MEASURED STRATIGRAPHIC SECTION, UPPER NANUSHUK FORMATION (CENOMANIAN), NINULUK BLUFF, ALASKA

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Preliminary Interpretive Report 2024-3

Oblique air photo showing the upper Nanushuk Formation and lower 40–50 m of the Seabee Formation exposed along the southeast bank of the Colville River. See figure 5 for an annotated version of photo.

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MEASURED STRATIGRAPHIC SECTION, UPPER NANUSHUK FORMATION (CENOMANIAN), NINULUK BLUFF, ALASKA

David L. LePain[1] and Russell A. Kirkham[2]

INTRODUCTION

LePain and others (2009) presented a detailed analysis of depositional systems recognized in the Nanushuk Formation in the eastern part of its outcrop belt in northern Alaska. They presented detailed segments of larger measured sections in the body of the report to illustrate facies associations and included more complete, although simplified, versions of sections from key locations in an appendix. The purpose of this brief report is to present a detailed measured section through the upper marginal-marine and marine part of the Nanushuk exposed on the south limb of Little Twist anticline at Ninuluk Bluff (see Mull and others, 2005; figs. 1–3 and sheet 1). This report is timely as several large oil discoveries have been announced in the past nine years in reservoirs near the base of the Nanushuk in the eastern part of the National Petroleum Reserve in Alaska (NPRA) and on State land on the east side of the Colville River Delta.

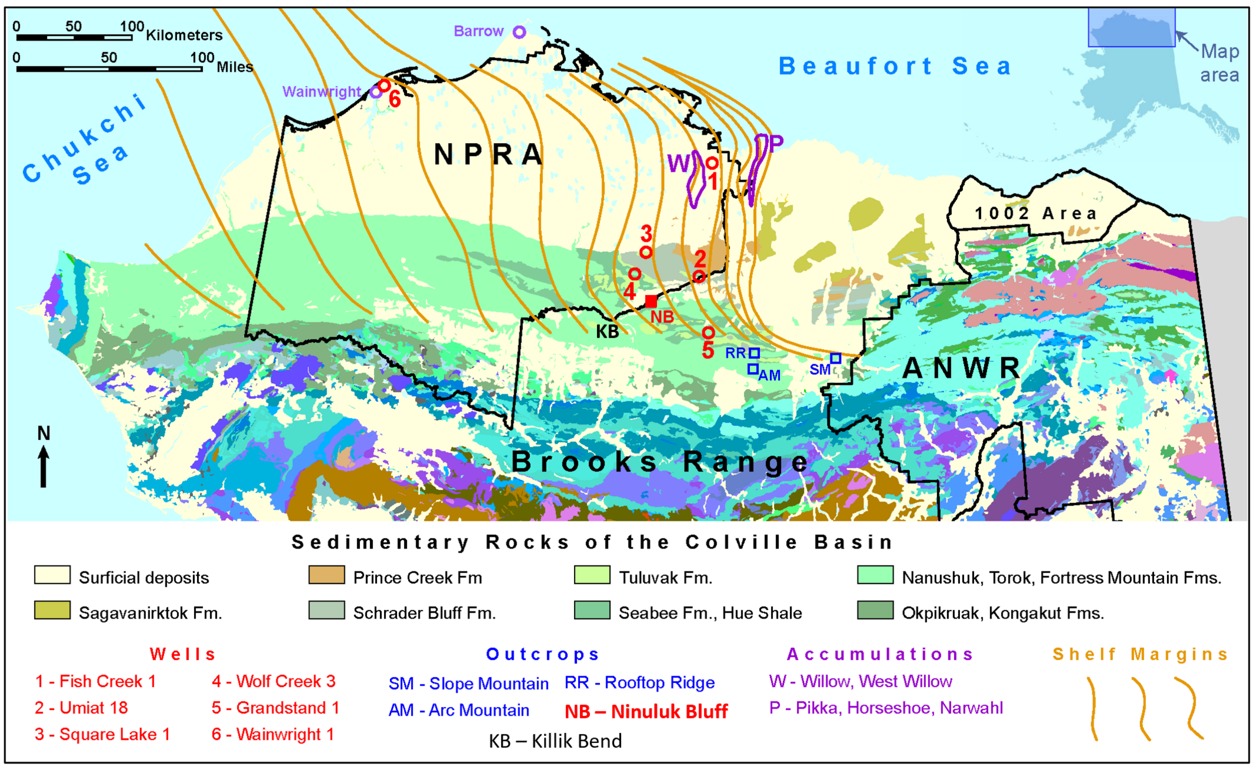

Figure 1. Simplified geologic map of northern Alaska showing the location of the Ninuluk Bluff study area (solid red square labeled NB; fig. 2). Purple polygons show the approximate locations of oil discoveries at Willow (W) and Pikka (P). Nanushuk lowstand shelf margins are from Houseknecht (2019). Geology from Wilson and others (2015). The upper part of the Nanushuk Formation in the northern and northeastern part of its outcrop belt consists of an intertonguing succession of nonmarine, marginal-marine and shallow marine deposits. Gross facies stacking patterns suggest this part of Nanushuk Formation was deposited under net transgressive conditions. At the scale of the map in this figure, the location of Umiat approximately corresponds to the location of the Umiat 18 well. See text for further explanation.

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Despite differences in stratigraphic position, shoreface–delta front and coastal plain deposits documented in this report serve as outcrop analogues for these recent discoveries and for undiscovered stratigraphic traps in the formation in an exploration fairway that extends from a short distance south of Umiat to the Beaufort Sea and from an ultimate Nanushuk shelf margin east of the Colville River to the Chukchi Sea coast. Not surprisingly, the area is the focus of significant exploration interest and development activities are underway in at least two of the recent discoveries (Willow and Pikka; see fig. 1). See Decker (2018) and Houseknecht (2019) for discussions of the Nanushuk's petroleum potential.

Figure 4 is an expanded version of the simplified Ninuluk Bluff measured section published by LePain and others (2009) showing the stratigraphy covered in the detailed section (sheet 1). Detailed measured sections from key Nanushuk outcrops along the Nanushuk River at Rooftop Ridge and Arc Mountain, and at Slope Mountain, were recently published (LePain and others, 2021a, 2021b, 2022). A companion report by Helmold and others (2021) presents a qualitative appraisal of reservoir quality in thin-sections collected from Nanushuk outcrops addressed in LePain and others (2009), including Ninuluk Bluff. The bedrock geology of Ninuluk Bluff and vicinity is shown in Mull and others (2005).

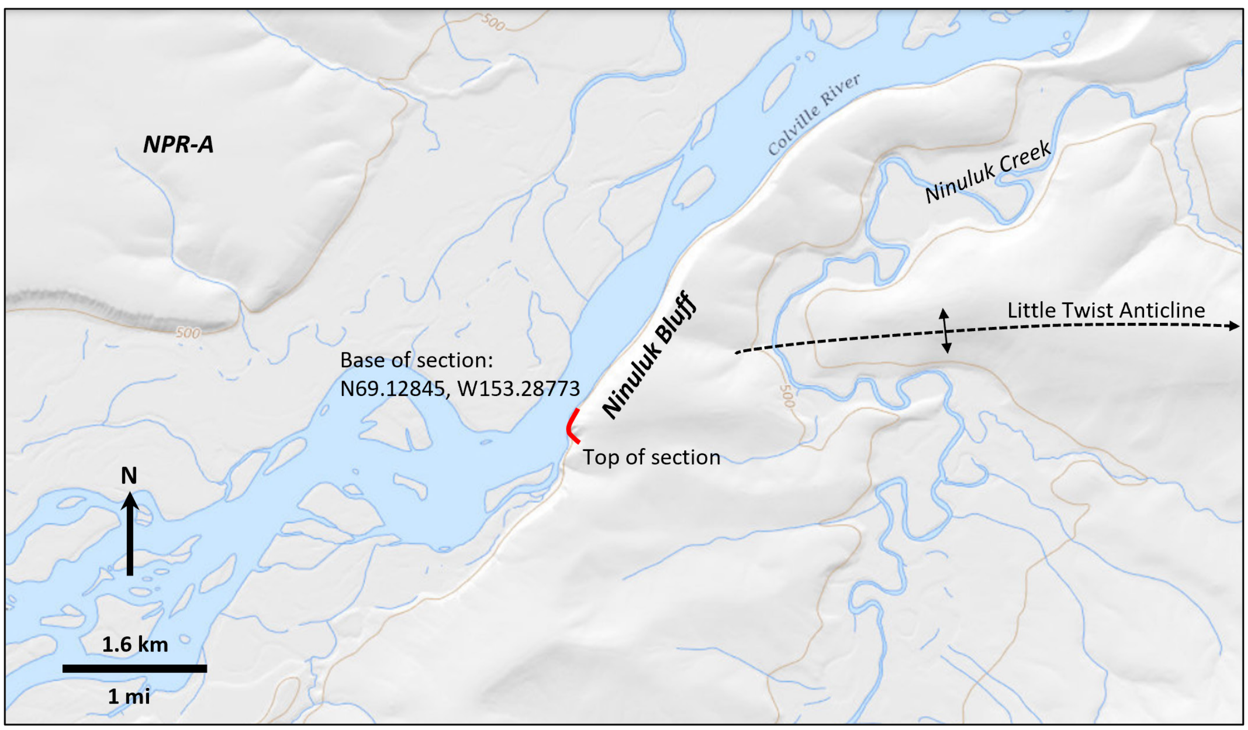

Figure 2. Shaded relief map showing the Ninuluk Bluff study area and location of the measured section addressed in this report (red line). Dashed black line shows the approximate location of Little Twist anticline, taken from Mull and others (2005)—arrow at east end indicates direction of plunge. Map from U.S. Geological Survey National Map. Datum for latitude and longitude is WGS 84.

