LITHOFACIES ANALYSIS OF THE WAINWRIGHT #1 CONTINUOUS CORE, WESTERN ARCTIC SLOPE, ALASKA: TRANSITION FROM LOWER TO UPPER DELTA PLAIN ENVIRONMENTS IN THE ALBIAN–CENOMANIAN NANUSHUK FORMATION

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INTRODUCTION

During summer 2007 the U.S. Geological Survey (USGS) drilled a 1,605-ft-deep test hole in the village of Wainwright, along the Beaufort Sea coast southwest of Barrow, Alaska (fig. 2-1). Continuous core was cut in the Nanushuk Formation from a depth of 75 to 1,605 ft. The purpose of this hole was to sample and measure the gas content of coal seams. A second well was drilled nearby for testing purposes. Both wells were logged by the USGS with a high-resolution gamma-ray logging tool. This testing was part of an effort by the USGS (Clark, 2014) to evaluate the coalbed methane potential of nonmarine Nanushuk strata and determine their viability as a reliable energy source for Wainwright (fig. 2-2).

The Wainwright #1 core provides an outstanding view of Albian–Cenomanian marginal-marine and nonmarine facies in the Nanushuk Formation (fig. 2-2) in an area characterized by widely scattered, low-lying outcrops. The core includes a thick succession of mud-dominated lower and upper delta plain facies that usually make poor outcrops. Where present in outcrop in the foothills belt north of the Brooks Range to the south and southeast, these facies are typically only exposed over short stratigraphic intervals. Thus the Wainwright #1 core offers a unique opportunity to examine these facies over a stratigraphic thickness never continuously exposed in outcrop.

This report includes the resulting core log (sheet 2-1) and facies analysis. Decker and LePain (2016 [this volume]) place the Wainwright core in a regional stratigraphic context and Helmold (2016 [this volume]) discusses the reservoir quality of sandstones represented in the core.

For detailed discussions of the regional significance of the Nanushuk Formation, refer to Huffman and others (1985, 1988), Molenaar (1985, 1988), Mull (1985), Houseknecht and Schenk (2001, 2005), Decker (2007), Houseknecht and others (2008), LePain and Kirkham (2001), and LePain and others (2008, 2009).

REGIONAL SETTING

The Nanushuk Formation and coeval outer-shelf, slope, and basinal deposits of the upper Torok Formation fill the western two-thirds of a large Mesozoic–Cenozoic peripheral foreland basin (figs. 2-1 and 2-2). The basin is east–west trending and extends from approximately the Alaska–Yukon border in the east to the Chukchi Sea coast in the west, and continues offshore to the Herald arch (Bird and Molenaar, 1992). The onshore part of the basin, referred to as the Colville basin, is bounded on its north side by the Barrow arch (fig. 2-1). The Barrow arch is a subsurface high that coincides approximately with the present-day north coast of Alaska, from Point Barrow to the Canning River, and represents a rift shoulder formed when Arctic Alaska separated from a northern landmass (present-day coordinates) in Neocomian time (Valanginian–Hauterivian) (Bird and Molenaar, 1992). The basin is bounded on its south side by the Brooks Range (fig. 2-1), an east–west-trending, north-vergent (present-day coordinates) fold and thrust belt (Moore and others, 1994). The fold and thrust belt consists of a thick stack of far-traveled allochthons emplaced northward during Neocomian time (Mull, 1985; Mayfield and others, 1988), in part contemporaneous with rifting to the north (Bird and Molenaar, 1992; Moore and others, 1994). The foreland basin formed in response to the load imposed by these allochthons (Mull, 1985; Mayfield and others, 1988), and was subsequently filled by detritus shed from them and from more distant sources on the Chukchi platform (and Russian Far East?).

The Nanushuk Formation is a succession of complexly intertonguing marine and nonmarine strata interpreted as marine shelf, deltaic, strandplain, fluvial, and alluvial overbank deposits (fig. 2-2; Huffman and others, 1985; LePain and others, 2009). Thickness estimates for the unit range from 9,020 feet in coastal exposures along the Chukchi Sea in the west (Ahlbrandt and others, 1979) to a zero edge ~46 mi (75 km) east of Umiat (fig. 2-1). Ahlbrandt and others (1979) and Huffman and others (1985) recognized three large deltas" in the Nanushuk. These deltas were probably fed by multiple rivers, with each river building a stack of delta lobes through time and, as such, are more appropriately referred to as deltaic complexes (LePain and others, 2009). The Corwin complex dominates the Nanushuk west of the Meade arch and was interpreted by Ahlbrandt and others (1979) and Huffman and others (1985) to have been constructed by river-dominated deltas. The Corwin complex received sediment from a large drainage basin that extended west of present-day Arctic Alaska (Molenaar, 1985). The western deltas prograded toward the east–northeast, and gradually filled the western two-thirds of the Colville basin (Houseknecht and Schenk, 2001; Houseknecht and others, 2008). East of the Meade arch Ahl-

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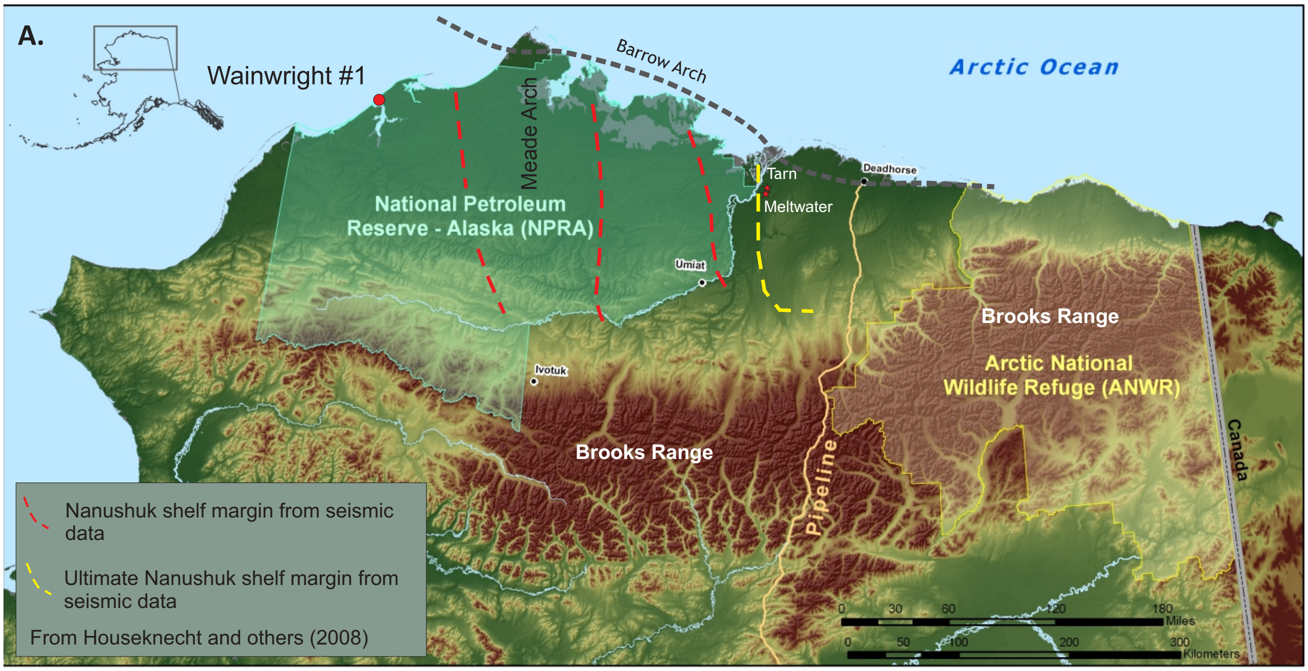


Figure 2-1. **A.** Shaded-relief map of northern Alaska, showing the location of the Wainwright #1 well. The red dashed lines show Nanushuk shelf edge positions in the Colville basin through time (younger toward the east); the yellow dashed line shows the ultimate Nanushuk shelf edge. Shelf edge positions shown here are schematic and taken from Houseknecht and others (2008). **B.** Aerial photograph showing the Village of Wainwright and the location of the Wainwright #1 well. Modified from Clark (2014).

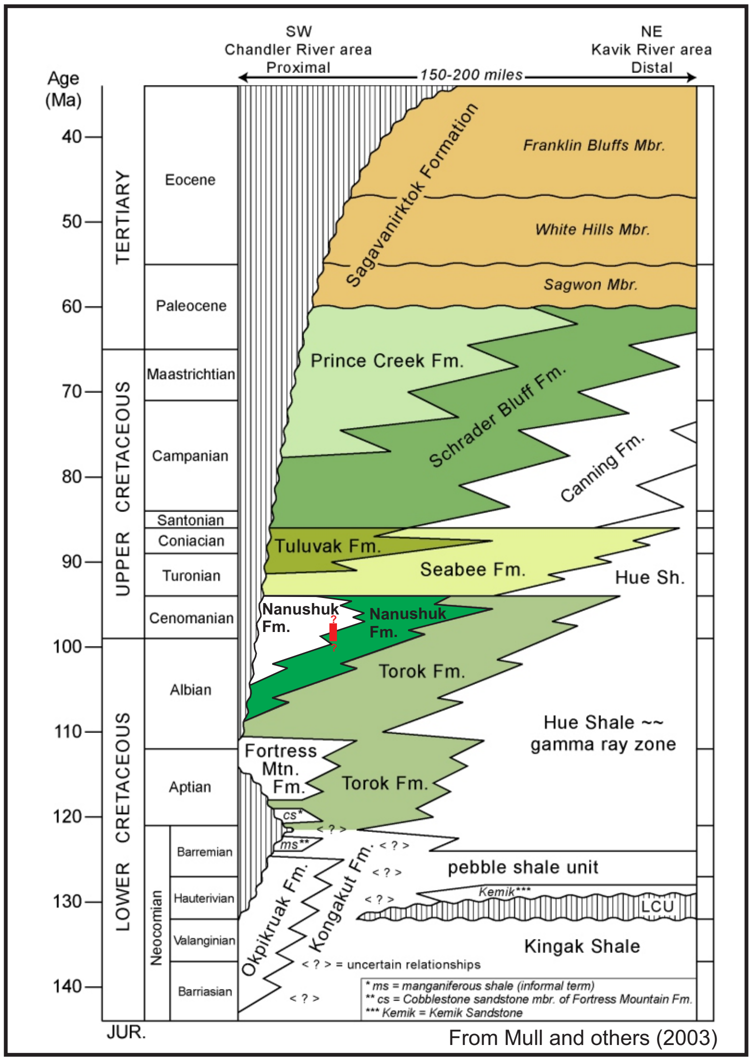


Figure 2-2. Stratigraphic correlation diagram from Mull and others (2003). The vertical red bar in the Nanushuk Formation shows the approximate stratigraphic position of the cored interval in the Wainwright #1 well. Nanushuk strata shown in green and white represent dominantly marine and dominantly nonmarine strata, respectively. Note this stratigraphic column is for the central North Slope; post-Cenomanian strata have not been recognized in the immediate vicinity of the Wainwright #1 well.

brandt and others (1979) and Huffman and others (1985) recognized two deltas (complexes), referred to as the Kurupa–Umiat delta and the Grandstand–Marmot delta. These deltas were fed by north-flowing rivers draining smaller catchment areas in the ancestral Brooks Range to the south (Huffman and others, 1985; LePain and others, 2009). Ahbrandt and others (1979) and Huffman and others (1985) interpreted these deltas as river-dominated, but noted a greater degree of wave influence. LePain and others (2009) interpreted these deltas as wave-modified to wave-dominated. Nanushuk strata in the Wainwright #1 core are part of the Corwin delta complex.

WAINWRIGHT #1 FACIES

Twelve facies have been recognized in the Wainwright #1 core and are summarized in table 2-1. Brief descriptions and interpretations of each are presented below. The degree of bioturbation is characterized using the ichnofabric index of Droser and Bottjer (1986), which ranges from an ichnofabric index of 1 for unbioturbated sediment (here referred to as "II 1") to ichnofabric index of 6 ("II 6") for bedding that is nearly or completely homogenized with no visible traces remaining of original physical sedimentary structures. The facies codes used in this report are adapted from Miall (1996) to accommodate marginal-marine and marine facies. Depths cited in this report are in feet; the thickness of fine-scale stratigraphic features are reported in tenths of feet and the metric equivalent is shown in parentheses.

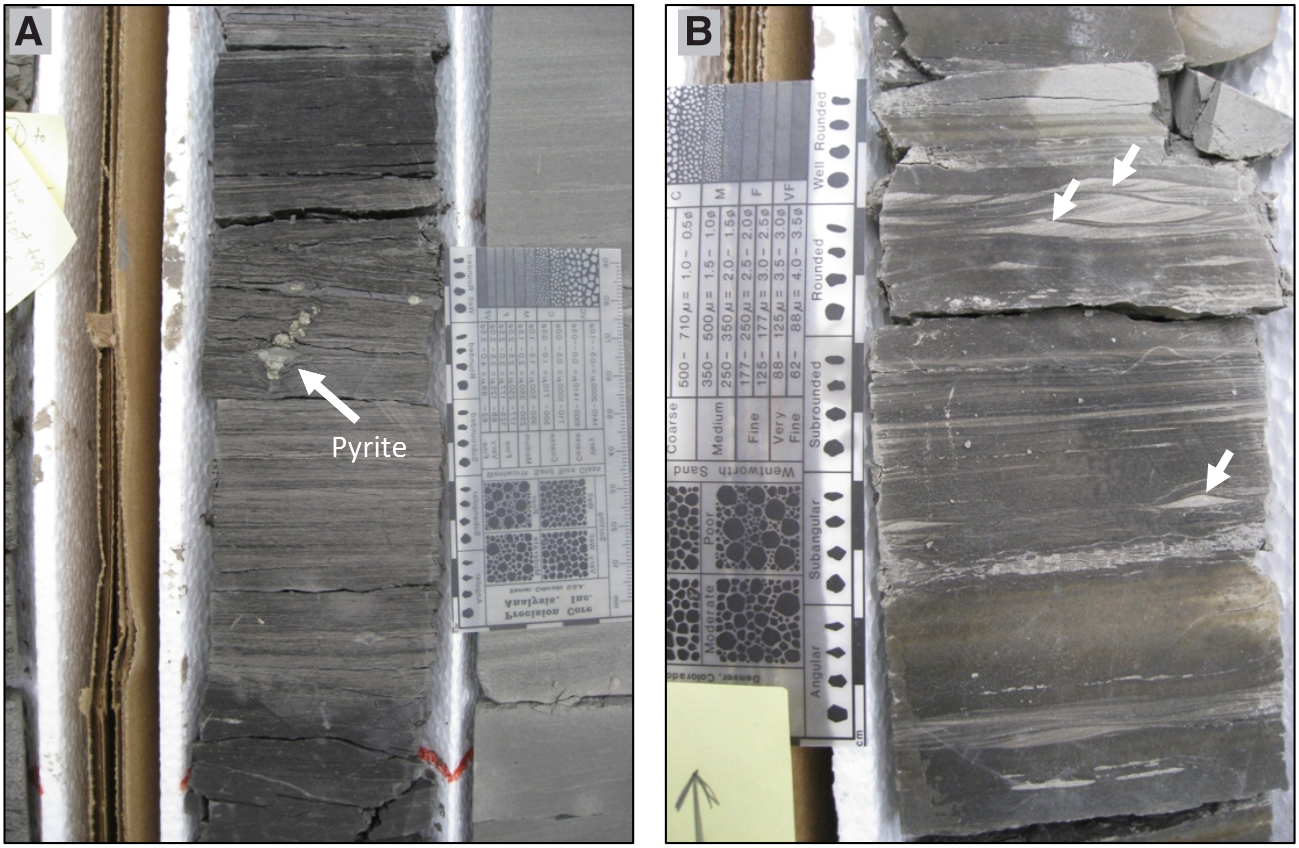
Fl—LAMINATED MUDSTONE

Description

Facies Fl consists predominantly of dark gray to brown claystone, siltstone, and mudstone characterized by plane-parallel lamination up to 0.15 in (4 mm) thick. Facies Fl commonly displays pronounced fissility (fig. 2-3A). Lamination is typically defined by alternating lighter and darker layers that correspond to slightly coarser and finer grain sizes, respectively (figs. 3A–B). Coarse siltstone to very-fine-grained sandstone is present locally as thin, commonly lenticular, laminae up to 1 in thick (2.5 cm; figs. 3B–C). Convolute laminations are present locally. Thinly interbedded sandstone is a minor component and includes

Table 2-1. Summary of facies recognized in core from the Nanushuk Formation, Wainwright #1 well.

