CHAPTER A: CORE DESCRIPTIONS, SEDIMENTOLOGY AND RESERVOIR POTENTIAL OF THE NANUSHUK FORMATION (ALBIAN–CENOMANIAN), EASTERN NATIONAL PETROLEUM RESERVE–ALASKA

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INTRODUCTION

This report presents core descriptions and a discussion of facies associations recognized in cores from the Nanushuk Formation in Fish Creek test well 1, Square Lake test well 1, Wolf Creek test well 3, and Umiat 18, located in the eastern part of the National Petroleum Reserve Alaska (NPRA), and Grandstand test well 1, located on state land south of Umiat (fig. 1). Cores from the Torok Formation in the Fish Creek and Grandstand test wells are also included. The four test wells were drilled as part of the U.S. Navy's extensive program to explore for oil in the NPRA from 1944 through 1953 which, at that time, was referred to as Naval Petroleum

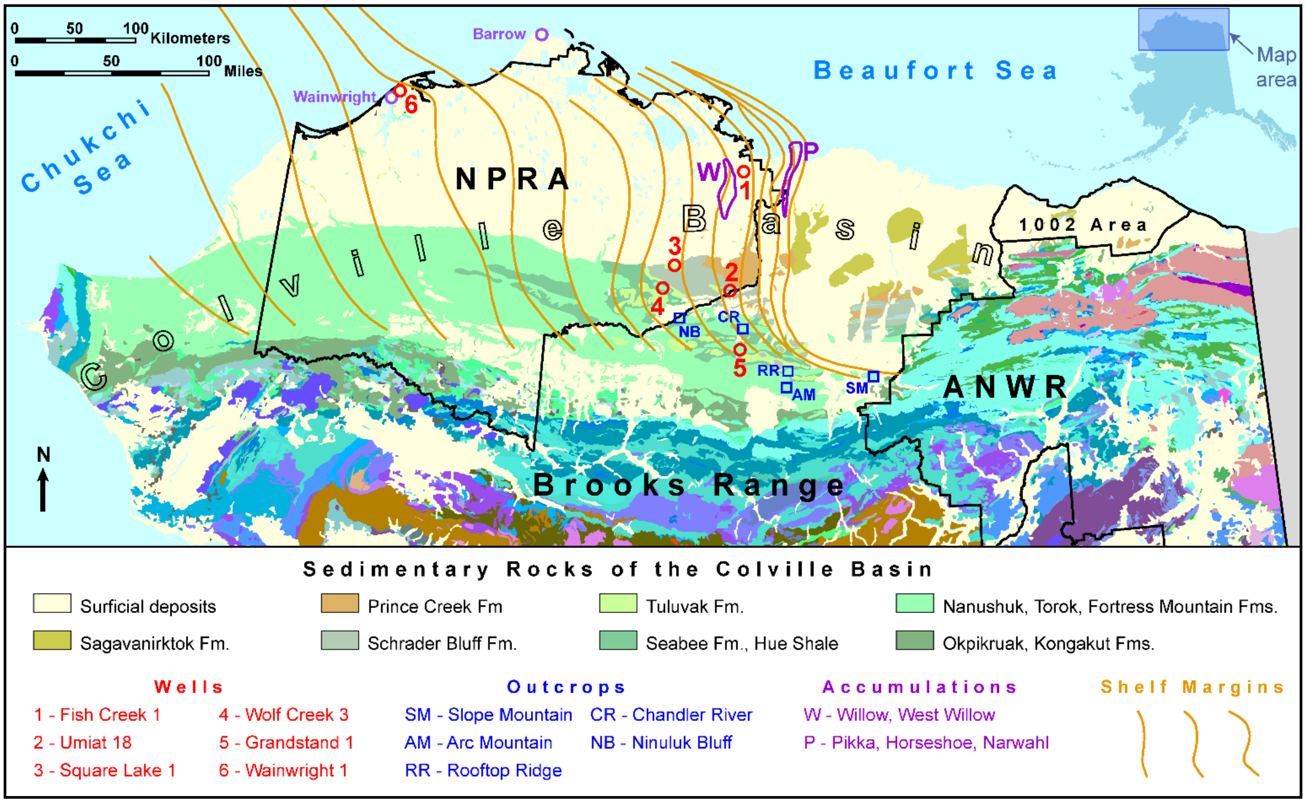

Figure 1. Simplified geologic map of northern Alaska showing the cored wells addressed in this report. Numbered dots correspond to wells: 1, Fish Creek 1; 2, Umiat 18; 3, Square Lake 1; 4, Wolf Creek 3; 5, Grandstand 1. Purple polygons show the approximate locations of Willow (W) and Pikka (P). Yellow lines show the approximate locations of Nanushuk lowstand shelf margins. Shelf margins from Houseknecht (2019). Geology from Wilson and others (2015).

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Reserve No. 4 and the exploration program as Pet 4 (Reed, 1958). The Pet 4 program included the drilling of several dozen wells and extensive geophysical and surface geological investigations (Reed, 1958). Cuttings were collected from the test wells at regular intervals and many wells were extensively cored. Lithological descriptions of cuttings and cores were carried out by U.S. Geological Survey geologists Florence Rucker Collins and Florence Robinson and published in the U.S. Geological Survey Professional Paper 305 series. Extensive investigations of the surface geology were summarized in the U.S. Geological Survey Professional Paper 303 series. Umiat 18 was drilled by Linc Energy in 2013 on the south limb of Umiat anticline, in the southeastern corner of the NPRA. Complete, detailed core descriptions accompanied by modern facies analyses are not available in the public domain for these wells. LePain and Kirkham (2001) and LePain and others (2017, 2018) presented core descriptions for selected segments of these wells and discussed implications for the depositional setting and reservoir potential of the Nanushuk in the eastern NPRA. This report presents the complete core descriptions.

The four U.S. Navy wells included in this report were drilled to test Cretaceous strata for oil and each was extensively cored (fig. 2). Fish Creek test well 1, referred to hereafter as Fish Creek 1, located approximately 1.5 miles (2.4 km) northeast of an oil seep, was spudded on May 17, 1949 in the Gubik Formation and reached total depth at 7,020 feet in the Torok Formation (Collins, 1959a; Bird, 1988). During the Pet 4 program, the Nanushuk was not recognized in the well (Collins, 1959b). Fish Creek 1 was sited near the center of a large gravity anomaly and was not drilled on a previously defined structure. The well was considered a stratigraphic test (Reed, 1958). Oil and a small volume of gas were encountered in thin sandstone and siltstone beds separated by beds of clay shale, which are now considered part of the Nanushuk Formation, and a small volume of oil was produced (Collins, 1959a). Square Lake test well 1, referred to hereafter as Square Lake 1, was spudded on January 26, 1952 in the Gubik Formation, and reached total depth at 3,987 feet in the upper Torok Formation (Collins, 1959b; Bird, 1988). Square Lake 1 was drilled to test Cretaceous rocks on an anticline defined by early reflection seismic data and resulted in discovery of a small gas field (Collins, 1959b). Wolf Creek test well 3, referred to hereafter as Wolf Creek 3, was spudded on August 20, 1952 in unconsolidated alluvium, encountered the Nanushuk Formation at a depth of 30 feet, and reached total depth at 3,760 feet in the upper Torok Formation (Collins, 1959b; Bird, 1988). Wolf Creek 3 was drilled on the crest of an anticline defined by surface mapping, with the objectives being to test for oil and gas below the depth of a gas-bearing sand encountered at 1,500 feet in the Wolf Creek 1 well and to better understand facies changes (Collins, 1959b). Minor shows of oil and a small amount of gas were encountered. Grandstand test well 1, referred to hereafter as Grandstand 1, was spudded on May 1, 1952 in unconsolidated alluvium, encountered the Nanushuk Formation at a depth of 110 feet, and reached total depth at 3,939 feet in the Torok Formation (Robinson, 1958; Bird, 1988). Grandstand 1 was drilled on the north limb of the Grandstand anticline to test for petroleum in sandstones of Early Cretaceous age (Robinson, 1958). No shows of oil or gas were encountered. All four test wells are vertical and measured depths equal true vertical depths.

Umiat 18 was spudded on March 10, 2013, in the Gubik Formation, and reached total depth at 2,600 feet measured depth in the Torok Formation (Alaska Oil and Gas Conservation Commission (AOGCC) Umiat 18 well history; fig. 2). The well was drilled on the south limb of Umiat anticline to confirm the presence of producible hydrocarbons (AOGCC Umiat 18 well history). This structure is east-southeast-trending and fault-cored (Herriott and others, 2018), and forms the trap for Umiat field (Molenaar, 1982). Oil was initially discovered at Umiat during the early years of the Pet 4 program and by the end of 1952 eleven test wells had been drilled. Umiat field is estimated to

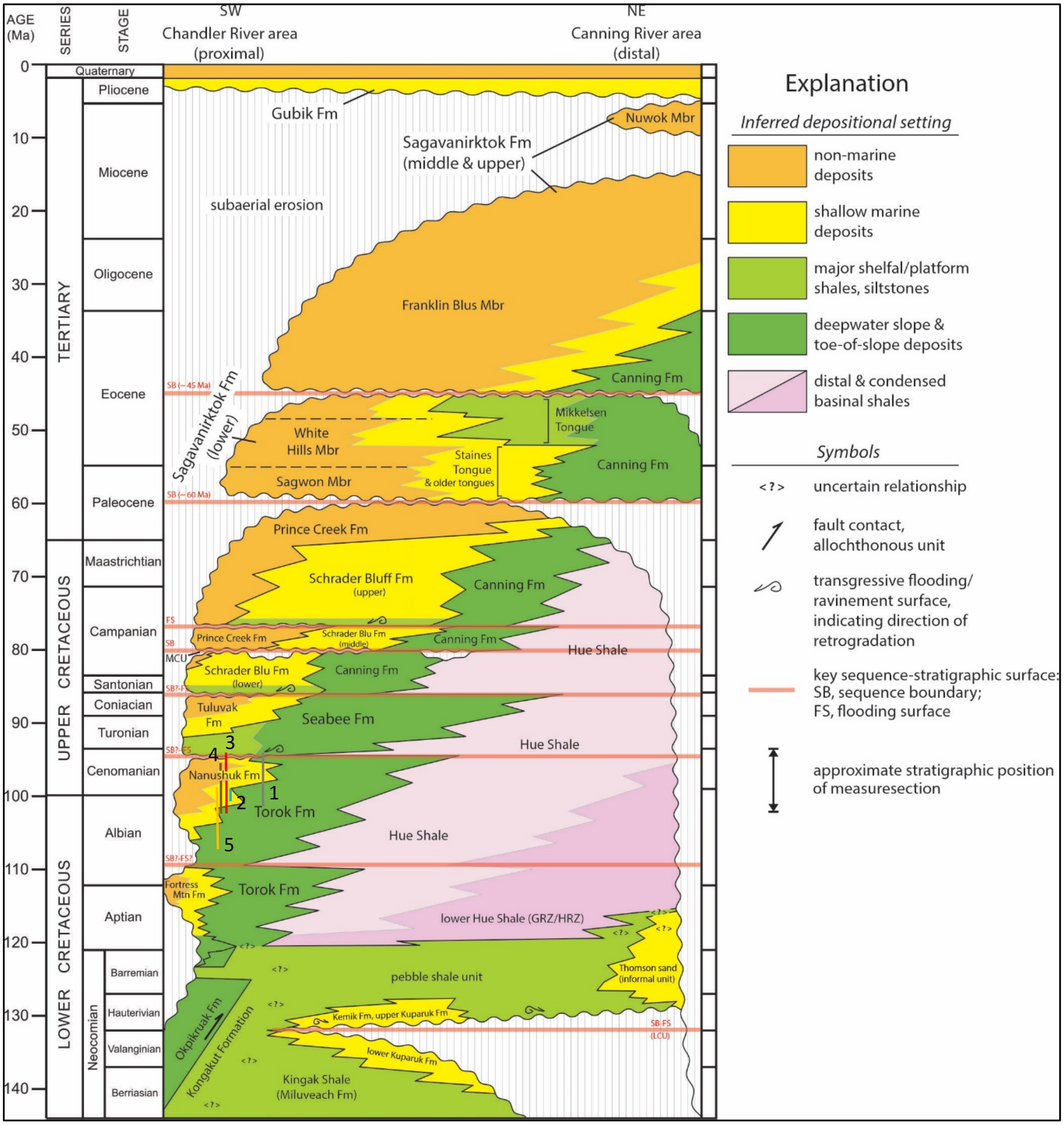


Figure 2. Generalized stratigraphy of the Brookian sequence, central North Slope, Alaska. The Kingak Shale, Kemik sandstone, and pebble shale unit comprise the Beaufortian sequence. The approximate stratigraphic positions of the cores addressed in this report are shown by the vertical lines. The gray line (1), Fish Creek 1; blue line (2), Umiat 18; red line (3), Square Lake 1; brown line (4), Wolf Creek 3; orange line (5), Grandstand 1. Modified from Decker and others (2009).

contain recoverable reserves of 70 MMBO (Molenaar, 1982). Shimer and others (2014) utilized the Umiat test wells from the Pet 4 program to investigate the sedimentology and reservoir properties of the Nanushuk Formation in this field.

GEOLOGIC SETTING

The wells addressed in this report penetrate Cretaceous strata of the Brookian sequence, including significant thicknesses of the Albian-Cenomanian Torok and Nanushuk Formations (fig. 2). These units comprise genetically related components of a giant clinothem that fills the western two-thirds of an east-west-trending Mesozoic–Cenozoic foreland basin extending from the Alaska-Yukon border in the east to the Chukchi Sea coast in the west, and continuing offshore to the Herald arch (figs. 1 and 3; Bird and Molenaar, 1992; Houseknecht, 2019). The onshore part of the foreland basin, referred to as the Colville basin, is bounded by a subsurface rift shoulder to the north and a north-vergent fold and thrust belt comprising the Brooks Range orogen to the south (figs. 1 and 3). The basin formed in response to the orogenic load and was subsequently filled by detritus shed from it, and from more distant sources on the Chukchi platform and Chukotka (Houseknecht, 2019; Helmold and LePain, 2021, this volume).

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; Ahlbrandt and others, 1979; Huffman and others, 1985, 1988; LePain and Kirkham, 2001; LePain and others, 2009; LePain and Decker, 2016; Houseknecht, 2019). 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 approximately 40 mi (65 km) east of Umiat (Houseknecht, 2019; fig. 1). Large river systems flowed east, down the axis of the foreland basin, supplying an enormous volume of sediment to delta, shelf, slope, and basin settings. Transverse rivers with steeper gradients flowed northward and northeastward from the ancestral Brooks Range, supplying sediments to the same range of depositional systems as the east-flowing river systems. The influence of these river systems can be seen on seismic data sets from which a series of eastward younging lowstand shelf margins have been mapped across the onshore east-west extent of the Nanushuk depositional system (fig. 1; Houseknecht, 2019). U/Pb ages on detrital zircons provide absolute age estimates for Nanushuk lowstand shelf margins, which range in age from 115 Ma in the west to 97.9–97.8 Ma (±0.7–1.1 Ma) in the east (Lease and Houseknecht, 2017). In the eastern part of the Nanushuk's depositional extent, shelf margins are sigmoid-shaped,

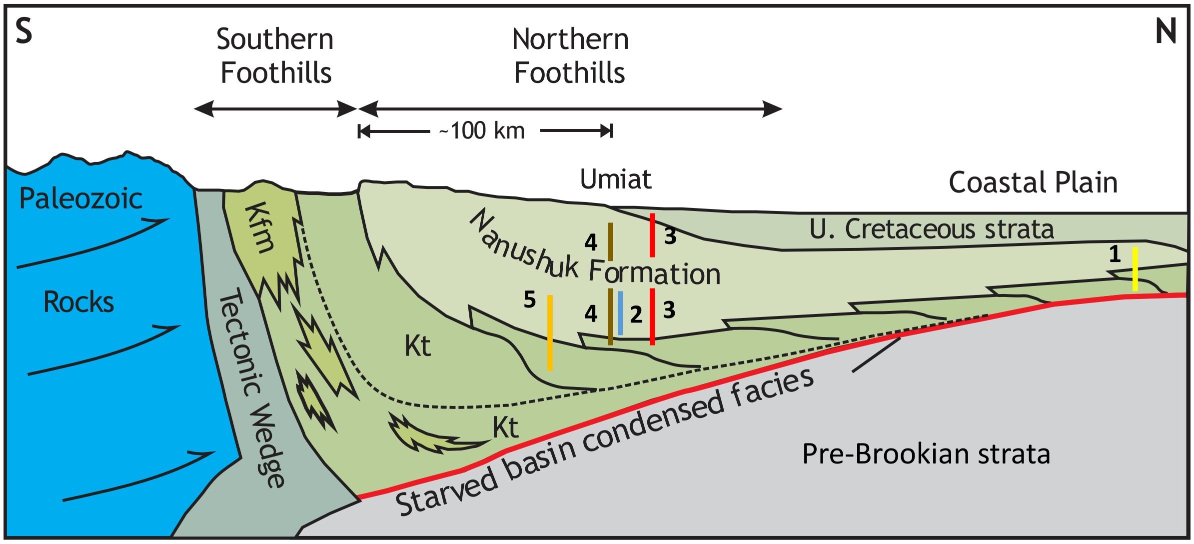


Figure 3. Generalized north-south cross-section through the Colville basin at the approximate longitude of Umiat showing the gross stratal geometries of Lower Cretaceous Brookian formations. The approximate stratigraphic positions of the cores addressed in this report are shown by the vertical lines. Kfm – Fortress Mountain Formation; Kt – Torok Formation. The yellow line (1), Fish Creek 1; blue line (2), Umiat 18; red line (3), Square Lake 1; brown line (4), Wolf Creek 3; orange line (5), Grandstand 1. Modified from Mull (1985) and Houseknecht and Schenk (2001).

trending north-south in the east-central NPRA, curving around to an east-west-trend on adjoining state lands to the south (fig. 1; Houseknecht, 2019, his fig. 5), showing the influence of east- and north-flowing river systems.

Early workers interpreted Nanushuk deltas as river-dominated (Brown and Fisher, 1969, their high-constructive delta model; Ahlbrandt and others, 1979; Huffman and others, 1985, 1988). Despite their river-dominated interpretation, Huffman and others (1985, 1988) recognized a greater wave influence on delta front facies east of the Meade arch. This change in delta style appears to correspond roughly to a pronounced change in shelf margin trajectory recognized in seismic datasets (Houseknecht, 2019). More recently, Nanushuk deltas in the eastern NPRA and in outcrop to the south and southeast have been interpreted as storm wave-influenced, consistent with earlier work (LePain and Kirkham, 2001; LePain and others, 2004; LePain and others, 2009; LePain and others, 2018). Tide-generated features have been observed locally in outcrop and in core, but the successions studied do not show a strong tidal signature overall.

A note of caution is warranted before proceeding. Coastlines that include deltaic depocenters tend to be complex. Coastal depositional systems can vary significantly along strike from deltaic headlands to broad interdistributary areas characterized by non-barred bays, barrier islands and associated back-barrier lagoons, estuaries, and strandplains, depending on the relative importance of sediment supply and river, wave, and tidal energy, which typically vary along strike in response to changes in coastal geomorphology (Boyd and others, 1992). Multiple contemporaneous deltas can vary from river-dominated to wave-dominated depending on their positions along the coastline and whether they face the open ocean or a low-energy coastal embayment, as documented for the Ferron Sandstone (Ryer and Anderson, 2004). A single delta lobe, the product of one progradational episode, can vary from strongly river-dominated to strongly wave-influenced along its progradational trajectory (Ryer and Anderson, 2004). Deltas can also display a distinct asymmetry due to oblique wave approach resulting in greater wave influence on the up-drift side and river influence on the down-drift side (Bhattacharya and Giosan, 2003). There is no reason to expect less complexity in Nanushuk coastal depositional systems.

FACIES ASSOCIATIONS IN CORE

Six facies associations are recognized in the studied cores. Most of the cores presented in this report are from the Nanushuk Formation, but a significant number of Torok cores that were cut in Fish Creek 1 and Grandstand 1 are included. Brief descriptions and interpretations of facies associations are presented here. Core descriptions are presented in sheets 1–5. Lithofacies comprising the six associations are summarized in table 1 and shown on the core descriptions but are not discussed in this report. The ichnofabric index of Droser and Bottjer (1986) is used to qualitatively characterize the degree of bioturbation in cores from Square Lake 1 and Wolf Creek 3; the bioturbation index of Taylor and Goldring (1993) is used to qualitatively characterize the degree of bioturbation in cores from Fish Creek 1 and Umiat 18; bioturbation was not characterized in cores from Grandstand 1. Specific ichnogenera identified while describing the cores are shown on the core descriptions at the depths where they were encountered. A similar suite of facies associations has been recognized in Nanushuk outcrops and in cores from Wainwright 1, and are described in detail, along with component facies, by LePain and others (2009) and LePain and Decker (2016). Photographs of core boxes from Fish Creek 1, Wolf Creek 3, Square Lake 1, and Grandstand 1 are from D'Agostino and Houseknecht (2002). Core box photographs of Umiat 18 were shot by Weatherford Laboratories for Linc Energy and are available from the Alaska Geologic Materials Center. All depths mentioned in this report and shown on sheets 1–5 are measured depths from the top

Table 1. Summary of facies recognized in core from the Nanushuk Formation, Fish Creek 1, Square Lake 1, Wolf Creek 3, Grandstand 1, and Umiat 18, eastern NPRA.