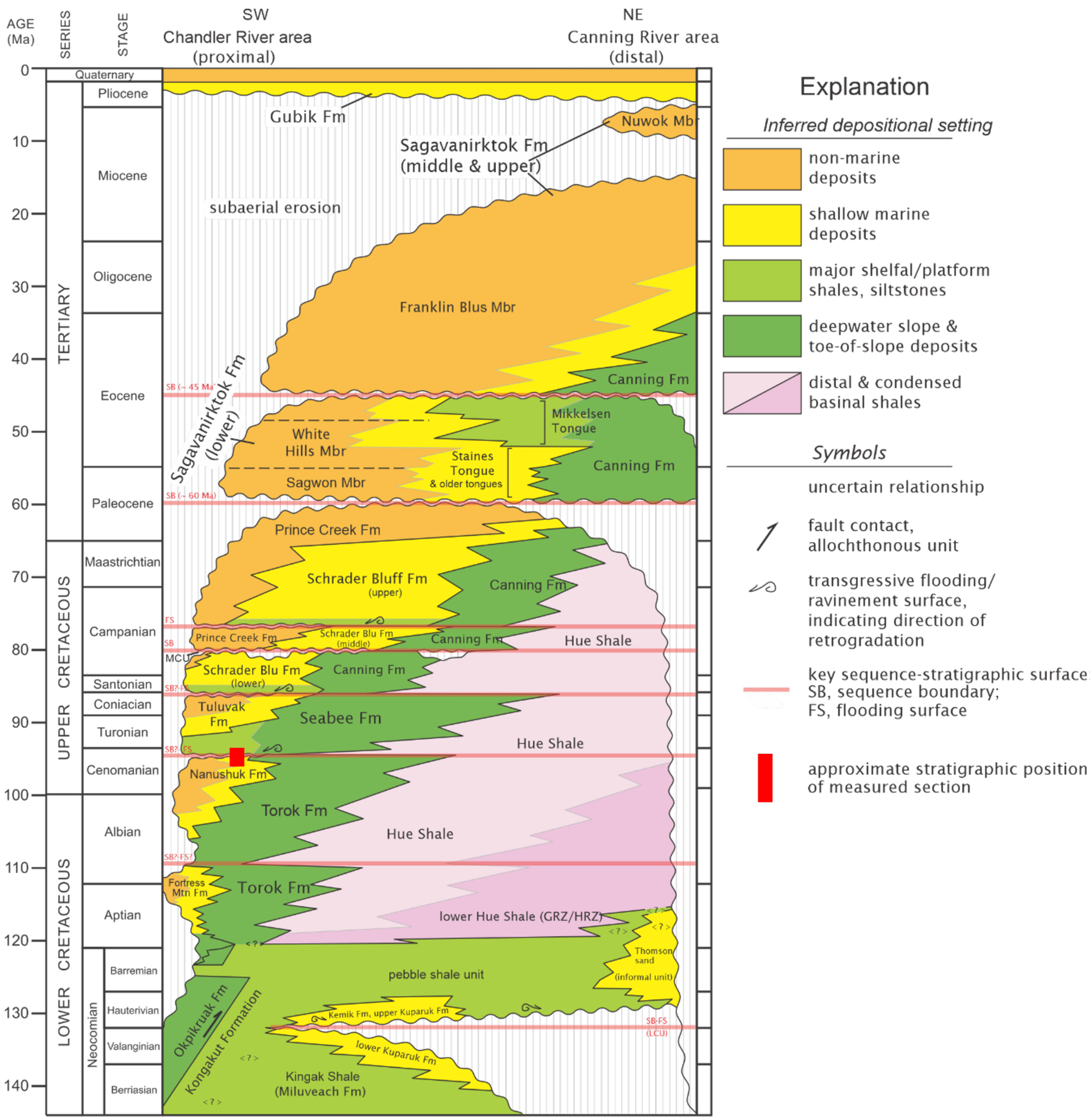

Figure 3. Simplified chronostratigraphic column and generalized sequence stratigraphy of the Brookian Sequence. The solid red line shows the approximate stratigraphic position of the detailed measured section in sheet 1. Modified from Decker and others (2009).

Figure 4, next page. Simplified version of measured section through the upper part of the Nanushuk Formation and lower part of the Seabee Formation on the south flank of the Little Twist anticline. Modified from LePain and others (2009). The section was originally measured by LePain and Kirkham in 2000. On subsequent visits to the site in 2002 and 2019 changes in river level allowed the section to be extended downward (toward the northeast). The resulting composite section is shown in simplified form in this figure and in detail on sheet 1. The resulting section represents the upper 183.9 m of the Nanushuk and is the type section for the Ninuluk Formation of former usage. This figure and sheet 1 include the lower 74.9 m of the Seabee Formation (not continuously exposed). See sheet 1 for key to symbols and lithologies.

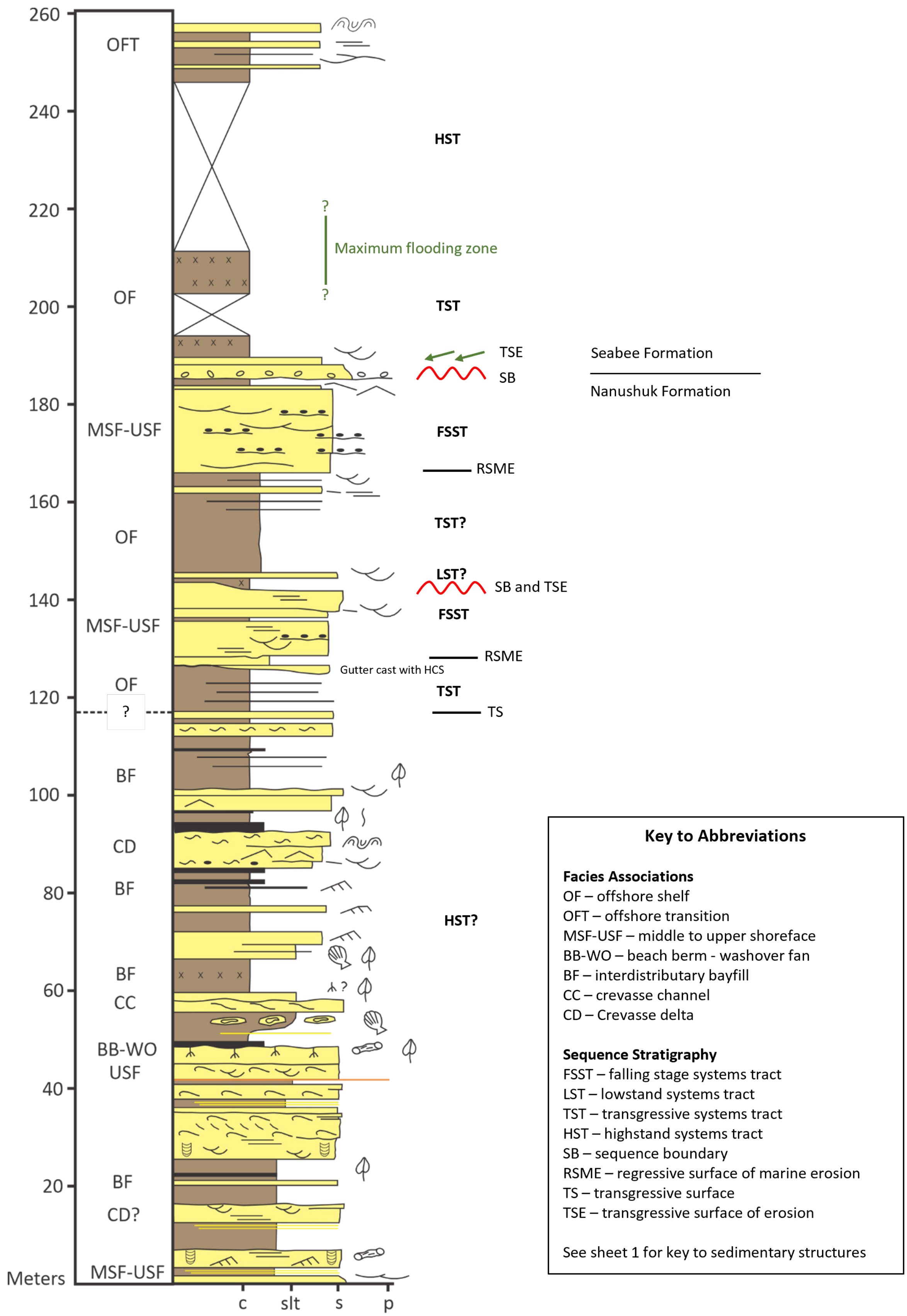

Figure 4. Caption on previous page.

STRATIGRAPHIC NOMENCLATURE

The upper 183.9 m of the Nanushuk Formation and the lower part of the overlying Seabee Formation are well-exposed on the south limb of the Little Twist anticline, where they intersect the southeast bank of the Colville River (figs. 2, 4, 5). Marginal-marine and marine strata making up the Nanushuk Formation in this exposure are Cenomanian age and were formerly assigned to the Niakogon Tongue (of Chandler Formation) and Ninuluk Formation (Detterman, 1956). Detterman (1956) designated Ninuluk Bluff the type section for the Ninuluk Formation.

Mull and others (2003) revised Cretaceous stratigraphic nomenclature in the Colville basin, including the Nanushuk, which had group rank and consisted of several units of formation rank. In the eastern third of its outcrop belt the formations that made up the Nanushuk Group reflected its gross stratigraphic organization. The lower part of the group consisted, in ascending order, of the marine Tuktu Formation and marginal-marine Grandstand Formation, reflecting the progradation of shelf and shorezone depositional elements (Detterman, 1956). Dominantly nonmarine deposits overlying the Grandstand were assigned to the Chandler Formation and represent the culmination of the progradational succession making up the lower and middle parts of the Nanushuk Group. The Ninuluk Formation and Niakogon Tongue (Chandler Formation) of former usage—recording an intertonguing succession of nearshore marine and nonmarine settings, respectively—were the uppermost and youngest formally defined units in the Nanushuk Group and were only recognized in the north-central and northeastern part of its outcrop belt (Detterman, 1956).

Mull and others (2003) reduced the group to formation rank—Nanushuk Group became Nanushuk Formation—and abandoned the older formation nomenclature. These authors subdivided the Nanushuk Formation into two informal units, including a lower dominantly marine unit and an upper dominantly nonmarine unit. This two-fold subdivision works well in the western and southern parts of its outcrop belt, where the overall depositional trend that is preserved in outcrop is unidirectional, grading from outer shelf marine settings to alluvial settings. The two-fold subdivision is unsatisfactory in the northeastern part of the outcrop belt and in the subsurface of the eastern NPRA, where the upper Nanushuk includes intertonguing marine and nonmarine deposits (Detterman's Ninuluk Formation and Niakogon Tongue), forming a net retrogradational (transgressive) succession that culminates in the ultimate drowning of alluvial and marginal-marine settings and the onset of starved shelf conditions recorded in the lower Seabee Formation (shown schematically on fig. 3). The measured section addressed in this report is through the upper part of an intertonguing succession of the Niakokon Tongue and Ninuluk Formation of former usage and extends 74.9 m into the overlying Seabee Formation (figs. 3–5, sheet 1).

SUMMARY OF STRATIGRAPHIC ORGANIZATION

To facilitate the discussion that follows, the detailed measured section is divided into intervals corresponding to the meterage shown on sheet 1. In addition, major sandstone bodies are numbered to assist the reader in linking the text below to the appropriate parts of the measured section.

Nanushuk Formation

0 m to 48.3 m

0 m to 25.2 m

The interval from 0 m to 48.3 m includes six sandstone bodies up to 10 m thick, labeled 1 through 6 on sheet 1, separated by poorly exposed mudstone successions up to 3.8 m thick (figs. 6–16). Facies evidence in all six sandstone bodies indicates a persistent marine influence and deposition in shorezone settings.