	Facies	Characteristics	Trace Fossils	Ichnofabric Index	Process Interpretation
Fl	Laminated mudstone	Dark gray to brown claystone, siltstone, and mixtures of clay and silt; plane-parallel laminated, locally developed fissility; appears unbioturbated. Minor interbedded coarse siltstone and very-fine-grained sandstone.	No trace fossils	II 1	Suspension settling in low-energy, subaqueous settings. Fissility due to subparallel alignment of clay particles resulting from burial-related compaction. Coarser-grained siltstone and very-fine-grained sandstone interbeds record deposition from episodic unidirectional currents and subsequent local reworking by short-period waves.
Fm	Massive mudstone	Medium gray to brown claystone, siltstone, and mixtures of clay and silt; lacks fine-scale lamination; locally includes admixed sand; blocky fabric and orange-brown siderite nodules are common; scattered rhizoliths, locally well preserved; common mottled, bioturbated appearance.	No discrete traces recognized	II 2–4?	Rapid deposition with no subsequent reworking by currents. Scattered rhizoliths and blocky fabric suggest period exposure and soil development. Mottled appearance may record pedogenesis or activity of burrowing organisms in subaqueous setting.
Fc	Carbonaceous mudstone	Dark gray to brown claystone, silty claystone, and clayey siltstone with abundant finely divided plant material; typically displays prominent fissility.	No trace fossils	II 1	Deposition of fine-grained sediment and plant material in subaqueous settings from weak currents.
C	Coal	Black and dark brown subbituminous coal in seams up to several feet thick. Most coal removed for testing; remaining seams consist of alternating bright and dull bands and include rare, thin clastic partings.	No invertebrate/ vertebrate trace fossils	II 1	In-place accumulation of dead vegetation in swamps on upper and lower delta plain.
Sr	Ripple cross-laminated sandstone	Light gray to beige coarse siltstone to fine-grained sandstone in beds up to a foot or more thick; locally includes muddy foreset laminae with relatively abundant plant detritus; locally preserved wave ripple bedforms and complex, bundled sets with scalloped lower set boundaries. Rhizoliths are locally preserved.	*Skolithos;* rare *Thalassinoides* ?	II 1–3	Deposition from unidirectional currents in which equilibrium current ripple bedforms developed and migrated down-current. Wave-ripple bedforms and complex sets of ripple cross-lamination with adjacent sets displaying foreset laminae dipping in opposite directions resulted from shoaling, short-period waves in shallow water. Where rhizoliths have been recognized, deposition occurred in shallow water or the beds were subsequently exposed.
Sx	Cross-bedded sandstone	Light gray to light brown, fine- to medium-grained sandstone with foreset laminae dipping 10–25 degrees relative to paleohorizontal; foresets appear planar and in sets from 0.3 to greater than 1 ft thick; normal size grading common in foreset laminae.	No trace fossils	II 1	Deposited from steady, unidirectional flows in which equilibrium dune bedforms developed. Cross-bed sets are the depositional record of migrating dune bedforms.
Slf	Plane-parallel laminated fine-grained sandstone	Light gray to light brown, moderately to well sorted, very-fine- to fine-grained sandstone in beds from 0.01 to 1 ft thick displaying plane-parallel to gently wavy lamination; parting lineation visible locally; local changes in dip direction of low-angle lamination over short vertical distances suggests hummocky cross-stratification (HCS). Some alternating sandstone and organic-rich silty sandstone laminae.	*Skolithos* , locally developed escape structures	II 1–3	Deposited under upper flow-regime conditions, most likely from unidirectional flows. Alternating sandstone and organic-rich silty sandstone laminae record fluctuating current strength, possibly related to tides. HCS, if present, records long-period storm waves.
Slm	Plane-parallel laminated medium-grained sandstone	Light gray to light brown medium-grained sandstone with plane-parallel laminae; alternating organic-rich, muddy laminae and organic-poor laminae locally.	No trace fossils	II 1	Deposited under upper flow-regime plane bed conditions, most likely from unidirectional flows.
Sm	Massive sandstone	Light gray to light brown, very-fine- to medium-grained sandstone characterized by an apparent lack of sedimentary structures; locally includes pebbles of gray chert, siderite, and mudstone rip-ups.	Locally burrow mottled	II 1–4	Records high sediment supply and/or rapid deposition with no subsequent traction transport.
Scb	Convolute laminated sandstone	Light gray to light brown, very-fine- to fine-grained sandstone in beds from 0.01 to greater than 1 ft thick; bedding and internal stratification, if present, are deformed and characterized by irregular, chaotic folds and steep bed/laminae dips; beds commonly broken.	*Thalassinoides* , *Teichichnus* , and *Skolithos*	II 1–4	Soft-sediment deformation. Several possible mechanisms; see text.
Sb	Burrow-mottled sandstone	Light gray to light brown, very-fine- to fine-grained sandstone in beds from 0.02 to 0.6 ft thick characterized by abundant trace fossils. Facies is rare.	*Phycosiphon* , *Skolithos* , *Teichichnus* , and *Thalas-sinoides* ; possible *Diplo-craterion* and *Rosselia*	II 3–4	Reworking of sand beds at or very near the depositional surface by burrowing organisms in a marine influenced setting.
SFh	Heterolithic sandstone and mudstone	Light gray to light brown coarse siltstone/very-fine- to fine-grained sandstone and dark gray to dark brown mudstone; sandstone and mudstone are thinly interbedded, beds from 0.01 to 0.5 ft thick.	*Skolithos*	II 1–3	Deposited under fluctuating energy conditions, possibly related to tides. Coarse silt and sand transported to depositional site as bedload and mudstone as suspended load.



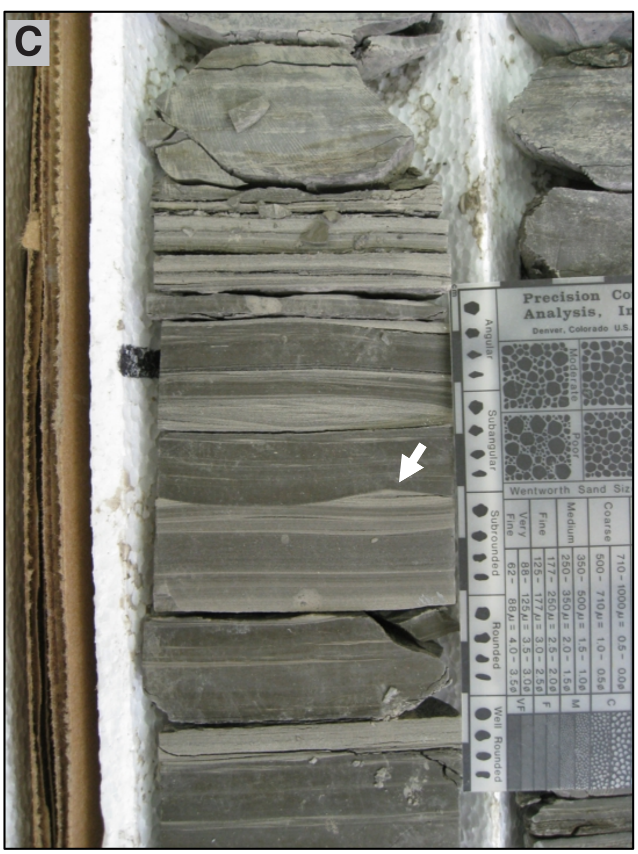


Figure 2-3. Photographs showing selected features in the laminated mudstone facies (Fl). Scale on edge of grain-size comparator in photos is marked in centimeters (2.54 cm = 1 inch). **A.** Dark gray to dark gray-brown mudstone with well-developed fissility at a depth of approximately 618.5 ft. Note pyrite (white arrow). **B.** Facies Fl, with interlaminated very-fine-grained sandstone at a depth of 241 ft. Note the starved symmetric to slightly asymmetric wave-ripple bedforms in some of the sandstone laminae (white arrows). The thin mud drapes separating these structures indicate times of reduced current strength, allowing mud to settle out of suspension. **C.** Facies Fl, with interlaminated very-fine-grained sandstone, between 1,296 and 1,298 ft. As the sandstone:mudstone ratio increases, facies Fl grades to facies SFh. Note the slightly asymmetric ripple bedform near the center of the photograph (white arrow), which is interpreted as a wave-generated structure.

plane-parallel lamination, ripple cross-lamination and, less commonly, appears massive. Slightly asymmetrical to symmetrical starved ripple bedforms are locally preserved in some sandstone lenses (white arrows in figs. 3B–C). Nodular siderite and pyrite are minor components of facies Fl (fig. 2-3a). As the number of sandstone interbeds increases, facies Fl grades to the heterolithic sandstone and mudstone facies (SFh) (fig. 2-3C). Facies Fl appears unbioturbated (II 1).

Interpretation

Facies Fl records deposition in subaqueous settings characterized by low-energy suspension sedimentation at locations that were beyond the day-to-day influence of higher-energy currents. Fissile mudstone records the subparallel alignment of platy, clay-sized particles resulting from burial and compaction. Plane-parallel laminated siltstone and sandstone record deposition from episodic unidirectional currents, whereas ripple cross-lamination records deposition from migrating two-dimensional current-ripple bedforms under lower-flow-regime conditions (Harms and others, 1975). Local reworking of sand by short-period waves in shallow water resulted in small symmetric to slightly asymmetric wave-ripple bedforms (figs. 3B–C; Collinson and Thompson, 1989). Preservation of fine-scale lamination and the absence of bioturbation indicate deposition in settings hostile to burrowing organisms, possibly due to reduced dissolved oxygen concentrations at or above the sediment–water interface, or a combination of low oxygen and salinity levels.

Fm—MASSIVE MUDSTONE

Description

Facies Fm consists of medium gray to brown claystone, siltstone, mudstone, and, locally, sandy mudstone. This facies is characterized by a lack of fine-scale lamination and other visible physical sedimentary structures, and lacks well-developed fissility. Facies Fm is locally characterized by a blocky fabric (fig. 2-4A) and commonly includes light orange–brown nodular siderite (fig. 2-4B). Larger siderite accumulations are shown on the core log (sheet 2-1) as siderite bands, which have parallel upper and lower boundaries that appear to conform to bedding. Rhizoliths are present locally (fig. 2-4C). Where present immediately below coal (facies C), facies Fm has a bleached appearance. As in facies Fl, laminae of coarse siltstone to fine-grained sandstone are present locally. As the number of sandstone interbeds increases, facies Fm grades to facies SFh. Discrete trace fossils are generally absent, but the common mottled appearance suggests bioturbation (II 2–4?).

Interpretation

Most examples of facies Fm record deposition of mudstone in shallow, subaqueous settings removed from sources of coarse-grained sediment. The massive texture resulted from high sedimentation rates from suspension with no subsequent reworking by currents (Collinson, 1968). The sporadic occurrence of moderately bioturbated siltstone and sandstone laminae is consistent with deposition from flood-generated, unidirectional flows that occasionally interrupted this low-energy setting. Examples of this facies that appear bioturbated below a measured depth of 104 feet are interpreted to record deposition in brackish to fully marine settings; examples above this depth record deposition in nonmarine, poorly to moderately drained overbank settings that were subjected to pedogenic modification. Locally developed blocky fabrics and root traces are recognized throughout the cored interval and record disturbance by plants and pedogenic processes (paleosols) operating on intermittently exposed substrates. The blocky fabric (breccia-like in some cases) in the upper part of the core (top of the cored interval to a measured depth of 104 feet) may be related to permafrost or pedogenesis. Siderite precipitated in the shallow subsurface shortly after deposition, and records reducing pore waters and the presence of organic material (Ho and Coleman, 1969; Potter and others, 2005).

Fc—CARBONACEOUS MUDSTONE

Description

Facies Fc consists of dark gray to dark brown claystone, silty claystone, and clayey siltstone (fig. 2-5A). Abundant finely divided plant material and prominent fissility are principal characteristics. Facies Fc typically includes alternating mudstone and carbonaceous mudstone laminae. An extreme example of this motif consists of alternating thin (up to 1-in- [2-cm-] thick) high-ash coal stringers and laminae of gray fissile mudstone (fig. 2-5B). Nodular siderite is present locally in minor quantities. Trace fossils are absent (II 1).

Interpretation

Facies Fc records deposition in subaqueous settings distal to sources of coarse-grained sediment. The abundance of fine-grained, well-preserved plant material is consistent with deposition in low-energy settings. Coal stringers record episodic accumulation of allochthonous plant material (up to several inches in pre-compaction thickness) in subaqueous settings that were subsequently buried by fine-grained sediment with less detrital organic material. Abundant plant matter resulted in low dissolved oxygen levels at the sediment–water interface and in the shallow subsurface (Potter and others, 2005), making the setting inhospitable to a burrowing infauna.

C—COAL

Description

Facies C consists of black to dark brown subbituminous coal in seams a few inches to several feet in thickness. Most coalbeds in the core have been removed (sampled) for various laboratory tests of coalbed methane potential (Clark, 2014). Remaining seams commonly include alternating bright and dull bands up to 0.05 in (1.3 mm) thick; clastic partings up to 0.05 in (1.3 mm) thick are present

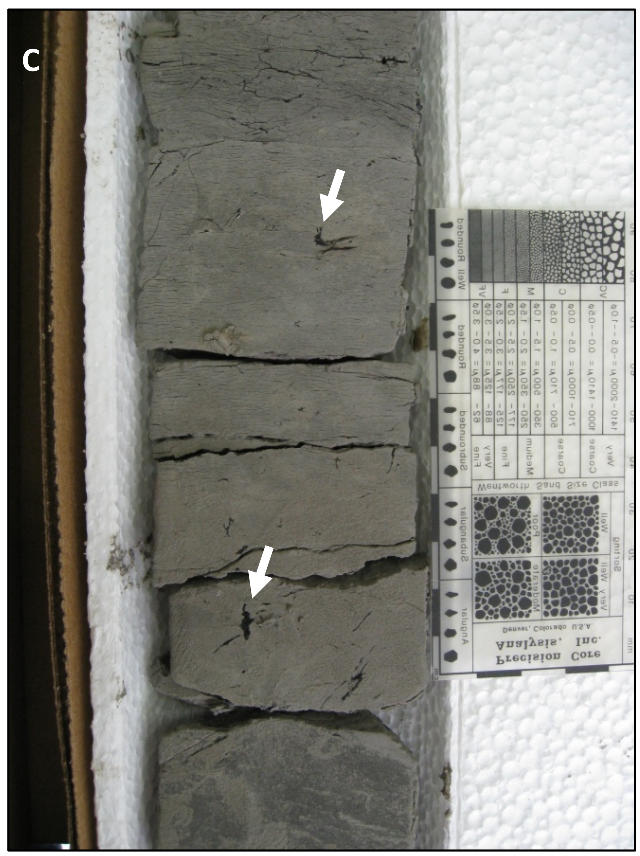


Figure 2-4. Photographs showing selected features in the massive mudstone facies (Fm). Scale on edge of grain-size comparator in photos is marked in centimeters. **A.** Blocky fabric commonly observed in facies Fm at a depth of approximately 83 ft (white arrows). **B.** Blocky to massive fabric in mudstone of facies Fm, with abundant irregularly shaped siderite nodules (white arrows) at a depth of 328 ft. **C.** Massive to slightly fissile mudstone of facies Fm, with rhizoliths (white arrows) at approximately 992 ft.

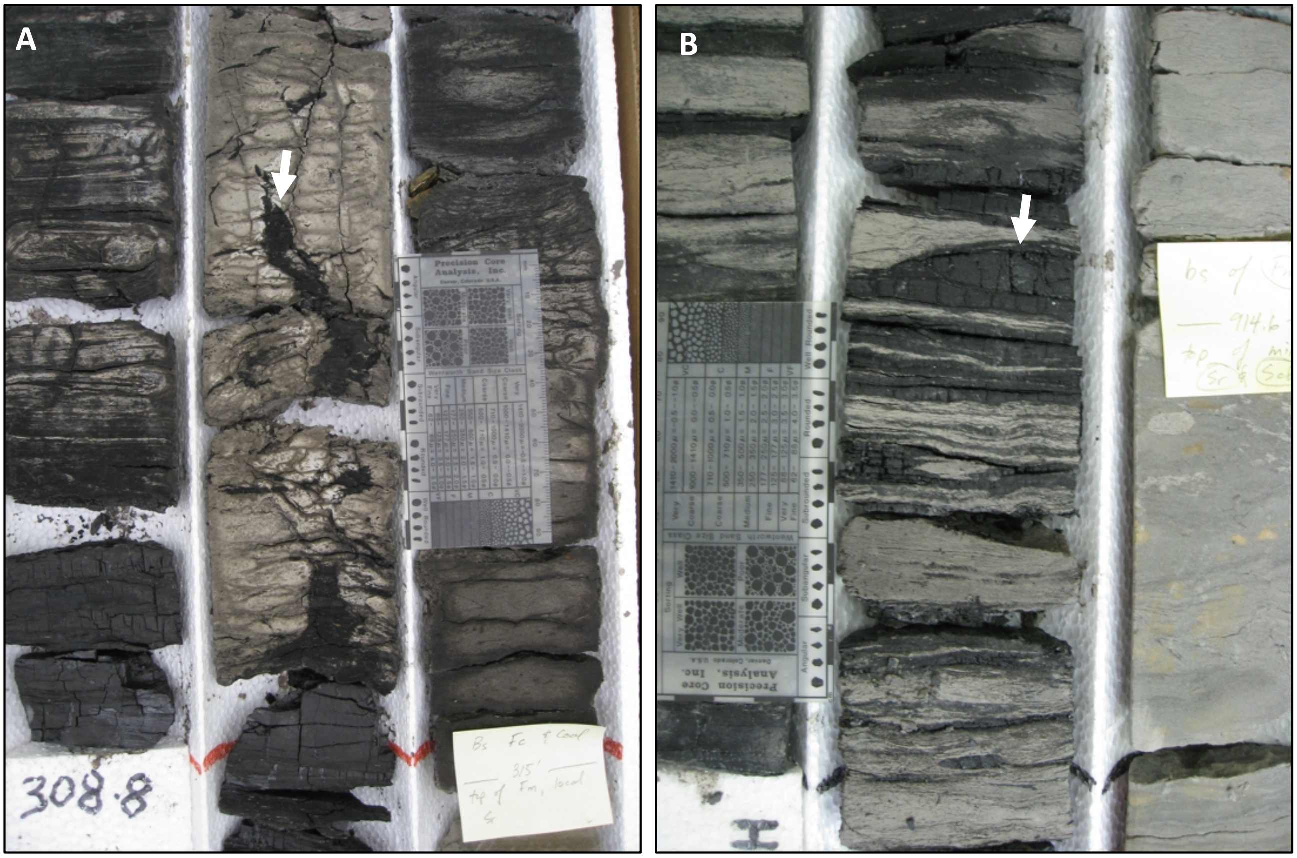


Figure 2-5. Photographs showing selected features in the carbonaceous mudstone facies. Scale on edge of grain-size comparator in photos is marked in centimeters. **A.** Dark brown carbonaceous mudstone of facies Fc above and below gray massive mudstone (Fm) between 308 and 315 ft depth. Note the large root structure in the gray mudstone filled with dark-brown carbonaceous mudstone (white arrow; facies Fc). **B.** Interlaminated, fissile mudstone and high-ash coal (white arrow) assigned to facies Fc at a depth of 912 ft.

locally. Figure 2-6 shows coalbeds remaining in the core after sampling between 557.7 and 568.1 ft.

Interpretation

Coal records deposition in peat swamps (mires) removed from sources of terrigenous clastic sediment (McCabe, 1984; Galloway and Hobday, 1996). Depositional settings include brackish-water swamps that fringed interdistributary bays on the lower delta plain, and freshwater swamps. The thicker peat accumulations in both settings were protected from active fluvial and distributary channels.

Sr—RIPPLE CROSS-LAMINATED SANDSTONE

Description

Facies Sr consists of light gray to beige coarse siltstone to fine-grained sandstone in beds up to a foot or more thick, with prominent cross-lamination in sets up to 0.2 ft (6.1 cm) thick. Some sand in facies Sr is poorly sorted and includes appreciable mud (fig. 2-6, darker brown laminae from 560 to 562.8 ft, and fig. 2-7A). Finely divided plant material, where present, is concentrated in muddy foreset laminae (fig. 2-6, 560.5 ft, and 7A–B). Mudstone is present as thin drapes up to 0.08 in (2 mm) thick (fig. 2-7C) and thicker interbeds up to a few tenths of a foot thick. Stoss-side laminae are rarely preserved and set boundaries are typically erosional. Sandstone beds have sharp basal and upper contacts. Simple and complex sets of ripple cross-laminae have been recognized, with the latter consisting of complexly interwoven bundled sets with foresets in adjacent sets dipping in opposite directions and displaying scalloped lower set boundaries (fig. 2-7C). Where mudstone overlies facies Sr, ripple bedforms are locally preserved and display symmetric to slightly asymmetric profiles. Representative sandstone laminae from facies Fl (figs. 2-3B and 2-3C) show thinly interbedded sandstone that includes small-scale wave-ripple bedforms; where ripple cross-laminated sandstone is the dominant lithology it is assigned to facies Sr. When facies Sr alternates with mudstone beds to form a rhythmic succession it is assigned to facies SFh. Bioturbation ranges from absent (II 1; fig. 2-7B–C) to moderate (II 2–4; fig. 2-7A shows a single escape burrow). *Skolithos* is most common; *Thalassinoides* has been recognized in some adjacent beds that may have been ripple cross-laminated prior to disruption by burrowing organisms.