Facies		Characteristics	Trace Fossils	Bioturbation Index (BI)	Ichnofabric Index (II)	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. Typically in undisturbed beds, but present locally in packages with apparent dips up to 25 degrees from paleohorizontal.	No trace fossils	0	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, in shallow marine settings, subsequent local reworking by short-period waves. Absence of bioturbation records stressed depositional setting due either to high sediment flux, low dissolved oxygen levels in bottom waters, or a combination of both factors. Dipping strata associated with small slide blocks.
Flb	Laminated bioturbated mudstone	Similar to Fl, but with slightly to moderately disrupted laminae due to sparse to moderate bioturbation. Intermediate between Fl and Fm.	Discrete trace fossils commonly visible, including *Phycosiphon* and *Palaeophycus*	1–4	2-4	Suspension settling in low-energy, subaqueous settings. Coarser-grained siltstone and very-fine-grained sandstone interbeds record deposition from episodic unidirectional currents and subsequent local reworking by short-period waves. Oxygenated bottom waters supported a diverse burrowing infauna.
Fm	Massive mudstone	Medium gray to brown clay shale, claystone, siltstone, and mixtures of clay and silt; lacks fine-scale laminations; blocky fabric and orange-brown siderite nodules are common; mottled appearance due to bioturbation, occassional vertical traces filled with coarser sediment.	Typically no discrete traces recognizable; vertical traces locally	1–5?	2-5?	Clay shale, claystone and fine siltstone deposited from suspension in low-energy, subaqueous settings. Coarser silt deposited from density underflows. Mottled appearance suggests sediment disruption by burrowing organisms in oxygenated setting.
Fc	Coal and carbonaceous mudstone	Thin coaly stringers up to 0.2 feet thick and carbonaceous mudstones; coals commonly include high ash content.	Discrete trace fossils rare	0-1	1-2	Low-lying, minor peat accumulations and/or rafted peat mats.
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; uniform foreset dip direction; locally preserved, small, asymmetric ripple bedforms. Rhizoliths are locally preserved.	*Skolithos*; rare *Thalassinoides*?	0–3	1-3 or 4	Deposition from unidirectional currents in which equilibrium current ripple bedforms developed and migrated down-current. Where rhizoliths have been recognized, deposition occurred in shallow water or the beds were subsequently exposed.
Swr	Ripple cross-laminated sandstone	Light gray to beige coarse siltstone to very fine-grained sandstone in beds up to 1 foot thick; locally preserved wave ripple bedforms and complex, bundled sets with scalloped lower set boundaries.	*Skolithos*	0-2	1-2	Reworking of silt and sand by short-period waves in shallow, subaqueous setting.
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.	No trace fossils	0	1	Deposited from steady, unidirectional flows in which equilibrium dune bedforms developed; foresets record down-current migration of bedforms.

Table 1, continued. Summary of facies recognized in core from the Nanushuk Formation, Fish Creek 1, Square Lake 1, Wolf Creek 3, Grandstand 1, and Umiat 18, eastern NPRA.

Facies		Characteristics	Trace Fossils	Bioturbation Index (BI)	Ichnofabric Index (II)	Process Interpretation
Sl	Plane-parallel laminated very fine to fine-grained sandstone	Light gray to light brown, moderately to well sorted, very-fine- to fine-grained sandstone in beds from 0.01 to greater than 1 ft thick displaying plane-parallel to gently wavy lamination; parting lineation visible locally. Some alternating sandstone and organic-rich silty sandstone laminae.	*Skolithos*, locally developed escape structures	0–3	1-3 or 4	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. Where associated with HCS, may record deposition from combined 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	0–4	1-4	Records high sediment supply and/or rapid deposition with no subsequent traction transport.
Shcs	Hummocky/swaley cross-stratified sandstone	Light gray to light brown, very fine- to fine-grained sandstone characterized by low-angle laminae dips, dip direction changes over short vertical distances (from inches up to one foot), low-angle laminae truncations below flat laminae to laminae dipping at low angles in opposite direction; parting lineation prominent locally. Where tentatively identified, swaley cross-stratification is shown on the core descriptions with a symbol and in the facies column as Sscs.	*Palaeophycus*, *Skolithos*, *Schaubcylindrichnus*, fugichnia	0-1?	1-2?	Records sediment reworking and deposition from waning, oscillatory-dominant combined flows above storm wave-base in marine setting.
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*	0–3?	1-3?	Soft-sediment deformation. Several possible mechanisms, but given context likely due to rapid deposition on muddy, water-rich substrates.
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 extensive intense bioturbation.	*Phycosiphon*, *Skolithos*, *Teichichnus*, and *Thalassinoides*; possible *Diplocraterion* and *Rosselia*	3–5	3-5	Reworking of sand beds at or very near the depositional surface by burrowing organisms in a marine or marine-influenced setting.
SFl	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*	0–3	1-3 or 4	Deposited under fluctuating energy conditions. Coarse silt and sand transported to depositional site as bedload and mudstone as suspended load.

Bioturbation index is from Taylor and Goldring (1993); Ichnofabric index is from Droser and Bottjer (1986). When our work on these core began in 2000 we used Droser and Bottjer's scheme (Wolf Creek 3 and Square Lake 1 test wells). When the Fish Creek and Umiat 18 cores were described in 2017 and 2018, we used Taylor and Goldring's scheme as it had become more widely used by sedimentologists.

of the Kelly bushing. Available information indicates the four test wells are vertical wells; Umiat 18 is slightly deviated (at total depth the measured depth in 2,600 feet whereas the true vertical depth is 2,515.36 feet).

Facies association 1 – Slope

Description – Facies association 1 (FA1) consists mostly of massive to thinly laminated, dark brown-gray to gray clay shale, silty clay shale, and mudstone (fig. 4A). Thin laminations are locally well-developed and defined by subtle color variations (lighter brown-gray to gray laminae alternating with darker laminae). Laminae of light to medium gray siltstone and very fine-grained sandstone are locally present and typically range in thickness from less than 0.01 feet to 0.1 feet (fig. 4B); sandstone in beds up to a few feet thick are rare (sheet 1, 6003.5–6007.1 feet). Siltstone and sandstone are either massive, internally laminated, or current ripple cross-laminated, and some laminae include two or three of these structures in an organized vertical sequence representing nearly complete to partial Bouma sequences (Tabcd, Tacd, Tbcd, Tb, Tcd) (fig. 4C). Fine-scale stratigraphy is generally undisturbed, except for locally developed convolute laminae and micro-load structures on the undersides of some coarser siltstone and very fine-grained sandstone laminae (fig. 4D). Visible indications of bioturbation, including discrete trace fossils and obvious bioturbation fabrics, are absent (BI 0?). In Fish Creek 1, bedding attitudes range from flat-lying to gently dipping (up to 10 degrees; fig. 4A). Some cores in the lower part of the cored interval from Grandstand 1 include dramatic examples of FA1 in which laminae dip up to 25 degrees from paleohorizontal throughout the vertical extent of the core (figs. 4E and 25). FA1 has only been recognized in Fish Creek 1 and Grandstand 1, where it comprises most of the cores from the Torok Formation (sheets 1 and 5).

Interpretation –FA1 was deposited in a slope setting from suspended plumes of fine-grained sediment discharged from deltaic distributaries

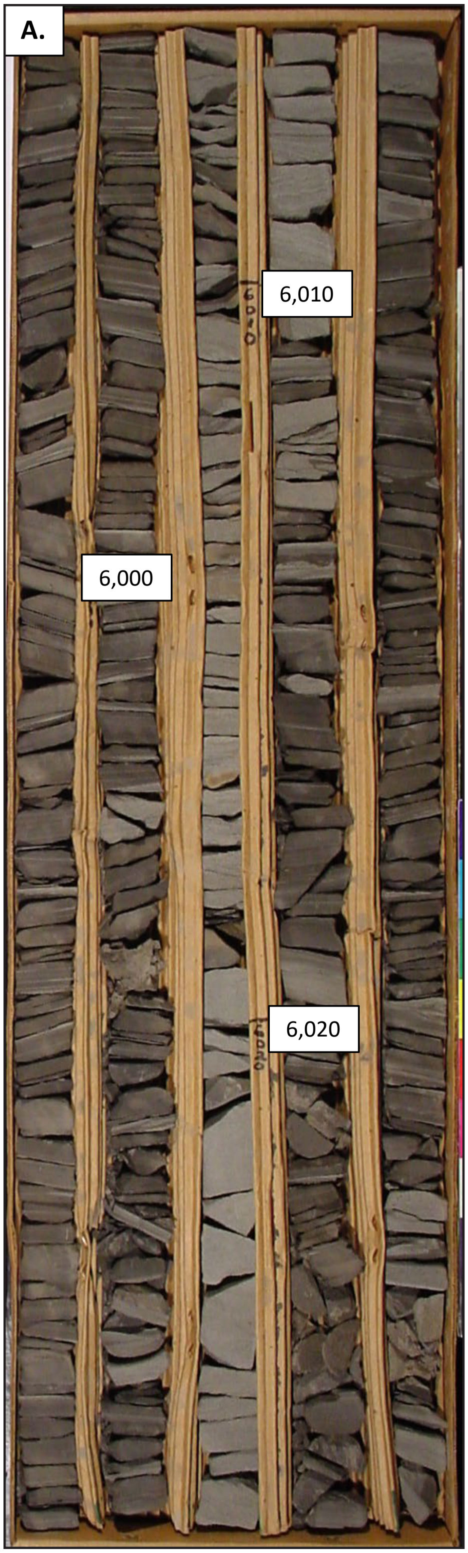


Figure 4. Photographs showing characteristics of FA1. **A.** Core box photograph showing the succession of silty clay shale, siltstone, and minor very fine-grained sandstone in the Torok between approximately 6,022–5,578 feet in Fish Creek 1. Each core row is 3.28 feet (1 meter) long. Core box photograph modified from D'Agostino and Houseknecht (2002).

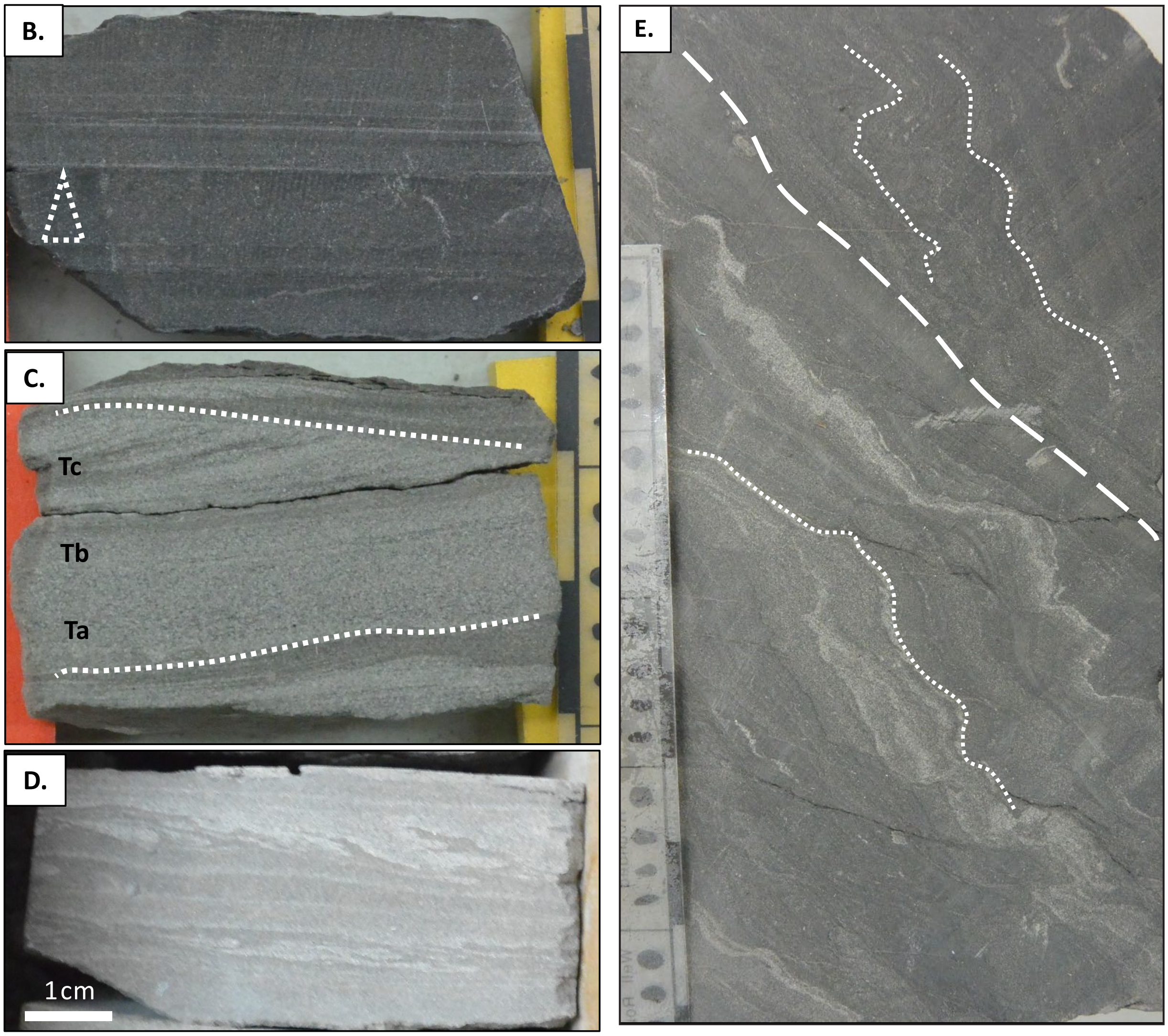


Figure 4. B. Laminae in the Torok Formation at 6,011.3 feet in Fish Creek 1. Note normal size grading in several laminae grading from fine siltstone to silty claystone. **C.** Very fine-grained sandstone with Bouma Tabc divisions at 5,582.4 feet in Fish Creek 1. **D.** Small-scale flame structures near the base of siltstone bed at 5,544.7 feet in Fish Creek 1. Horizontal white bar is 0.39 inches (1 cm) long. **E.** Dipping laminae of silty clay shale and siltstone at 3,738 feet in Grandstand 1. Dashed white line (long dashes) shows contact between two packages of strata dipping at slightly different angles (white dotted lines). Scale in all photos graduated in centimeters.

up-dip to the west and southwest (Houseknecht and Schenk, 2001). Laminated mudstones were deposited from fluid mud layers or very dilute turbidity currents. Coarser-grained laminae and beds of siltstone and sandstone with complete and partial Bouma sequences represent dilute turbidites, possibly related to the distal reaches of hyperpycnal flows (Mulder and others, 2003). Houseknecht and Schenk (2001) noted that bioturbation in slope mudstones of the Torok is rare, consistent with the absence of bioturbation fabrics in facies association 1. Packages of dipping laminae in Grandstand 1 are interpreted to be part of small slide blocks.

Facies association 2 – Distal Shelf

Description – Facies association 2 (FA2) consists of medium brown-gray to gray clay shale, silty clay shale, and mudstone. Medium to light gray to light brown siltstone and very fine-grained sandstone are common to abundant in solitary laminae (less than 0.01 feet thick) and thin beds up to approximately

0.3 feet thick (fig. 5A); siltstone and sandstone also comprise horizontally laminated successions up to 10 feet thick (sheet 1, 3,171–3,181 feet). Internally, siltstones and sandstones are massive to horizontally laminated (fig. 5B, Sheet 1, Fish Creek 1 3,378.2 feet); ripple cross-laminations are present locally, as are graded laminae. Fine-grained carbonaceous material is concentrated along the top of some siltstone and sandstone laminae, and most are slightly micaceous. The degree of bioturbation in mudstone,

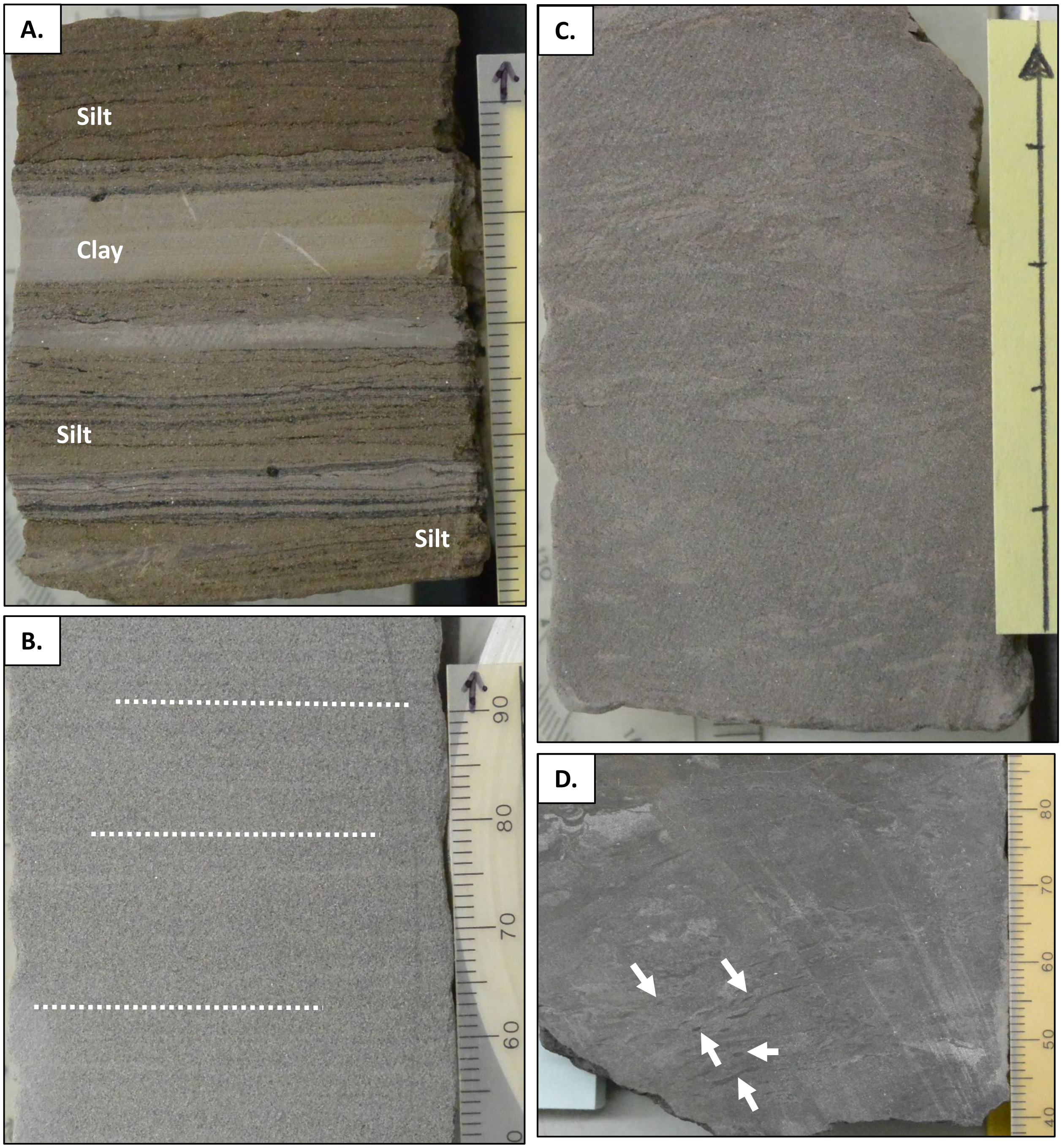


Figure 5. Photographs showing characteristics of FA2. **A.** Undisturbed siltstone and claystone laminae at 2,977 feet in Fish Creek 1. Brown color in siltstone due to residual oil. BI 0. **B.** Unbioturbated, faintly laminated siltstone at 3,384 feet in Fish Creek 1. BI 0. **C.** Bioturbated mudstone at 2,963.2 feet in Fish Creek 1. BI 3–4. Bioturbation appears to be absent, or rare, in Torok slope deposits and is common in the distal shelf facies. **D.** Burrow-mottled mudstone at 3,742 feet Wolf Creek 3. Note Phycosiphon burrows near base of core (white arrows). BI 4-5. Visible scale in all photographs in centimeters; scale in A, B, and D also graduated in millimeters.

siltstone and sandstone ranges from absent (figs. 5A–B, BI 0) to intense (figs. 5C–D, BI 4–5), but is typically absent to moderate (BI 0–3). Bioturbation appears to define a distal *Cruziana* ichnofacies. FA2 differs from FA1 by the greater number of thin siltstone and sandstone laminae and the common presence of bioturbation. FA2 comprises most of the Nanushuk cores in Fish Creek 1 (sheet 1, 3,981–2,700 feet) and is common in the deeper cores from Wolf Creek 3 (sheet 2, 3,740–3,746 feet), Square Lake 1 (sheet 3, 3,910–3,987 feet), and Grandstand 1 (sheet 5, 2,694–2,710 feet). Based on Collins' (1959b) cuttings descriptions, this association is likely common in many of the deeper uncored intervals in Wolf Creek 3, Square Lake 1, and Grandstand 1. FA2 is likely gradational above FA1, except where associated with sea level lowstands.