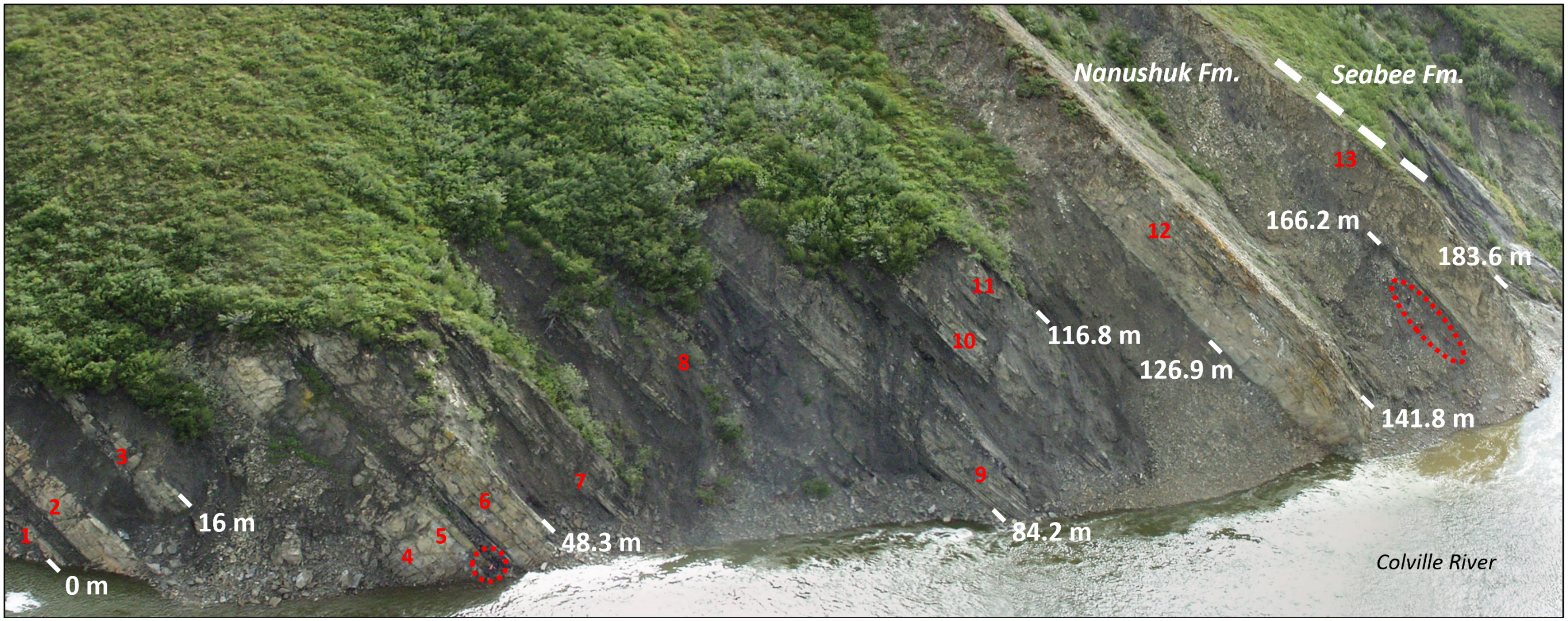

Figure 5. Oblique air photo showing the upper Nanushuk Formation and lower 40–50 m of the Seabee Formation shown in fig. 4 and sheet 1. View toward west-southwest. Note the Nanushuk–Seabee contact shown by the dashed white line is 0.3 m higher than the top of the sandstone body at 183.6 m. Approximately 10 to 12 m of additional Nanushuk section is very poorly exposed below the base of the measured section (below 0 m). Sandstone bodies form prominent resistant units throughout the upper Nanushuk at this location. Sandstone bodies discussed in the text are numbered from 1 to 13 (red font). Sandstone bodies from 0 m to 48.3 m record deposition in lower delta plain and proximal shoreline settings, including interdistributary bay or estuarine settings and shoreface environments (sheet 1); sandstone from 48.3 m to 116.8 m record deposition in interdistributary bay settings and include crevasse channel-fills, splay sandstone sheets, bayhead/crevasse deltas; sandstone bodies between 116.8 m and the top of the Nanushuk at 183.9 m are interpreted to record deposition in shoreface settings; 0.3 m of mudstone at the top of the formation (183.6 m to 183.9 m) records deposition in interdistributary bay or offshore settings (see sheet 1). See text for details. Dashed circle and oval enclose geologists for scale. Flow in river is right to left.

The intervening mudstones include at least one coal seam indicating deposition in a coastal swamp setting for at least one of the mudstone successions but the depositional setting for the other mudstones is poorly constrained. The base of the first body is not exposed but includes fine-grained sandstone with low-relief concave-upward laminations (SCS—swaley cross-stratification?) and horizontal plane-parallel laminae (fig. 6A). This part of the sandstone body appears unbioturbated (BI 0). The body fines upward in the upper 0.4 m to very fine-grained sandstone with wave ripple cross-laminations and common to abundant *Diplocraterion* burrows (BI 2–3; fig. 6B). A thin heterolithic succession separates the basal sandstone from a coarsening-upward sandstone succession extending from 2.95 m to 6.6 m comprising the second body (figs. 7 and 8A–D). Sandstone beds in this body include current-generated (unidirectional) structures, horizontal, plane-parallel laminations, abundant small plant fragments and scattered log impressions in the lower 1.4 m (figs. 8A–C). The upper 0.5 m includes plane-parallel laminations accentuated by abundant macerated terrestrial plant fragments, scattered pelecypod shell impressions (casts), and a few large *Inoceramus* shell impressions (fig. 8D). The sandstone body from 12 m to 15.6 m (third sandstone body) is very fine-grained through most of its thickness, but fine-grained sandstone in a bed 20 cm thick caps the body. The lower 30 cm of the body includes possible hummocky cross-stratification (HCS), overlain by approximately 2 m of wavy, discontinuous laminae that represent poorly defined small-scale trough cross-stratification (fig. 9A–C). Sandstones are sparsely bioturbated (BI 1?), but the upper 0.5 m is highly to intensely bioturbated (BI 4–5) and includes scattered small pelecypod valve impressions. A thin mudstone overlies the sandstone bed at 15.6 m and is, in turn, overlain by an intensely bioturbated (BI 4–5), 10 to 15 cm thick bed of fine-grained sandstone.

25.2 m to 36 m

The sandstone body from 25.2 m to 36 m (fourth sandstone body) was deposited above a poorly exposed coal-bearing mudstone interval. Bivalve shell fragments and sporadic bioturbation are conspicuous features. The basal bed in the fourth sandstone body (from 25.2 m to 25.5 m) includes abundant *Diplocraterion* burrows (BI 3?; fig. 10A) and is overlain by 8.2 m of sandstone with small- to medium-scale trough cross-stratification and horizontal, plane-parallel laminae with abundant *Inoceramus* fragments oriented parallel to bedding (fig. 10B–C), and scattered pockets of *Inoceramus* fragments mixed in with coalified wood fragments (fig. 10D). The upper 1.8 m of this sandstone body includes moderately to intensely bioturbated, very fine-grained sandstone beds (fig. 10E) with abundant coalified plant fragments. The fourth body is capped by a thin bed of chert and quartz pebbles (sheet 1, 36 m) interpreted as a lag deposit.

36 m to 40.9 m

The fifth sandstone body is a coarsening-upward succession 4.9 m thick that grades from very fine-grained to medium-grained sandstone and includes abundant large coalified wood and *Inoceramus* shell fragments oriented parallel to bedding, the latter includes some large valves with intact shell material (fig. 11A–B). The upper 20–30 cm is moderately bioturbated, including *Diplocraterion* and possibly *Arenicolites* burrows. (BI 3; fig. 11C). The fifth and sixth sandstone bodies are separated by a poorly exposed thin mudstone succession (fig. 12A, white arrow).

41.5 m to 48.3 m

The sixth sandstone body (41.5 m to 48.3 m) is 6.8 m thick, includes abundant coalified plant fragments and a prominent chert-quartz pebble lag in the lower 30 cm (fig. 12B), low-relief medium-scale trough cross-stratification (fig. 13A), and common scour surfaces overlain by scattered chert and quartz pebbles and *Inoceramus* shell fragments forming discontinuous accumulations locally (fig. 13B–C). The sandstone bed at the top of the body includes small rhizoliths and abundant coalified woody material (fig. 13D–E).

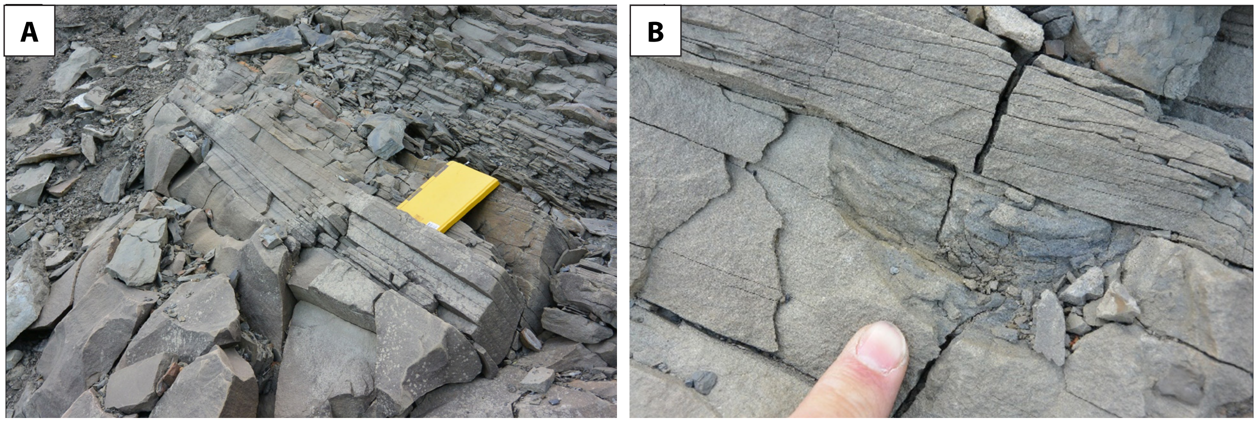

Figure 6. Selected photographs showing features in the first sandstone body at the base of the measured section. **A.** Sandstone between 0.5 m and 1.2 m (top of notebook) with concave-upward surfaces below the top of the notebook. When traced laterally many of these surfaces are discontinuous, 1 m to 2 m wide, and resemble swaley cross-stratification (SCS). Interval shown fines upward from fine- to very fine-grained sandstone and siltstone (above top of notebook). Notebook is 22 cm long. **B.** *Diplocraterion* burrow at 1.1 m. *Diplocraterion* burrows crowd the upper 20 cm of this bed (1.0-1.2 m; BI 3). The lower 1.0 m appears unbioturbated (BI 0). *Diplocraterion* is common in lower and middle shoreface settings (distal *Skolithos* ichnofacies), in sandy tidal flats, and in estuarine channel deposits (Pemberton and others, 2001).

Figure 7. Photograph showing thinly interbedded siltstone and very fine-grained sandstone between 1.2 m and 2.95 m in the measured section. Bioturbation in siltstone and sandstone is sparse to low (BI 1–2). Due to the thinly interbedded nature of siltstone and sandstone in this interval, sandstone beds are shown schematically on Sheet 1.