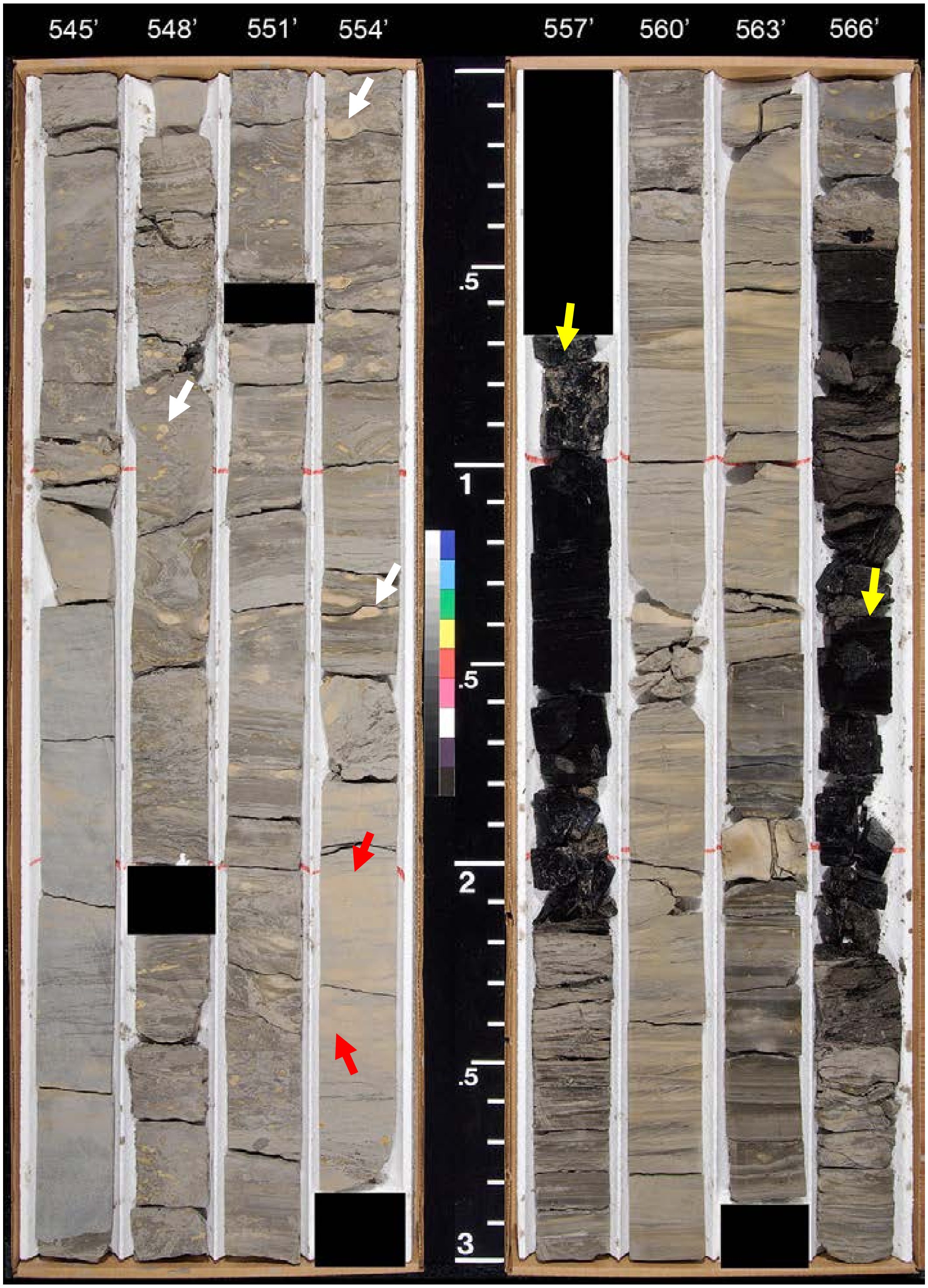
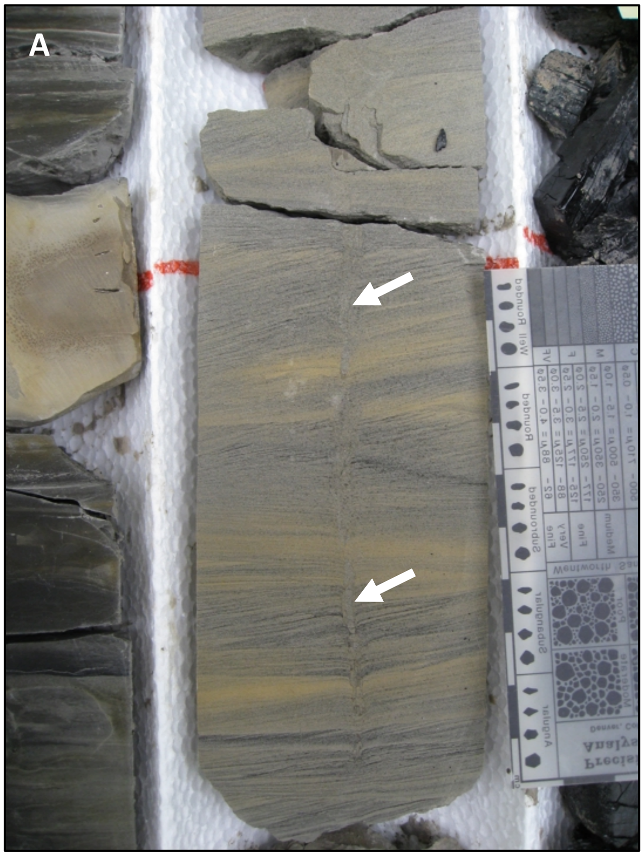


Figure 2-6. Core photograph showing coal between 556.8 and 568.3 ft (yellow arrows), and interbedded mudstone, muddy sandstone, and sandstone with abundant siderite nodules between 545 and 557 ft (white arrows). Note sideritic cement in sandstone from 555.8 to 556.8 ft (red arrows). Note: Each core box holds 12 ft of core in four 3-ft-long rows; depth in feet is shown at the top of each row. The scale between boxes is marked in feet and tenths of a foot. All core boxes shown in subsequent figures are marked in the same way.



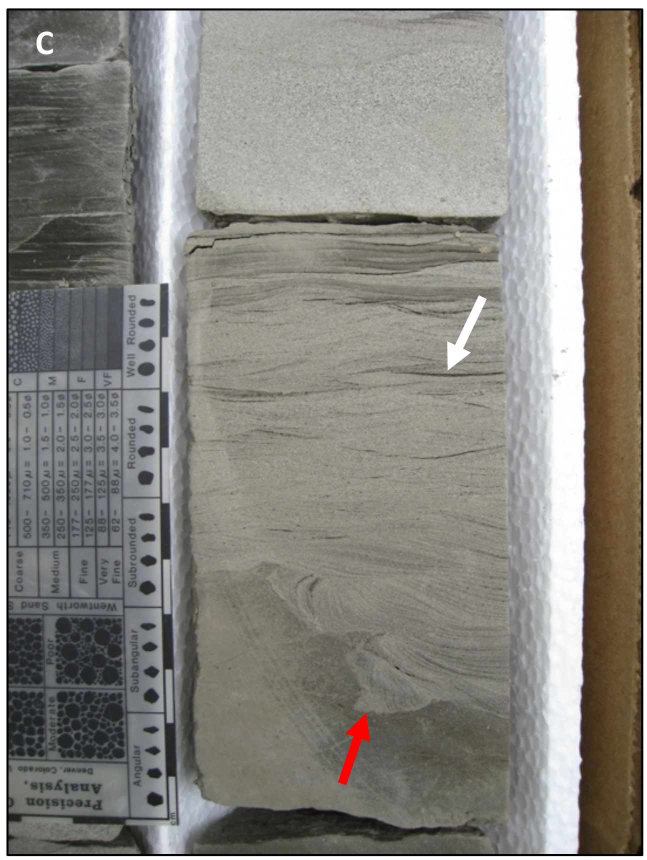


Figure 2-7. Photographs showing selected features in the ripple cross-laminated sandstone facies (Sr). Scale on edge of grain-size comparator in photos is marked in centimeters. **A.** Stacked sets of ripple cross-laminae penetrated by a single vertical escape burrow between 562 and 565 ft (white arrows; II 2). **B.** Stacked sets of ripple cross-laminae at a depth of 463.5 ft. Stoss-side laminae are not preserved and sets display low climb angles (white arrow). Note muddy foreset laminae (darker-colored laminae). **C.** Stacked sets of ripple cross-laminae at 687.5 ft. Note the complexly interwoven sets with boundaries dipping to the right and left, suggesting a wave origin. Note discontinuous clay drape (white arrow). The lowest set sank into the underlying muddy sand/sandy mud (red arrow) due to a slight density contrast.

Interpretation

Ripple cross-laminated sandstone of facies Sr represents the depositional record of small, migrating two- and three-dimensional dunes in a subaqueous setting under lower-flow-regime conditions (Simons and others, 1965; Harms and others, 1975; Allen, 1984). Most cross-lamination in this facies is interpreted as forming initially from unidirectional currents under conditions of relatively low sediment supply such that stoss-side laminae were not preserved (type A ripple drift cross-lamination of Jopling and Walker, 1968; figs. 2-7A–B). Subsequent reworking locally by small, short-period shoaling waves is indicated by preserved small-scale, symmetrical to nearly symmetrical, wave-ripple bedforms (figs. 2-3B and C show examples from facies Fl) and the complexly interwoven bundled sets of cross-lamination present in some sand beds (for example, de Raaf and others, 1977; fig. 2-7C).

Sx—CROSS-BEDDED SANDSTONE

Description

Facies Sx consists of light gray to light brown, fine- to medium-grained sandstone characterized by foreset laminae that dip 10–25 degrees relative to paleohorizontal (figs. 2-8A–B). Foresets appear planar and comprise sets 0.3 ft to more than 1 ft (9–30+ cm) thick. Normal size grading in foreset laminae is common; slight color changes associated with different grain-size fractions and organic debris serve to accentuate foreset stratification. Thin, diffuse pebble lags (1–2 clasts thick) are locally present in facies Sx, usually at or near the base of sets, and consist primarily of sideritic mudstone and mudstone clasts (fig. 2-8B, clasts scattered between 1,088 and 1,095 ft); quartz and chert clasts are present in some lags. Trace fossils have not been recognized in this facies (II 1).

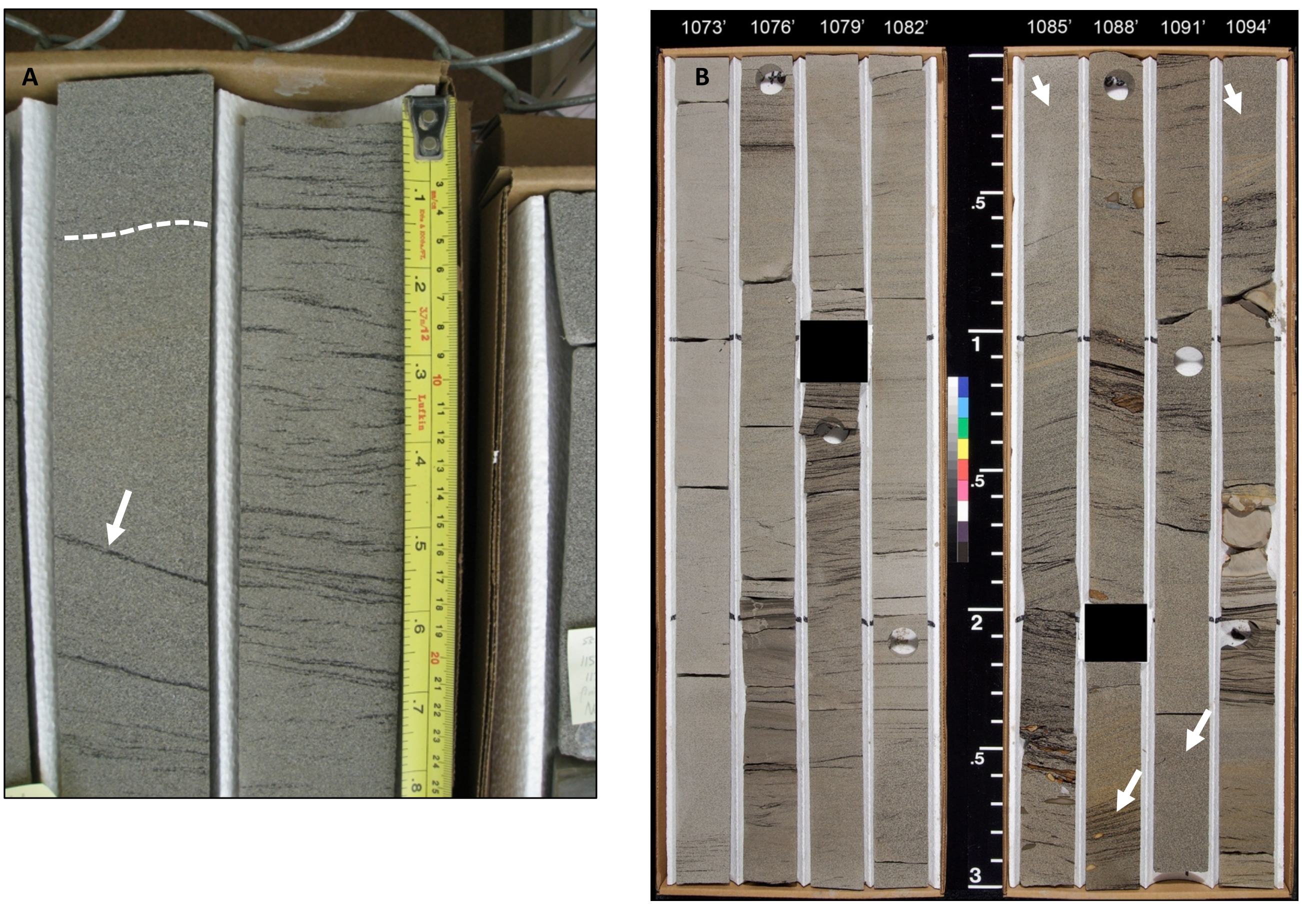


Figure 2-8. Photographs showing selected features in the cross-bedded sandstone facies (Sx). **A.** Planar foresets in medium-grained sandstone; some foreset laminae are lined with carbonaceous debris (white arrow; depth approximately 1,151.6 ft). Dashed white line marks upper set boundary. Tape measure marked in centimeters (right side) and tenths of a foot (left side). **B.** Core photo of channel-fill succession between 1,097 and 1,073 ft that includes multiple sets of cross-bedded sandstone (white arrows).

Interpretation

Cross-bedded sandstone of facies Sx represents the depositional record of migrating dunes developed in sand in a subaqueous setting in response to unidirectional lower-flow-regime currents (Simons and others, 1965; Harms and others, 1975; Collinson and Thompson, 1989). Planar foresets suggest dunes were characterized by relatively straight crestlines (two-dimensional; Ashley, 1990), but the limited view provided by one core precludes further analysis. Preserved set thicknesses represent only a fraction of original dune heights. Pebbles comprising lags were transported only during events having the highest flow velocities, such as floods. Sideritic mudstone and mudstone clasts were most likely derived from facies Fm and, to a lesser extent, Fc and Fl, as flood currents scoured muddy substrates and entrained iron-rich concretionary masses that were forming at shallow burial depths in adjacent interdistributary bays.

Slf—PLANE-PARALLEL LAMINATED FINE-GRAINED SANDSTONE

Description

Facies Slf consists of light gray to light brown, moderately to well sorted, very-fine- to fine-grained sandstone in beds characterized by plane-parallel, flat to gently wavy laminae 0.05 to 0.4 in (1–10 mm) thick (figs. 2-9A, C–D). Laminae dipping at low angles that gradually change dip direction up- or down-section over short stratigraphic distances are suggestive of hummocky cross-stratification (fig. 2-9E). Sandstones most commonly have sharp contacts with bounding beds (sandstone and mudstone), but gradational upper contacts with mudstones have been observed. Lamination is commonly defined by subtle grain-size changes and/or the presence of finely divided plant fragments (figs. 2-9A and C); siderite as clasts and in-place cemented zones are present locally. Parting lineation is visible on some parting surfaces. Rarely, facies Slf includes alternating laminae of sandstone and organic-rich silty sandstone that gradually change thickness and abundance in vertical succession, forming a repetitive motif (fig. 2-9D, from 1,102.7 to 1,099.2 ft) that is gradational to facies SFh. Bioturbation ranges from absent (II 1) to moderate (II 3–4); most beds are either unbioturbated or only sparsely bioturbated with *Skolithos*. Some vertical traces are likely escape structures.

Interpretation

Plane-parallel lamination and parting lineation in sandstones of facies Slf record deposition under upper-flow-regime plane bed conditions (Simons and others, 1965; Harms and others, 1975; Allen, 1984), most likely from unidirectional currents. Alternating laminae of sandstone and organic-rich silty sandstone record fluctuations in current velocity from higher velocity, when finer material (silt and small plant fragments) was maintained in suspension or winnowed from the depositional interface, to lower velocity when silt and organic material carried in suspension settled with minimal subsequent transport. Alternating current strength may have resulted from tides (Dalrymple, 1992).

Slm—PLANE-PARALLEL LAMINATED MEDIUM-GRAINED SANDSTONE

Description

Facies Slm shares characteristics in common with facies Slf, but is coarser grained and lacks bioturbation (II 1). It consists of light gray to light brown-gray, moderately to well sorted, fine- to medium-grained sandstone characterized by plane-parallel, flat laminae from 0.04 to 0.5 in (1–13 mm) thick (figs. 2-9B and D, white arrows). Alternating laminae of organic-rich, muddy sandstone and organic-poor, mud-free sandstone are locally present.

Interpretation

Plane-parallel lamination in facies Slm records deposition under upper-flow-regime plane bed conditions associated with unidirectional currents (Simons and others, 1965; Southard, 1971; Harms and others, 1975; Allen, 1984). The coarser grain size and apparent low detrital mud content characteristic of this facies indicate deposition from higher-velocity currents than were responsible for facies Slf, which did not allow mud and finer-grained sand to settle out of suspension. As in facies Slf, locally occurring, interlaminated, organic-rich, muddy sandstone and organic-poor, mud-free sandstone suggest deposition from rhythmically alternating lower-energy and higher-energy flows, possibly associated with tides. The absence of trace fossils is consistent with deposition in high-energy settings characterized by fresh or low-salinity brackish water.