Interpretation – FA2 was deposited in a distal shelf setting, below storm wave base. Clay shale, silty clay shale, and mudstone were deposited from plumes of suspended sediment discharged from deltaic distributaries and from plumes of fine-grained sediment re-suspended by major storms affecting the Nanushuk shelf. Siltstone and very fine-grained sandstone were deposited from frequent dilute shelf turbidity currents (turbidites; Mulder and Alexander, 2001) and possibly hyperpycnal flows (hyperpycnites; Mulder and others, 2003; Bhattacharya and MacEachern, 2009) that reached middle to outer shelf settings. Some examples of FA2 could have been deposited in upper slope settings during sea level lowstands. We recognize that distal shelf and slope settings can include similar processes and facies, making it difficult to differentiate successions deposited in these settings without seismic data.

Facies association 3 – Offshore Transition—Prodelta

Description – Facies association 3 (FA3) consists of interbedded mudstone, siltstone, and very fine- to fine-grained sandstone commonly forming the lower part of sandier-upward successions (fig. 6A, above 3,908 feet, and fig. 6B). Silty clay shale is present locally as a minor component. Mudstone beds are dark to medium gray, range in thickness from 0.01 feet to over 1 foot, and include a variety of facies, including horizontally laminated, current and wave ripple cross-laminated, and highly bioturbated beds (table 1). Siltstone and sandstone are medium to light gray and occur as thin laminae and beds ranging in thickness from less than 0.01 foot to approximately 1.5 feet. Sandstone is moderately- to well-sorted and bounding contacts tend to be sharp and planar, or sharp with minor erosional relief. Some beds include features found in dilute turbidites (Tabc, Ta, Tab, Tbc, Tc beds; fig. 7A, stacked Ta laminae, and fig. 8A, solitary Tab bed marked by white triangle). Horizontal, plane-parallel lamination, current ripple cross-lamination (fig. 7B), wave-ripple cross-lamination (fig. 7C), and soft-sediment deformation features (fig. 7D) are common to abundant in siltstone and sandstone. In some sandstone beds, horizontal laminations grade up- and down-section over short stratigraphic distances (less than a foot) to gently dipping laminations, and lamina dip directions commonly reverse, suggesting the presence of hummocky cross-stratification (HCS; fig. 7E, Square Lake 1, approximately 3,595 feet). Bioturbation in mudstone is generally moderate to intense (BI 3–5; figs. 8A–D), and is sporadic in siltstone and sandstone, ranging from absent (fig. 7E, BI 0) to intense (BI 4–5; figs. 8C and E). Where present in the latter lithology, bioturbation is greatest in the uppermost part of beds (0.05 to 0.2 feet; fig. 8E), but can extend through the entire thickness of thinner beds (fig. 8C). Bioturbation defines a *Cruziana* ichnofacies and discrete traces are commonly recognizable, including *Planolites*, *Palaeophycus*, *Schaubcylindrichnus*, *Phycosiphon*, *Teichichnus*, and *possible Rosselia and Chondrites* (figs. 8A–E).

FA3 differs from FA2 in the greater abundance of sandstone beds, paucity of clay shales, and greater variety of sedimentary structures. FA3 is common in cores from the lower part of the Nanushuk in Wolf Creek 3, Square Lake 1, Grandstand 1 and Umiat 18 (sheets 2–5), and is also present in cores

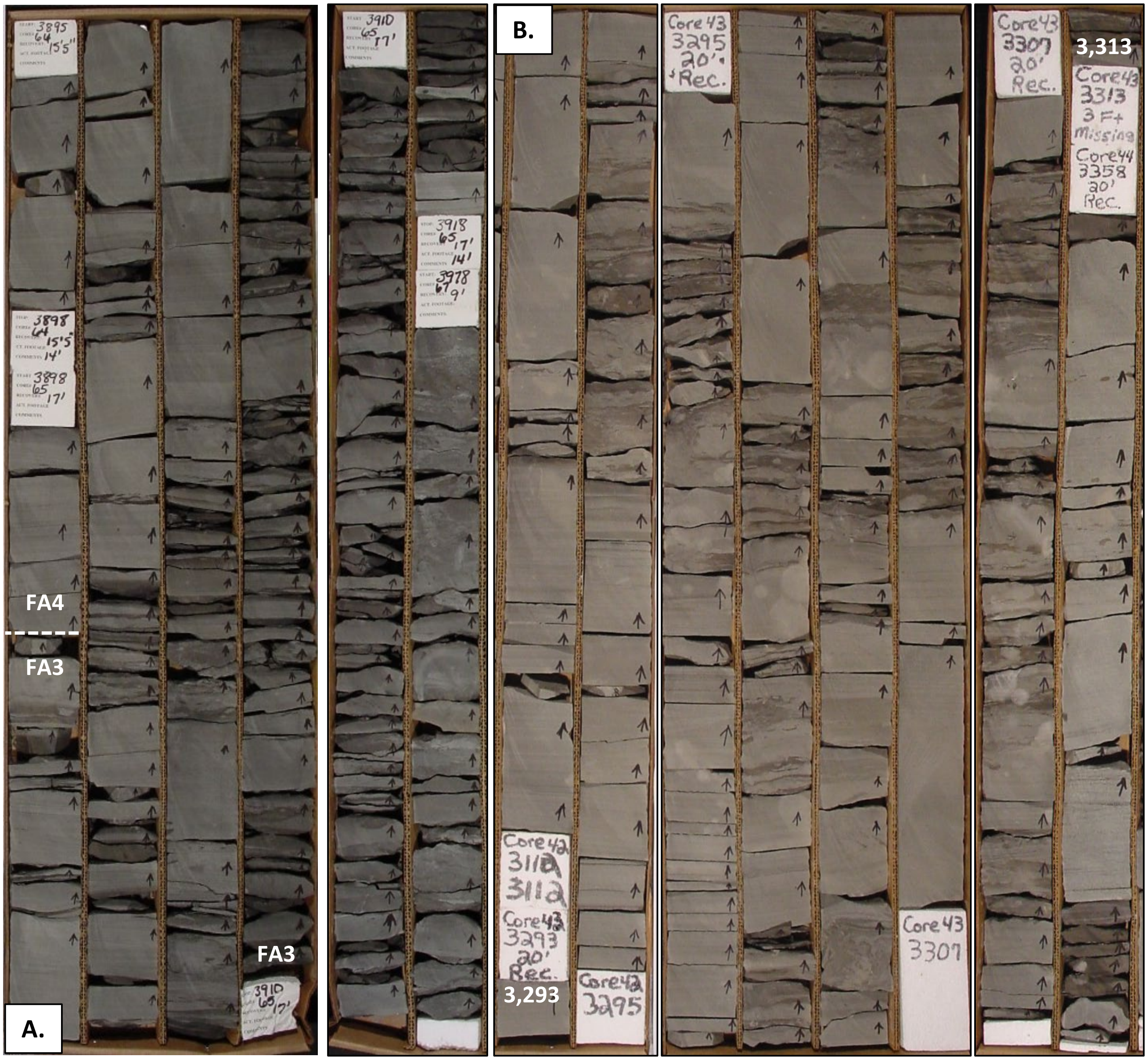


Figure 6. Core box photographs showing gross lithologies in FA3. **A.** Cored part of a coarsening-upward parasequence from 3,898.5 feet (white dashed line) to 3,910 feet (FA3 label bottom center of box) in Square Lake 1 assigned to FA3 showing lithologic characteristics. In distal settings FA2 commonly grades up-section to FA3, and the two associations differ in the greater number of sandstone interbeds in the latter. **B.** Cored part of a coarsening-upward parasequence consisting of FA3 from 3,293 feet to 3,313 feet in Wolf Creek 3. Cuttings and the SP log suggest FA3 forms part of the base of a parasequence that continues up-section to approximately 3,120 feet (Sheet 6). Each core row is 3.28 feet (1 meter) long. Core box photos modified from D'Agostino and Houseknecht (2002).

from the upper part of the formation in Square Lake 1 (sheet 3). Based on cuttings descriptions (Collins, 1959b; Robinson, 1958), this association is likely common in the intervening uncored intervals in Wolf Creek 3, Square Lake 1, and Grandstand 1. FA3 is gradational above FA2.

Interpretation – In the Wolf Creek 3 and Square Lake 1 cores, FA3 includes facies elements common to wave-influenced offshore transition settings (see Walker and Plint, 1992; Reading and Collinson, 1996), but also includes features typically found in river-dominated proximal prodelta

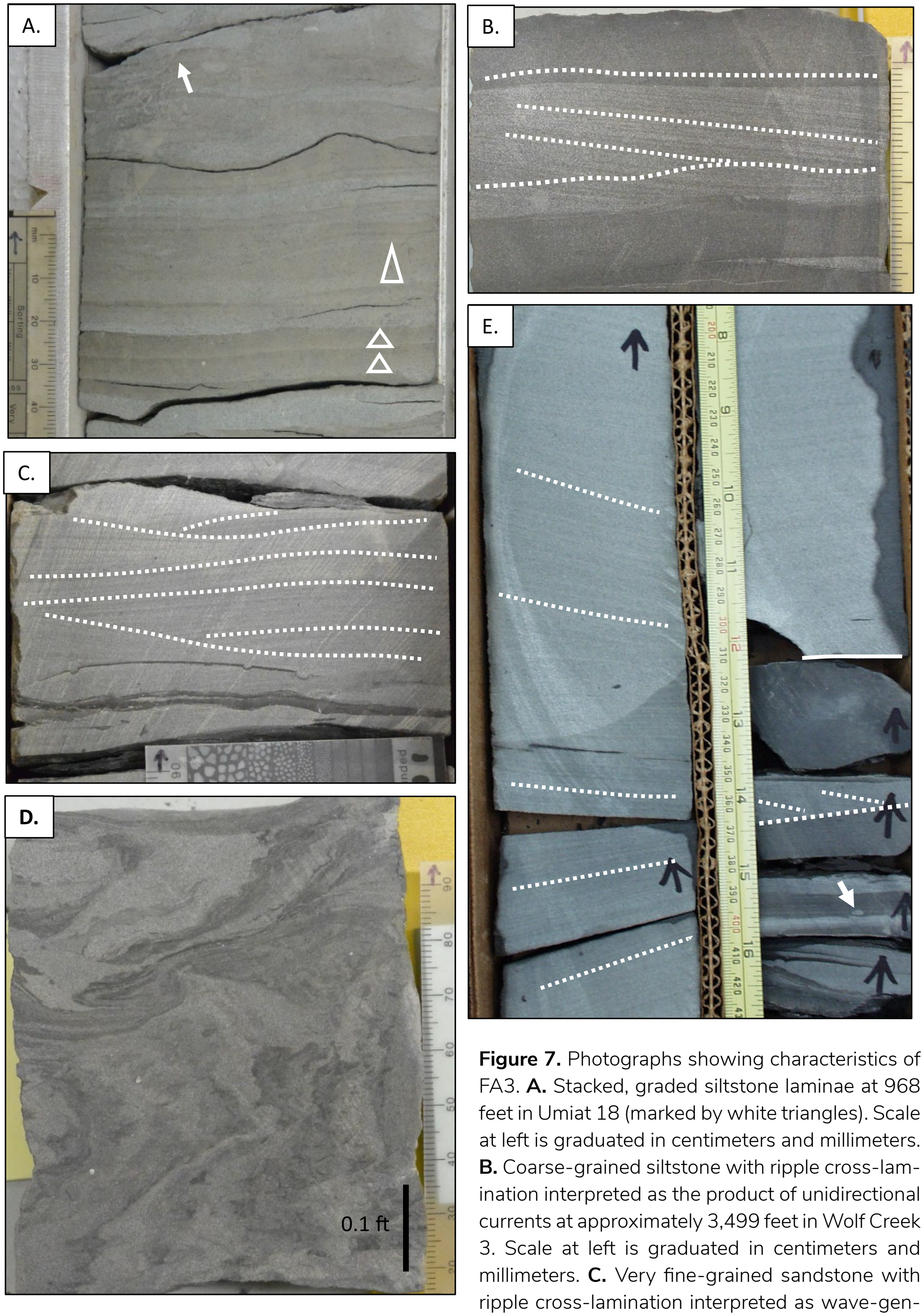
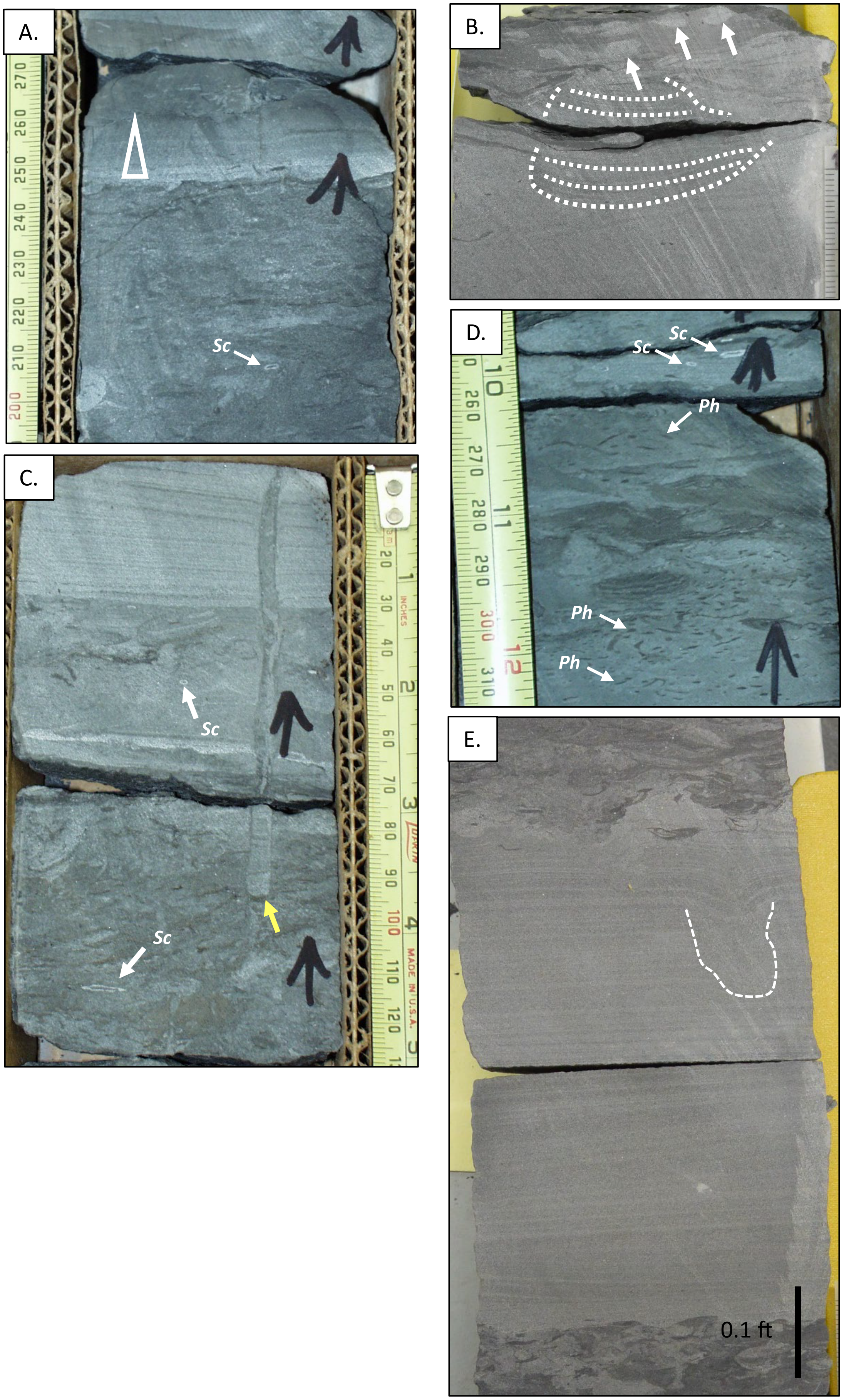


Figure 7. Photographs showing characteristics of FA3. **A.** Stacked, graded siltstone laminae at 968 feet in Umiat 18 (marked by white triangles). Scale at left is graduated in centimeters and millimeters. **B.** Coarse-grained siltstone with ripple cross-lamination interpreted as the product of unidirectional currents at approximately 3,499 feet in Wolf Creek 3. Scale at left is graduated in centimeters and millimeters. **C.** Very fine-grained sandstone with ripple cross-lamination interpreted as wave-generated at 2,692.7 feet in Wolf Creek 3. Grain size card is 5 cm wide. **D.** Soft-sediment deformed siltstone and darker colored mudstone at 3,305 feet in Wolf Creek 3. Scale at left is graduated in centimeters and millimeters. **E.** Plane lamination in a sandstone bed at approximately 3,595 feet in Square Lake 1. Note the low-angle dip of laminations and the gradual change in dip direction from the base of the photograph to the top in the core to the left of the yellow tape measure. These dip changes are attributed to HCS. The core to the right of the tape measure (above solid white line) is a sandstone with very subtle changes in lamina dip angles, which are also attributed to HCS. Yellow tape measure is graduated in inches (right side) and centimeters (left side).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successions (see Scott and Fisher, 1969; Galloway and Hobday, 1996; Bhattacharya, 2006). In these wells, FA3 is classified as undifferentiated offshore transition—prodelta. In the Umiat 18 and Grandstand 1 cores, FA3 lacks abundant wave-generated structures and includes elements more typically ascribed to river-dominated prodelta successions and are shown as prodelta deposits.

In cores from Wolf Creek 3 and Square Lake 1, the abundance of sedimentary structures attributable to deposition under upper flow regime conditions and waning oscillatory flows suggest storm-related deposition (tempestites) between fairweather and maximum storm wave base in offshore transition and wave-influenced prodelta settings (Walker and Plint, 1992; Reading and Collinson, 1996). Thin beds resembling Bouma Ta, Tab, and Tac suggest deposition from thin, concentrated density flows, whereas Tbc and Tc beds suggest deposition from dilute turbidity currents (hyperpycnal flows?), with both flow types emanating directly from distant distributary channels (Mulder and others, 2003; Bhattacharya and MacEachern, 2009; Olariu and others, 2010), or originating from the failure of distributary mouth bars (Bhattacharya, 2006). Interbedded mudstone was deposited during the waning stages of storm events and from plumes of suspended fine-grained sediment discharged from deltaic distributaries. During ensuing fairweather conditions, burrowing organisms colonized muddy substrates, resulting in pervasive disruption of original depositional fabrics.

In contrast to offshore transition-prodelta deposits in the Wolf Creek 3 and Square Lake 1 wells, FA3 in Umiat 18 and Grandstand 1 includes coarse silt and very fine-grained sand deposited from density underflows that emanated from distributaries during flood events as frontal splays and, possibly, hyperpycnal flows that resemble dilute turbidites, and are interpreted as prodelta deposits (Galloway and Hobday, 1996; Mulder and others, 2003). The high sediment supply and freshwater flux created a high-stress environment which suppressed the activity of burrowing organisms (MacEachern and others, 2005). Wave-formed sedimentary structures are not common in FA3 in cores from these wells and bioturbation is more variable than in the Wolf Creek 3 and Square Lake 1 cores, which is consistent with deposition in more river-dominated prodelta settings (sheets 4 and 5).