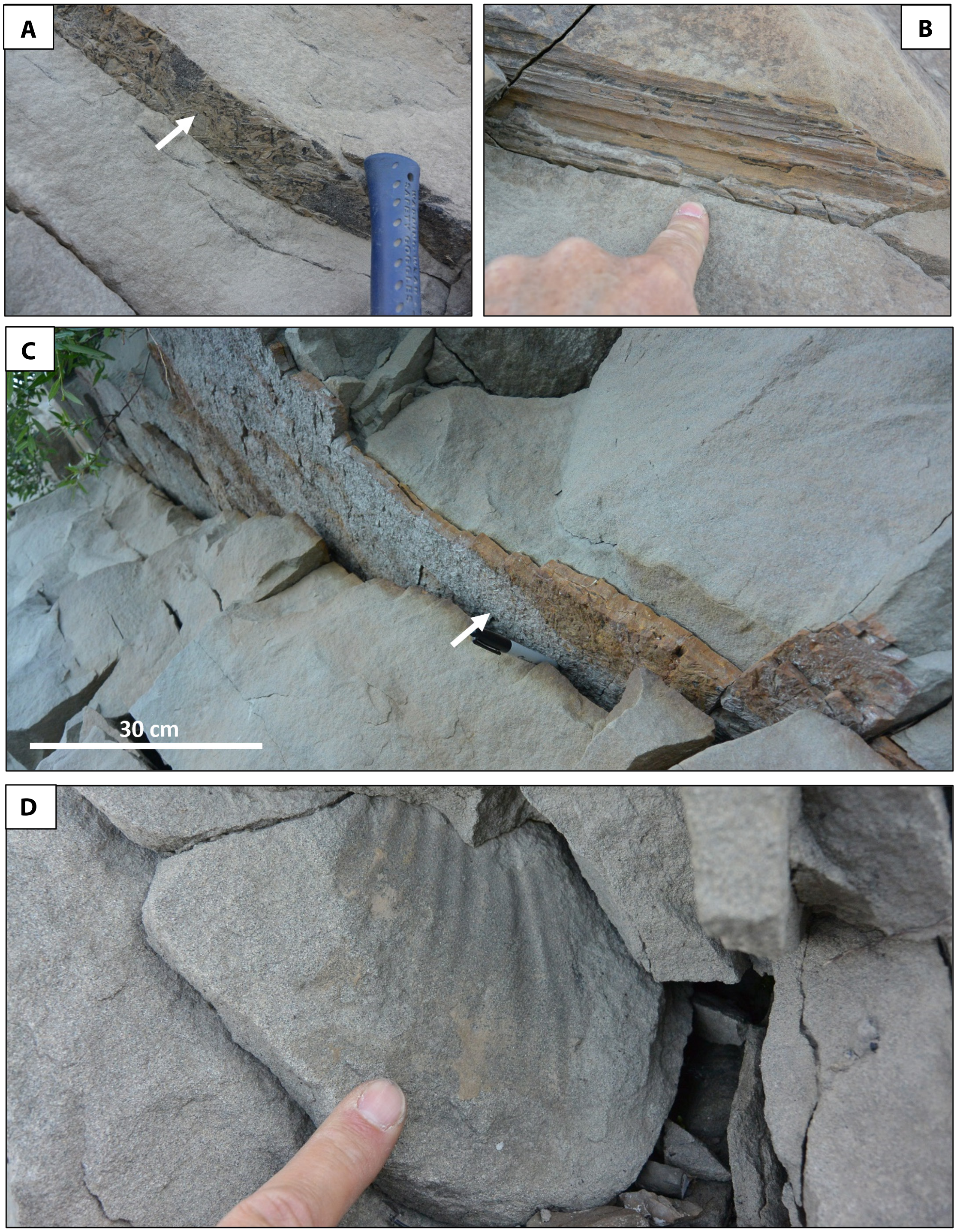

Figure 8. Photographs showing features in the second sandstone body from 2.95 m to 6.6 m in the measured section. **A.** Carbonaceous wood fragments on the underside of a bed of very fine-grained sandstone at 3.6 m. Visible part of hammer handle is 10 cm long. **B.** Large log impression on the underside of a bed of fine-grained sandstone at 4.5 m. The black material is coalified wood. **C.** Siderite cemented band approximately 2 cm thick with abundant small plant fragments at 5.4 m. **D.** Well-preserved impression of an *Inoceramus* shell at 6.45 m. *Inoceramids* were epifaunal bivalves that commonly lived on muddy substrates in shallow marine settings by byssal attachment to shell fragments, or other material, on the seafloor (Kennedy, 1981). The size of this valve impression suggests minimal transport to the depositional site.

The first, second, fourth, and fifth sandstone bodies in the 0 m to 48.3 m interval are interpreted as shoreface deposits, the third sandstone body as a crevasse channel-fill or crevasse delta succession (favored), and the sixth sandstone body as either a crevasse channel-fill (favored) or sharp-based shoreface deposit capped by foreshore, beach berm, and backshore facies. The sporadic occurrence of a low-diversity trace fossil assemblage and abundant transported shell fragments is consistent with deposition in marginal-marine settings, possibly characterized by fluctuating salinity levels.

48.3 m to 116.8 m

The interval from 48.3 m to 116.8 m consists predominantly of mudstone with interbedded tabular sandstone, bituminous coal seams, and several thin altered tephras (sheet 1, figs. 5 and 14A–G).

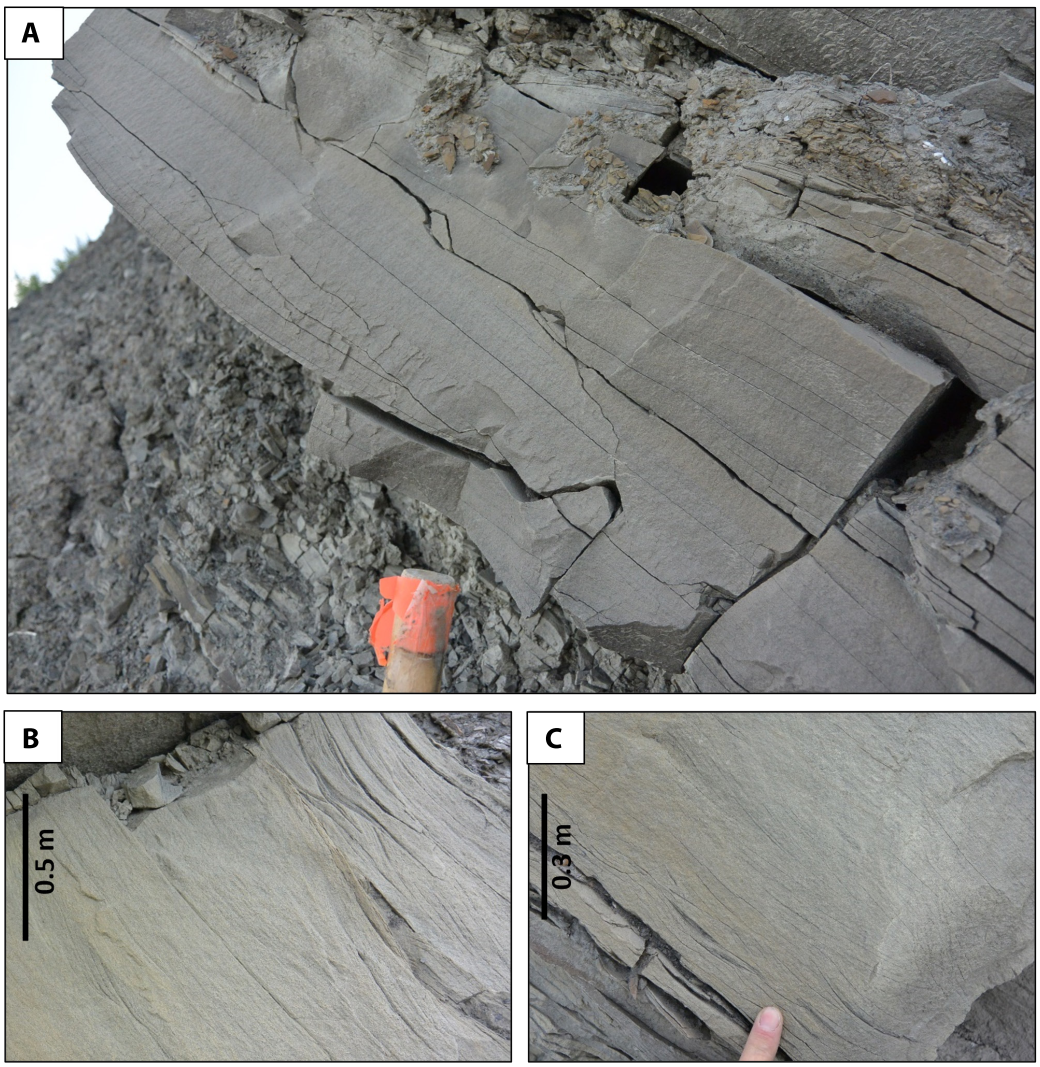

Figure 9. Photographs showing features in the third sandstone body between 12 m and 15.6 m in the measured section. **A.** Sandstone with plane-parallel to wavy, horizontal laminations between 12 m and 13 m. Note low-relief concave-upward parting surfaces in the lower 15 cm of the body visible in the upper left quarter of the image. Convex-upward laminations are present along strike in this bed, suggesting the presence of HCS. Visible part of wood staff is 4 cm long. **B, C.** Very fine-grained sandstone with small- to moderate-scale trough cross-stratification between 15.0 m and 15.6 m.

A 20-cm-thick bituminous coal seam rests on the rooted sandstone bed at 48.3 m (figs. 13D and 14A). This seam is overlain by mudstone with tabular beds of siltstone and very fine-grained sandstone up to 20 cm thick. The interval from 48.3 m to 109 m includes several additional coal seams (fig. 14E), including one approximately 1.9 m thick (sheet 1, 90.1 m to 92 m). Tephras are thin (up to 2–3 cm thick) and weather a light pale-yellow color forming distinctive layers among the dark colored mudstones (fig. 14B, white arrow). Sandstone beds include horizontal, plane-parallel laminations or small-scale current ripple cross-laminations, or are massive (structureless). At least one sandstone includes current ripple bedforms

