence stratigraphy of the Triassic Shublik Formation, Tenneco Phoenix #1 well, North Slope, Alaska, U.S.A.: Organic Geochemistry, v. 24, p. 257-272.

TAILLEUR, I.L., 1964, Rich oil shale from northern Alaska, U.S. Geological Survey Professional Paper 475-D, p. D131-D133.

TOURTELOT, H.A., and TAILLEUR, I.L., 1971, The Shublik Formation and adjacent strata in northeastern Alaska: description, minor elements, depositional environments, and diagenesis, U.S. Geological Survey Open-File Report 71-462, 62 p.

VAN WAGONER, J.C., POSAMENTIER, H.W., MITCHUM, R.M., VAIL, P.R., SARG, J.F., LOUTIT, T.S., and HARDENBOL, J., 1988, An overview of the fundamentals of sequence-stratigraphy and key definitions, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posmentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea-Level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists Special Publication: Tulsa, Oklahoma, p. 39-45.

ZAITLIN, B.A., DALRYMPLE, R.W., and BOYD, R., 1994, The stratigraphic organization of incised-valley systems associated with relative sea-level changes, *in* Dalrymple, R.W., Boyd, R., and Zaitlin, B.A., eds., Incised-valley systems: origin and sedimentary sequences: Society of Economic Paleontologists and Mineralogists Special Publication: Tulsa, Oklahoma, p. 45-62.