Facies association 4 – Shoreface—Delta Front

Description – Facies association 4 (FA4) consists of sandier-upward successions up to 88 feet thick that typically start with thinly interbedded mudstone and very fine-grained sandstone, grading up-section to amalgamated light tan to light gray, very fine- to fine-grained sandstone. Mudstone is gray to dark gray and ranges from unbioturbated to pervasively bioturbated (figs. 9A–B). The narrow range of grain

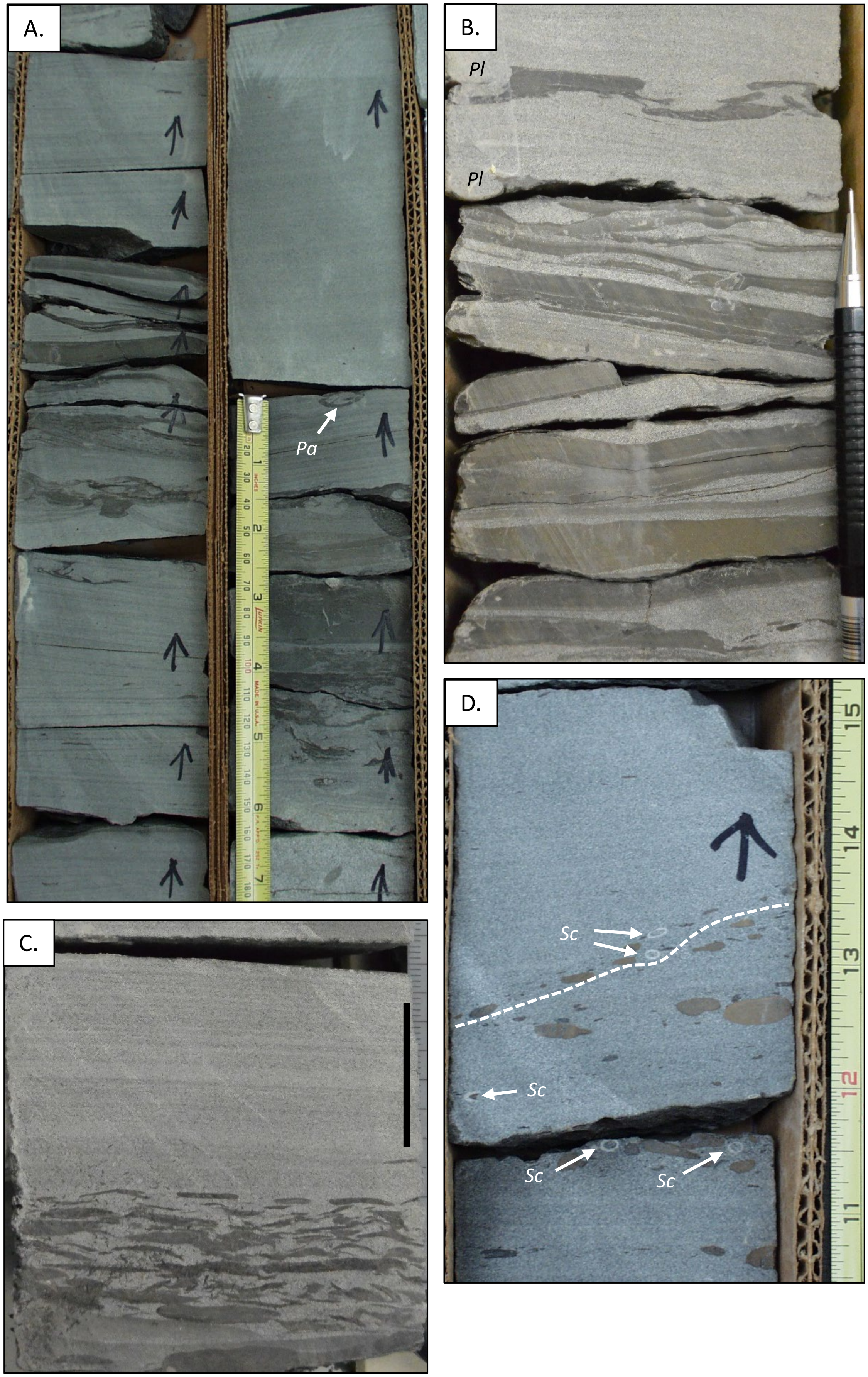
Figure 8, previous page. Core photographs showing bioturbation in FA3 in cores from Wolf Creek 3 and Square Lake 1. **A.** Moderately to highly bioturbated mudstone at 3,902 feet in Square Lake 1, Note pervasive bioturbation in mudstone and the solitary *Schaubcylindrichnus* burrow (white Sc). Discontinuous black streaks visible in vicinity of the Schaubcylindrichnus burrow are *Phycosiphon* burrows. Note also normal size grading in the fine-grained sandstone near the top of the photograph (white triangle). Tape measure graduated in centimeters. **B.** *Teichichnus* burrow in ripple cross-laminated sandstone at 2,183.5 feet in Wolf Creek 3. Scale at right graduated in millimeters. **C.** Interbedded very fine-grained sandstone and intensely bioturbated mudstone at 3,217 feet in Square Lake 1. Sandstone is wave-ripple cross-laminated. Note the escape burrow extending from the mudstone upward through the overlying sandstone bed (yellow arrow marks base of burrow). Tape measure graduated in inches (right side) and centimeters (left side). **D.** *Phycosiphon (Ph)* and *Schaubcylindrichnus (S)* burrows in sandstone interbedded with dark gray mudstone at 3,221 feet in Square Lake 1. Note, most Phycosiphon burrows are unlabeled. Tape measure graduated in inches (right side) and centimeters (left side). **E.** Interbedded very fine-grained sandstone and mudstone at 3,302.5 feet in Wolf Creek 3. Mudstones are highly bioturbated (BI 3-4) and include irregular shaped patches of sandstone. The sandstone bed has sharp bounding contacts with mudstone – the lower contact is characterized by micro-relief due either to turbulent scour or loading, whereas the upper contact is highly disrupted due to burrowing organisms and the degree of bioturbation decreases abruptly downward in the sand bed (BI 2-3 to BI 0-1). The bioturbated upper mudstone likely records the near total disruption of the upper part of the sandstone bed. Note the re-burrowed burrow (outlined by dashed white line), and downward deflected laminations above it, near the right edge of the photo in the sandstone bed.

sizes present in sandstone makes identification of individual event beds in amalgamated successions difficult in some cores, unless mudstone rip-up clast lags or prominent scour surfaces associated with slight color changes are present (figs. 9C–D). Normally graded sandstone beds are common in the lower part of FA4, where they are interbedded with mudstone. Sandstone throughout the association most commonly include massive beds, beds with plane-parallel horizontal laminae, and low-angle dipping laminae, but cross-bedding and current- and wave-ripple cross-lamination are present locally. Mudstone rip-ups are common and locally sideritic (figs. 9C–D). Soft-sediment deformation is common in sandstone beds in the lower part of the association. Low-angle dipping laminae similar to low-angle laminations described in FA3, in which dip directions change gradually up and down the core are common and similarly attributed to HCS (figs. 10A–D). Macerated terrestrial plant debris is common and ranges from few fragments on parting surfaces to abundant debris covering these surfaces. Locally, laminae are accentuated by abundant macerated plant material and larger coalified fragments appear jumbled together in some beds. Broken and abraded *Ditrupa* and pelecypod fragments are locally common (fig. 11A). Bioturbation defines a mixed *Cruziana—Skolithos* ichnofacies, and ranges from sparse to intense (BI 1–5), decreasing progressively toward the top of the association, where it is generally absent to low (BI 0–2) in examples from distal settings, and is absent to sparse (BI 0–1) in more proximal settings. Recognizable ichnogenera include *Planolites* (fig. 11B), *Palaeophycus* (figs. 11C–D), *Schaubcylindrichnus (*fig. 9D*), and Macaronichnus* (fig. 11E); *Asterosoma* and *Teichichnus* are rare (fig. 11F). Escape traces are present locally as are re-burrowed burrows (figs. 11C–D). In some cores, notably Umiat 18, the plane-parallel laminations appear fuzzy and indistinct, resembling cryptobioturbation (MacEachern and others, 2005). FA4 is gradational above FA3 and is common in cores from Wolf Creek 3, Square Lake 1, Grandstand 1, and Umiat 18 (sheets 2–5).

Interpretation – In the Wolf Creek 3 and Square Lake 1 cores, FA4 includes facies elements common to both shoreface and delta front settings (Walker and Plint, 1992; Bhattacharya, 2006; Clifton, 2006), and is interpreted as a progradational storm wave-modified delta front succession. On the core descriptions, most examples of this association are labeled shoreface-delta front, unless there are clear facies criteria for interpreting the succession as a more typical high-energy shoreface (Walker and Plint, 1992; Ryer and Anderson, 2004; Clifton, 2006) or river-dominated delta front succession (Scott and Fisher, 1969; Bhattacharya and Walker, 1991; Ryer and Anderson, 2004; Bhattacharya, 2006).

FA4 in Wolf Creek 3 and Square Lake 1 includes abundant horizontal laminae interbedded with gently dipping laminae interpreted as HCS. The combination of both types of laminae in vertical succession within a single bed (Sl→Shcs) suggest event deposition from waning oscillatory flows associated with long-period storm waves (Duke and others, 1991). The abundance of trace fossils and sporadic occurrence of broken and abraded pelecypod shell fragments are common elements of high-energy shoreface successions.

Figure 9, next page. Photographs showing selected characteristics of FA4 in Wolf Creek 3 and Square Lake 1. **A.** Very fine-grained sandstone with thin mudstone interbeds in lower shoreface-distal delta front deposits at 2,034 feet in Wolf Creek 3. The disrupted mudstone laminae with patches of sandstone are likely a bioturbation fabric (BI 2–3). Note the *Palaeophycos* burrow *(Pa)*. Tape measure is graduated in centimeters (left side) and inches (right side). **B.** Very fine-grained sandstone with thin mudstone interbeds in lower shoreface-distal delta front deposits at 3,859.3 feet in Square Lake 1. Note *Planolites* burrows *(Pl)*. The base of the upper bed containing the *Planolites* burrow includes apparent load structures. Visible part of pencil is 0.28 feet long (85 cm). **C.** Plane-parallel, horizontal laminations in very fine-grained sandstone above a basal mudstone clast-rich layer at the base of a sandstone bed at 3,890.7 feet in Square Lake 1. Black line is one inch long (2.54 cm). **D.** Plane-parallel, horizontal laminations above and below a prominent scour surface (white dashed line) at 3,493 feet in Square Lake 1. Note the abundant sideritic mudstone rip-up clasts below the scour surface and scattered mudstone clasts resting on the surface. Note also the *Schaubcylindrichnus (Sc)* burrows. Tape measure graduated in inches.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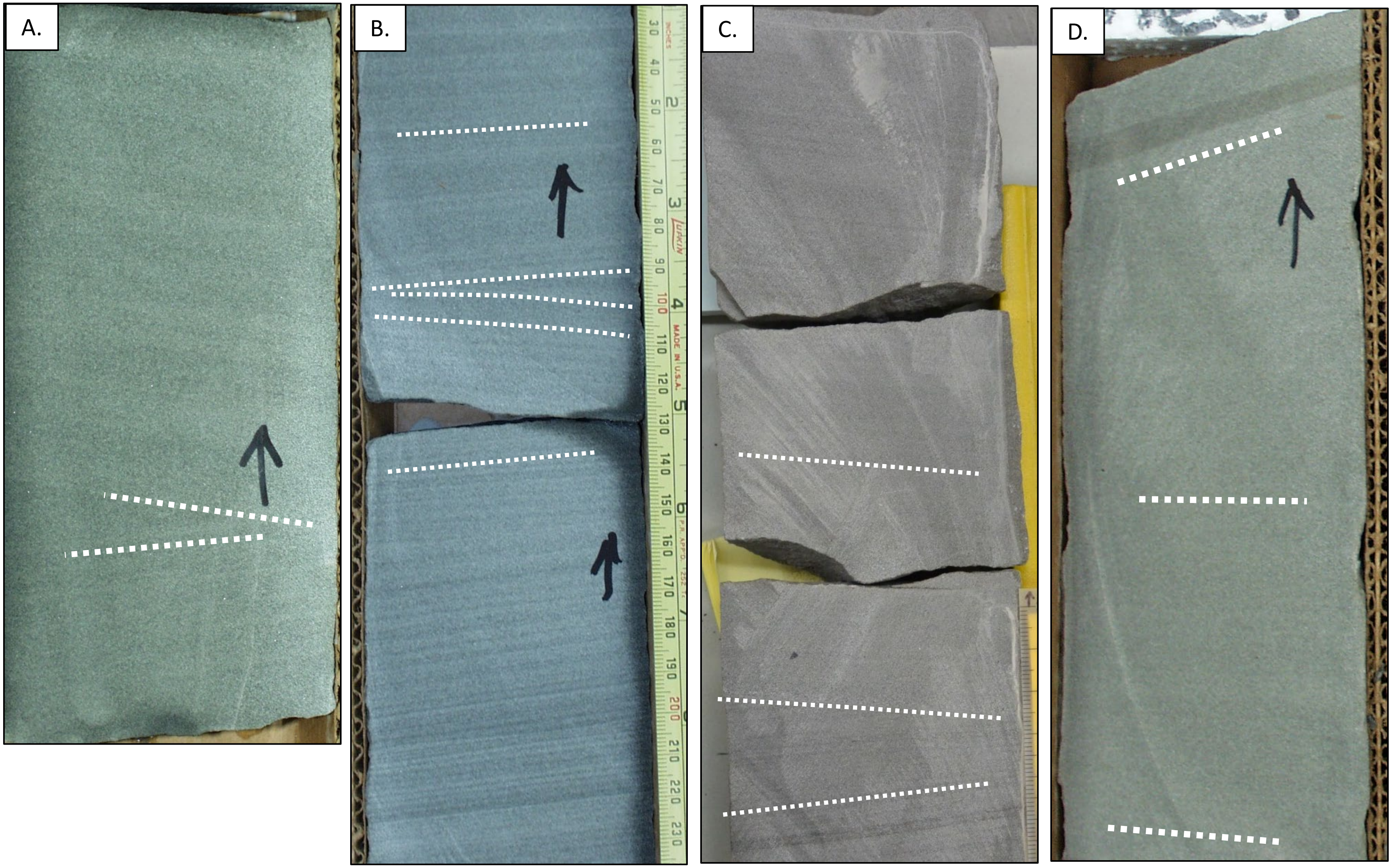
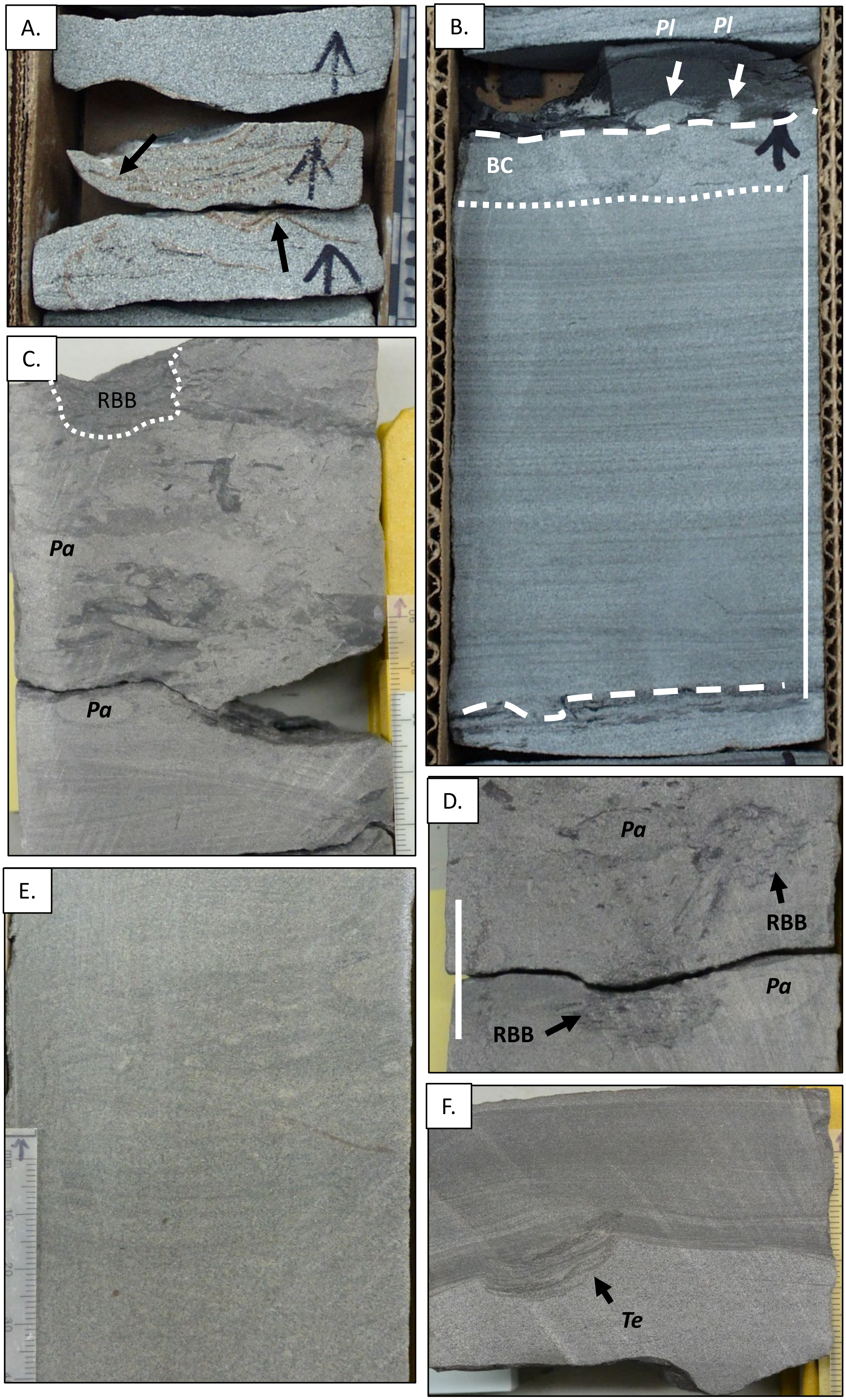


Figure 10. Photographs showing key features in amalgamated sandstone of FA4. Low-angle laminations at 3,872 feet (**A**) and 3,095.5 feet (**B**) in Square Lake 1. Low-angle laminations at 2,182 feet (**C**) and 2,156.5 feet (**D**) in Wolf Creek 3. Note the changes in dip direction (dotted white lines) in each photograph. These laminae are interpreted as HCS.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Bioturbation is most abundant in lower and middle shoreface settings where conditions are most suitable for preservation and tends to be absent or scarce in the more proximal reaches. These features, combined with the sporadic occurrence of abundant macerated plant debris (phytodetrital pulses of MacEachern and others, 2005), suggest deposition in a storm-wave influenced shoreface–delta front setting, with plant material transported to the depositional site by longshore currents from distant distributary channel mouths (sheets 2 and 3; LePain and Kirkham, 2001; LePain and others, 2017). Assuming this interpretation is correct, powerful storm waves shaped the nearshore marine setting during Nanushuk time at least in the southeastern part of the NPRA. Facies in Nanushuk outcrops south of Umiat include similar successions with abundant storm wave-generated sedimentary structures (HCS and swaley cross-stratification (SCS); LePain and others, 2009).

The absence of abundant wave-formed structures in the Umiat 18 and Grandstand 1 cores suggest that storm waves did not significantly impact this part of the Nanushuk coast when the cored successions were deposited, and that the delta front environment was more river-dominated overall than at the Wolf Creek 3 and Square Lake 1 locations. The sporadic occurrence of trace fossils (moderate to intense bioturbation locally) and the common presence of terrestrial plant material, sometimes in large quantities, are consistent with greater river influence (sheets 4 and 5; MacEachern and others, 2005).

Facies association 5 – Distributary Channel and Mouth bar

Description – Facies association 5 (FA5) consists of amalgamated very fine- to fine-grained sandstone successions ranging in thickness from approximately 7 feet to over 50 feet. Amalgamated sandstone includes abundant horizontal plane-parallel laminae, wave- and current-ripple cross-laminae, and macerated terrestrial plant debris (figs. 12A–C). Larger, coalified plant fragments are locally common (fig. 12D), as are trough cross-bedding (fig. 12E) and massive sandstone. Mudstone intraclasts and soft-sediment deformed beds are common (fig. 12F). Broken and abraded bivalve shell fragments (*Inoceramus*) aligned parallel to bedding are common near the tops of some coarsening-upward (CU) successions (fig. 13A). Bioturbation is absent to sparse (BI 0 to 2; fig. 13B), but is moderate to intense locally (fig. 13C). Some examples of FA5 grade down-section to interbedded mudstone and very fine-grained sandstone of FA3, while others grade down-section to amalgamated sandstones of FA4. FA5 has been tentatively identified in cores from Wolf Creek 3 (sheet 2, 2,661–2,673 feet, 2,330–2,359 feet, and 1,646–1,656 feet), Square Lake 1 (sheet 3, 1,716–1,723 feet and 1,657–1,694 feet), Umiat 18 (sheet 4, 777–833 feet), and possibly in Grandstand 1 (sheet 5, 829–837 feet).

The uppermost part of some CU successions consist of fine-grained sandstone overlying a scour surface (fig. 14A; sheet 2, scour surface 2,665 feet in Wolf Creek 3; sheet 3, scour surface inferred in gap between 1,694 feet and 1,695 feet in Square Lake 1). This sandstone includes abundant hori-

Figure 11, previous page. Photographs showing macrofossils and trace fossils in FA4. **A.** *Inoceramus* shell fragments (black arrows) in fine-grained sandstone at 1,849.5 feet in Square Lake 1. The grain size card along the right edge of the photograph is graduated in centimeters. **B.** Bioturbation fabric at 3,552 feet in Square Lake 1. The white dashed lines mark the base and top of a single sandstone event bed. The lower 90 percent of bed is largely undisturbed, whereas the upper part was thoroughly bioturbated after deposition (between white dotted and dashed lines). Note the mudstone drape with *Planolites* burrows (white arrows). White vertical line is 0.35 ft long. **C.** The bioturbated upper part of an event bed at 3,042.5 feet in Wolf Creek 3. Note the wave ripple cross-lamination in the unbioturbated part of the bed in lower part of image. Note *Palaeophycus* burrows (*Pa*) and re-burrowed burrow (RBB). **D.** Upper part of a sandstone bed at 3,034 feet in Wolf Creek 3. The upper 0.3 ft of the bed is highly to intensely bioturbated (BI 4–5). Note the *Palaephycus* burrows (*Pa*) and re-burrowed burrows (RBB). The white line is 1 inch. **E.** *Macaronichnus* burrows in amalgamated sandstone at 1,924 feet in Wolf Creek 3. **F.** *Teichichnus* burrow at the top of the current ripple-laminated sandstone bed at 3,376.7 feet in Wolf Creek 3.