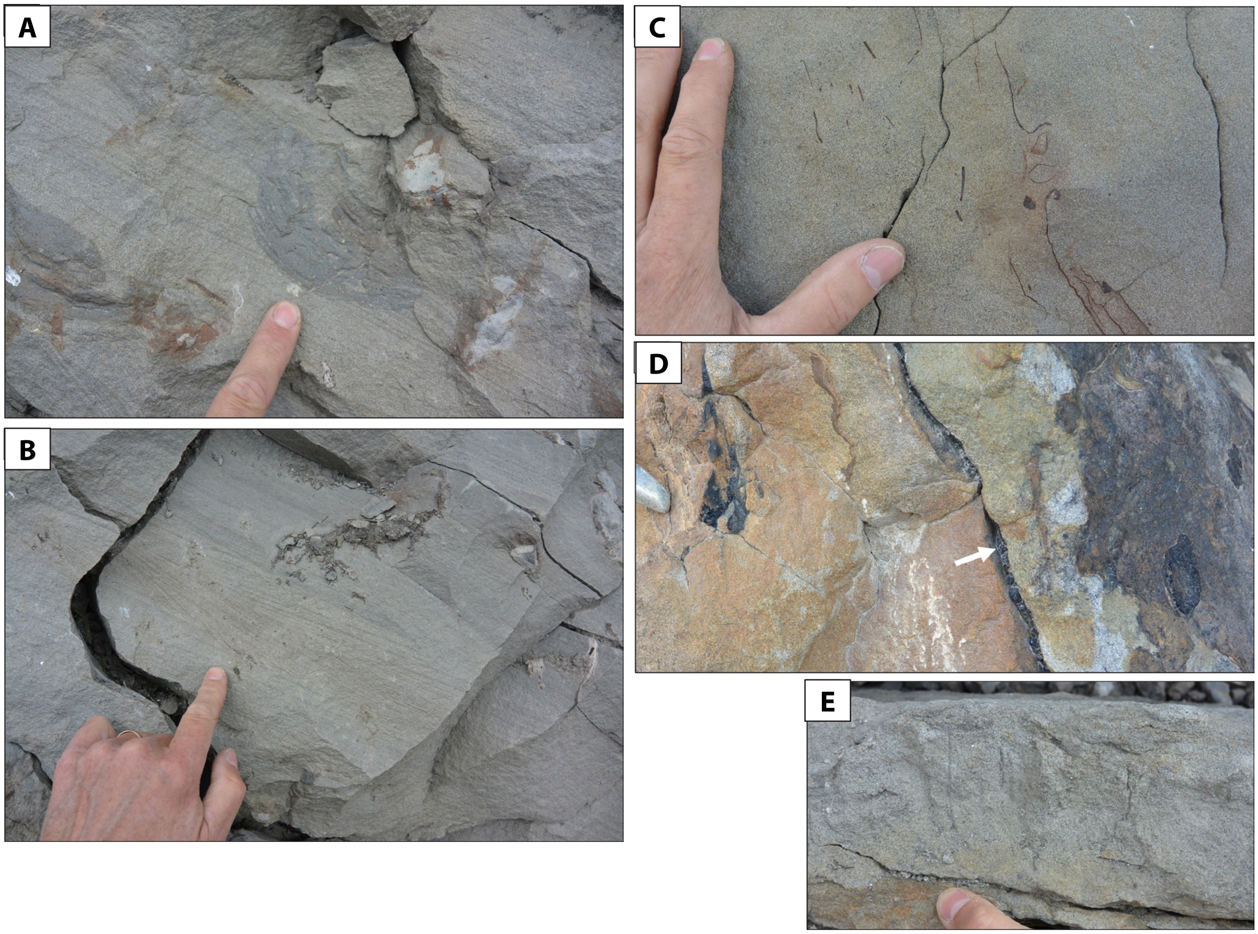

Figure 10. Photographs showing features in the fourth sandstone body from 25.2 m to 36 m in measured section. **A.** Very fine-grained sandstone at 25.5 m with abundant *Diplocraterion* burrows. *Diplocraterion* burrows in some parts of this bed are so crowded that the vertical shafts of adjacent burrows are nearly in contact (BI 3+). Sandstone bed includes plane-parallel laminations and low-relief trough cross-stratification in sets 5–20 cm thick. **B.** Very fine-grained sandstone at 26.5 m with stacked sets of trough cross-stratification. Set thicknesses range from 5 to 25 cm. Bed appears unbioturbated (BI 0). **C.** Very fine- to fine-grained sandstone with scattered *Inoceramus* shell fragments at 30.7 m. Sandstone in parts of this interval appears massive and in other parts plane-parallel, horizontal laminations are faintly visible. Beds appear unbioturbated (BI 0). **D.** Very fine- to fine-grained sandstone with scattered pockets of *Inoceramus* and coalified wood fragments at 34.2 m. The coaly material to the right of the scratch marks (arrow) extends parallel to bedding at least 30 cm and is a coalified, flattened piece of wood. Wood impressions are present on some parting surfaces. Physical sedimentary structures are not preserved and the bed appears highly to intensely bioturbated (BI 4–5). Tip of hammer pick is 2 cm long. **E.** Moderately to intensely bioturbated (BI 3–5) bed of fine-grained sandstone at 35 m. *Skolithos*, or possibly *Arenicolites*, burrows are visible above the geologist's finger. Some vertical burrows have a thin carbonaceous lining.

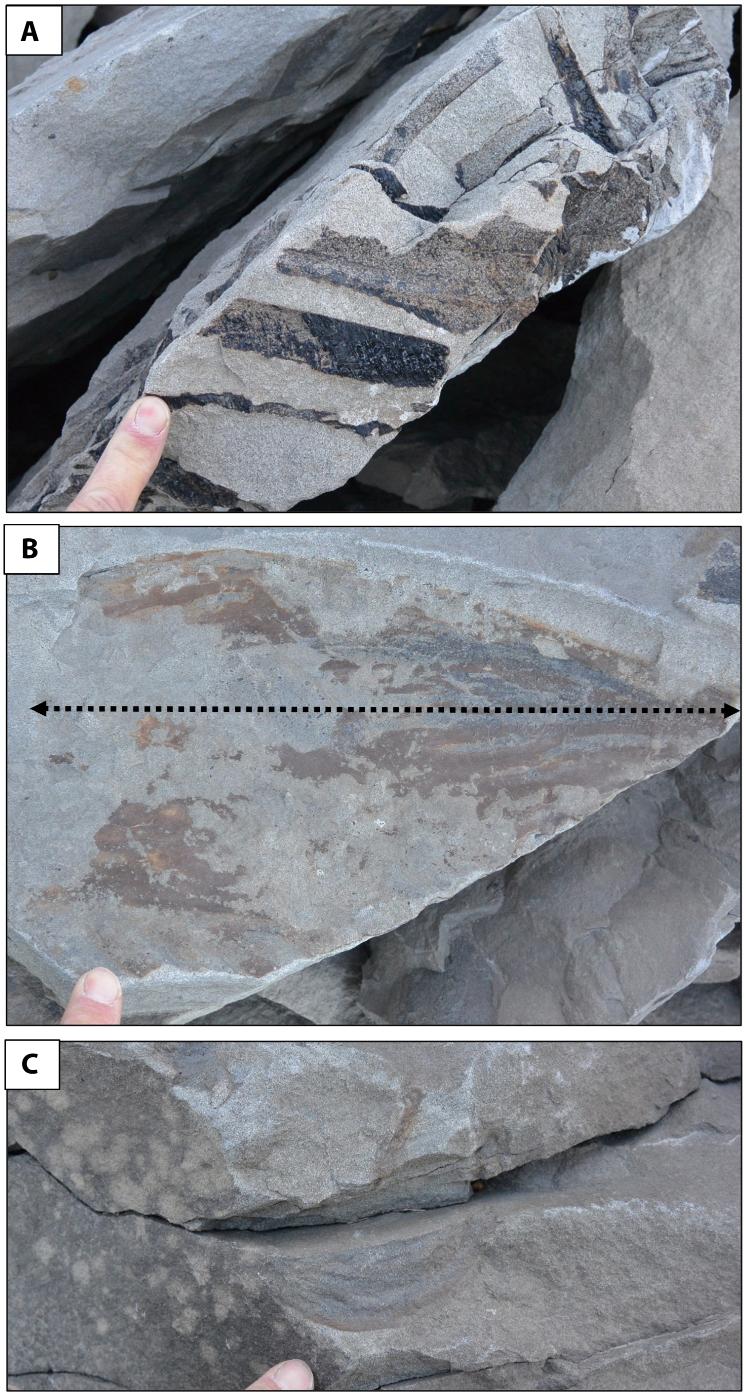

Figure 11. Photographs showing selected features in the fifth sandstone body from 36 m to 40.9 m. **A.** Block of medium-grained sandstone bed at 40.5 m with large pieces of coalifed wood preserved on parting surfaces. Visible part of finger is 7 cm long. **B.** Block of fine-grained sandstone with large *Inoceramus* shell from approximately 39 m. The brown areas are original shell material. Visible part of shell is 25 cm long (dashed line with arrows heads at each end). Visible part of finger is 2.5 cm long. Sandstone beds between 37.7 m and 40.7 m include abundant, smaller *Inoceramus* fragments aligned parallel to bedding, but distinct laminations are not visible. **C.** *Diplocraterion* burrow in sandstone bed at top of coarsening-upward succession at 40.9 m.

in which the crest region has been planed off forming a flat-topped current-ripple bedform (sheet 1, 76.8 m). Small pelecypod valves of a single species are present on some bed surfaces but are not abundant. Bioturbation in mudstones is difficult to assess but appears to be absent to sparse (BI 0–1); bioturbation in tabular sandstones ranges from absent to low (BI 0–2). This succession records deposition in a protected interdistributary bay, lagoon, or estuary characterized by brackish water or fluctuating salinity conditions with scattered swamps around the landward perimeter (see Elliott, 1974; Bhattacharya, 2006). Flat-topped current ripple bedforms indicate transport of sand by unidirectional currents and subsequent reworking of the crest regional by short-period waves (Allen, 1984), which is consistent with deposition in a shallow water setting subjected to episodic or periodic transport of sand by flood-related or tidal currents, respectively. Eruptions from distant volcanoes, most likely in Chukota, resulted in several thin tephras that were subsequently altered to bentonite.

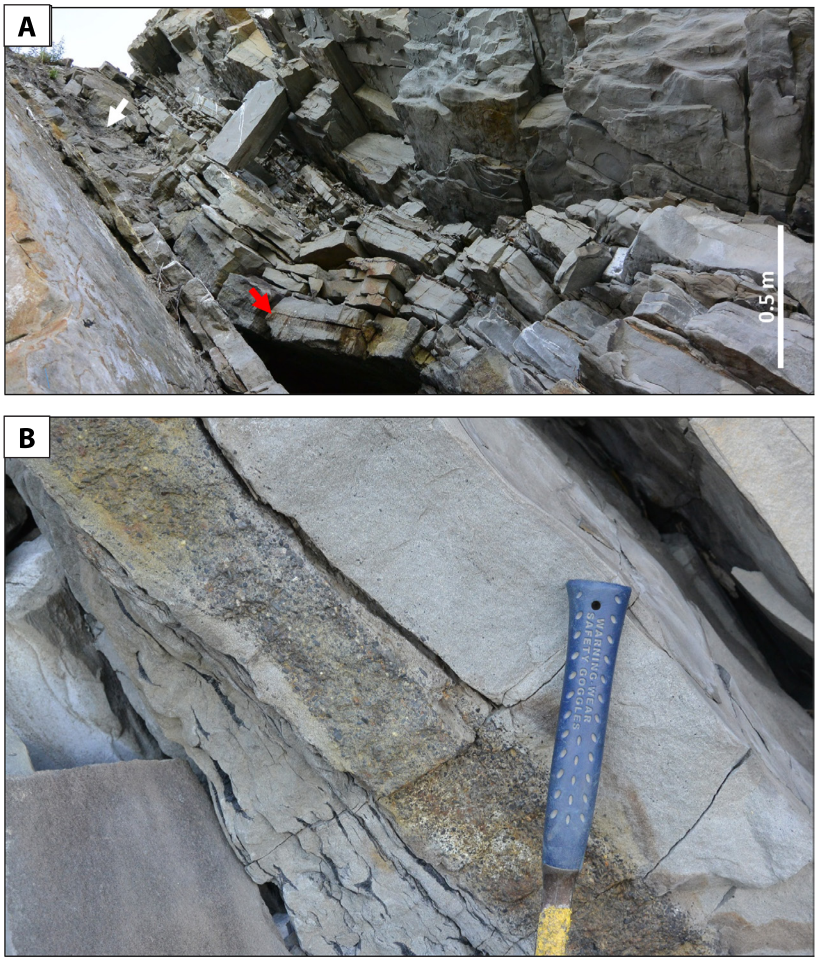

Figure 12. Photographs showing recessive weathering mudstone between 40.6 m and 41.5 m. **A.** View upslope showing mudstone (white arrow) largely covered by blocks of sandstone that have fallen from the lower 60 to 70 cm of the overlying sandstone succession (sixth sandstone body from 41.5–48.3 m). The red arrow points to center of a 25-cm-thick bed of chert-quartz pebble conglomerate that fell from the overlying sandstone body. **B.** Block of fine-grained sandstone that includes a 10-cm-thick bed of chert-quartz pebble conglomerate (red arrow in fig. 12A). Note the bed of fine-grained, trough cross-stratified sandstone with coalified wood fragments (black material visible in bed) below the conglomerate—this bed forms the base of the sixth sandstone body. The conglomerate thickens upslope to 25 cm over a lateral distance of approximately 6 m. Visible part of hammer handle is 28 cm long.