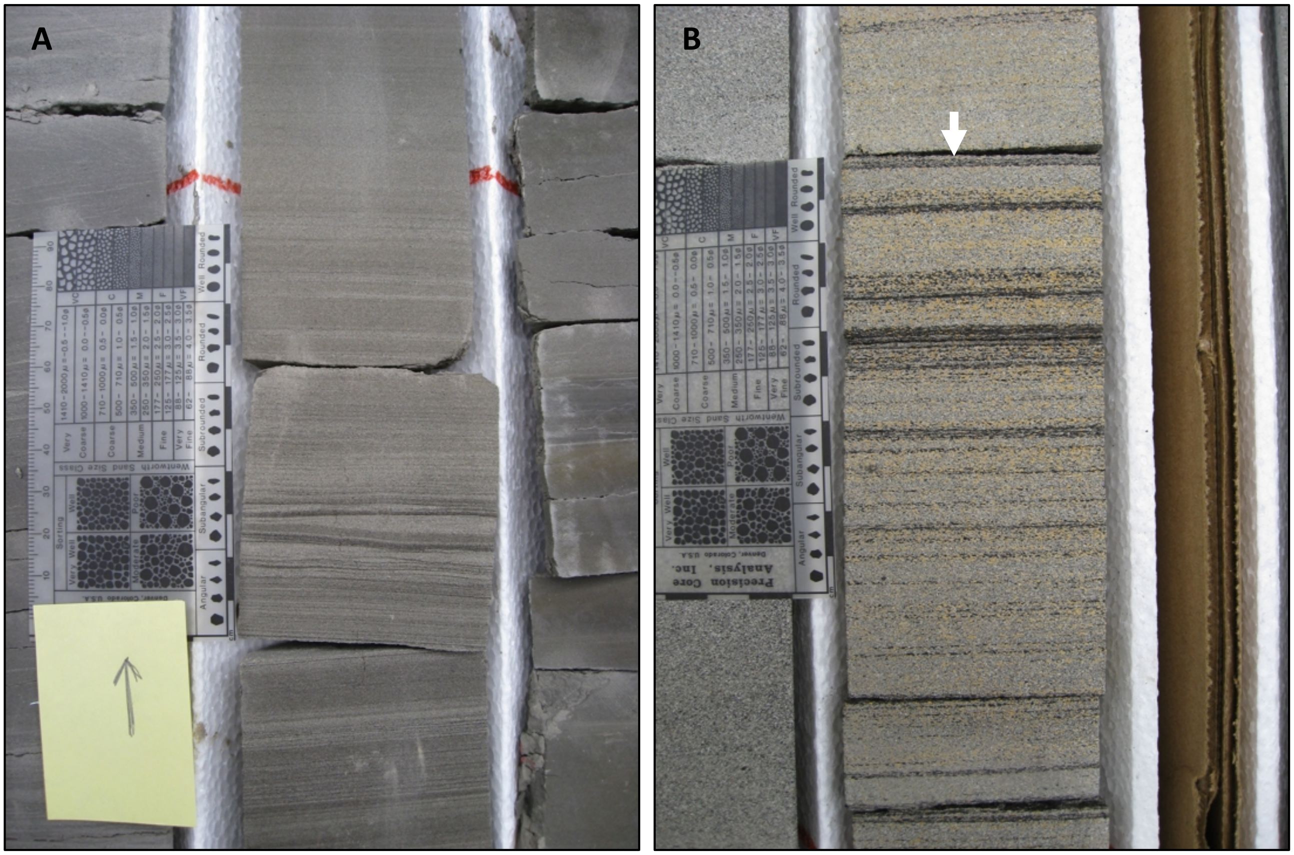
Sm—MASSIVE SANDSTONE

Description

Facies Sm consists of light gray to light brown, very-fine- to medium-grained sandstone in beds 0.01 to 1.0 ft (0.3–30 cm) thick characterized by an apparent lack of sedimentary structures (fig. 2-10). Sandstones of this facies have sharp bounding contacts with underlying facies, whereas the upper contact with mudstone can be sharp or gradational. Plant fragments ranging in size from coffee grounds (fine sand-size) to greater than 0.1 ft (3 cm) are present locally as thin, discontinuous drapes. Pebbles are present locally and include light gray chert, siderite, and mudstone rip-ups (fig. 2-10). Thin siderite-cemented zones or bands are also present. Bioturbation ranges from absent (II 1) to moderate (II 3–4). Where bioturbation is present, discrete traces of known affinity have not been identified.

Interpretation

Facies Sm is interpreted to record rapid deposition with limited or no subsequent traction transport sufficient for equilibrium bedforms to develop (Collinson, 1968; Bhattacharya and Walker, 1991). It is possible that grain-



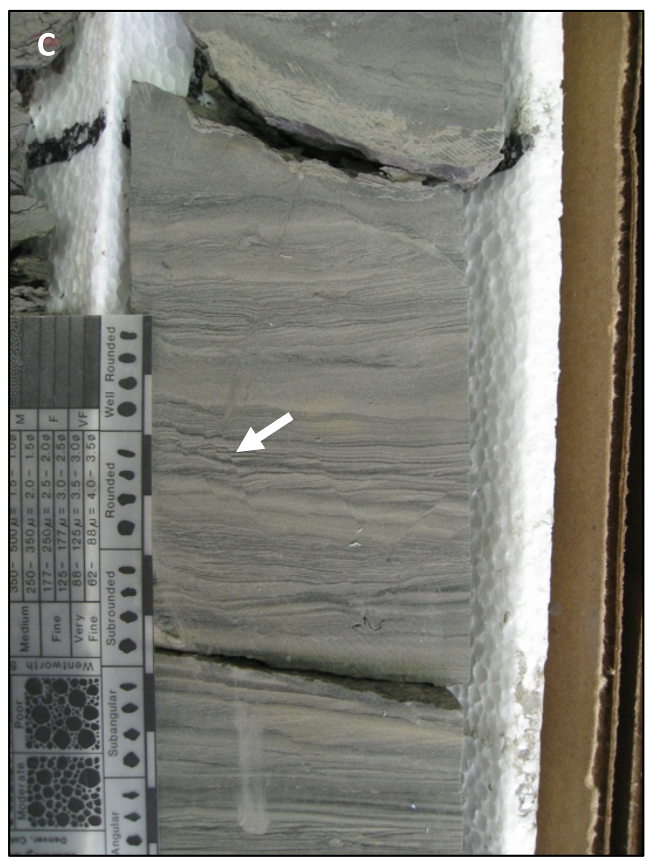


Figure 2-9. Photographs showing selected features in the plane-parallel laminated sandstone facies (Slf and Slm). Scale on edge of grain-size comparator in photos A–C is marked in centimeters. **A.** Well-developed plane-parallel laminae in facies Slf near 624 ft (red line on core tray). **B.** Plane-parallel lamination in facies Slm at 651.5 ft (white arrow). Dark-colored laminae are rich in carbonaceous debris. **C.** Plane-parallel laminae disrupted by small-scale normal faults at approximately 1,318.3 ft (white arrow) in facies Slf.

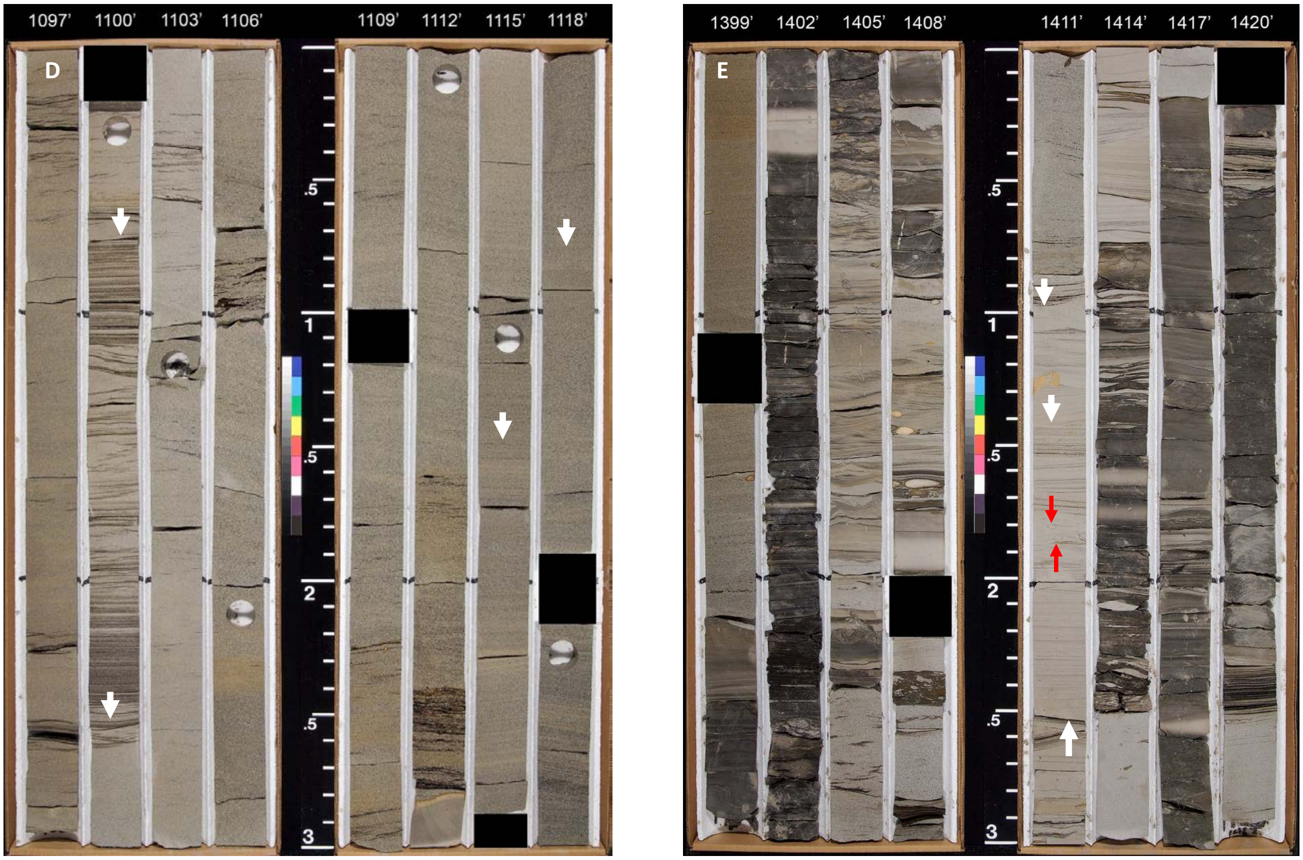


Figure 2-9 (continued). Photographs showing selected features in the plane-parallel laminated sandstone facies (Slf and Slm). **D.** Plane-parallel laminated sandstone (facies Slm) in a channel-fill succession between 1,100.7 and 1,102.5 ft (white arrows). **E.** Possible hummocky cross-stratification between 1,412 and 1,413.5 feet (white arrows). Red arrows show possible *Paleophycos* burrows.

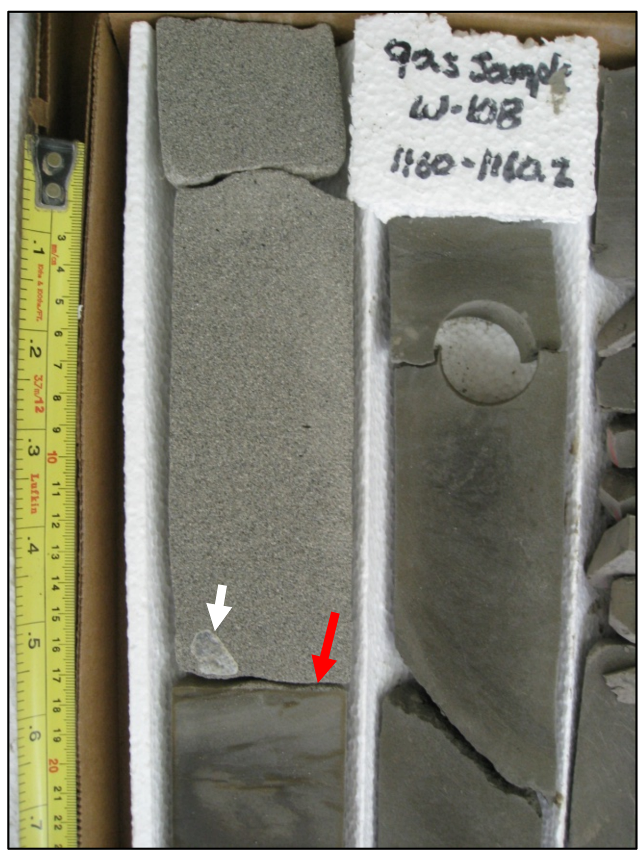


Figure 2-10. Photograph showing massive sandstone (facies Sm) at a depth of 1,157 ft. The contact at 1,157.8 ft (red arrow) marks the base of a thick, amalgamated channel complex (amalgamated distributary channel fills) that extends upsection to a depth of 1,060.5 ft. Note chert pebble (white arrow). The distributary channel fill truncates disrupted sandy siltstone interpreted as subaqueous levee deposits (below chert pebble and in core on right side of photo). Tape measure marked in centimeters along right edge and tenths of a foot along left edge.

size contrasts and compositional variations are so slight in this facies that sedimentary structures are effectively masked. Without other investigative tools, this possibility is difficult to test.

Scb—CONVOLUTE LAMINATED SANDSTONE

Description

Facies Scb consists of light gray to light brown, very-fine- to fine-grained sandstone in beds less than 0.01 ft (much less than 1.0 mm) thick to greater than 1.0 ft (30 cm) thick that are characterized by deformed laminae (figs. 2-11A–E). Sandstones typically have sharp bounding contacts with mudstones or other sandstone beds; however, gradational upper contacts with muddy lithologies are present. Deformation includes steeply dipping, wavy laminae, tight upright and recumbently folded laminae, broken laminae, detached and folded masses of sandstone encased in mudstone and siltstone (figs. 2-11D–E), and a variety of combinations of these deformation styles. Deformation typically results in a chaotic appearance that is accentuated by the presence of interlaminated mudstone. Original sedimentary structures are recognizable and include plane-parallel lamination and ripple cross-lamination; massive laminae are also present (fig. 2-11E). Siderite as clasts and irregular-shaped nodules is present locally. Bioturbation ranges from absent (II 1) to moderate (II 3–4). Trace fossils include *Phycosiphon* (and/or *Helminthopsis*), *Rhizocorallium*, *Skolithos*, *Teichichnus*, *Thalassinoides*, and *Planolites*. No single bed includes all of these traces and most beds include only a few genera.

Interpretation

Facies Scb records sand beds that were originally deposited as facies Sr, Sl, and Sm and subsequently deformed prior to lithification. Plausible deformation mechanisms include: (1) subaqueous deposition of sand on lower-density, uncompacted mud and subsequent foundering of the sand bed (Allen, 1984); (2) subaqueous deposition of sand on an inclined surface and subsequent deformation from downslope creep and/or sliding (Allen, 1984); (3) subaqueous sand deposition and subsequent deformation by gas escaping from underlying mud with decaying terrestrial plant material (Coleman and others, 1964); (4) sand deposition and subsequent deformation by large organisms (such as dinosaurs—"dinoturbation"; Fiorillo and others, 2010); (5) subaqueous sand deposition and subsequent deformation from frictional drag at the interface between a sandy bedform and an overlying moving water column (Allen, 1984); and (6) seismogenic shaking (Greb and Dever, 2002). Given the nature of sediment deformation in the Wainwright core, each of the first three mechanisms could have contributed, at least locally, to soft-sediment deformation features recognized in this facies. The fourth mechanism—deformation by large organisms (dinosaurs)—was clearly operating in nonmarine and very shallow marginal marine settings on the North Slope during middle Albian time, as recently documented by Fiorillo and others (2010). Mechanisms 1, 3, and 4 most likely contributed to some soft-sediment deformation features observed in the Wainwright core. Deformation by frictional drag is considered unlikely, judging from a lack of preferred orientation of bed dips. Given the tectonic setting (foreland basin), mechanism 6 is possible but difficult to test.

Sb—BURROW-MOTTLED SANDSTONE

Description

Facies Sb consists of light gray to light brown, very-fine- to fine-grained sandstone in beds 0.02 to 0.6 ft (0.6–18.3 cm) thick, characterized by burrowed fabrics. Bounding contacts with other beds are typically sharp. This facies is differentiated from the other sandy facies by the higher degree of bioturbation: beds are typically moderately to highly bioturbated (II 3–4; fig. 2-12). Recognizable traces include *Phycosiphon*, *Skolithos Teichichnus*, and *Thalassinoides*. *Diplocraterion* and *Rosselia* may be present in some beds. Reburrowed traces are present locally (fig. 2-12, *Phycosiphon* in *Teichichnus*). Facies Sb is rare in the Wainwright #1 core.

Interpretation

Facies Sb records reworking of sand beds at or very near the depositional surface by burrowing organisms. The trace fossils recognized are all common in shallow marine shoreface and proximal shelf settings (*Cruziana* and *Skolithos* ichnofacies assemblages; Pemberton and others, 1992), and the genera recognized define a relatively moderate- to high-diversity assemblage. This suggests colonization of sandy substrates in subaqueous settings characterized by hospitable conditions for a burrowing infauna. We interpret this facies to record pauses in sedimentation or complete abandonment of depositional sites following storm events in marine-influenced settings characterized by near normal to normal marine salinities (MacEachern and others, 2007a; Howard, 1975).

Sfh—HETEROLITHIC SANDSTONE AND MUDSTONE

Description

Facies SFh consists of a heterolithic association of thinly interbedded light gray to light brown very-fine- to fine-grained sandstone and dark gray to dark brown mudstone. Sandstone and mudstone beds range from less than 0.01 to 0.5 ft (0.3–15.2 cm) thick and alone each would be assignable to one of the sandstone facies (Slf, Sr, or Sm) or mudstone facies (Fl or Fm) described above (except facies C; figs. 13A–E). Sandstone contacts with underlying mudstone are sharp and range from wavy planar (figs. 13C–E) to irregular (figs. 13A–B); upper contacts range from sharp to gradational and many sandstone beds are normally graded (fig. 2-13D). The presence of gutter casts attests to the erosive nature of some of the flows that

Figure 2-11. Photographs showing selected features in the convolute-bedded sandstone facies (Scb). Scale on edge of grain-size comparator in all photos is marked in centimeters. **A.** Convolute-bedded sandstone at a depth of 1,487 ft (black line in middle core tray). In its undeformed state this sand was likely plane-parallel laminated. **B.** Steeply dipping rumpled laminae in muddy sandstone (white arrow) at a depth of approximately 1,210.4 ft. Note possible small-scale fault offsets (at and to the right of red arrow). **C.** Deformed mudstone and sandstone at a depth of 1,219.5 ft. Note the vertical escape burrow filled with sandstone in the laminated interval above the deformed package (white arrow). Note also the small-scale high-angle reverse fault (red arrow).