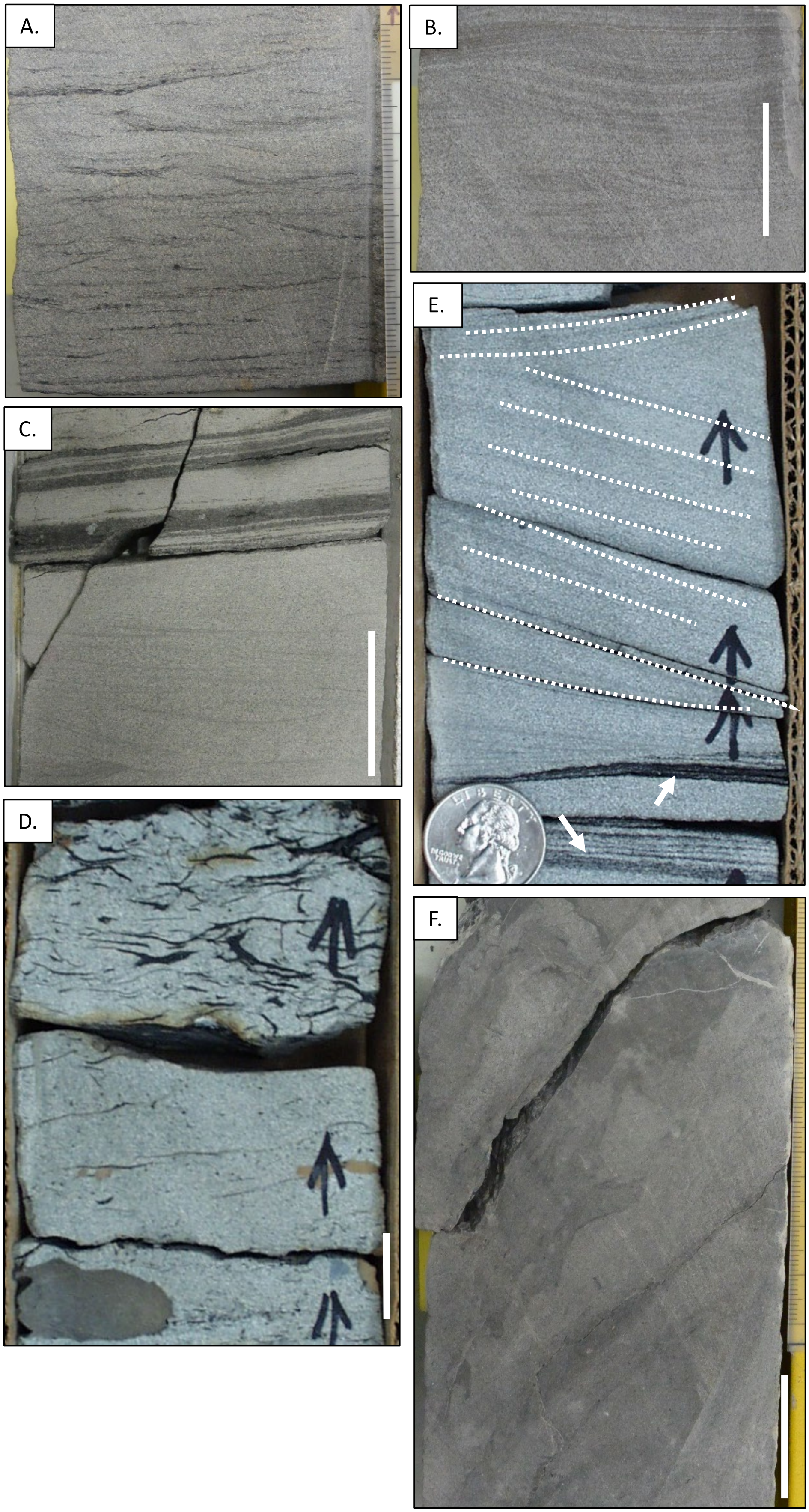

Figure 12. Photographs showing selected features of FA5 interpreted as distributary channel-mouth bar deposits. **A–B.** Wave-ripple cross-lamination at 2,333 feet and 2,113 feet in Wolf Creek 3, respectively, interpreted as mouth bar deposits reworked by fairweather waves. Dark colored laminae in A are rich in macerated plant fragments. Grain size card along the right side of A is graduated in millimeters and centimeters. White line in B is 0.08 feet long. **C.** Wave-ripple cross-lamination at 794 feet in Umiat 18. Note the dark colored carbonaceous laminae near top of image. White bar is 0.1 feet long. **D.** Large, coalified woody fragments at 2,116.5 feet in Wolf Creek 3. Note the sideritic mudstone rip-up clasts. White bar is 0.07 feet long. **E.** Trough cross-bedding in fine-grained sandstone at 2,116 feet in Wolf Creek 3. Some foreset laminae immediately above the quarter have a slight concave-upward geometry, which is consistent with trough cross-bedding. Note carbonaceous laminae near the quarter (white arrows). Quarter for scale. **F.** Soft-sediment deformed beds of siltstone (light colored lithology) and mudstone (darker lithology). Siltstone either foundered in a mudstone host due to a density contrast, or represents a small failure on the flank of a distributary mouth bar. White bar is 1 inch in length and scale on the grainsize card visible along the right edge of the image is graduated in millimeters and centimeters.

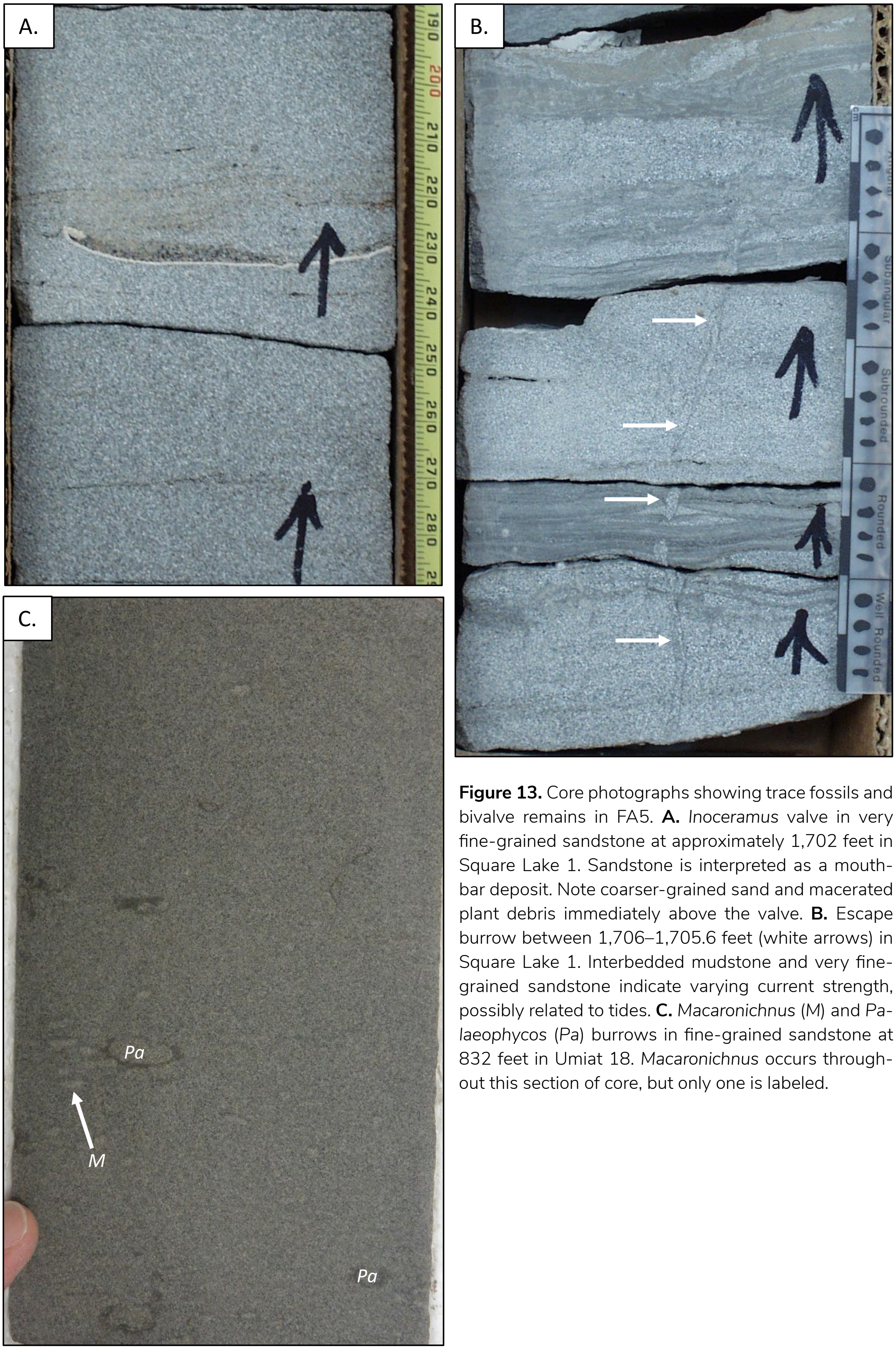

Figure 13. Core photographs showing trace fossils and bivalve remains in FA5. **A.** *Inoceramus* valve in very fine-grained sandstone at approximately 1,702 feet in Square Lake 1. Sandstone is interpreted as a mouth-bar deposit. Note coarser-grained sand and macerated plant debris immediately above the valve. **B.** Escape burrow between 1,706–1,705.6 feet (white arrows) in Square Lake 1. Interbedded mudstone and very fine-grained sandstone indicate varying current strength, possibly related to tides. **C.** *Macaronichnus* (*M*) and *Palaeophycos* (*Pa*) burrows in fine-grained sandstone at 832 feet in Umiat 18. *Macaronichnus* occurs throughout this section of core, but only one is labeled.

zontal plane-parallel laminae and cross-bedding (figs. 14B). Bivalve shell fragments (Square Lake 1, 1,694–1,674 feet) and possible pedogenic features are locally prominent. Bioturbation is typically absent (BI 0; fig. 14A–B), but some solitary traces are present locally (BI 1) and a few intervals are characterized by low (BI 2) to moderate bioturbation (BI 3). These successions are tentatively identified in Wolf Creek 3 (sheet 2, 2,661–2,665 feet), Square Lake 1 (sheet 3, 1,637–1,694 feet), and Umiat 18 (sheet 4, 777–796.8 feet). Where this sandstone is present, it rests erosionally above gradationally based deposits of FA5, or above either FA3 or FA4.

Interpretation – Most examples of FA5 in the studied cores are interpreted as distributary mouth bar deposits; the coarser-grained successions capping some examples of the association are interpreted as distal distributary channel deposits. Flow expansion and velocity reduction at the seaward end of distributary channels results in an abrupt decrease in flow capacity and competence, resulting in deposition of a bar deposit at the channel mouth, with subsequent

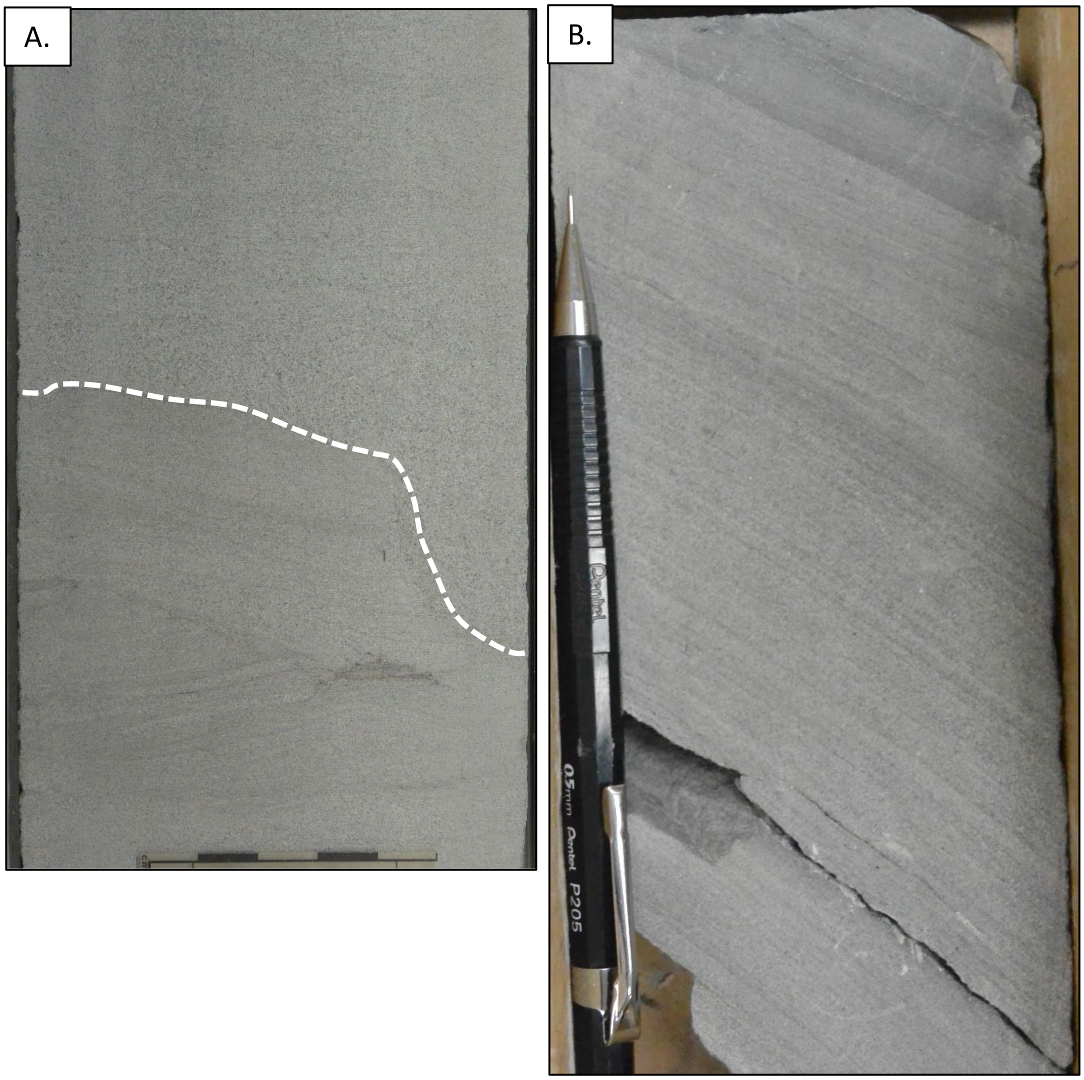

Figure 14. Core photographs showing sedimentary characteristics of FA5 interpreted as distributary channel deposits. **A.** Scour surface at 796.5 feet (dashed white line) truncating current ripple cross-laminae in Umiat 18. Scale at base of photograph graduated in centimeters. **B.** Foreset laminae associated with cross-bedding at 2,661.5 feet in Wolf Creek 3. Visible part of pencil is 0.43 feet long.

channel bifurcation around mouth bar deposits (Scott and Fisher, 1969). Mouth bar deposits are typically reworked by shoaling waves to form strike-elongated subaqueous sand bodies (Bhattacharya, 2006). In the resulting deposits mouth bar facies commonly dominate over distributary channel-fill facies and the two can be difficult to differentiate with confidence. For this reason, most examples of facies association

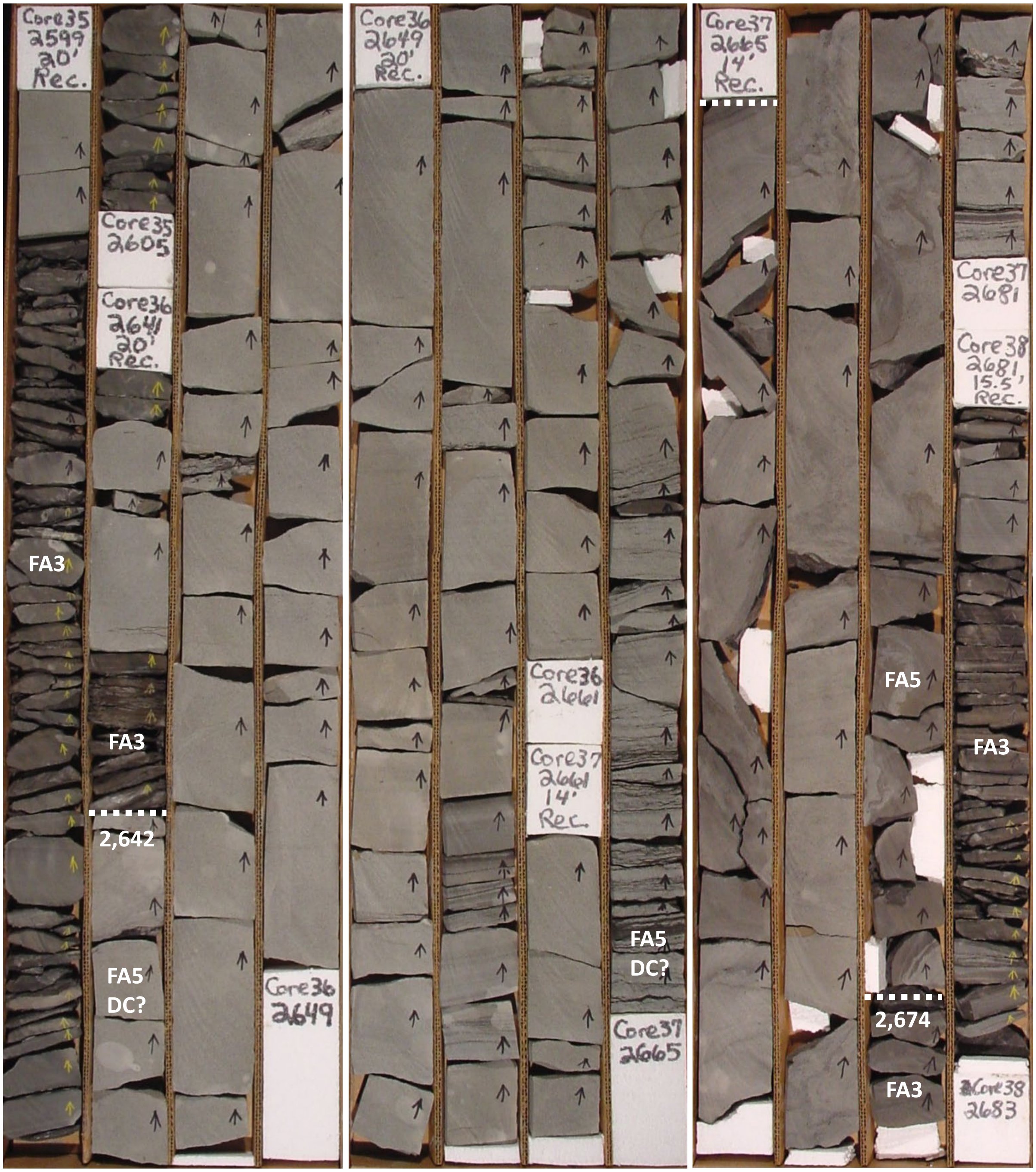

Figure 15. Core box photographs showing a continuously cored succession through FA5 from approximately 2,674 feet (lower white dashed line in second row of core from right) to 2,642 feet (upper white dashed line in second row of core from left) in Wolf Creek 3. Note the sandier-upward trend and soft-sediment deformation (deformed section between dashed white lines in core 37), interpreted as mouth bar deposits. The dark laminations immediately above the 2,665 foot mark in the box are carbonaceous mudstones at the base of a distributary channel-fill that extends up to 2,642 feet. The carbonaceous laminae above 2,665 feet may record a tidal influence. Each core row is 3.28 feet (1 meter) long. Core box photos modified from D'Agostino and Houseknecht (2002).

5 in the core descriptions include undifferentiated mouth bar and distributary channel deposits, with the exception of a few occurrences where these components are tentatively recognizable (fig. 15 and sheet 2, Wolf Creek 3, from 2,642 to 2,674 feet, 2,330 feet to 2,359 feet, 2,241 feet to 2,247 feet; fig. 16, sheet 3, Square Lake 1, from 1,715.5 feet to 1,722.5 feet and from 1,637 feet to 1,694 feet; sheet 4, Umiat 18, from 777 feet to 833.5 feet; sheet 5, Grandstand 1, 829 feet to 837 feet).