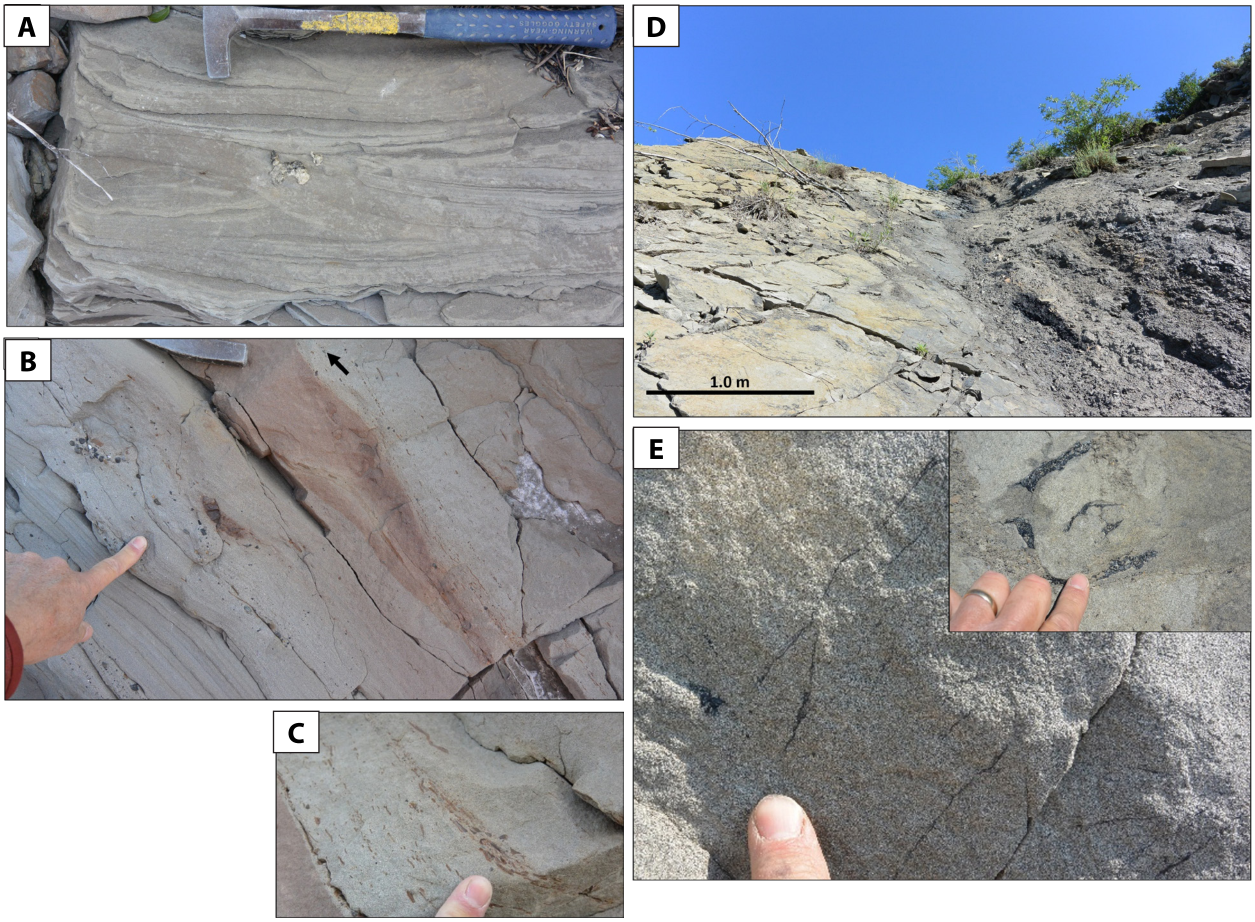

Figure 13. Photographs showing selected features in the sixth sandstone body from 41.5 m to 48.3 m. **A.** Low-relief trough cross-stratification in fine-grained sandstone at 42 m. The low-relief geometry of the concave-up laminae in some sets resemble small-scale swaley cross-stratification. The bed appears unbioturbated (BI 0). Hammer is 42 cm long. **B.** Amalgamated beds of fine-grained sandstone from 43.5 m to 44.1 m. Note the scattered gray chert pebbles and *Inoceramus* shell fragments in the bed supporting the hammer head. The pebbles line discontinuous scour surfaces. The beds appear unbioturbated (BI 0). **C.** *Inoceramus* shell fragment lag above geologist's finger. Note scattered shell fragments below the lag and to the left of finger. The shell lag is located along strike in the direction indicated by the black arrow in fig. 13B (at same stratigraphic level). **D.** View of bed surface at 48.3 m. Surface is covered with wood impressions and includes numerous rhizoliths. A 20-cm-thick seam of bituminous coal sits atop this sandstone bed but is covered by colluvium in this photograph (sheet 1). **E.** Delicate rhizoliths in sandstone from 48.1 m to 48.3 m (immediately below coal seam). Visible part of finger is 3 cm long. Inset photograph shows coalified wood fragments on bed surface at 48.3 m. Visible part of index finger is 6 cm long in inset photograph. The sandstone body records deposition in either a crevasse channel (favored) or shoreface setting. The upper 2.5 m of the sandstone body is interpreted as beach berm–backshore deposits.

Several heterolithic mudstone–sandstone and amalgamated sandstone bodies 4–6 m thick interrupt the mudstone-dominated succession described above (sandstone bodies 7 through 11 on sheet 1). The stratigraphically lowest body is a heterolithic fining-upward package from 55.6 to 59.6 m (seventh sandstone body; figs. 14A, C and sheet 1) that includes a basal bed approximately 60 cm thick of medium-grained sandstone with sigmoid-shaped foresets discontinuously lined with small chert and quartz pebbles. Sandstone beds above the sigmoid cross-stratified bed are dominantly very fine-grained and include small-scale trough cross-stratification and current ripple cross-lamination. Coalified plant fragments and pelecypod valve impressions are present on some sandstone bed surfaces (fig. 14D) and are locally abundant. Sandstone and mudstone appear unbioturbated (BI 0). Approximately 0.4 m below the sigmoid cross-bedded sandstone is a foundered bed of fine-grained sandstone (ball and pillow structure; white arrows in fig. 14C, sheet 1, 55.2 m).

Heterolithic successions from 66.9–69.8 m, 84.2–90.1 m, and 96.5–102.6 m (eighth, ninth, and tenth sandstone bodies on sheet 1) coarsen upward from interbedded siltstone and very fine-grained sandstone in the lower parts to amalgamated very fine- to fine-grained sandstone in the upper parts (figs. 14F, 15A). These successions include a mix of current-generated and wave-generated sedimentary structures, including small-scale trough cross-stratification, current-ripple cross-lamination, wave-ripple cross-lamination, and wave-ripple bedforms on bed tops (figs. 15B–C and 16A–B). Thin mudstone drapes on sandstone beds are commonly sideritized, as are some siltstones in mudstone successions, forming distinctive orange-brown colored bands (figs. 14F–G, 15A–C). Poorly preserved plant fragments are common to abundant on some bedding planes and are thoroughly mixed in with sand locally (sheet 1, 88.4–90.1 m and 112.9–115.5 m).

The lowest heterolithic body (seventh sandstone body, sheet 1) is interpreted as the fill of a small crevasse channel. The foundered bed below the sigmoid cross-bedded sandstone is probably related to the crevasse event and likely represents abrupt sand deposition on a soft, low strength (or no strength) soupy substrate immediately following the crevasse event and subsequently sinking into the underlying mud. The higher bodies are variously interpreted as a minor levee deposit or a small crevasse delta (eighth sandstone body), a wave-reworked bayhead delta (ninth sandstone body) and stacked small crevasse deltas (tenth sandstone body). The eleventh sandstone body is interpreted as a crevasse channel or emergent splay complex. Sandstone bodies deposited in these settings have been described in detail by Elliott (1974), Bhattacharya and Walker (1991), Bhattacharya (2006), and Ryer and Anderson (2004)

116.8 m to 126.9 m

The interval from 116.8 m to the base of the thick sandstone body at 126.9 m consists dominantly of mudstone with few thin tephra beds up to 3 cm thick and beds of very fine-grained sandstone ranging in thickness from a few centimeters to approximately 75 cm (fig.17A–B). Coal seams are absent in this interval and several sandstone beds include HCS. A laterally discontinuous bed of fine-grained sandstone fills a large scour at 125.25 m (fig. 17B, rock hammer resting on sandstone filling scour). Micropaleontologic samples collected from mudstones yielded foraminifera characteristic of marine (inner neritic) environments (LePain and others, 2009). This interval is interpreted to record deposition in offshore shelf to offshore transition settings between storm and fairweather wave-base and the sandstone beds are storm deposits (tempestites). The sandstone filling the scour at 125.25 m is interpreted as a gutter cast.

126.9 m to 183.9 m

Two thick sandstone bodies separated by a poorly exposed mudstone succession form most of the remaining 57.0 m of the Nanushuk Formation at Ninuluk Bluff (sheet 1, figs. 5, 17A–B, 18A–B, and 19A–C). The lower sandstone body (12 on sheet 1, from 126.9 m to 141.8 m) is 14.9 m thick, has a sharp contact with underlying mudstone (fig. 17A–B) and is split in two parts. The lower part is 7.8 m thick and consists of amalgamated sandstone beds with numerous low-relief scour surfaces overlain by discontinuous chert and quartz pebble lags and medium- to large-scale, low-relief trough cross-stratification (fig. 18A-B). The latter resembles SCS locally. Some beds change thickness laterally over several meters distance (fig. 18A). Low-relief foresets are present locally and resemble low-relief 2-D bedforms (fig. 18B). The upper few meters of the lower part fines-upward from fine-grained sandstone to very fine-grained sandstone,

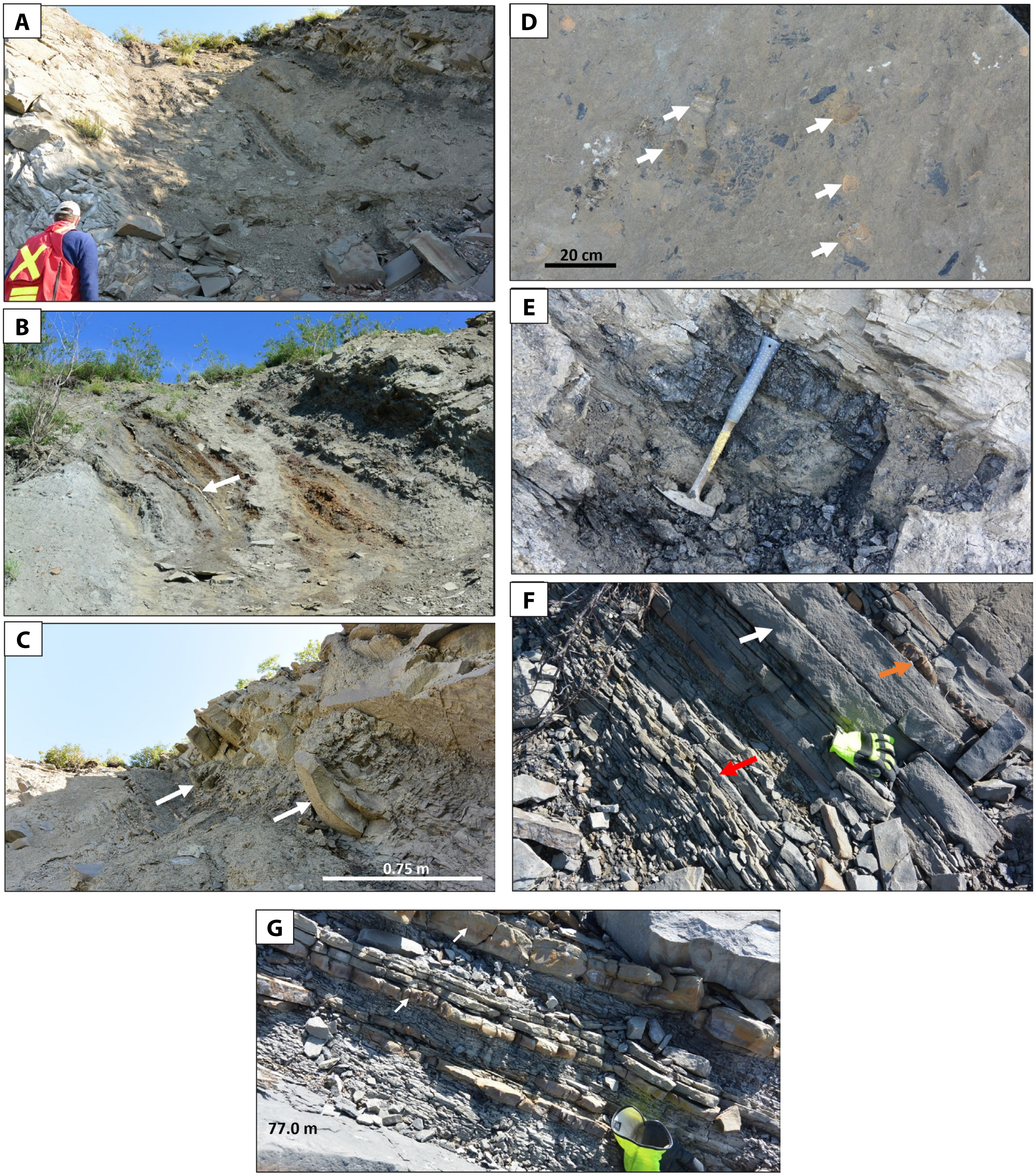

Figure 14, full caption on next page. Photographs showing selected features in the mudstone-dominated succession from 48.3 m to 116.8 m.