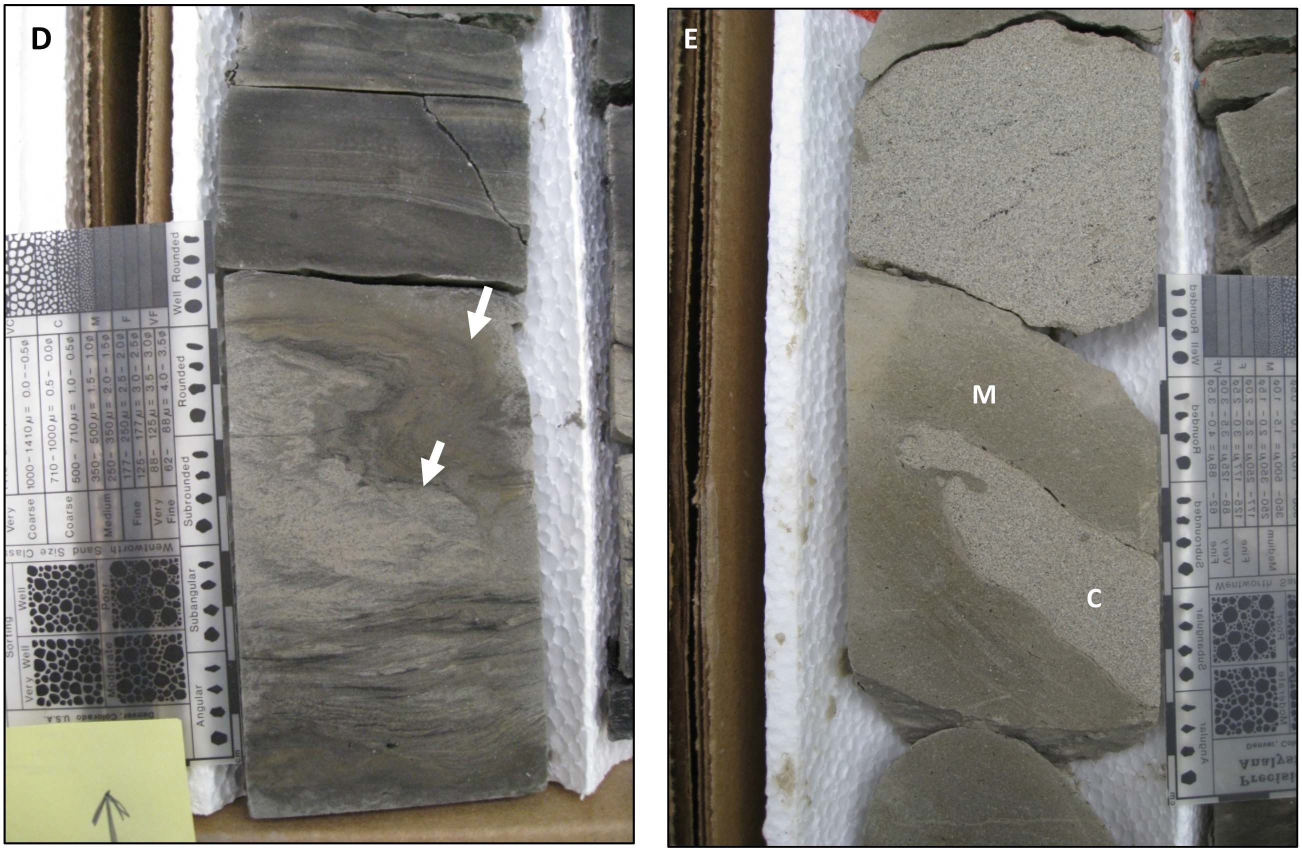


Figure 2-11 (continued). Photographs showing selected features in the convolute-bedded sandstone facies (Scb). Scale on edge of grain-size comparator in all photos is marked in centimeters. **D.** Convolute bedded mudstone and sandstone (white arrows) at a depth of 114.5 ft. **E.** Finger-shaped protrusion of clean sandstone (white C) that projects upward into muddy sandstone (white M) at a depth of 595.5 ft.

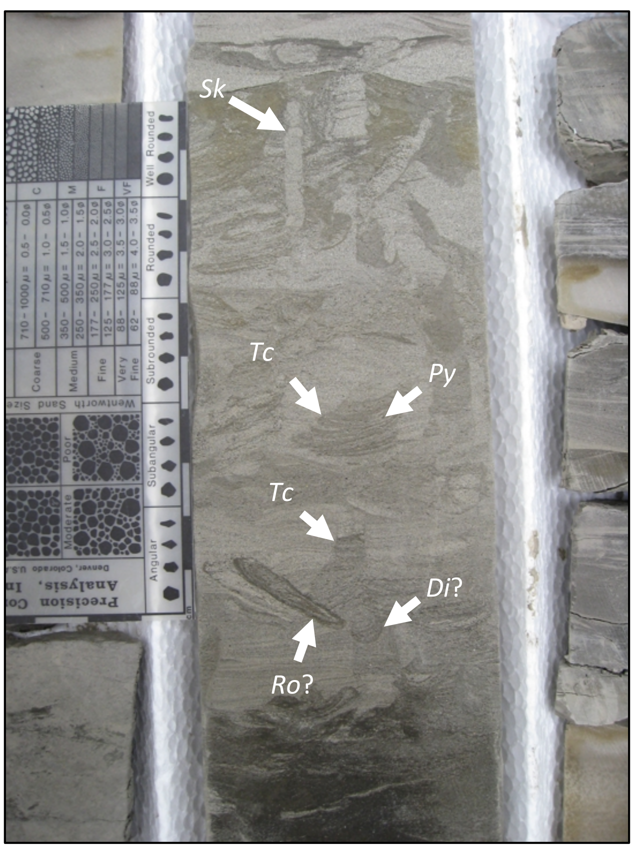
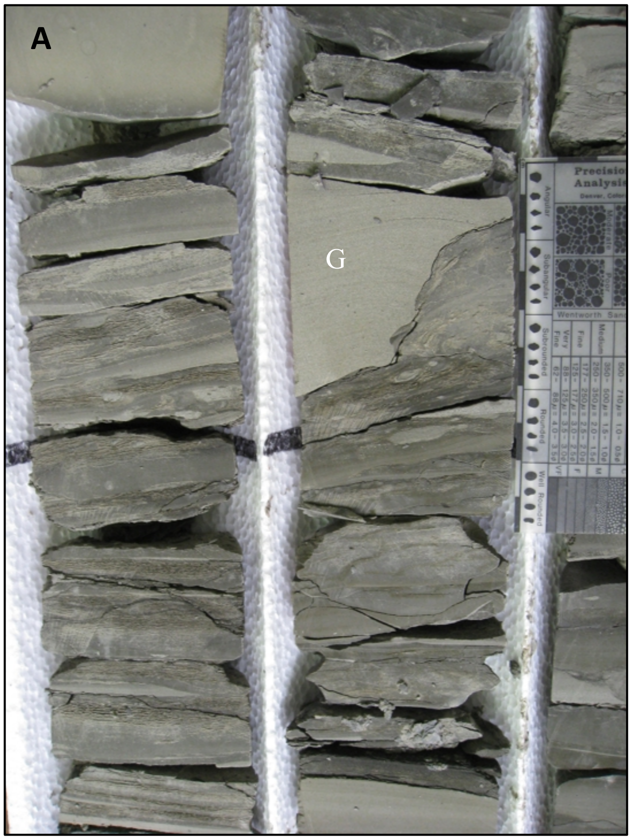
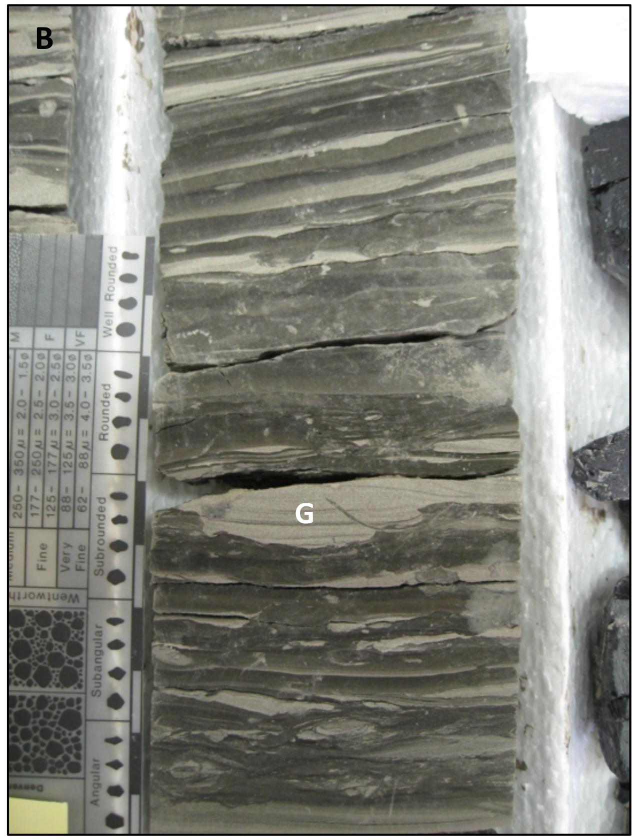


Figure 2-12. Photograph showing selected features in the burrow-mottled sandstone facies (Sb). Scale on edge of grain-size comparator in photo is marked in centimeters. Bioturbated sandstone at a depth of 717.5 ft (II 4) shows visible trace fossils, including ***Teichichnus* (Tc), *Skolithos* (Sk), *Phycosiphon* (Py)** (or ***Helminthopsis***); and possible ***Diplocraterion* (DI)** (some ***Skolithos*** could be ***Diplocraterion***) and ***Rosselia* (Ro)**. Note ***Phycosiphon*** or ***Helminthopsis*** traces within ***Techichnus*** traces.





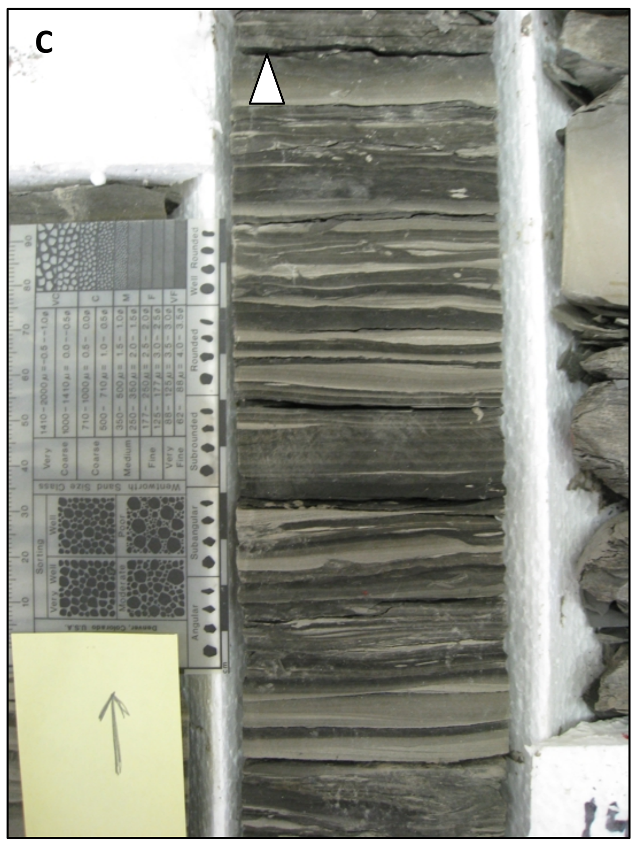


Figure 2-13. Photographs showing selected features in the heterolithic sandstone and mudstone facies (SFh). Scale on edge of grain-size comparator in all photos is marked in centimeters. **A.** Thinly interbedded sandstone and mudstone of facies SFh near a depth of 1,579 ft (black line on core tray at left). Note the relatively large gutter cast (white G), indicating that at least some of the flows that transported sand to this location were highly erosive. **B.** Thinly laminated sandstone and mudstone of facies SFh at a depth of approximately 1,455.5 ft. Note the small gutter cast (white G). **C.** Interlaminated sandstone and mudstone of facies SFh at a depth of 1,454.5 ft. Note subtle normal grading in some sandstone laminae (white triangle).

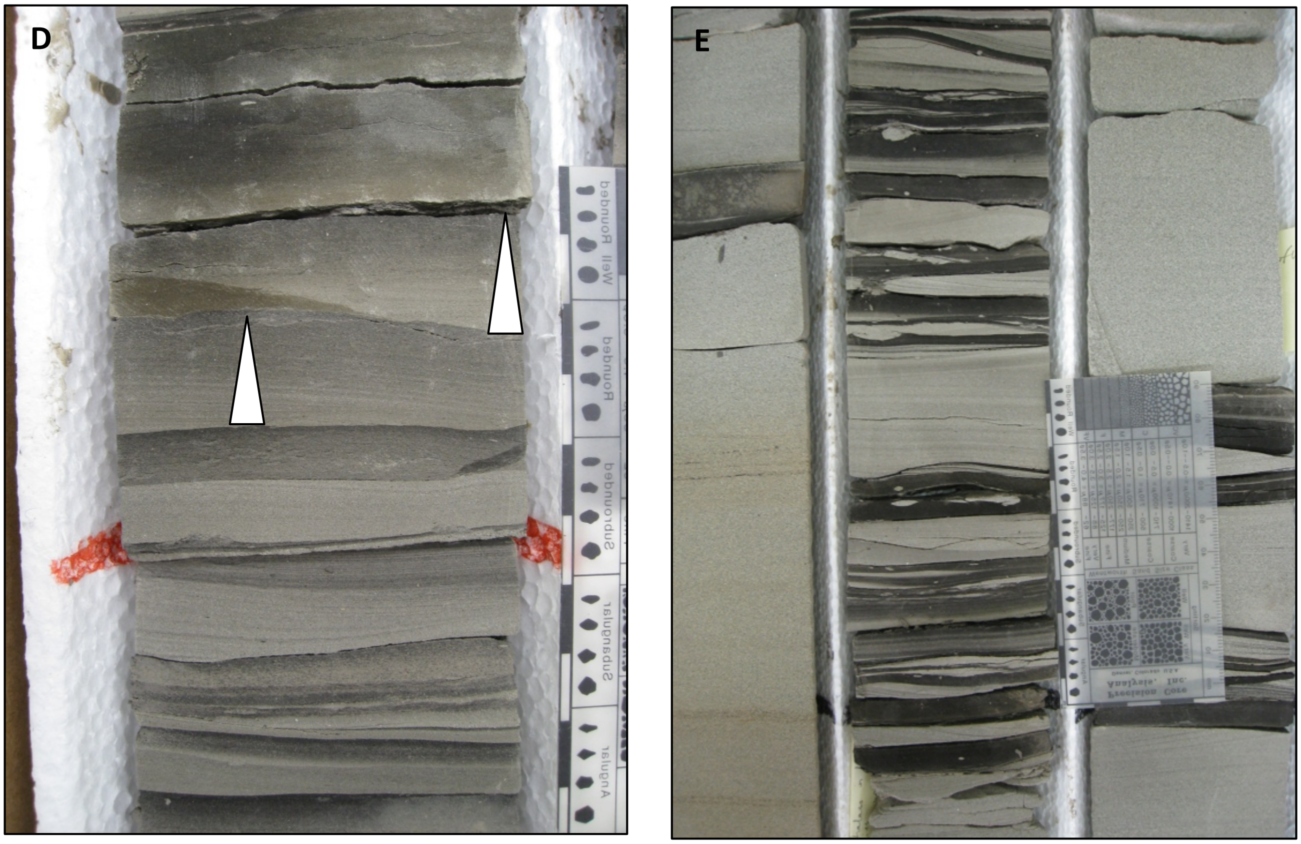


Figure 2-13 (continued). Photographs showing selected features in the heterolithic sandstone and mudstone facies (SFh). Scale on edge of grain-size comparator in all photos is marked in centimeters. **D.** Normally graded sandstone (white triangles) and minor interbedded mudstone of facies SFh at a depth of 607 ft (red line in core tray). **E.** Interbedded sandstone and mudstone of facies SFh at a depth of 1,476 ft (black line in center core tray). Note the relatively thick sandstone beds in this example of facies SFh (middle core).

transported sand to the depositional site (figs. 13A–B). Definition of this facies is more arbitrary than others in the core: it is the presence of thinly interlaminated sandstone and mudstone in roughly equal abundance forming a repetitive succession that distinguishes facies SFh from other facies. Bioturbation ranges from II 1 to II 3. *Skolithos* is the only genera recognized.

Interpretation

Facies SFh records deposition under fluctuating energy conditions. Sand and coarse silt were transported to the depositional site as bedload and suspended load by turbulent flows associated with relatively-high-energy events. Graded sandstone beds indicate deposition from waning density currents—possibly hyperpycnal flows—though the classic signature of such deposits has not been recognized in this core (Mulder and others, 2003, their fig. 2-9). Interbedded mudstones record deposition from suspension during the waning phase of high-energy events and suspension settling during the intervening lower-energy periods. Given only this one core it is difficult to be more specific in interpreting this facies. Periodic fluctuation in flow strength and direction due to tides is a reasonable interpretation (Thomas and others, 1987; Nio and Yang, 1991) as is episodic overbank flooding and deposition on subaqueous levees (Coleman and others, 1964; Elliot, 1974).

FACIES ASSOCIATIONS AND DEPOSITIONAL SETTING

The 12 facies outlined in the previous section combine to define six facies associations that, collectively, record deposition in lower delta plain to upper delta plain (upper 190 ft of core) settings (fig. 2-19). These correspond closely to the depositional record of several subenvironments on the delta plain of the Mississippi River (Fisk and others, 1954; Coleman and Gagliano, 1965; Bhattacharya, 2006), including interdistributary bays, distributary channels, crevasse channels, minor mouth bars/crevasse deltas, and channel levees. Like most delta plain successions, facies associations comprising the Wainwright core stack to form a complex succession (compare Fisk and others, 1954; Coleman and others, 1964; Fisher and others, 1969; Horn and others, 1978; Bhattacharya and Walker, 1991). Unequivocal interpretation of the depositional environment is difficult for many segments of the core due to the one-dimensional view afforded by a single core through a complex suite of deltaic subenvironments.

Trace fossils and bioturbation fabrics provide valuable information that helps in constraining environmental interpretations of the Wainwright core. Lower delta plain settings in high-constructional, river-dominated deltas are characterized by low-lying marsh and swamp lands interrupted by lakes and interdistributary bays (Fisher and others, 1969). With the constant input of fresh water from riverine sources, water over most of the lower delta plain is fresh to brackish (Coleman and others, 1964). Bioturbation is common in the lower 1,300 ft of the Wainwright core. Most of the identifiable trace fossils are common components in open marine siliciclastic shelf, shoreface, and deltaic successions and include traces assignable to either the *Cruziana* or *Skolithos* ichnofacies assemblages (MacEachern and others, 2007a; Pemberton and others, 1992). Trace fossils recognized include *Diplocraterion*(?), *Skolithos*, *Rhizocorallium*, *Rosellia*(?), *Teichichnus*, *Thalassinoides*, *Paleophycos*, *Phycosiphon* (and/or *Helminthopsis*), and *Planolites*. These genera, taken as an assemblage, resemble high-diversity assemblages in settings characterized by normal marine salinities (Pemberton and others, 1992; MacEachern and others, 2007a). Despite their recognition in the Wainwright core, most bioturbated beds include only a few genera (some only one) and, as a result, are interpreted as low-diversity assemblages that record ecological stress (Pemberton and Wightman, 1992; MacEachern and others, 2007b). The beds with many genera probably record short-lived perturbation of "normal" conditions for the depositional sites that allowed a diverse infaunal assemblage to persist for a brief period.