Facies Association 6 – Bayfill

Description – Facies association 6 (FA6) consists mainly of an irregular succession of brown to brown-gray mudstone and thinly interbedded siltstone and very fine- to fine-grained sandstone

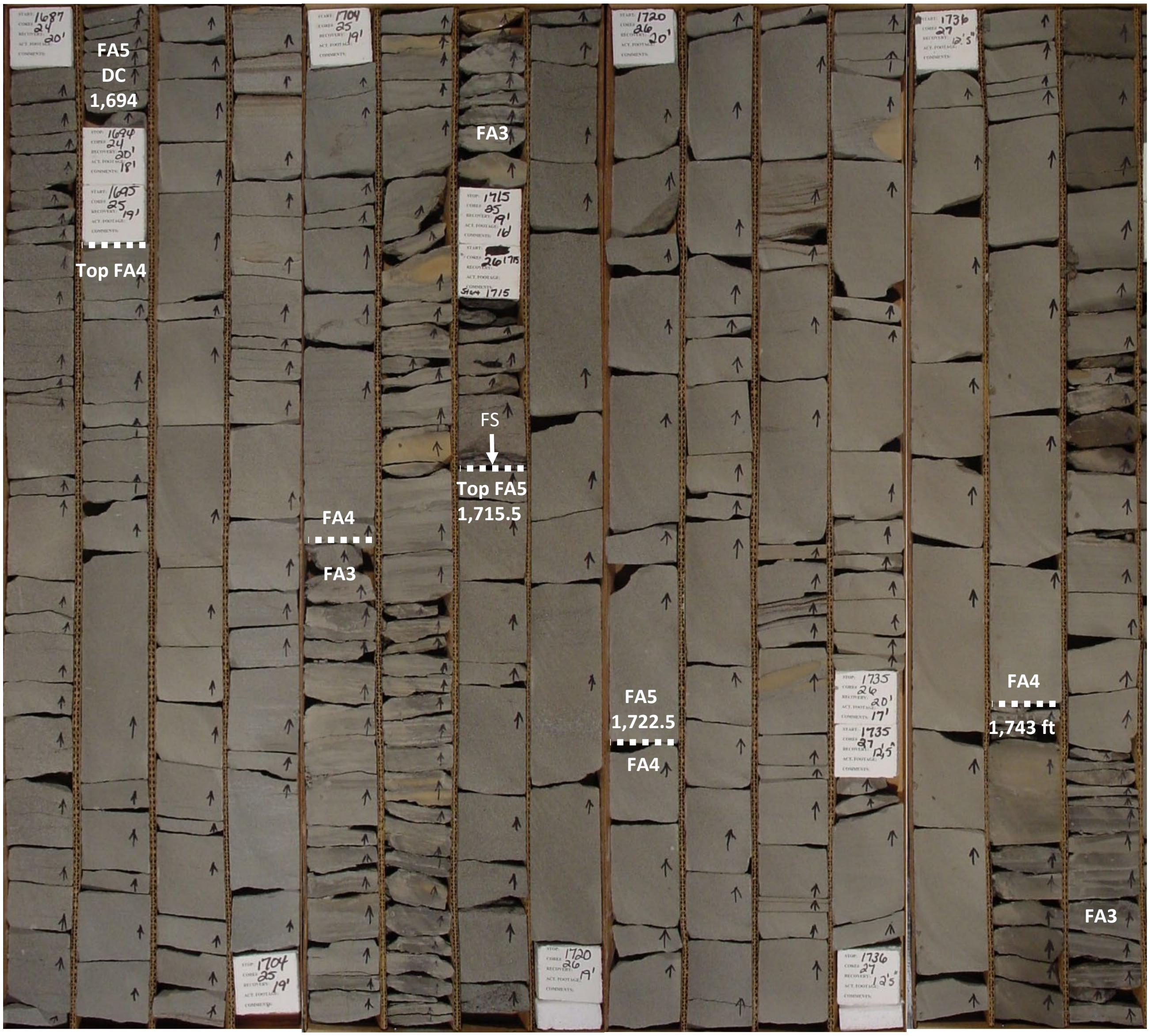

Figure 16. Core box photographs showing a continuously cored succession of FA3, FA4, and FA5 from approximately 1,743 feet to 1,637 feet in Square Lake 1. Core box photographs for this figure continue on next page. The oldest FA5 succession, interpreted as mouth bar deposits, grades upward from FA3 and lower very fine-grained sandstone of FA4 to upper very fine-grained sandstone of FA5 (contact at 1,722.5 feet), and is capped by a flooding surface at 1,715.5 feet (white dashed line labeled FS). The FA5 succession from 1,694 feet to 1,657 feet is interpreted as a distributary channel-fill succession (only 1,694 feet to 1,687 feet is shown in photograph). DC, distributary channel; MB, mouth bar. Each core row is 3.28 feet (1 meter) long. Core box photos modified from D'Agostino and Houseknecht (2002).

(fig. 17A–C). Mudstones appear massive to thinly laminated; macerated plant fragments are locally abundant and serve to accentuate laminations. Carbonaceous mudstone, high-ash coal stringers, and small coal clasts are present locally, as are rare small pieces of amber (sheet 3, Square Lake 1, 2,056 feet and 2,020 to 2,021.5 feet). Siltstone and sandstone beds range from less than 0.1 to approximately 1 foot thick and include horizontal, plane-parallel laminae, current and wave ripple

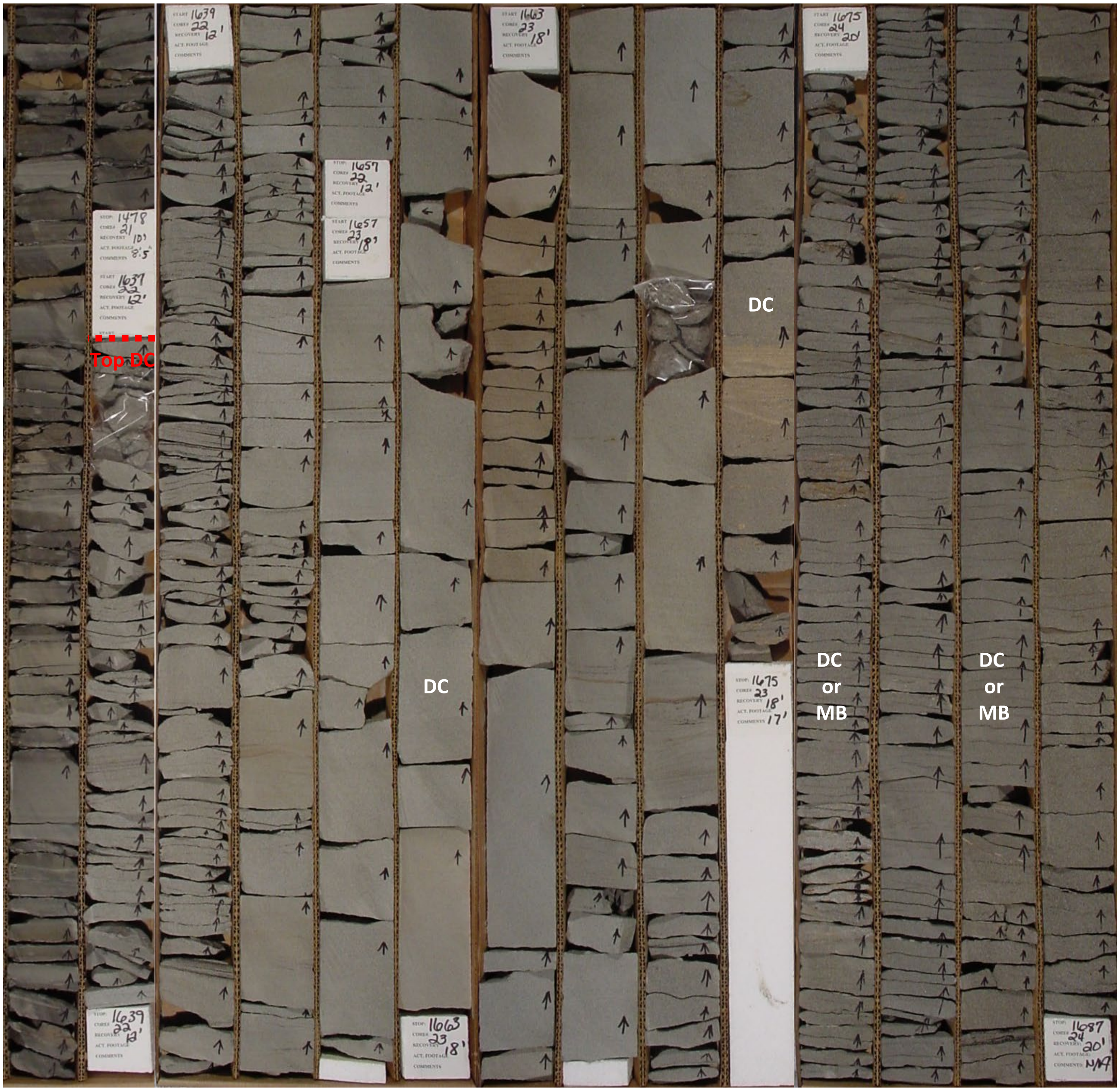

Figure 16, continued. Core box photographs showing a continuously cored succession of FA3, FA4, and FA5 from approximately 1,743 feet to 1,637 feet in Square Lake 1. Core box photographs for this figure continue on next page. The oldest FA5 succession, interpreted as mouth bar deposits, grades upward from FA3 and lower very fine-grained sandstone of FA4 to upper very fine-grained sandstone of FA5 (contact at 1,722.5 feet), and is capped by a flooding surface at 1,715.5 feet (white dashed line labeled FS). The FA5 succession from 1,694 feet to 1,657 feet is interpreted as a distributary channel-fill succession (only 1,694 feet to 1,687 feet is shown in photograph). DC, distributary channel; MB, mouth bar. Each core row is 3.28 feet (1 meter) long. Core box photos modified from D'Agostino and Houseknecht (2002).

cross-laminae (figs 17B-C), and soft-sediment deformation features (fig. 17D); massive textures are also common (fig. 17A). Bioturbation is highly variable, ranging from absent (BI 0) to intense (BI 5-6) in mudstone and sandstone (figs. 18A–C). Trace fossils include *Schaubcylindrichnus*, *Teichnichnus* (fig. 18A–B), and *Phycosiphon* (fig. 18C). One bed at approximately 1,645.5 feet in Wolf Creek 3 includes irregular, carbonaceous mud-filled vertical structures of uncertain affinity that may be rhizoliths (fig. 18D). Where FA6 rests above FA4 or FA5, the contact is typically sharp (fig. 19; sheet 2, Wolf Creek 3, 1,887 feet; sheet 4, Umiat 18, 777 feet; sheet 5, Grandstand 1, 829 feet, though bayfill interpretation is questionable). Cores 33 (below 1,886 feet) through 43 in Square Lake 1 are interpreted as FA6; the interval between cores 43 and 44 was not cored, but cuttings suggest the contact is sharp (sheet 3, Square Lake 1, 2,852–3,027 feet).

The irregular successions described above are interrupted locally by sand-dominated successions. Two varieties are recognized: 1. Sharp-based fining-upward successions up to five feet thick (sheet 2, Wolf Creek 3, 1,571–1,576 feet; sheet 3, Square Lake 1, 2,020–2,032 feet); and 2. Gradational coarsening-upward successions up to 15 feet thick (sheet 2, Wolf Creek 3, 1,716–1,726 feet and 1,645.5–1,656 feet; sheet 3, Square Lake 1, 1,912.5–1,928.5 feet). Sandstone in both varieties include horizontal, plane-parallel laminae and ripple cross-laminae. The geometry of ripple cross-laminae suggests reworking of sand by small waves. HCS, or possibly SCS, is present in some coarsening-upward successions (sheets 2 and 3).

Interpretation –The irregular succession characteristic of most examples of FA6 resembles interdistributary bay deposits documented in the central Appalachians by Horne and others (1978), the Dunvegan Formation by Bhattacharya and Walker (1991), and the Ferron Sandstone Member of the Mancos Shale by Ryer and Anderson (2004). Interdistributary bay deposits account for most of the cored Nanushuk Formation in the Wainwright 1 well in the western NPRA (LePain and Decker, 2016) and are common in outcrop to the south (LePain and others, 2009). Thin sandstone interbeds up to 1 foot thick represent overbank splay deposits. The sharp-based fining-upward sandstone and gradational coarsening-upward sandstone successions are interpreted as crevasse channel-fills and crevasse delta-front deposits, respectively (Elliot, 1974). The latter includes distributary mouth bar deposits associated with crevasse channels. Highly variable bioturbation is attributed to varying water salinity owing to frequent incursions of fresh floodwaters from nearby distributary channels. Highly bioturbated muddy sandstones with low diversity trace fossil assemblages are consistent with this interpretation (Pemberton and Wightman, 1992).

STRATIGRAPHIC ORGANIZATION AND IMPLICATIONS FOR DELTA STYLE

Analysis of facies stacking patterns in vertical sections provides important insights on depositional environments and their migration patterns through time. The graphic core descriptions for Wolf Creek 3, Square Lake 1, Grandstand 1, and Fish Creek 1, as portrayed in sheets 1–3 and 5, are not readily suitable for this type of analysis due to the non-uniform scale at which they were drafted. The scale of the cored intervals is uniform, but the scale in thick, uncored intervals is compressed, resulting in the false impression that the succession penetrated in the wells includes more sand than is actually present. Collins (1959a, 1959b) and Robinson (1958) do not provide process-response sedimentologic analyses and their graphic logs provide only lithologic information. Adding to the challenge is the absence of modern log suites for these four wells—only spontaneous potential (SP) and resistivity (short and long normal) logs are available—and the fact that some sands in each well were not cored (see Collins, 1959a, plate 32; and Collins, 1959b, plates 29 and 30). To help overcome these issues, sheet 6 shows simplified versions of the core descriptions drafted at a uniform scale. Umiat 18 is included on sheet 6 for comparison.

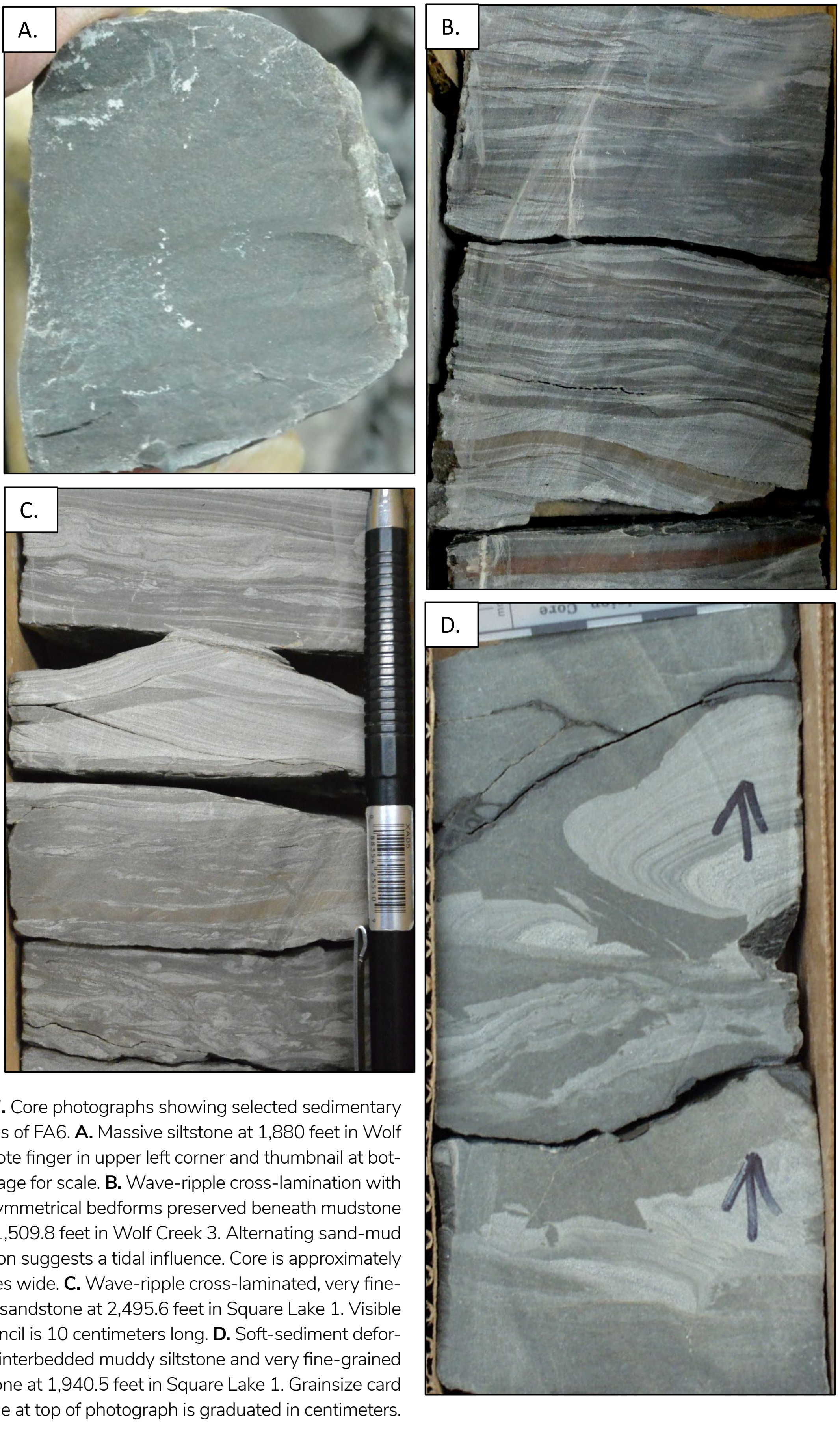

Figure 17. Core photographs showing selected sedimentary features of FA6. **A.** Massive siltstone at 1,880 feet in Wolf Creek 3. Note finger in upper left corner and thumbnail at bottom of image for scale. **B.** Wave-ripple cross-lamination with nearly symmetrical bedforms preserved beneath mudstone drapes at 1,509.8 feet in Wolf Creek 3. Alternating sand-mud deposition suggests a tidal influence. Core is approximately 2.25 inches wide. **C.** Wave-ripple cross-laminated, very fine-grained sandstone at 2,495.6 feet in Square Lake 1. Visible part of pencil is 10 centimeters long. **D.** Soft-sediment deformation in interbedded muddy siltstone and very fine-grained sandstone at 1,940.5 feet in Square Lake 1. Grainsize card visible at top of photograph is graduated in centimeters.

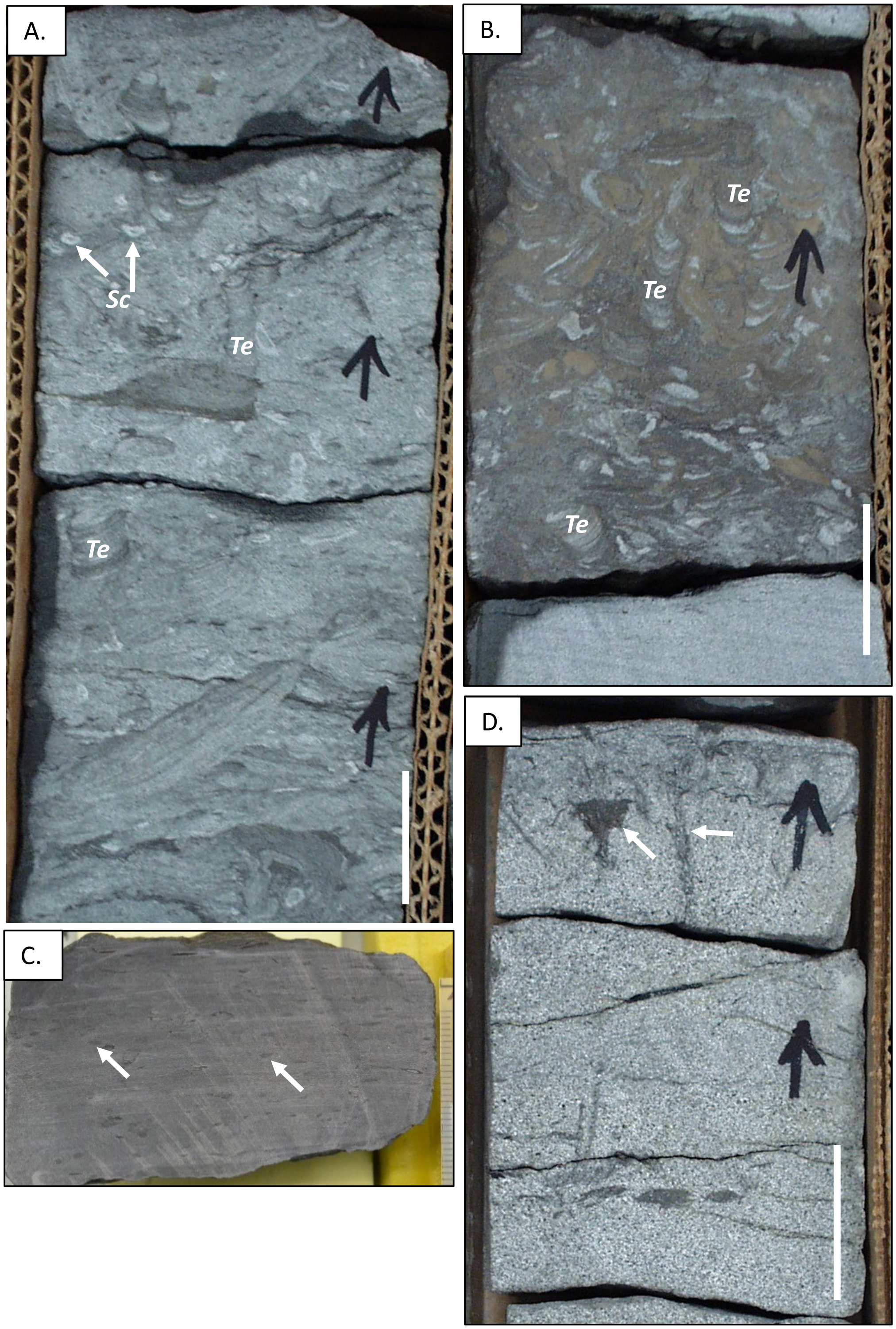

Figure 18. Core photographs showing bioturbation in FA6. **A.** Highly to intensely bioturbated (BI 4–5) muddy sandstone at 2,497.5 feet in Square Lake 1. Several examples of *Schaubcylindrichnus* (Sc) and *Teichichnus* (T) are present. White line is 1 inch long. **B.** Highly to intensely bioturbated muddy sandstone (BI 4–5) with many *Teichichnus* (T) burrows at 2,498 feet in Square Lake 1. White line is 1 inch long. **C.** Mudstone with abundant *Phycosiphon* burrows (white arrows point to a few examples) at 1,731 feet in Wolf Creek 3. Absence of visible bleached halo around traces suggests these might be *Helminthopsis* burrows instead of *Phycosiphon*. Scale along the right edge of the photograph is graduated in millimeters. **D.** Fine-grained sandstone with discrete vertical burrows at 1,645.5 feet in Wolf Creek 3, including features interpreted as rhizoliths. Funnel-shaped trace (white arrow on left side of image) is filled with carbonaceous mudstone. This piece of core appears to be missing in the split archived at the Alaska Geologic Materials Center. White line is 1 inch long.