Figure 14, previous page. Photographs showing selected features in the mudstone-dominated succession from 48.3 m to 116.8 m. **A.** View toward the west showing the mudstone interval from 48.3 m to approximately 56.8 m. This succession includes several thin tabular sandstone beds ranging in thickness from a few centimeters up to 20 cm. The mudstone was deposited in a back-barrier lagoonal—interdistributary bay—estuarine setting and the tabular sandstones represent splay sand sheets or thin washover deposits (transported by storm surges landward over a beach berm). The fining-upward sandstone package visible in the upper right corner of the image corresponds to the lower part of the seventh sandstone body from 55.6 m to 59.6 m (fig. 14C and sheet 1). **B.** Photograph showing mudstone from 102.8 m to approximately 105.9 m. Dark brown weathering material is mudstone with abundant macerated terrestrial plant fragments. The pale-yellow layer (white arrow) is a thin tephra altered to bentonite. The depositional setting is the same as that inferred for the interval shown in fig. 14A. **C.** View west showing the upper part of the mudstone succession shown in fig. 14A and the base of the seventh sandstone body, a fining-upward heterolithic package from 55.6 m to approximately 56.2 m (top at 59.6 m). Note the foundered sandstone blocks (white arrows). The heterolithic succession is interpreted as a crevasse channel-fill deposit that experienced intermittent flow, or a constant flow that was modulated by tidal currents (flood tides, slack water, ebb tides in a diurnal or semidiurnal cycle). **D.** Bedding plane view of a tabular sandstone bed at approximately 58.2 m showing coalified plant fragments and small bivalves (white arrows). **E.** Bituminous coal seam at 80.8 m. Hammer is 42 cm long. **F.** Base of minor coarsening- and thickening-upward sandstone succession from approximately 75.3 m to approximately 77.0 m. Thinly bedded sandstone near the base is very fine-grained (red arrow) and fine-grained near the top (white arrow). Orange arrow near right side of image marks the base of a sideritized mudstone layer. Glove for scale. **G.** Mudstone interval overlying sandstone at approximately 77.0 m with interbedded siderite-cemented siltstone and very-fine-grained sandstone (white arrows). Glove in lower right corner for scale.

includes horizontal, plane-parallel laminations and is capped by a discontinuous zone of siderite-cemented sandstone (sheet 1). A thin bed of very fine-grained sandstone with abundant carbonaceous plant debris caps the lower part of the sandstone body and is overlain by a few centimeters of sideritic, silty clayshale. This silty clayshale is abruptly overlain by the upper part of the sandstone body, which is 7.1 m thick, coarsens-upward from fine- to medium-grained sandstone, and consists of amalgamated sandstone beds. Horizontal, plane-parallel laminations are the dominate physical sedimentary structure, interrupted locally by low-relief scours filled with planar-tangential cross-stratification (sheet 1, approximately 136 m to 137.5 m). Shell fragments and trace fossils have not been found in either part. This sandstone body is interpreted as a sharp-based shoreface succession capped by upper shoreface to foreshore deposits. Thinly bedded sandstone and clayshale separating the lower and upper part mark a temporary pause in shoreface progradation and might be analogous to Storms and Hampson's (2005) discontinuity surfaces. Alternatively, the lower part of the sandstone body could represent the fill of a distributary channel.

The upper sandstone body (13 on sheet 1) extends from 166.2 m to 183.6 m, is 17.4 m thick, and consists almost entirely of fine-grained sandstone (figs. 19A–C and 20A). Beds are amalgamated and contacts are difficult to identify due to uniform grain size, except where scour surfaces lined with chert and quartz granules and pebbles are present (fig. 19A). The lower 6 m of the body is horizontal, plane-parallel laminated and includes at least one sandy chert-quartz pebble conglomerate bed up to 20 cm thick. Amalgamated sandstone beds with possible HCS are present between approximately 174.5–177 m (fig. 19B). The upper part of the body includes plane-parallel laminations that appear organized in wedge-shaped sets (figs. 19C). The body is overlain by a thin succession of very fine-grained sandstone that is succeeded by approximately 30 cm of chippy to platy weathering silty shale (figs. 20A–B). A nearly continuous layer of siderite concretions caps the siltstone (figs. 20B–C). Like the lower body, the upper sandstone body is interpreted as a sharp-based shoreface succession capped by foreshore deposits. Overlying very fine-grained sandstone and siltstone are interpreted as either a thin wedge of bayfill or lagoonal deposits or an offshore shelf deposit. Palynological data suggest the latter interpretation. If the latter is correct, a flooding surface is present at the top of the shoreface–foreshore sandstone body (183.6 m).

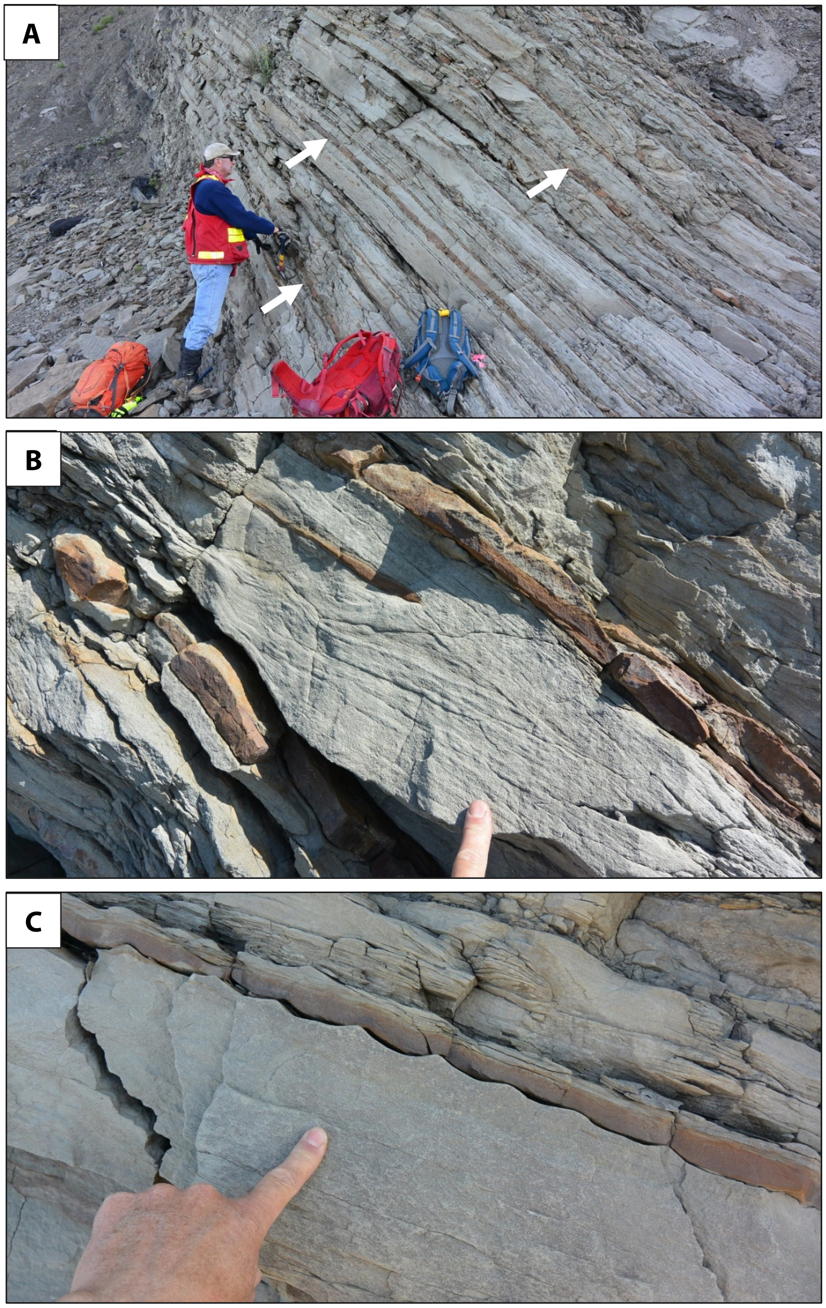

Figure 15. Selected photographs showing features in the ninth sandstone body from 84.2 m to 90.1 m. **A.** Thin- to medium-bedded, very fine- to fine-grained sandstone with interbedded siderite cemented siltstone. Siltstone partings separating moderate to highly bioturbated (BI 3–4), thin sandstone beds with patchy siderite cemented areas characterize the lower 60 cm of the sandstone body (sheet 1). The interval from approximately 85 m to 86.1 m consists of interbedded very fine- and fine-grained sandstone with small- to medium-scale trough cross-stratification (fig. 16B) and wave ripple cross-laminae (fig. 16C) and appears unbioturbated (BI 0?). Physical sedimentary structures are not obvious in the upper 1.8 m of the sandstone body, which includes abundant macerated plant material and larger plant fragment with a jumbled texture (BI 4–5?). The rhythmic character of bedding and common presence of mudstone drapes indicates regularly fluctuating energy conditions and a tidal influence. Geologist is 2 m tall. **B.** Medium-scale trough cross-stratified, fine-grained sandstone at approximately 85 m. Set thickness ranges from 10 cm to 20 cm thick. Visible part of finger is 7 cm long. **C.** Wave ripple cross-laminated, fine-grained sandstone. Note the well-developed wave ripple bedforms below the siderite cemented layer.