Bioturbation ranges from absent (II 1), to one or two recognizable traces in an otherwise undisturbed bed (II 2) interstratified with beds that appear undisturbed, to single beds and successions (multiple beds) that are moderately bioturbated (II 3–4). The trace fossil assemblages and their distribution demonstrate a persistent marine influence during deposition of the lower 1,300 ft of the cored succession and, at times, water may have approached normal marine salinities.

Facies associations are briefly described and interpreted in this section, followed by a depositional model that integrates features recognized in the Wainwright #1 core.

INTERDISTRIBUTARY BAY

The interdistributary bay association is composed of several facies including massive mudstone (Fm), laminated mudstone (Fl), laminated fine-grained sandstone (Slf), ripple cross-laminated fine-grained sandstone (Sr), massive sandstone (Sm), minor burrow-mottled sandstone (Sb), minor convolute-bedded sandstone (Scb), heterolithic sandstone and mudstone (SFh), carbonaceous mudstone (Fc), and coal (sheet 2-1). Mudstone facies are most abundant and interbedding of the various facies forms a complex succession (fig. 2-14). This complexity is reflected in the gamma-ray profile, which is typically highly serrated (sheet 2-1). Many sandstone and mudstone beds are bioturbated (facies Sb and Fm?) with ichnofabric indices ranging from II 2 to II 4. The interdistributary bay association envelops most of the remaining associations.

The suite of facies outlined above records deposition in low-energy, shallow-water settings between deltaic distributary channels. The facies association is similar to modern interdistributary bay deposits described from the lower delta plain of the Mississippi River in classic works by Coleman and others (1964) and Coleman and Gagliano (1965), and closely resembles deposits recognized in many ancient deltaic successions (Carboniferous of southwestern England by Collinson, 1968; Elliott, 1976; Carboniferous of eastern North America by Horn and others, 1978; Cenomanian of northwestern Alberta by Bhattacharya and Walker, 1991; Late Cretaceous of Utah by Ryer and Anderson, 2002). Interdistributary bay deposits have been recognized elsewhere in the Nanushuk Formation by Huffman and others (1985, 1988), LePain and Kirkham (2001), and LePain and others (2008; 2009).

The interdistributary bay setting was interrupted episodically by incursions of coarser-grained sediment as flood waters in nearby channels overtopped poorly developed levees and transported fine-grained sand in suspension and as bedload in sheet flows depositing facies Slf, Sr, Sm, and Scb (fig. 2-14). Mudstones containing a few thin sandstone interbeds record splay deposition in settings distal to channels, whereas many thin to thick sandstone beds and amalgamated sandstone beds indicate deposition proximal to active channels. Wave-ripple cross-lamination in some sand beds indicates local reworking by short-period waves (shallow water). Trace fossils recognized in this association define a low-diversity assemblage consistent with deposition in a brackish water setting (Pemberton and Wightman, 1992). Syneresis cracks recognized at a depth of 1,532 ft indicate fluctuating salinity, which is consistent with deposition in an interdistributary bay setting characterized by frequent changes in the relative supply of freshwater and seawater.

The scarcity of storm-wave-generated structures (possible hummocky cross-stratification only at approximately 589 ft, between 513 and 514 ft, between 1,412 and 1,413 ft, and at 1,475.5 ft; sheet 2-1; figs. 2-9E and 14) is consistent with deposition in low-energy bays protected from open marine conditions. Coal and carbonaceous mudstone are relatively common and demonstrate the presence of peat swamps along the perimeter of many bays in locations removed from sources of coarse-grained sediment (Fisher and others, 1969; Horn and others, 1978; Bhattacharya and Walker, 1991).

The thick interdistributary bay-fill succession between 1,242 and 1,495 ft is a good example of this association (sheet 2-1). This interval includes thinly laminated mudstone that accumulated in a quiet-water setting distal to active channels—the thin laminations indicating little, if any, disturbance by burrowing organisms after deposition (sheet 2-1; fig. 2-14; 1,375.5–1,396 ft). This interval also includes a succession of interbedded mudstone (largely

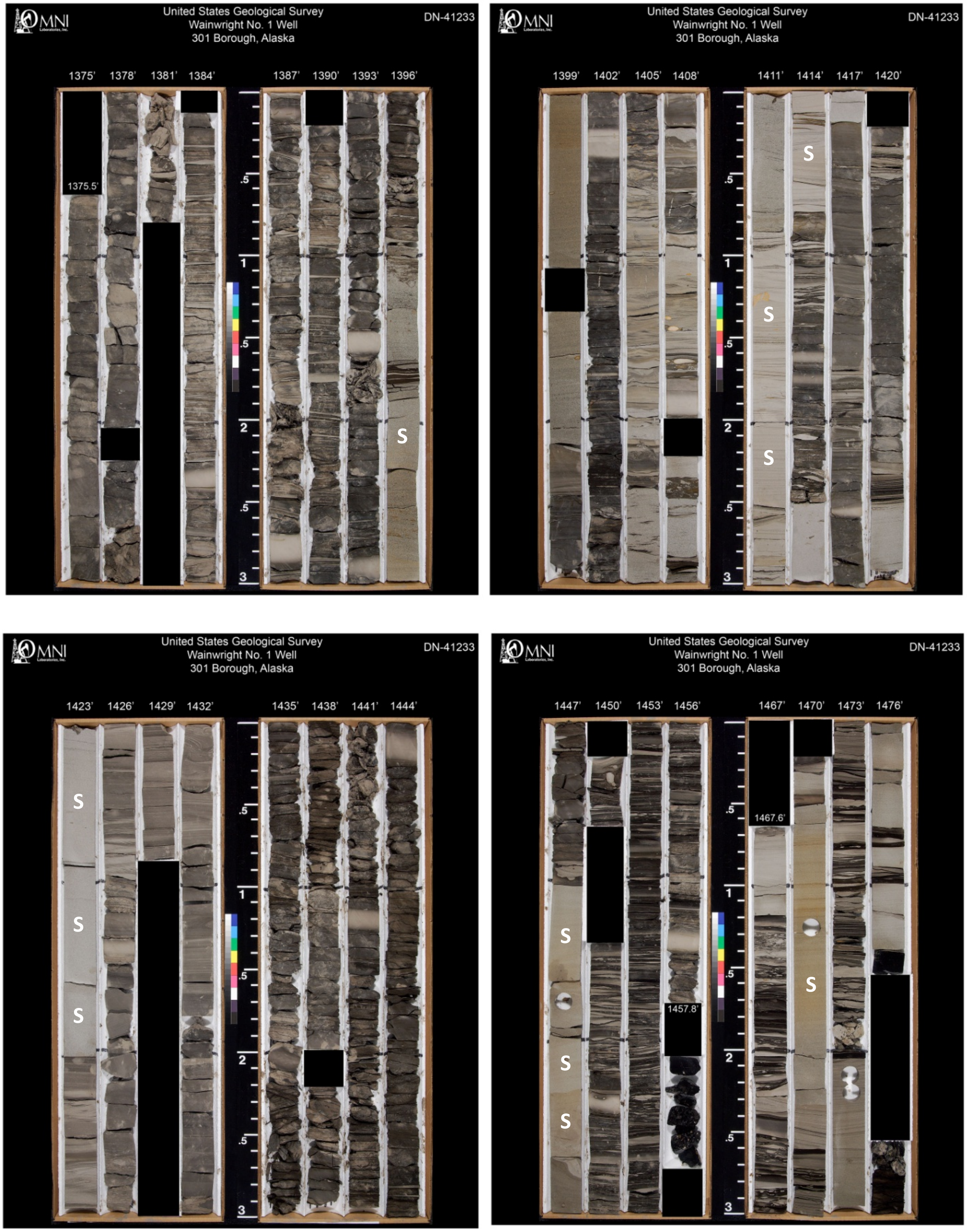


Figure 2-14. Core photos, showing the typical expression of the interdistributary bay association. The base of the succession shown is at a depth of 1,479 ft, corresponding to the lower right corner of the lower right photo; the top of the succession shown is at a depth of 1,375 ft, corresponding to the upper left corner of the upper left photo. The interdistributary bay succession consists of dark brown to dark gray mudstone with numerous thin sandstone laminae and several thicker sandstone beds interpreted as tabular crevasse-splay deposits. Sandstones are light tan to light reddish tan; selected beds are marked with a white S. The black rectangles correspond to coals that were removed for laboratory analysis.

Fl with minor Fm and Fc) and sandstone (Slf, Sr, and Scb) interpreted as splay sand sheets (fig. 2-14; 1,396–1,476 ft).

CHANNEL

The channel association consists of cross-bedded sandstone (Sx), fine- to medium-grained, plane-parallel laminated sandstone (Slm), massive sandstone (Sm), and ripple cross-laminated sandstone facies (Sr; sheet 2-1). The association has sharp bounding contacts with mudstones of the interdistributary bay association and sandy siltstones and thin sandstones of the levee association. The lower contact is erosive and the association is characterized by a fining-upward grain-size motif and barrel- to bell-shaped gamma-ray profile. Fine- to medium-grained cross-bedded sandstone (Sx) and plane-parallel laminated sandstone (Slm) comprise the lower and middle portion of most channel fills; these facies grade upsection to fine-grained, ripple cross-laminated sandstone. Internal erosion surfaces are common and are often overlain by siderite clast or mudstone chip lags.

A thick succession from 1,060.5 to 1,157.7 ft includes at least two fining-upward successions interpreted as two amalgamated channel fills (distributary channels; sheet 2-1; fig. 2-15). The lowest is capped by a siderite band a few inches thick (at 1,095.6 ft), whereas the uppermost foot or so of the upper fining-upward succession includes rhizoliths and is overlain by carbonaceous mudstone of the interdistributary bay association (fig. 2-15, above 1,060.5 ft). Collectively, the fine-grained, ripple cross-laminated sand, siderite bands, and rhizoliths (only in the uppermost succession) capping these two channel-fill successions indicate waning flow and channel abandonment. The upper fining-upward succession either represents rejuvenation of the same channel or reoccupation of the same location by a different channel. Repetitive mudstone drapes on sandstone between 1,153.3 and 1,154.5 ft, and interbedded, fine-grained, ripple cross-laminated sandstone (facies Sr) and plane-parallel-laminated sandstone (facies Slm and Slf), both including mud drapes, between 1,100 and 1,102.5 ft, suggest a tidal influence (fig. 2-15). Rhizoliths capping the uppermost succession (1,060—1,061 ft) indicate the depositional surface was either emergent or in shallow enough water that marsh-type plants were able to grow.

The facies composition and thickness of channel fills recognized in the Wainwright core are comparable to channel deposits recognized in other ancient deltaic successions (Dunvegan Formation of Bhattacharya and Walker, 1991; Ferron Sandstone of Ryer and Anderson, 2002; Wilcox Group of Galloway, 1968), and in outcrops of the Nanushuk Formation (McCarthy, 2003; LePain and others, 2009). Subsurface data suggest the amalgamated channels from 1,060.5 to 1,157.7 ft and 619.3 to 667 ft are part of channel belts that have regional extent in the depositional dip direction (northeast to the east; Decker, 2016 [this volume]). If the 97-ft-thick succession shown in fig. 2-15 and discussed in the previous paragraph is the depositional record of a single channel, it was comparable in size (at least scour depth) to the modern Mississippi River along its lower reaches in Louisiana (see channel cross-sections in Fisk, 1947).

CREVASSE CHANNEL

The crevasse channel association consists largely of ripple cross-laminated sandstone (Sr), and minor fine-grained, plane-parallel laminated sandstone (Slf), massive sandstone (Sm), and convolute bedded sandstone (Scb). This association has a sharp lower contact with mudstone, can have a sharp or gradational upper contact with mudstone, and has a fining-upward grain-size motif and blocky- to bell-shaped gamma-ray profile (sheet 2-1; fig. 2-16, base; fig. 2-17, 587.5 to 593.3 feet). The crevasse channel association is differentiated from the distributary channel association by sediment grain size and total thickness—the former being thinner and consisting of finer-grained sand. With these criteria, it is still possible that some occurrences of the distributary channel association have been misidentified as crevasse channel fills. Further blurring this distinction is that large crevasse channels can evolve into major distributaries under the right conditions (Elliot, 1974).

The crevasse channel association represents the fill of relatively long-lived channels that cut through distributary channel levees. Channels were cut during major flood events and acted as conduits for transporting relatively coarse-grained sediment to quiet water settings in adjacent interdistributary bays (Coleman and others, 1964; Elliott, 1974). The fining-upward grain-size trends recognized in some crevasse channel fills record waning flow and gradual abandonment. Bioturbation, if present, is limited to the upper part of crevasse channel fills, indicating that flow velocities were too strong and/or freshwater from the feeder channels made conditions inhospitable for burrowing organisms when channels were active (fig. 2-16). Burrowing organisms (or colonizing plants) were able to colonize the substrate only after channels were abandoned and sedimentation rates were greatly reduced (Elliott, 1976).

MINOR MOUTH BAR/CREVASSE DELTA

The minor mouth bar/crevasse delta association, referred to hereafter as the mouth bar association, consists of laminated mudstone (Fl), massive mudstone (Fm), ripple cross-laminated sandstone (Sr), fine-grained plane-parallel laminated sandstone (Slf), convolute-bedded sandstone (Scb), and heterolithic sandstone and mudstone (SFh; sheet 2-1). The mouth bar association gradationally overlies interdistributary bay deposits and is overlain abruptly by either crevasse channel-fill deposits or additional interdistributary bay deposits. A prominent coarsening-upward grain-size trend characterizes this association and examples typically grade upward from mudstone or interbedded mudstone and sandstone near the base to dominantly sandstone near the top (sheet 2-1;

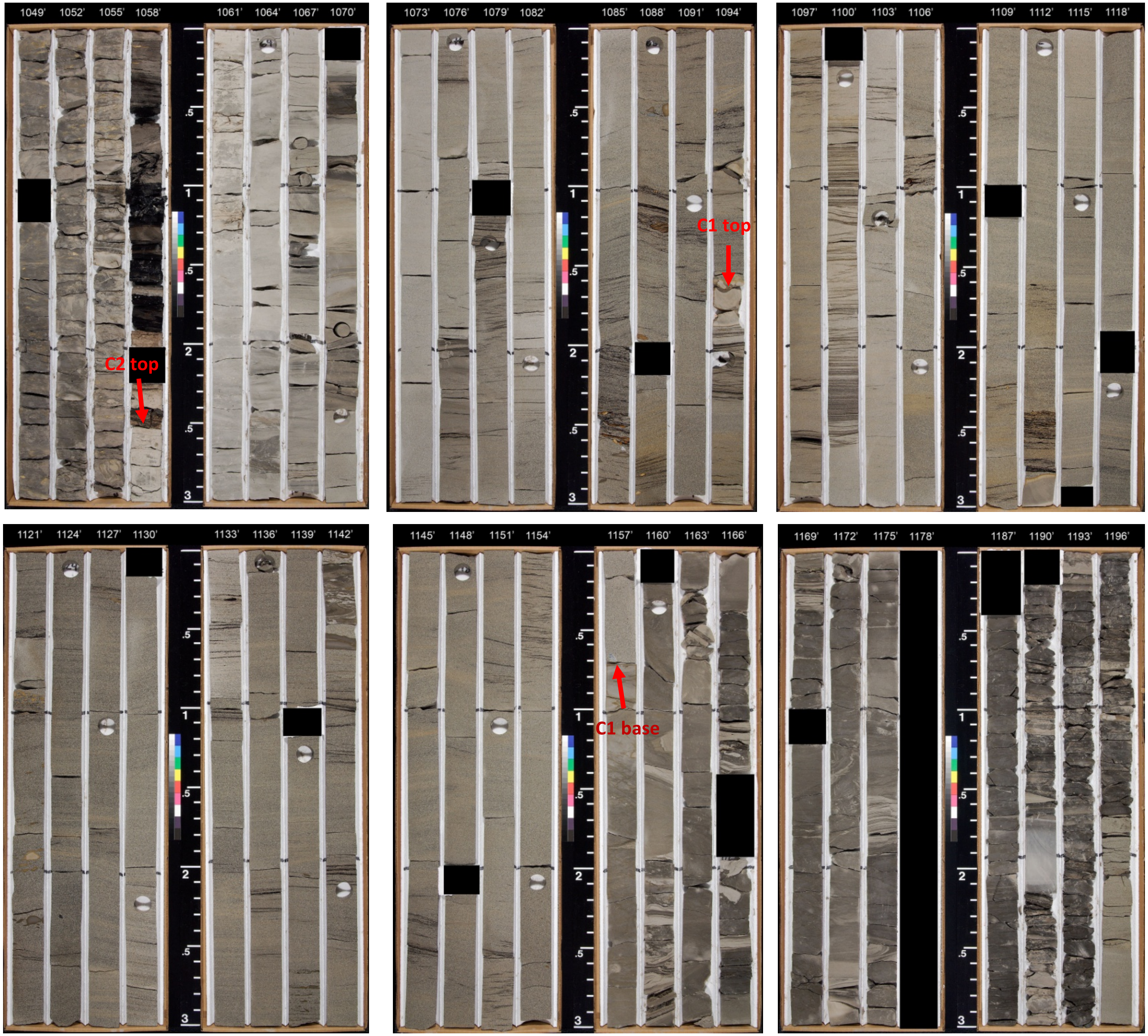


Figure 2-15. Core photos, showing a 97-ft-thick sandstone succession interpreted as an amalgamated package of at least two distributary channel fills. The oldest channel fill extends from 1,095.6 ft to the base of the package at 1,157.7 ft (C1 top and base, respectively, on core photograph), and the youngest channel fill extends from 1,060.5 ft (C2 top on core photograph) to 1,095.6 ft. The coarsening-upward succession (indicated by the gradual color change upsection from medium gray to light gray and tan) between 1,170 ft and the base of the lower channel fill at 1,157.8 ft is interpreted as a subaqueous levee deposit.

fig. 2-17; approximately 593.3 to 601 ft). The association records gradual progradation of mouth bars into quiet water interdistributary bay settings from the downstream ends of crevasse channels (Fisk and others, 1954; Coleman and others, 1964; Elliot, 1974).

The vertical succession through this association closely resembles mouth bar deposits recognized in modern interdistributary bay successions of the Mississippi River (Fisk and others, 1954; Coleman and others, 1964; Coleman and Gagliano, 1965; Elliott, 1974) and in ancient deltaic successions (Elliott, 1976; Horn and others, 1978; Bhattacharya and Walker, 1991), including the Nanushuk Formation (LePain and Kirkham, 2001; McCarthy, 2003; LePain and others, 2009). Examples that include mudstone at their base and culminate in amalgamated sandstone beds record a complete progression from distal mouth bar to crevasse channel deposits (fig. 2-17; 587.5 to 593.3 ft, interpreted as crevasse channel fill).