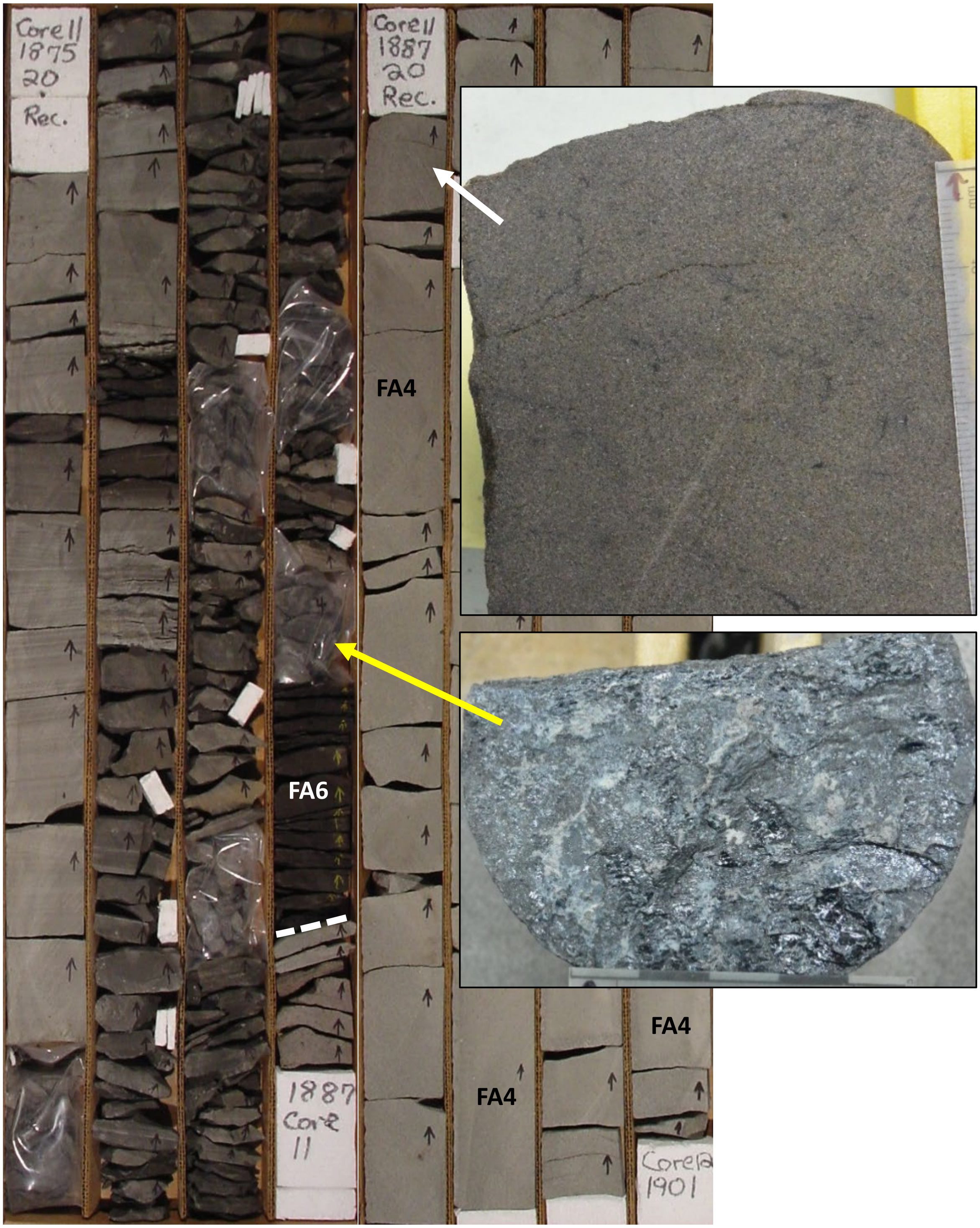

Figure 19. Core box photograph showing part of the splits of cores 11 and 12 from Wolf Creek 3 archived at the USGS Core Research Center. Inset photos taken of core archived at the Alaska Geologic Materials Center. Note the contact between sandstone of FA4 and carbonaceous mudstone with coal stringers of FA6 above 1,887 feet (dashed white line). The upper inset photo shows sandstone at the top of FA4 (white arrow) with irregular-shaped wisps of carbonaceous mudstone imparting a mottled appearance resembling a pedogenic fabric. If correct and the fabric is pedogenic, FA4 was emergent prior to burial beneath FA6. Grainsize card along right side of image is graduated in millimeters and centimeters. Lower inset photograph shows a coaly stringer at base of FA6 and immediately above sandstone of FA4 (yellow arrow). Note edge of grain size card graduated in centimeters at base of photo. Core box photograph from D'Agostino and Houseknecht (2002). Each row in core box photograph is 3.28 feet long (1 meter).

Despite the lack of gamma ray logs for the older wells, the SP log response can usually be tied to lithologies in the studied cores with some confidence, allowing use in the uncored intervals, along with cuttings descriptions (Collins, 1959a, 1959b; Robinson, 1958) and the overall stratigraphic context relative to nearby cored intervals, to infer lithologies, facies, and their stacking patterns.

Fish Creek 1

Using Bird's (1988) formation top, the Fish Creek 1 well penetrated approximately 1,220 feet of Nanushuk strata, with the cored intervals consisting entirely of distal shelf deposits of FA2, and 2,910 feet of the Torok Formation, with the cored intervals consisting mostly of unbioturbated slope deposits of FA1 (sheets 1 and 6). The bioturbated mudstone (BI 2–3) in core 42 is in the upper part of the Torok Formation, based on the formation top at 4,110 feet TVD (Bird, 1988), and it represents the first definitive occurrence of visible bioturbation in core. The bioturbation and light color of this mudstone contrast sharply with the dark brown-gray to gray, unbioturbated clay shale and mudstone in cores 43 through 75, interpreted as slope deposits (sheet 1), suggesting the upper 90 to 100 feet of the Torok Formation includes distal shelf deposits (topset Torok, see Houseknecht and Schenk, 2001). The absence of bioturbation fabrics in FA1 (cores 43–75), with the sole exception of possible sparse bioturbation in core 57 (sheet 1), is consistent with the observation of Houseknecht and Schenk (2001) that bioturbation is rare in slope deposits of the Torok. Thus, the Fish Creek 1 well penetrated a thick, progradational succession of slope mudstone overlain by a thinner succession of distal shelf deposits. Slope deposits in this well correspond to prominent clinoform reflectors on seismic sections (Houseknecht and others, 2008; Houseknecht, 2019). According to Weimer (1987, his fig. 6), approximately the lower 1,200 feet of the Fish Creek 1 well (5,800–7,020 feet TVD) consists of lower slope deposits involved in the Fish Creek slide. No evidence of disrupted bedding was noted in cores 63 to 75, indicating the part of the slide block penetrated by the well includes relatively coherent stratigraphy. The prominent left deflection on the SP log starting around 4,110 feet suggests the presence of a sandy succession up to 40 feet thick at the base of the Nanushuk Formation (sheet 6, approximately 4,110–4,070 feet), possibly associated with a sea level lowstand.

Umiat 18

The graphic core description and gamma ray log for Umiat 18 define three progradational parasequences from a depth of approximately 1,150 feet to 777.8 feet (labeled Kn1 through Kn3 on sheet 4). Note the lower part of Kn1 was not cored and the down-hole extent and lithological character are inferred from the gamma ray log (sheets 4 and 6; uncored part of Kn1 is shown with a dashed red line). The gamma log suggests at least two additional sandier-upward parasequences between approximately 1,420 to 1,150 feet (dashed red lines on left side of gamma ray log, sheet 4) that are likely part of the Nanushuk Formation. These five parasequences define a progradational succession with each successively younger parasequence recording deposition in more proximal settings. In the cored interval, each parasequence consists, in ascending order, of heterolithic deposits of FA3 grading up-section to amalgamated sandstones of FA4 (sheet 4). In Umiat 18, FA3 and FA4 in Kn1 and Kn2 define shoaling-upward prodelta to delta front successions capped by sharp marine flooding surfaces. FA3 is inferred to comprise the lower, uncored part of Kn1. The two sandier-upward parasequences recognizable on the gamma ray log below Kn1 are interpreted as the distal expression of delta front cycles/shingles comprising the lower 250–300 feet of the Nanushuk Formation. The cored succession below 777.4 feet records deposition of delta lobes that were influenced more by riverine processes than by shoaling waves (river-dominated).

The upper 67.4 feet of the cored interval is a mudstone-dominated succession that appears different than the prodelta successions at the base of Kn2 and Kn3 and different than the bayfill successions interpreted in the Wolf Creek 3 and Square Lake 1 cores (sheet 4). The flooding surface at approximately 777.4 feet overlies bioturbated sandstone at the top of a sand body in Kn3 interpreted as a distributary channel-fill. This surface is overlain by a little over six feet of interbedded light gray mudstone and bioturbated (BI 2–3) fine-grained sandstone that is, in turn, overlain by approximately 21 feet of brown-gray, massive to finely laminated mudstone that is unbioturbated (BI 0), except for a thin interval from approximately 761.8 feet to 762.2 feet that is moderately bioturbated (BI 3). Delicate, thin-walled, disarticulated, monospecific pelecypod valves are present at discrete intervals in the mudstone below the bioturbated interval, but are not abundant (fig. 20A); similar pelecypod valves are abundant above the bioturbated interval, between 761.3 feet and 759.0 feet (fig. 20B). Most of the pelecypod shells are oriented parallel to bedding and many shells are oriented convex side up and many others convex side down. The mudstone interval above the friable sandstone (top at 749.5 feet) is highly to intensely bioturbated (BI 4–5?) and includes abundant *Helminthopsis* (or *Phycosiphon*) burrows. The interbedded mudstone and sandstone above the flooding surface from 777.4–768 feet are interpreted to record reworking of underlying distributary channel-fill, mouth bar, and delta-front successions that were present nearby. The unbioturbated mudstone interval records deposition in a setting that was inhospitable to a burrowing infauna, possibly due to an oxygen deficiency, or brackish water, or both. The thin-walled shell material suggests a low energy setting where it originated and minimal transport to the depositional site by low-energy currents capable of moving the valves without destroying the delicate shell material. The depositional setting is provisionally interpreted as an interdistributary bay (bayfill) that was initially characterized by either anoxic bottom conditions and/or brackish water. If this interpretation is correct, the surface shown on sheet 4 at 777.4 feet is not a flooding surface, but merely represents a facies contact in a normal progradational succession from distributary channel deposits (FA5) to overlying interdistributary bayfill deposits (FA6).

Wolf Creek 3

Wolf Creek 3 spudded in a thin mantle of unconsolidated deposits, penetrated the top of the Nanushuk Formation at a depth of 30 feet (below top of Kelly bushing; Collins, 1959b), and reached total depth in the upper part of the Torok Formation at 3,760 feet (Bird, 1988). Based on Bird's (1988) formation top, the preserved thickness of Nanushuk in this well is 3,545 feet (sheets 2 and 6). The absence of a younger bedrock formation above the Nanushuk indicates an unknown thickness of strata in the upper part of the unit is missing due to uplift and erosion. The 47 cores cut from the well are distributed throughout the lower 2,100 feet of the formation and uppermost Torok. Cores and the SP log document an aggradational-progradational stack of marine parasequences at least 1,635 feet thick (cores 46 through lower part of core 11) that grade upward to interbedded marine and marginal marine facies in the upper 412 feet of the cored succession (cores 11 through 1). The marine parasequences in cores 46 through the lower part of 11 contain abundant features commonly associated with storm-influenced lower to middle shoreface and delta front environments, including possible HCS, wave ripple cross-lamination, unidirectional current indicators, graded beds, mudstone rip-up clasts, small- and large-scale soft sediment deformation structures, abundant macerated terrestrial plant fragments and larger coalified material, and a locally abundant and diverse suite of trace fossils representing widespread bioturbation by a mixed *Cruziana-Skolithos* ichnofacies assemblage. Many of these features are associated with discrete event beds, including classic shallow marine storm deposits (Walker and others, 1983; Duke and others, 1991) and the deposits of density underflows that emanated from distributary channels (frontal splays and/or hyperpycnites; Myrow and Southard, 1996; Mulder and others, 2003; Bhattacharya and MacEachern, 2009). Collectively, these features suggest the interval from approximately 3,522 feet to 1,887 feet represents a progradational succession of storm wave influenced delta lobes composed of

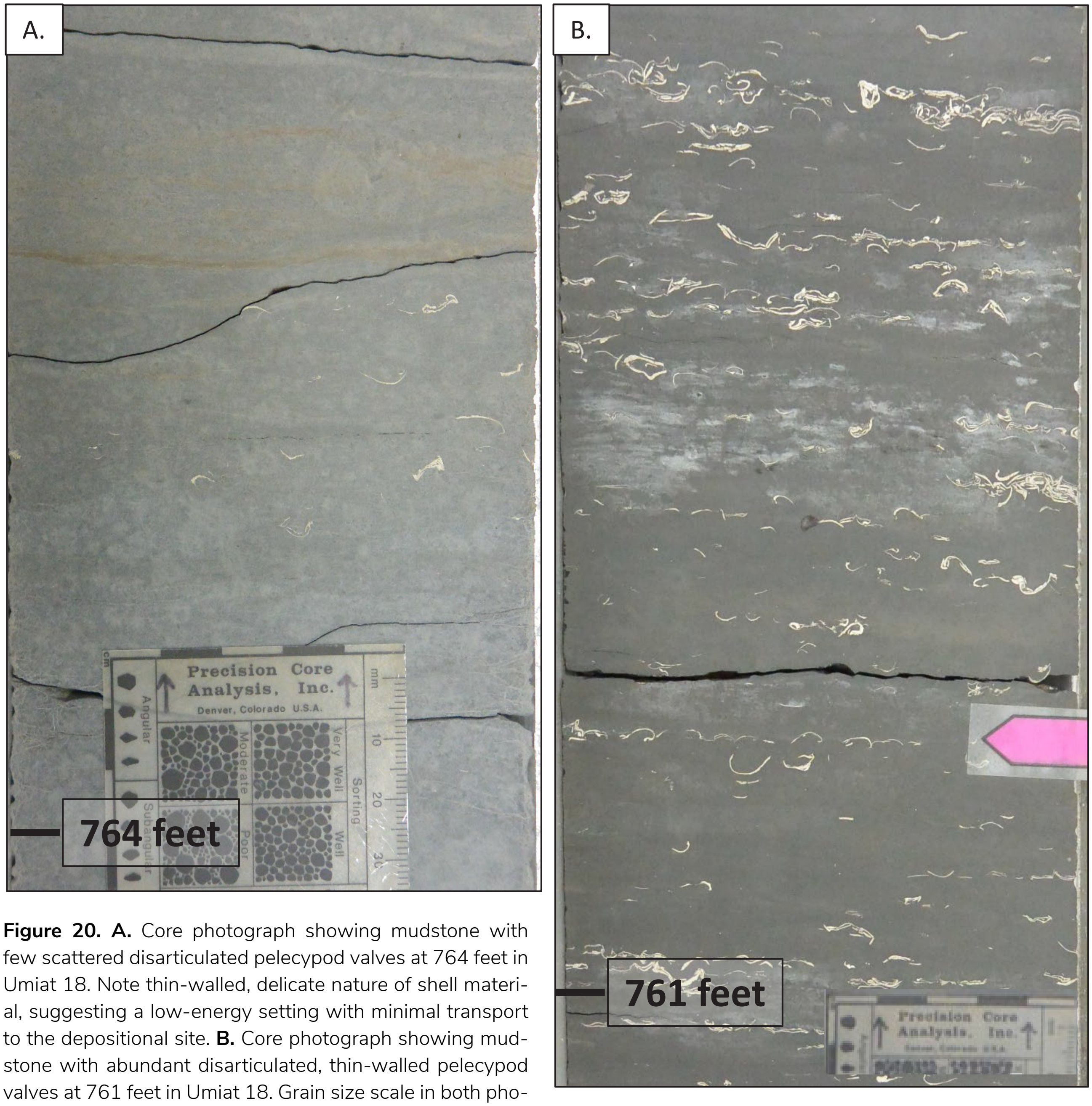

Figure 20. A. Core photograph showing mudstone with few scattered disarticulated pelecypod valves at 764 feet in Umiat 18. Note thin-walled, delicate nature of shell material, suggesting a low-energy setting with minimal transport to the depositional site. **B.** Core photograph showing mudstone with abundant disarticulated, thin-walled pelecypod valves at 761 feet in Umiat 18. Grain size scale in both photographs graduated in millimeters and centimeters.

a repeating stack of FA3, FA4, and FA5 that gradually become more proximal up-section (sheet 2; fig. 21, see caption for additional discussion).

The SP log and cuttings suggest the flooding surfaces bounding these parasequences are not represented in most of the cores (sheet 6). Most of the lower parasequences consist of offshore transition to lower shoreface–distal delta front deposits and their associated flooding surfaces most likely mark an unknown thickness of sandy strata removed through wave ravinement processes associated with ongoing subsidence and transgressive reworking of abandoned delta lobes (cf. Penland and others, 1988). In all of these parasequences, even though only captured in a few cores, the flooding surface represents an abrupt relative sea level rise. A notable exception to this pattern, is documented in core 11, where carbonaceous mudstone interpreted as bayfill facies rests on a brown-gray, fine-grained sandstone with a mottled appearance suggestive

Figure 21. Core box photograph showing the lower part of core 14 (1,945 feet) through the upper part of core 20 (2,045 feet) in Wolf Creek 3. The upper part of core 20 includes amalgamated sandstone of FA4 overlain by a flooding surface at 2,035 feet. This surface is overlain by a thin interval of FA3 or the distal expression of FA4 that grades upward to amalgamated sandstone of FA4 by approximately 2,028 feet. A flooding surface is inferred in the interval between 1,955 feet and 1,977 feet, but that interval is not present in the preserved cores and this surface is shown in the photograph at 1,977 feet. The overlying bioturbated mudstone is tentatively interpreted as offshore transition-prodelta deposits of FA3, but could represent bayfill deposits of FA6, in which case the prominent facies change from sandstone to mudstone shown at 1,977 feet represents uninterrupted shoreline-lower delta plain progradation. Each core row is 3.28 feet (1 meter) long. Core box photos modified from D'Agostino and Houseknecht (2002).

of pedogenic processes (fig. 19). If correctly interpreted, this contact is not a flooding surface, but instead represents an exposure surface and the contact between sandy shorezone or beach berm facies and backshore mudstone in a normal regressive succession. This has been observed at several locations in outcrop to the south and southeast (LePain and others, 2009; LePain and others, 2021a; LePain and others, 2021b).

Square Lake 1

A complete thickness of the Nanushuk Formation was penetrated in Square Lake 1 where, based on Bird's (1988) formation top, the unit is 2,310 feet thick (sheets 3 and 6). The 44 cores cut in the formation are distributed throughout this thickness and document an aggradational–progradational–retrogradational stacking pattern. Despite the lack of robust age control, the retrogradational part of the Nanushuk in Square Lake 1 is likely correlative with the Ninuluk Formation of former usage (Cenomanian age). Core 67, the deepest core in the well, includes bioturbated mudstone with few thin beds of bioturbated very fine-grained sandstone of the distal shelf association (FA2; sheet 3, topset Torok). Based on core, cuttings descriptions (Collins, 1959b), and the SP log, the well penetrated a thick stack of offshore transition–shoreface/delta front parasequences from approximately 3,978 feet to 2,683 feet (repetitious facies stacking pattern of FA2/FA3 to FA4). Cores over this depth interval (cores 66 through 43) contain abundant features commonly associated with storm–wave–influenced lower to middle shoreface environments (HCS, wave ripple cross-lamination, and a widespread, high degree of bioturbation), and some features commonly found in river-dominated deltaic successions (graded beds, abundant macerated terrestrial plant fragments, convolute beds, and unidirectional current indicators). As such, this succession is interpreted as a series of storm-wave-modified delta lobes similar to the succession documented in Wolf Creek 3. Figure 22 shows cores 66 through 61, which include the lowest well-defined parasequence captured in core – note the possible presence of HCS, abundant horizontal laminae, wave ripple cross-laminae, and mudstone rip-up clasts, all of which are common features in high-energy, storm wave-influenced shoreface settings. Cores, cuttings, and the SP log motif from cores 66 through 46 (3,918 to 3,087 feet) are consistent with a progradational stack of sandier-upward parasequences typical of a prograding series of storm wave-influenced delta lobes (sheets 3 and 5).

The sandy succession in cores 45 and 44 has a slight coarsening-upward grain size trend, is thoroughly bioturbated but includes some preserved remnants of wave ripple cross-laminae, which are consistent with deposition in a lower energy, lower to middle shoreface setting (FA4) or an abandoned distributary mouth bar (FA5). An alternative interpretation based on the SP log response through this interval (3,066 feet to 3,027 feet), although not favored, is that it represents the fill of an abandoned distributary channel (FA5). A flooding surface is inferred at the top of core 44, or in the uncored interval between 2,970 and the top of the core. Cuttings and the SP log through the overlying uncored interval indicate a succession of interbedded clay shale, siltstone, and minor sandstone, possibly similar to the lithologies in core 43. Fine-grained lithologies in core 43 are moderately to highly bioturbated, indicating deposition in a marine setting interpreted as distal bayfill (FA6). Facies deposited on the seaward side of an interdistributary bay open to the sea could be similar, and indistinguishable, from facies deposited in a distal shelf setting. Given the overall context, we favor the distal bayfill interpretation.

Core 42 through the lower 10 feet of core 33 (from approximately 2,683 feet to 1,886 feet) penetrate a succession of interbedded mudstone, siltstone, and sandstone (sheet 3). Mudstone is generally moderately to highly bioturbated (BI 3 to 5), but locally is sparsely bioturbated (BI 1) with only slightly disrupted horizontal laminations. Abundant carbonaceous plant material on parting surfaces in core 40, thin accumulations of carbonaceous claystone (or high-ash coal) in cores 38 and 37, including possible rhizoliths in core

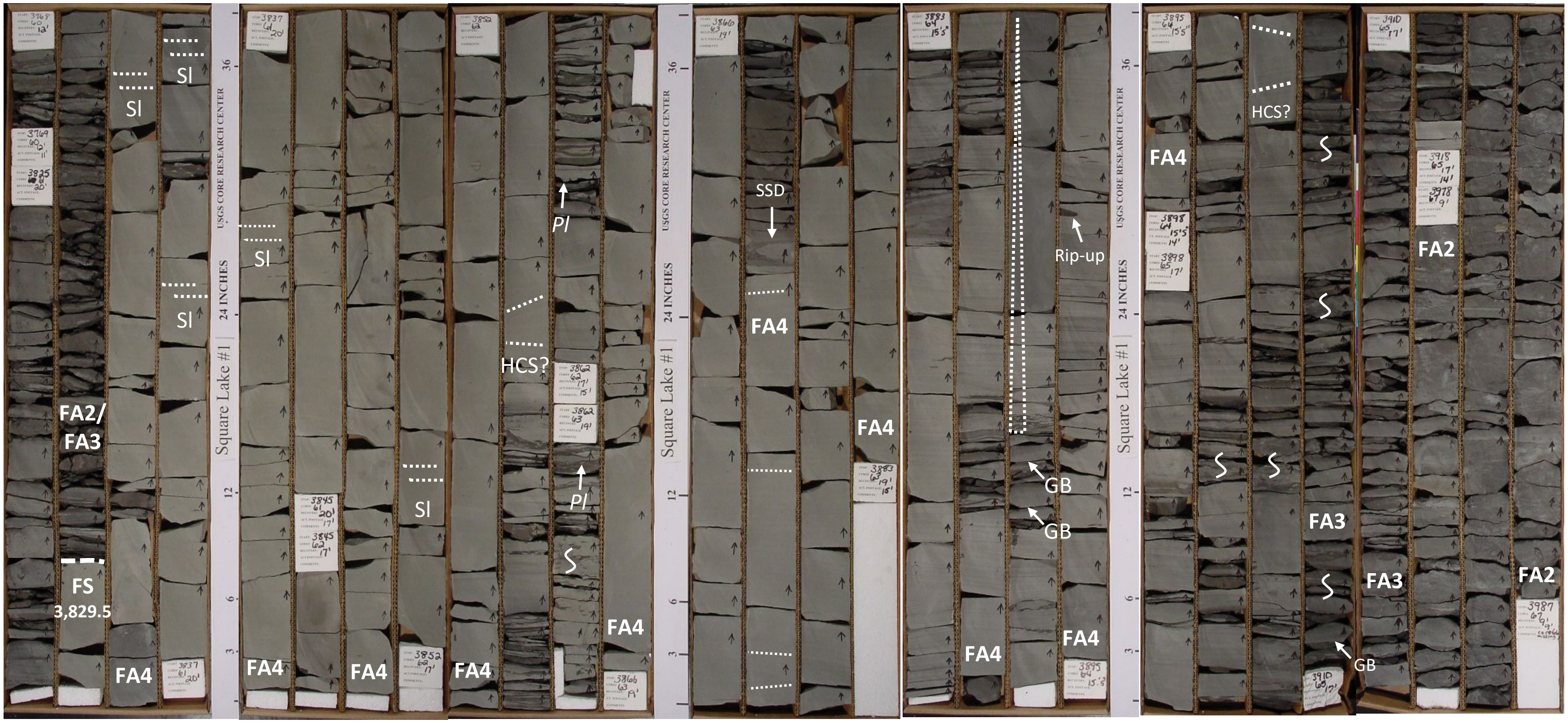

Figure 22. Core box photographs from Square Lake 1 showing the sandier-upward succession from 3,918 feet to approximately 3,829.5 feet, illustrating the gradual change up–section from FA3 to FA4. Note the interval from 3,910 feet to 3,918 feet is core 66 and is mislabeled as core 65 in these boxes (USGS split). The lower nine feet of core 67 consist of FA2. The vertical stacking pattern records progradation of a storm-wave-influenced delta lobe. The heavy white dashed line denotes the flooding surface at the top of the parasequence at 3,829.5 feet. Note the possible HCS, abundant horizontal laminations (Sl), thin graded beds (GB with white arrow pointing to base of bed), thick graded bed shown with white dashed triangle, soft-sediment deformation (SSD), and *Planolites* burrows (Pl). Bioturbation shown by white curvilinear line, as defined on Sheets 1–5. Each core row is 3.28 feet (1 meter) long. Core box photos modified from D'Agostino and Houseknecht (2002).

37, suggest deposition in a lower delta plain bayfill setting (FA6). Abundant very fine- to fine-grained sandstone in thin to medium, solitary beds (sheet 3, cores 41 and 38) distributed in random order, and similar beds arranged in both coarsening- and fining-upward successions (sheet 3, cores 35 and 34 from approximately 1,931 feet to 1,912.5 feet, and core 37 from 2,032 feet to 2,020 feet, respectively) record deposition as overbank splays, small crevasse deltas, and abandoned crevasse channels, respectively (Elliot, 1974). The latter two emanated from distributary channels through breaches in flanking levees inferred to be nearby. The degree of bioturbation in the sandstone ranges from absent (BI 0) to moderate (BI 3) and recognizable traces suggest a low to moderate diversity assemblage consistent with deposition in an interdistributary bay setting (FA6), with salinities ranging from near normal marine to brackish due to episodic incursions of fresh water during floods (Bhattacharya, 2006).

The quartz-chert pebble lag at approximately 1,886 feet in core 33 marks a dramatic change in facies stacking pattern (fig. 23 and sheet 3). The lag rests on an erosion surface that truncates bayfill facies and is overlain by shoreface–delta front deposits. The origin of the pebble lag is unclear—it could represent a remnant of coarser-grained material that bypassed the site during the falling stage and early lowstand systems tracts, or a transgressive lag deposited on a sequence boundary. In the former scenario, the lag rests on a regressive surface of marine erosion and in the latter, the lag rests on a composite surface consisting of a sequence boundary that was modified during the ensuing transgression (ravinement). The latter is the favored interpretation (LePain and Kirkham, 2001; LePain and others, 2018), but good quality seismic data are needed to determine which is correct. The few feet of interbedded fine-grained sandstone and mudstone immediately above the pebble lag is sparsely bioturbated and includes wave ripple cross-lamination (in sandstone); the amalgamated sandstone package from 1,884–1,841 feet (upper part of core 33 and continuing in cores 32 and 31) includes abundant horizontal laminae and conspicuous broken and abraded pelecypod fragments of the genus *Inoceramus* (fig. 23). The SP log response through this interval is barrel-shaped (sheet 6). The succession below the pebble lag is interpreted as highstand deposits and above as a shoreface-delta-front succession associated with a subsequent lowstand of relative sea level (or forced regression during falling relative sea level).

LePain and others (2009) recognized two sharp-based shoreface successions in the upper 190 feet of the Nanushuk at Ninuluk Bluff, located approximately 30 miles south of Square Lake 1, that they interpreted as forming during falling stage systems tracts. Available data are insufficient to allow correlation of the pebble lag at 1,886 feet in Square Lake 1 to the outcrop at Ninuluk Bluff. A similar surface has not been identified in the Wolf Creek 3 well, located approximately 14 miles to the southwest of Square Lake 1, where the corresponding succession may have been removed due to uplift and erosion on the Wolf Creek anticline (Mull and others, 2005).

The remaining Nanushuk cores from Square Lake 1 (sheet 3, cores 30 to 22; SP log shown on sheet 6) document a stack of parasequences comprised of offshore transition/distal prodelta (FA3), shoreface-delta front (FA4), and mouthbar deposits (FA5). Very fine- and fine-grained sandstone with few broken *Inoceramus* shells in core 24 is interpreted as proximal mouth bar-distributary channel-fill deposits (FA5). Closely spaced carbonaceous-rich laminae between 1,728–1,726 feet in core 26 suggest possible tidal influence. Robust age control is not available for this interval, but some sandstone appears tuffaceous, as seen in the upper part of the Nanushuk (Cenomanian) in outcrops along the Colville River.

Grandstand 1

Grandstand 1 spudded in a mantle of unconsolidated deposits, penetrated the top of the Nanushuk Formation at a depth of 110 feet (below top of Kelly bushing), and reached total depth in the Torok Formation at 3,939 feet (Robinson, 1958). Based on facies criteria observed in core, the Torok—Nanushuk contact is placed in the depth interval between cores 44 and 45 (fig. 24; sheet 5, 2,712 feet to 2,926 feet), which is slightly deeper than Robinson's (1958) placement of the contact at 2,650 feet, and significantly deeper than Bird's (1988) placement at 1,070 feet. Core 45 consists of unbioturbated silty clayshale dipping approximately 20 degrees that is interpreted as slope deposits that were involved in a mass-wasting event (FA1; fig. 24). Core 44 consists of moderately to highly bioturbated silty clayshale and interbedded lightly bioturbated siltstones interpreted as distal shelf deposits (FA2). Core 46 includes sparsely bioturbated silty clayshale of FA1 and is the only core below core 44 that includes visible bioturbation. All deeper cores (core 47 to 52) are devoid of visible bioturbation and record deposition in a slope setting with conditions unfavorable to burrowing infaunas. Core 46 may record a sea level lowstand during which a low diversity, burrowing infauna colonized part of the upper slope. The

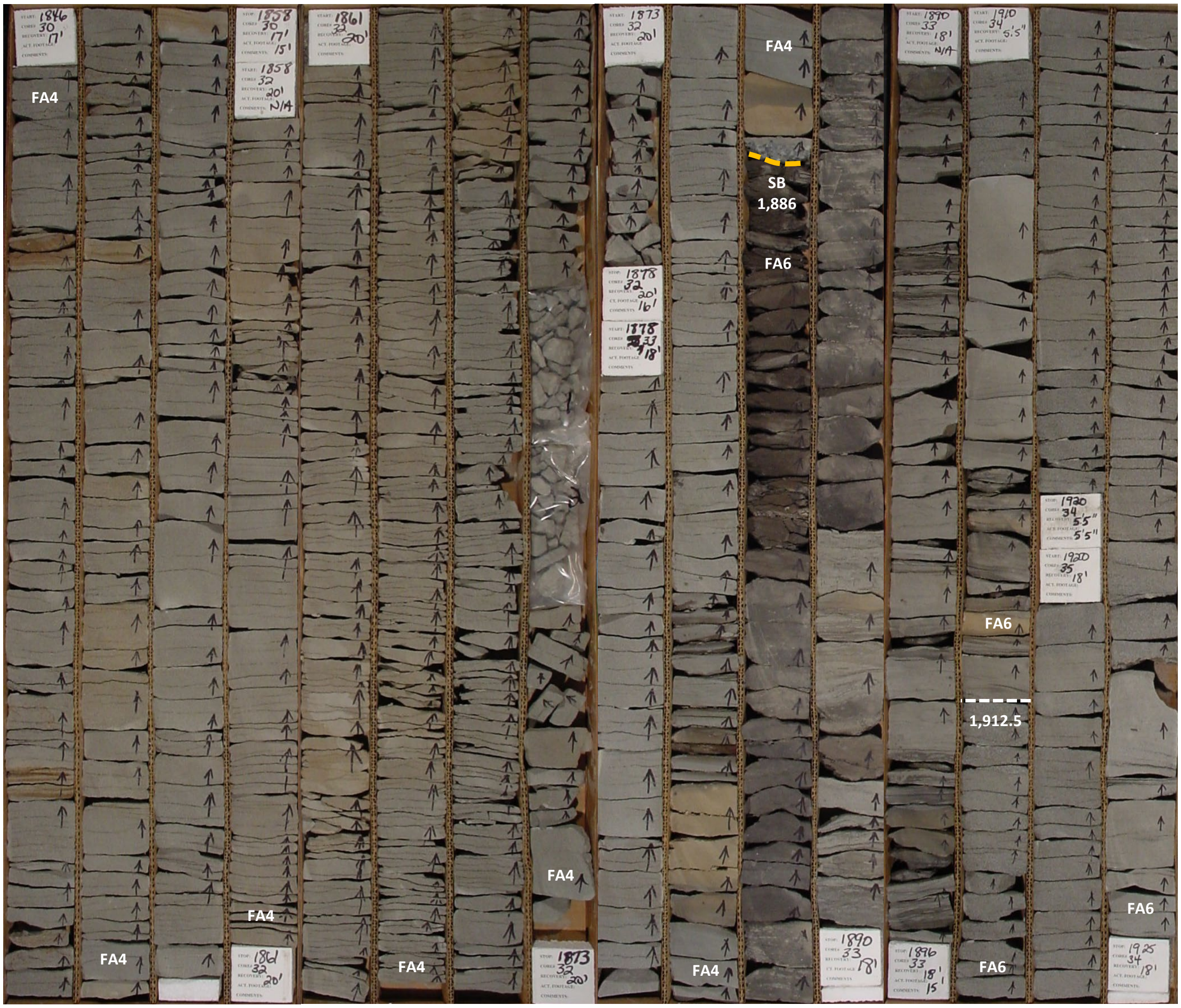

Figure 23. Core box photographs from Square Lake 1 showing bayfill deposits (FA6) truncated by an erosion surface at 1,886 feet marked by a chert-quartz pebble lag. This surface is interpreted as a sequence boundary (SB) that was subsequently modified during transgression. The overlying shoreface—delta front succession that extends to the top of core 31 (1,841 feet, not shown in this figure) is interpreted as a lowstand deposit unrelated to the pebble lag (or related to forced regression during a subsequent episode of falling relative sea level). Core 31 is mislabeled in photograph as core 30. Each core row is 3.28 feet (1 meter) long. Core box photographs modified from D'Agostino and Houseknecht (2002).

Figure 24. Core box photographs from Grandstand 1 showing slope (FA1) deposits of the Torok Formation in core 45 and distal shelf deposits (FA2) of the Nanushuk Formation in cores 44 through 42. Note the dip of strata in core 45 and the absence of bioturbation fabrics. These features suggest deposition in a slope setting that experienced occasional mass-wasting events. Note the bioturbated appearance of cores 44 through 42, which is interpreted to indicate deposition in a distal shelf setting, below storm wave base. Each core row is 3.28 feet (1 meter) long. Core box photographs modified from D'Agostino and Houseknecht (2002).

slope setting at this location was prone to small- to moderate-sized mass-wasting events manifesting as rotational slump blocks (cores 52, 50, 49, 47, and 45; fig. 25). Smaller scale soft-sediment deformation is evident in some of these cores (fig. 25, white arrows). Core 45's position between bioturbated mudstones in cores 46 and 44, and a short stratigraphic distance below our placement of the Nanushuk–Torok contact, leaves open the possibility that it represents a shelf-edge failure.

The shallower cores from Grandstand 1 record an aggradational-progradational stack of distal shelf, prodelta, shoreface-delta front, delta front, and bayfill deposits. Core 21 is tentatively interpreted as mouthbar deposits of FA5, and cores 20 and 19 as distributary channel deposits, also of FA5. Core 10 from 829 feet to approximately 833.3 feet is interpreted as mouth bar deposits, but the prominent scour surface suggests this interval could be a thin distributary channel-fill succession. The retrogradational package present in the cored succession in the upper part of the Nanushuk in Square Lake 1 is not present in the cores from Grandstand 1, possibly due to uplift and erosion associated with the Grandstand anticline. Overall, the cored succession below a depth of 791 feet consists of a stack of deltaic parasequences that record deposition in more river-dominated settings than documented in the Wolf Creek 3 and Square Lake 1 cores.

RESERVOIR POTENTIAL

The sandier-upward parasequences captured in the studied cores represent episodes of shorezone-nearshore progradation punctuated by marine flooding surfaces. In accordance with Walter's Law, progradation of a single storm wave-influenced delta lobe should produce a sandier-upward succession consisting of the following facies associations, in ascending order, offshore transition—prodelta (FA3), shoreface—delta front (FA4), capped by the most shoreline proximal deposits, depending on position along the coastline. Capping associations can include distributary mouth bar (FA5), distributary channel-fill (FA5), and a variety of off-channel axis deposits, including spit, foreshore, eolian dune, and bayfill facies (FA6). Foreshore and eolian dune facies have not been recognized in the studied cores, and spit deposits would be difficult to recognize in a single one-dimensional core. In all of the wells, with the exception of Fish Creek 1, older, more distal parasequences lack these proximal caps and the sandier-upward successions are truncated by marine flooding surfaces that are overlain by muddy distal shelf or offshore transition deposits (FA2 or FA3, respectively). In more proximal settings, some sandier-upward parasequences culminate in distributary mouth bar-channel deposits (FA5) that are truncated by marine flooding surfaces and overlain by offshore transition-prodelta deposits (FA3). In a few cores from the most proximal settings in Wolf Creek 3, Square Lake 1, and Grandstand 1, the most proximal parasequences are capped by muddy bayfill deposits (FA5) resting on sandstones with poorly developed rhizoliths.

Sandier-upward deltaic parasequences represent attractive stratigraphic traps, with overlying muddy facies potentially providing an effective reservoir topseal. Shorezone facies associations overlain by muddy sealing facies could comprise leaky traps if connected to a distributary channel capable of serving as a conduit for continued up-dip migration of hydrocarbons. Erosion associated with transgressive reworking at the top of distal parasequences and many of the more proximal parasequences resulted in top-truncated shoreline-delta lobe shingles in which the upper part of progradational successions is missing. If erosion removed a

Figure 25, next page. Core box photographs from Grandstand 1 showing slope (FA1) deposits of Torok Formation in cores 49 through 45. Note the dip of strata in all cores and the absence of bioturbation fabrics. These features suggest deposition in a slope setting that experienced occasional mass-wasting events manifested here as rotated slump blocks. Note smaller-scale soft-sediment deformation in core 49 (white arrows). Each core row is 3.28 feet (1 meter) long. Core box photographs modified from D'Agostino and Houseknecht (2002).


Core 49 2717
Core 45 2926 20' Rec.
Core 45 2932 20' Rec.
Core 49 3730 12' Rec.
Core 49 3733 12' Rec.
Core 45 2946 ' Rec.
Core 46 3170 19.5 Rec
Core 49 3742
Core 50 3902 8' Rec.
Core 45 2932
Core 46 3171
Core 49 3733

significant thickness of section, it is possible that thinner distributary channel-fills were completely removed, thereby eliminating one of the primary conduits for stratigraphic trap leakage. The amount of section removed by wave ravinement during transgression varies from inches to over 130 feet (Kraft and others, 1987, Nummedal and Swift, 1987), with an estimated average ranging from 32–66 feet in the Cretaceous Western Interior (Bhattacharya and Willis, 2001; Bergman and Walker, 1988). The low end of this average range is potentially enough to completely remove a distributary channel-fill, thus eliminating a potential conduit for leakage. A 97-foot-thick sandstone body consisting of at least two amalgamated channel-fills was documented in the Nanushuk in the Wainwright 1 well (LePain and Decker, 2016). The high end of the average range of section removed by transgressive ravinement is not enough to remove the entire thickness of a composite channel-fill of similar thickness, but the high end of the overall range documented by Kraft and others (1987) and Nummedal and Swift (1987) would remove the entire thickness of the composite channel in the Wainwright 1 well. The stratigraphic trap potential of delta lobes near the base of the formation, combined with available data that suggests Torok slope deposits represent effective hydrocarbon carrier beds (Hayba and others, 2002), makes them highly attractive exploration targets from the central part of the NPRA to the terminal Nanushuk shelf margin east of the Colville River. Recent discoveries at Willow, West Willow, and Pikka demonstrate the stratigraphic trap potential of Nanushuk lowstand shelf-margin deltas (Houseknecht, 2019). Shoreface and delta front parasequences in highstand settings overlain by transgressive mudstone could also represent attractive exploration targets if conduits for up-dip leakage of fluids are absent and the deposits have access to charge. An outcropping bed of friable sandstone in the upper part of the Nanushuk at Rooftop Ridge, southeast of Umiat, emits a light hydrocarbon odor demonstrating at least some access to charge in highstand deposits at that location (RR next to blue square on fig. 1; LePain and others, 2021).

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