Most examples of this association in the Wainwright core lack wave-ripple cross-lamination, a structure that is commonly recognized in mouth bar deposits from other deltaic successions. The absence of wave-formed structures suggests deposition in low-energy bay settings below fair-weather wave base. Fair-weather wave base in open marine settings lies between 16 and 50 ft (Walker, 1984) and is likely to occur at much shallower depths in protected bays such that mouth bar deposits could easily escape reworking by waves if the depositional surface did not build to within a few feet of the water surface. Gradual subsidence from compaction of underlying muds further ensured these mouth bar sands escaped wave reworking.

CHANNEL LEVEE

The channel levee association consists of laminated and massive mudstone (facies Fl and Fm) and convolute bedded sandstone (Scb; sheet 2-1). Soft-sediment deformed beds,

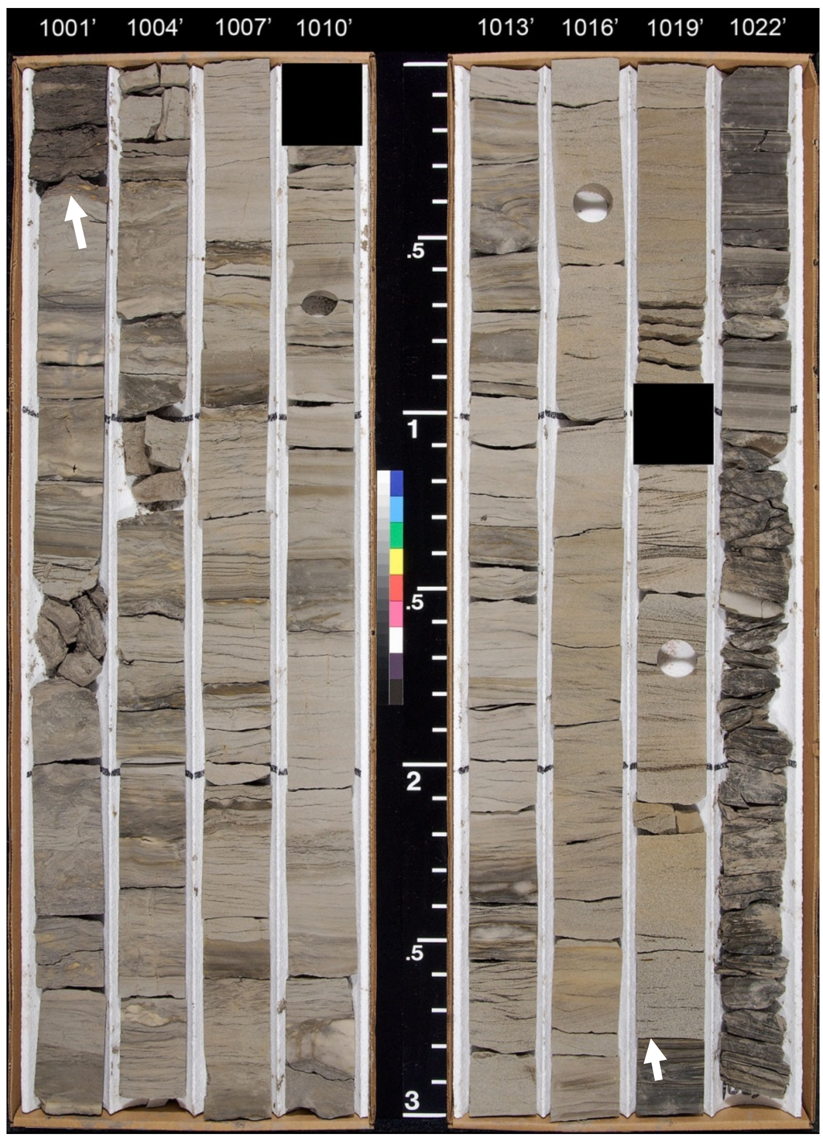


Figure 2-16. Core photo, showing a fining-upward succession between 1,001.4 and 1,021.8 ft, interpreted as the fill of a crevasse channel. Note the sharp contact with underlying mudstones of the interdistributary bay association (white arrow at 1,021.8 ft) and the fining-upward grain-size motif indicated by the gradually increasing mud content in channel fill (gradually increasing number of dark-colored beds toward the top of the package, from approximately 1,001.4 to 1,015.6 ft). The contact with overlying mudstones is sharp (white arrow at 1,001.4 ft). The fining-upward motif records gradual abandonment of the crevasse channel.

bioturbation textures, and in-place siderite(?) concretions are characteristic of this association. The basal contact with underlying associations (most commonly interdistributary bay) is gradational (sheet 2-1; fig. 2-15; ~1,175 to 1,193 ft recording a transition from bayfill to distal levee), whereas the upper contact is typically sharp (fig. 2-15; 1,157.7 ft). The association is characterized by a subtle to prominent coarsening-upward grain-size motif. Both the channel levee and distributary mouth bar associations are characterized by coarsening-upward grain-size motifs and include similar facies. Given these similarities and limitations imposed by a single core, interpretation as channel levee deposits and our ability to clearly distinguish them from mouth bar deposits is questionable. Channel levee deposits have been recognized in the Nanushuk in outcrop (LePain and Kirkham, 2001; McCarthy, 2003; LePain and others, 2009).

ALLUVIAL FLOOD BASIN

The alluvial flood basin association consists of laminated mudstone (Fl), massive mudstone (Fm), carbonaceous mudstone (Fc), and coal (C), with interbedded ripple cross-laminated sandstone (Sr), heterolithic sandstone and mudstone (SFh), and minor convolute-bedded sandstone (Scb; sheet 2-1). Figure 2-18 shows core from a depth of 123 to 226 ft and represents a typical example of this association in the Wainwright well. The upper 104 ft of core (not shown in fig. 2-18) commonly appears brecciated or disrupted, which may have resulted from permafrost or pedogenic processes. Scattered rhizoliths and possible soil peds suggest the presence of paleosols.

This association is interpreted as the deposits of a poorly drained alluvial flood basin. The absence of marine trace fossils distinguishes this association from the interdistributary bay association and provides the basis for differentiating lower delta plain deposits from upper delta plain deposits (Fisk and others, 1954; Bhattacharya,

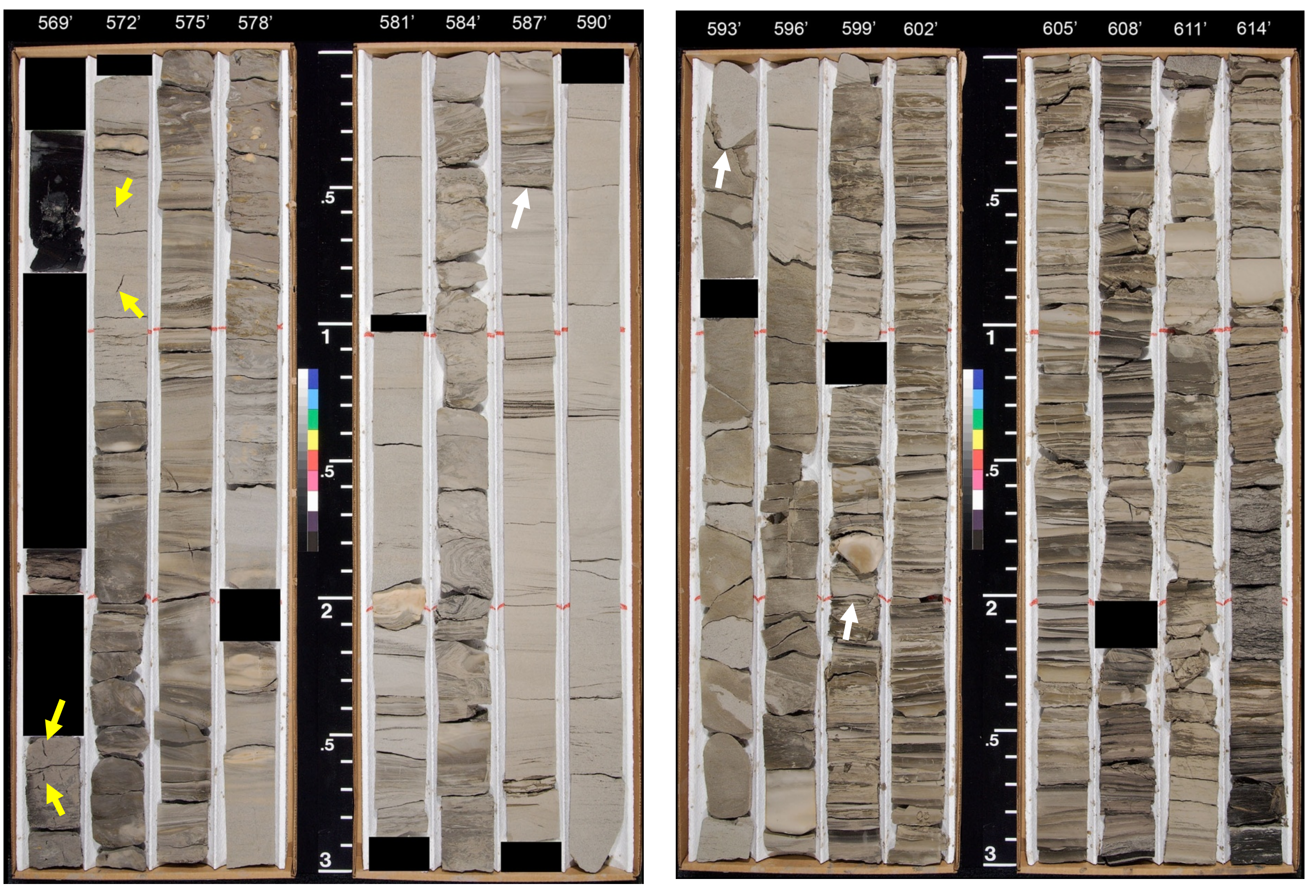


Figure 2-17. Core photo, showing prominent coarsening-upward succession (approximately 593.3 to 601 ft; white arrows) interpreted as the deposits of a crevasse delta. The erosion surface separating light-colored clean sandstone from darker-colored muddy sandstone to sandy siltstone at 593.3 ft (white arrow) is interpreted as a scour surface marking the base of a small crevasse channel that cut into crevasse delta mouth bar deposits. The mudstone and muddy sandstone above the upper white arrow (587.5 ft) may record gradual abandonment of the crevasse channel. Sandstones above 584.2 ft are probably splay sandstone sheets. Note rhizoliths in sandstone at 572. 6 ft, 572.9 ft, and in mudstone at 571.6 and 571.7 ft (yellow arrows).

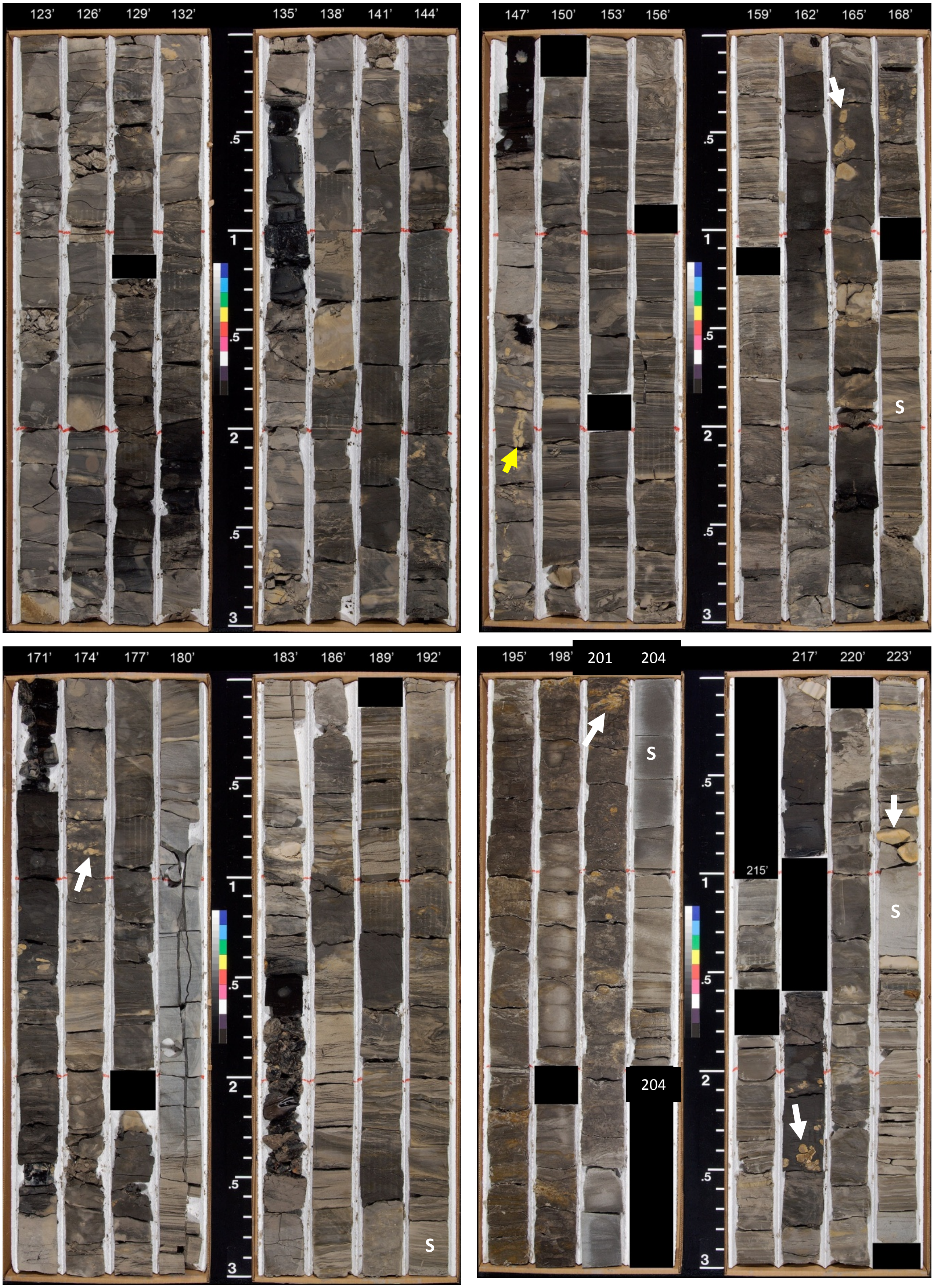


Figure 2-18. Core photos, showing a thick mudstone succession from 123 to 226 ft interpreted as alluvial flood basin deposits (upper delta plain). The lighter-colored beds are sandstones that were deposited as tabular splays (white S). Note the sideritized rhizolith(?) at 149 ft (yellow arrow) and the siderite nodules throughout (selected nodules shown with white arrows).

2006). Alluvial floodbasin deposits have been recognized in outcrops of the Nanushuk Formation south of Umiat (McCarthy, 2003; LePain and others, 2009).

DEPOSITIONAL MODEL

The suite of facies and facies associations recognized in the Wainwright #1 well is consistent with deposition in a lower delta plain setting characterized by interdistributary bays, major channels, and associated subenvironments (levees, crevasse channels, etc.; fig. 2-19). The persistent presence of a moderate to low diversity suite of marine trace fossils throughout much of the lower 1,300+ ft of core suggests that interdistributary bays were routinely characterized by brackish water and, for brief periods, may have had normal marine salinities. The suite of facies and the lack of obvious trace fossils above a depth of 265 ft is consistent with deposition in a poorly drained alluvial (upper delta) plain setting. Subsurface and core data suggest the thick channel deposits between 1,060.5 and 1,157.7 ft and between 619.3 and 667 ft represent attractive analogs for potential reservoirs in topsets up depositional dip (west) from the ultimate Nanushuk shelf edge on the central North Slope (see Houseknecht and others, 2008, their figs. 1 and 3). The absence of significant thicknesses of sandstones with abundant wave-generated structures, including hummocky cross-stratification, is consistent with deposition in a river-dominated deltaic setting (Bhattacharya, 2006). This is also consistent with previous interpretations of Nanushuk deltas west of the Meade arch as river dominated (Ahlbrandt and others, 1979; Huffman and others, 1985).

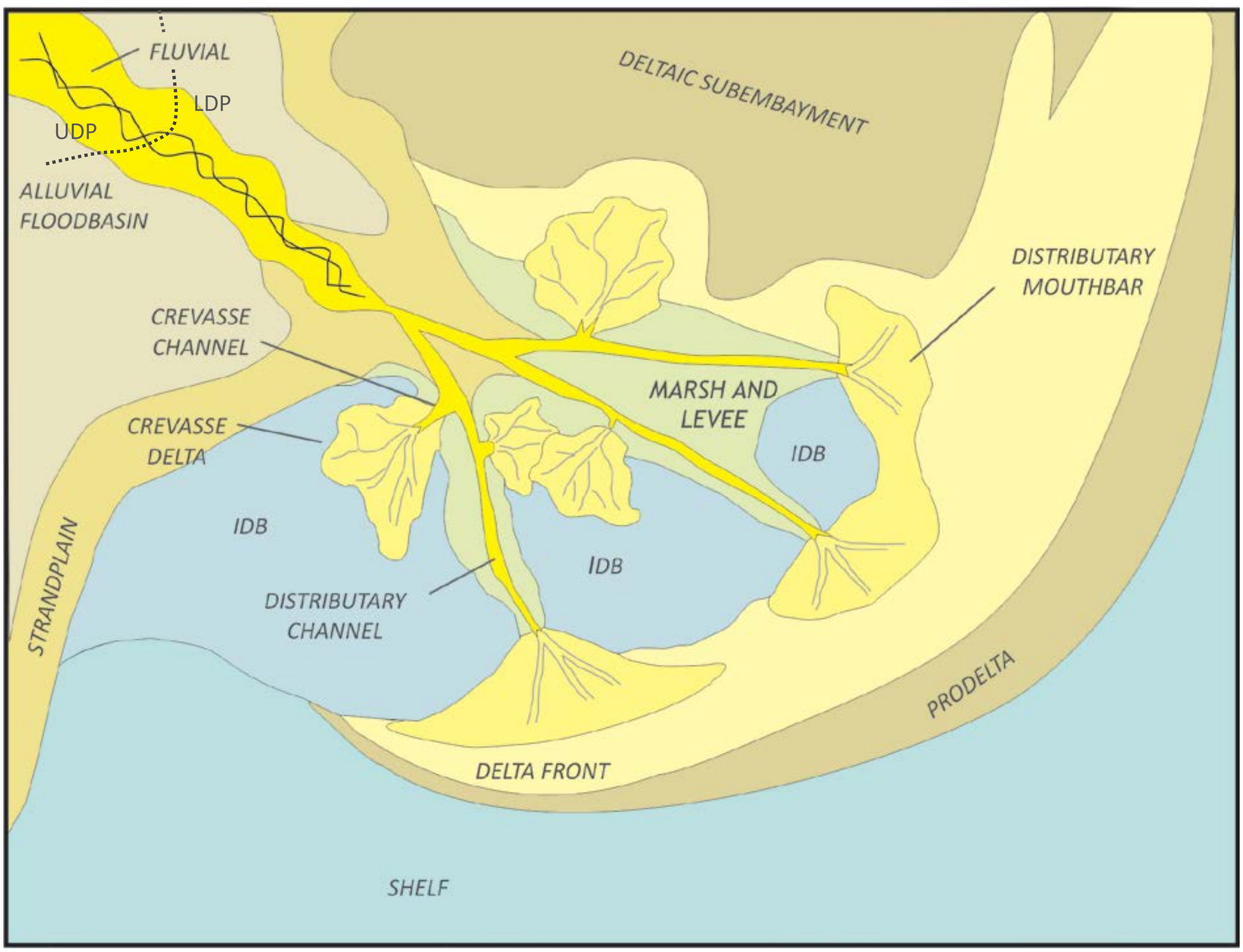


Figure 2-19. Generalized drawing showing a delta lobe and its subenvironments (modified from LePain and others, 2009). The progression of environments recorded in the core, from base to top, defines a progradational succession starting with prodelta or interdistributary bay mudstones and thin-bedded sandstone with trace fossils suggestive of reduced salinity conditions, and ending in an alluvial flood basin package lacking marine indicators. The interdistributary bayfill succession in the lower 85 percent of the core is punctuated by numerous splay sandstones, crevasse channel fills, distributary channel fills, and at least one levee succession. IDB = interdistributary bay; LDP = lower delta plain; UDP = upper delta plain.

CONCLUSIONS

Our facies analysis of the Wainwright #1 core has identified 12 lithofacies, which combine to define six facies associations. Facies associations include most of the subenvironments associated with river-dominated deltas, including interdistributary bay, distributary channel, channel levee, crevasse channel and delta, and splay sand sheets. The interdistributary bay association dominates the cored interval and envelops all other associations in the lower 1,340 ft of core; the alluvial flood basin association dominates the upper 265 ft of core. Trace fossils are common and locally abundant in the lower 1,340 ft of the cored succession, but have not been identified in the upper 265 ft. Trace fossils include genera belonging to both the *Cruziana* and *Skolithos* ichnofacies. The massive mudstone facies (Sm) commonly appears burrow mottled, while most sandstone beds having trace fossils appear only lightly bioturbated. These beds usually only include traces belonging to a few genera, defining low- to moderate-diversity assemblages. A few sandstone beds are moderately to highly bioturbated. These beds include high-diversity assemblages consisting of several genera typically found in open marine settings. The distribution of facies associations and trace fossil assemblages allow distinction of lower and upper delta plain settings. The lower 1,340 ft of core records a persistent marine influence (mostly brackish water, with only a few beds recording normal marine salinity) and represents deposition in a lower delta plain setting. Marine trace fossils are absent in the upper part of the cored succession, which comprises alluvial flood basin, mire, and splay sand associations deposited in an upper delta plain setting removed from marine influence. The suite of facies associations documented in the Wainwright #1 core is consistent with deposition in a river-dominated deltaic setting.

Core from the Wainwright #1 well provides important information on the reservoir potential of the Nanushuk Formation. The thick channel complex between 1,065.5 and 1,157.7 ft appears to have significant regional extent (Decker and LePain, 2016 [this volume]) and represents an attractive reservoir target. This channel complex is encased in mudstones of the interdistributary bay association, which would serve as an effective stratigraphic trap for hydrocarbons. Thinner channel deposits have also been recognized in the core between 619 and 667 ft that are also encased in a mudstone-dominated succession. Judging from this core and analog data from outcrops to the south and southeast (Huffman and others, 1985, 1988; LePain and others, 2008, 2009), it is reasonable to infer that stacked reservoirs could easily be present in the formation in the subsurface of the central North Slope. This conclusion is consistent with core from exploration wells in the central and eastern NPRA (LePain and Kirkham, 2001). See Helmold (2016 [this volume]) for information on the reservoir quality of the cored succession.

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REFERENCES CITED

Ahlbrandt, T.S., Huffman, A.C., Fox, J.E., and Pasternack, I., 1979, Depositional framework and reservoir quality studies of selected Nanushuk Group outcrops, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 14–31.

Allen, J.R.L., 1984, Sedimentary structures, their character and physical basis (unabridged; one-volume edition)—Developments in sedimentology, 30: Amsterdam, Netherlands, Elsevier, 663 p.

Ashley, G.M, 1990, Classification of large-scale subaqueous bedforms—A new look at an old problem: Journal of Sedimentary Petrology, v. 60, no. 1, p. 160–172.

Bhattacharya, J.P., 2006, Deltas, *in* Posamentier, H.W., and Walker, R.G., eds., Facies Models Revisited: SEPM Society for Sedimentary Geology, Special Publication 84, p. 237–292.

Bhattacharya, J.P., and Walker, R.G., 1991, River- and wave-dominated depositional systems of the Upper Cretaceous Dunvegan Formation, northwestern Alberta: Bulletin of Canadian Petroleum Geology, v. 39, no. 2, p. 165–191.

Bird, K.J., and Molenaar, C.M., 1992, The North Slope foreland basin, Alaska, *in* Macqueen, R.W., and Leckie, D.A., eds., Foreland basins and fold belts: AAPG Memoir 55, p. 363–393.

Clark, A.C., 2014, Coalbed natural gas exploration, drilling activities, and geologic test results, 2007–2010, Wainwright, Alaska: U.S. Geological Survey Open-File Report 2014-1004, 65 p. doi:10.3133/ofr20141004

Coleman, J.M., and Gagliano, S.M., 1965, Sedimentary structures, Mississippi River deltaic plain, in Middleton, G.V., ed., Primary sedimentary structures and their hydrodynamic interpretation: SEPM Special Publication 12, p. 133–148.

Coleman, J.M., Gagliano, S.M., and Webb, J.E., 1964, Minor sedimentary structures in a prograding distributary: Marine Geology, v. 1, no. 3, p. 240–258. doi:10.1016/0025-3227(64)90062-3

Collinson, J.D., 1968, The sedimentology of the Grindslow shales and Kinderscout grit—A deltaic complex in the Namurian of northern England: Journal of Sedimentary Petrology, v. 39, no. 1, p. 194–221. doi:10.1306/74D71C17-2B21-11D7-8648000102C1865D

Collinson, J.D., and Thompson, D.B., 1989, Sedimentary structures, 2nd edition: London, Unwin Hyman, 207 p.

Dalrymple, R.W., 1992, Tidal depositional systems, *in* Walker, R.G., and James, N.P., eds., Facies models—Response to sea level change: Geological Association of Canada, p. 195–218.

Decker, P.L., 2007, Brookian sequence stratigraphic correlations, Umiat Field to Milne Point Field, west-central North Slope, Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2007-2, 19 p., 1 sheet. doi:10.14509/15758

Decker, P.L., and LePain, D.L., 2016 [this volume], Subsurface relationships of Albian–Cenomanian shallow marine to nonmarine topsets of the Nanushuk Formation, northwestern NPRA, northern Alaska, *in* LePain, D.L., ed., Stratigraphic and reservoir quality studies of continuous core from the Wainwright #1 coalbed methane test well, Wainwright, Alaska: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2016-3, 56 p. doi:10.14509/29655

de Raaf, J.F.M., Boersma, J.R., and Van Gelder, A., 1977, Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland: Sedimentology, v. 24, no. 4, p. 451–483. doi:10.1111/j.1365-3091.1977.tb00134.x

Droser, M.L., and Bottjer, D.J., 1986, A semiquantitative field classification of ichnofabric: Journal of Sedimentary Petrology, v. 56, no. 4, p. 558–559.

Elliot, T., 1974, Interdistributary bay sequences and their genesis: Sedimentology, v. 21, no. 4, p. 611–622. doi:10.1111/j.1365-3091.1974.tb01793.x

Elliot, T., 1976, Upper Carboniferous sedimentary cycles produced by river-dominated, elongate deltas: Journal of the Geological Society of London, v. 132, no. 2, p. 199–208. doi:10.1144/gsjgs.132.2.0199

Fiorillo, A.R., Decker, P.L., LePain, D.L., Wartes, M.A., and McCarthy, P.J., 2010, A probable *Neoceratopsian manus* track from the Nanushuk Formation (Albian, northern Alaska): Journal of Iberian Geology, v. 36, no. 2, p. 165–174. doi:10.5209/rev_JIGE.2010.v36.n2.4

Fisher, W.L., Brown, L.F., Scott, A.J., and McGowan, J.A., 1969, Delta systems in the exploration for oil and gas—A research colloquium: Austin, TX, The University of Texas at Austin, Bureau of Economic Geology, 78 p.

Fisk, H.N., 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity: Vicksburg, MS, U.S. Corps of Engineers, Waterway Experiment Station, v. II, 74 plates.

Fisk, H.N., Kolb, C.R., McFarlan, Edward, Jr., and Wilbert, L.J., Jr., 1954, Sedimentary framework of the modern Mississippi delta [Louisiana]: Journal of Sedimentary Petrology, v. 24, no. 2, p. 76–99.

Galloway, W.E., 1968, Depositional systems of the Lower Wilcox group, north-central Gulf Coast basin: Transactions—Gulf Coast Association of Geological Societies, v. 18, p. 275–289.

Galloway, W.E., and Hobday, D.K., 1996, Terrigenous clastic depositional systems: Berlin, Springer-Verlag, 489 p.

Greb, S.F., and Dever, G.R., 2002, Critical evaluation of possible seismites—Examples from the Carboniferous of the Appalachian basin, *in* Ettensohn, F.R., Rast, N.R., and Brett, C.E., eds., Ancient seismites: Geological Society of America Special Paper 359, p. 109–125.

Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: SEPM Short Course No. 2, lecture notes, 161 p.

Helmold, K.P., 2016 [this volume], Sedimentary petrology and reservoir quality of Lower Cretaceous Nanushuk sandstones, USGS Wainwright #1 test well, western North Slope, Alaska, *in* LePain, D.L., ed., Stratigraphic and reservoir quality studies of continuous core from the Wainwright #1 coalbed methane test well, Wainwright, Alaska: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2016-3, 56 p. doi:10.14509/29657

Ho, Clara, and Coleman, J.M., 1969, Consolidation and cementation of Recent sediments in the Atchafalaya basin: Geological Society of American Bulletin, v. 80, no. 2, p. 183–192.

Horn, J.C., Ferm, J.C., Caruccio, F.T., and Baganz, B.P., 1978, Depositional models in coal exploration and mine planning in Appalachian region: AAPG Bulletin, v. 62, no. 12, p. 2,379–2,411. doi:10.1306/C1EA5512-16C9-11D7-8645000102C1865D

Houseknecht, D.W., and Schenk, C.J., 2001, Depositional sequences and facies in the Torok Formation, National Petroleum Reserve–Alaska (NPRA), *in* Houseknecht, D.W., ed., NPRA core workshop—Petroleum plays and systems in the National Petroleum Reserve–Alaska: Society for Sedimentary Geology (SEPM) Core Workshop Notes, v. 21, p. 179–199. doi:10.2110/cor.01.01.0179

Houseknecht, D.W., and Schenk, C.J., 2005, Sedimentology and sequence stratigraphy of the Cretaceous Nanushuk, Seabee, and Tuluvak Formations exposed on Umiat Mountain, north-central Alaska: U.S. Geological Survey Professional Paper 1709-B, 18 p.

Houseknecht, D.W., Bird, K.J., and Schenk, C.J., 2008, Seismic analysis of clinoform depositional sequences and shelf-margin trajectories in Lower Cretaceous (Albian) strata, Alaska North Slope: Basin Research, v. 21, no. 5, p. 644–654. doi:10.1111/j.1365-2117.2008.00392.x

Howard, J.D, 1975, The sedimentological significance of trace fossils, *in* Frey, R.W., ed., The study of trace fossils: New York, Springer-Verlag, p. 131–146.

Huffman, A.C., Ahlbrandt, T.S., and Bartsch-Winkler, S., 1988, Sedimentology of the Nanushuk Group, North Slope, *in* Gryc, George, ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 281–298. http://dggs.alaska.gov/pubs/id/4159

Huffman, A.C., Ahlbrandt, T.S., Pasternack, Ira, Stricker, G.D., and Fox, J.E., 1985, Depositional and sedimentologic factors affecting the reservoir potential of the Cretaceous Nanushuk Group, central North Slope, *in* Huffman, A.C., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 61–74. http://dggs.alaska.gov/pubs/id/4561

Jopling, A.V., and Walker, R.G., 1968, Morphology and origin of ripple-drift cross-lamination with examples from the Pleistocene of Massachusetts: Journal of Sedimentary Petrology, v. 38, no. 4, p. 971–984. doi:10.1306/74D71ADC-2B21-11D7-8648000102C1865D

LePain, D.L., and Kirkham, R., 2001, Potential reservoir facies in the Nanushuk Formation (Albian–Cenomanian), central North Slope, Alaska—Examples from outcrop and core, *in* Houseknecht, D.W., ed., NPRA Core Workshop: Petroleum plays and systems in the National Petroleum Reserve – Alaska: SEPM Core Workshop No. 21, p. 19–36.

LePain, D.L., Decker, P.L., and Wartes, M.A., 2008, Measured sections and preliminary interpretations of the Nanushuk Formation exposed along the Colville River near the confluences with the Awuna and Killik rivers, *in* Wartes, M.A., and Decker, P.L., ed., Preliminary results of recent geologic field investigations in the Brooks Range foothills and North Slope, Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2008-1D, p. 41–45, 4 sheets. doi:10.14509/16088

LePain, D.L., McCarthy, P.J., and Kirkham, Russell, 2009, Sedimentology and sequence stratigraphy of the middle Albian–Cenomanian Nanushuk Formation in outcrop, central North Slope, Alaska: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2009-1, 78 p., 1 sheet. doi:10.14509/19761

MacEachern, J.A., Bann, K.L., Pemberton, S.G., and Ginras, M.K., 2007a, The ichnofacies paradigm—High-resolution paleoenvironmental interpretation of the rock record, *in* MacEachern, J.A., Bann, K.L., Gingras, M.K., and Pemberton, S.G., eds., Applied ichnology: SEPM Short Course Notes 52, Tulsa, Oklahoma, p. 27–64.

MacEachern, J.A., Pemberton, S.G., Bann, K.L., and Ginras, M.K., 2007b, Departures from the archetypal ichnofacies—Effective recognition of physic-chemical stresses in the rock record, *in* MacEachern, J.A., Bann, K.L., Gingras, M.K., and Pemberton, S.G., eds., Applied ichnology: SEPM Short Course Notes 52, Tulsa, Oklahoma, p. 65–93.

Mayfield, C.F., Tailleur, I.L., and Kirschner, C.E., 1988, Bedrock geologic map of the National Petroleum Reserve in Alaska, *in* Gryc, George, ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 187–190, scale 1:500,000.

McCabe, P.J., 1984, Depositional environments of coal and coal-bearing strata, *in* Rahmani, R.A., and Flores, R.M, eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Paper 7, p. 13–42.

McCarthy, P.J., 2003, Alluvial facies and paleosols in the Cretaceous Nanushuk Formation, Kanayut River, North Slope, Alaska—Preliminary results from the 2001 field season: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2003-1, 19 p. doi:10.14509/2920

Miall, A.D., 1996, The geology of fluvial deposits: Berlin, Springer-Verlag, 582 p.

Molenaar, C.M., 1985, Subsurface correlations and depositional history of the Nanushuk Group and related strata, North Slope, Alaska, *in* Huffman, A.C., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 37–59.

Molenaar, C.M., 1988, Depositional history and seismic stratigraphy of Lower Cretaceous rock in the National Petroleum Reserve in Alaska and adjacent areas, *in* Gryc, George, ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 593–621.

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: Geological Society of America, The Geology of North America, v. G-1, p. 49–140.

Mulder, Thierry, Syvitski, J.P.M., Migeon, Sebastien, Faugeres, J.-C., and Savoye, Bruno, 2003, Marine hyperpycnal flows—Initiation, behavior, and related deposits—A review: Marine and Petroleum Geology, v. 20, no. 6-8, p.861–882. doi:10.1016/j.marpetgeo.2003.01.003

Mull, C.G., 1985, Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska, *in* Huffman, A.C., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 7–36. http://dggs.alaska.gov/pubs/id/4559

Mull, C.G., Houseknecht, D.W., and Bird, K.J., 2003, Revised Cretaceous and Tertiary stratigraphic nomenclature in the Colville Basin, northern Alaska: U.S. Geological Survey Professional Paper 1673, 59 p. http://dggs.alaska.gov/pubs/id/4052

Nio, S.D., and Yang, C.S., 1991, Diagnostic attributes of clastic tidal deposits—A review, *in* Smith, D.G., Reinson, G.E., Zaitlin, B.A., and Rahmani, R.A., eds., Clastic tidal sedimentology: Canadian Society of Petroleum Geologists Memoir 16, p. 3–27.

Pemberton, S.G., and Wightman, D.M., 1992, Ichnological characteristics of brackish water deposits, *in* Pemberton, S.G., ed., Applications of ichnology to petroleum exploration—A core workshop: SEPM Core Workshop 17, p. 141–167.

Pemberton, S.G, Frey, R.W., Ranger, M.J., and MacEachern, J.A., 1992, The conceptual framework of ichnology, *in* Pemberton, S.G., ed., Applications of ichnology to petroleum exploration—A core workshop: SEPM Core Workshop 17, p. 1–32.

Potter, P.E., Maynard, J.B., and Depetris, P.J., 2005, Mud and mudstones—Introduction and overview: Berlin, Springer-Verlag, 297 p.

Ryer, T.A., and Anderson, P.B., 2002, Facies of the Ferron Sandstone [chapter 3], *in* Chidsey, T.C., ed., Geological and petrophysical characterization of the Ferron Sandstone for 3-D simulation of a fluvial–deltaic reservoir: Utah Geological Survey Miscellaneous Publication 02-6. www.mapstore.utah.gov/mp02-6.html

Simons, D.B., Richardson, E.V., and Nordin, C.F., Jr., 1965, Sedimentary structures generated by flow in alluvial channels, *in* Middleton, G.V., ed., Primary sedimentary structures and their hydrodynamic interpretation—A symposium: SEPM Special Publication, v. 12, p. 34–52. doi:10.2110/pec.65.08.0034

Southard, J.B., 1971, Representation of bed configurations in depth–velocity–size diagrams: Journal of Sedimentary Petrology, v. 41, no. 4, p. 903–915. doi:10.1306/74D723B0-2B21-11D7-8648000102C1865D

Thomas, R.G., Smith, D.G., Wood, J.M., Visser, John, Calverley-Range, E.A., and Koster, Emlyn, 1987, Inclined heterolithic stratification—Terminology, description, interpretation and significance: Sedimentary Geology, v. 53, no. 1-2, p. 123–179. doi:10.1016/S0037-0738(87)80006-4

Walker, R.G., 1984, Shelf and shallow marine sands, *in* Walker, R.G., ed., Facies models, 2nd edition: Geoscience Canada Reprint Series 1, p. 141–170.