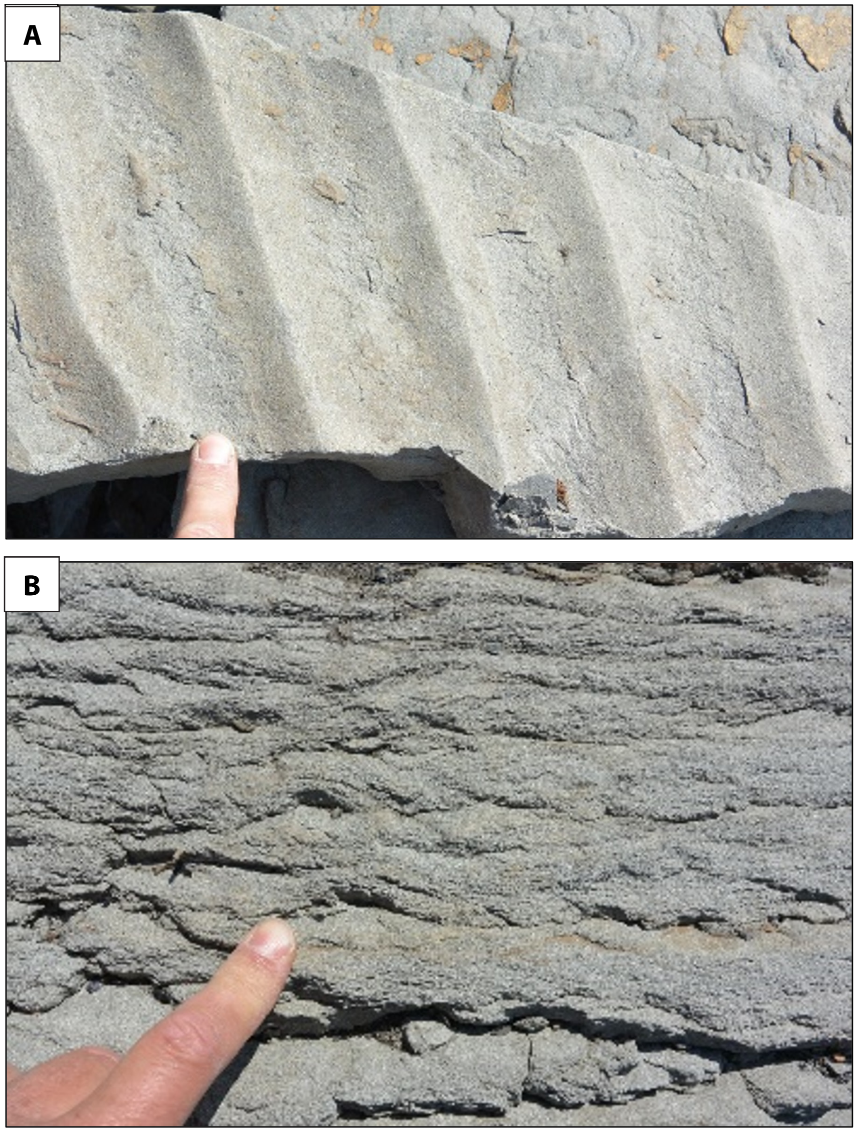

Figure 16. Photographs showing selected features in the coarsening-upward sandstone body from 96.5 m to 102.6 m. **A.** Wave ripple bedforms near 100 m. Wave ripple bedforms and wave ripple cross-laminations are common in this sandstone body, indicating short period waves reworked crevasse delta deposits. **B.** Small-scale trough cross-laminations at approximately 101 m. The 20–40 cm-thick packages are interpreted to record modulation of current strength by tides.

Seabee Formation

183.9 m to 192.7 m

A discontinuous chert–quartz pebble conglomerate overlies the siderite layer at 183.9 m and marks the base of the Seabee Formation (figs. 20B–C, sheet 1). The lower 8.8 m of the Seabee is a fining-upward succession that grades from medium-grained sandstone to slightly silty clayshale with few thin interbeds of coarse siltstone to very fine-grained sandstone. Medium-grained sandstone appears structureless, but is exposed on a moderately steep dip slope covered with scattered colluvial debris making access difficult (slope above and to the left of geologist's head in figs. 21A). Silty clayshale above the fining-upward sandstone succession includes discrete thin tephra beds up to a few centimeters thick (fig. 21A). The lower 8.8 m of the Seabee is interpreted to record deposition in middle to lower shoreface, offshore transition, to offshore settings.

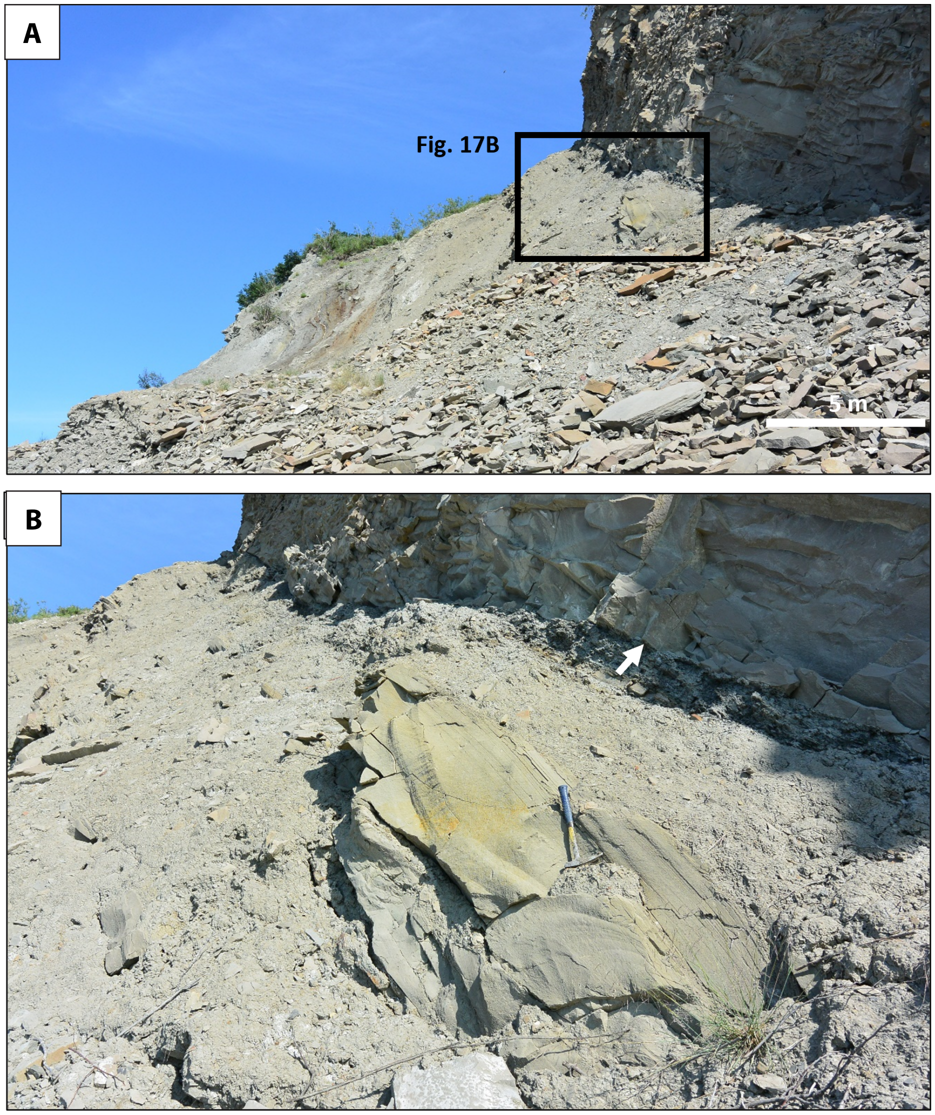

Figure 17. Photographs showing selected features in the mudstone succession from approximately 116 m to the base of the sandstone body at 126.9 m. **A.** Mudstone from approximately 118 m to 126.9 m showing thin to medium beds of very fine- to fine-grained sandstone. Some sandstone beds appear massive, and some have HCS. The black rectangle shows the view in fig. 17B. Mudstones in this interval are interpreted to record deposition in offshore shelf (distal shelf) to offshore transition settings. **B.** Large gutter cast filled with HCS sandstone at 125.25 m. Note the sharp contact with the sandstone body at 126.9 m (white arrow). Hammer is 42 cm long.

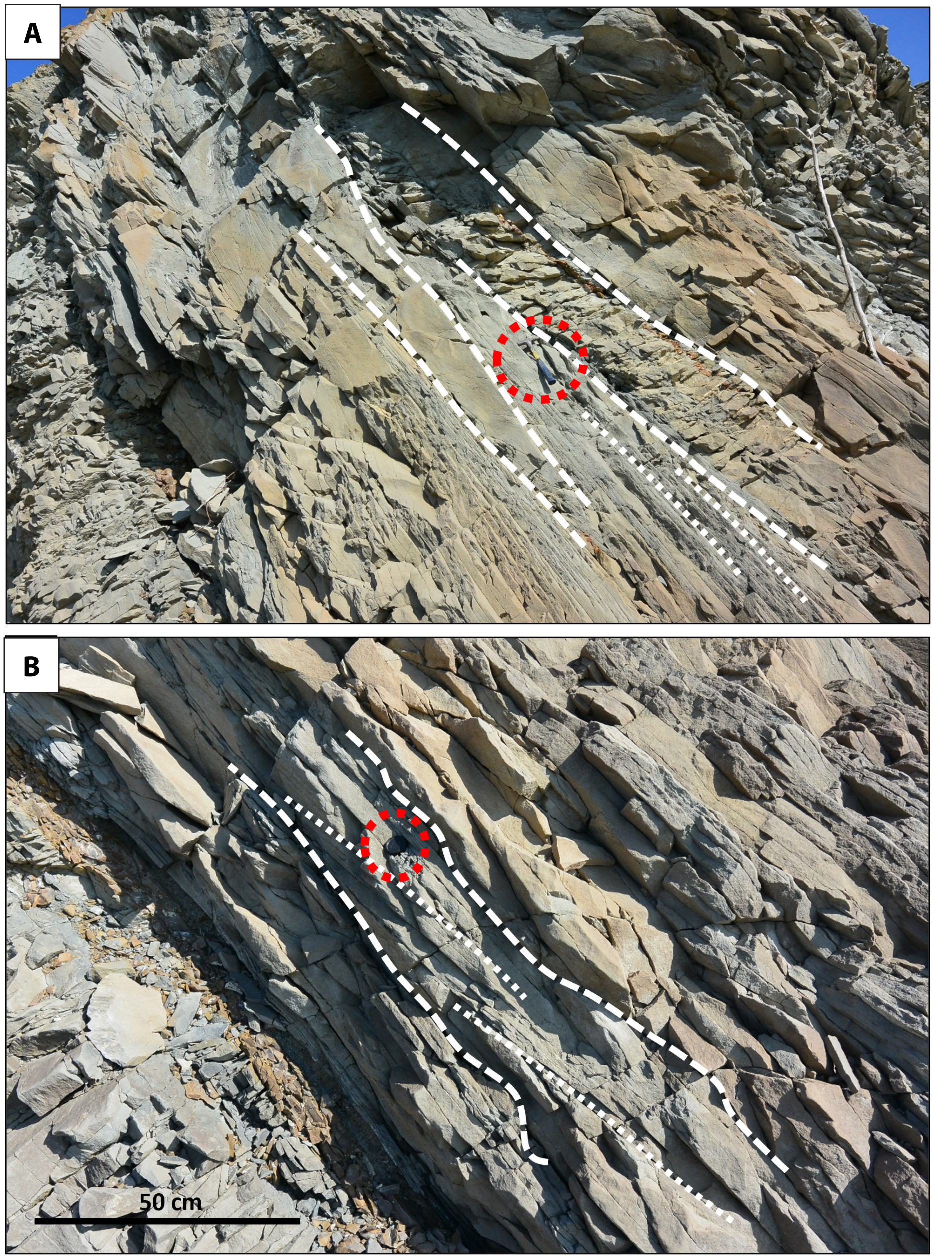

Figure 18. Photographs showing selected features in the twelfth sandstone body from 126.9 m to 141.8 m. **A.** Bedding geometry between approximately 131 m and 134 m. Note lateral changes in bed thickness (dashed white lines). Sandstones are unbioturbated (BI 0). Dashed red circle shows hammer for scale—handle is 42 cm long. **B.** Low-angle planar-tabular foresets overlain by trough cross-stratified fine-grained sandstone at approximately 128 m. Sandstones are unbioturbated (BI 0). The sandstone body from 126.9 m to 141.8 m is interpreted to record deposition in a middle to upper shoreface setting. The sharp contact with underlying mudstones suggests deposition during an episode of falling relative sea level and forced regression. Dashed red circle shows camera lens cap for scale—diameter of cap is 4.5 cm.

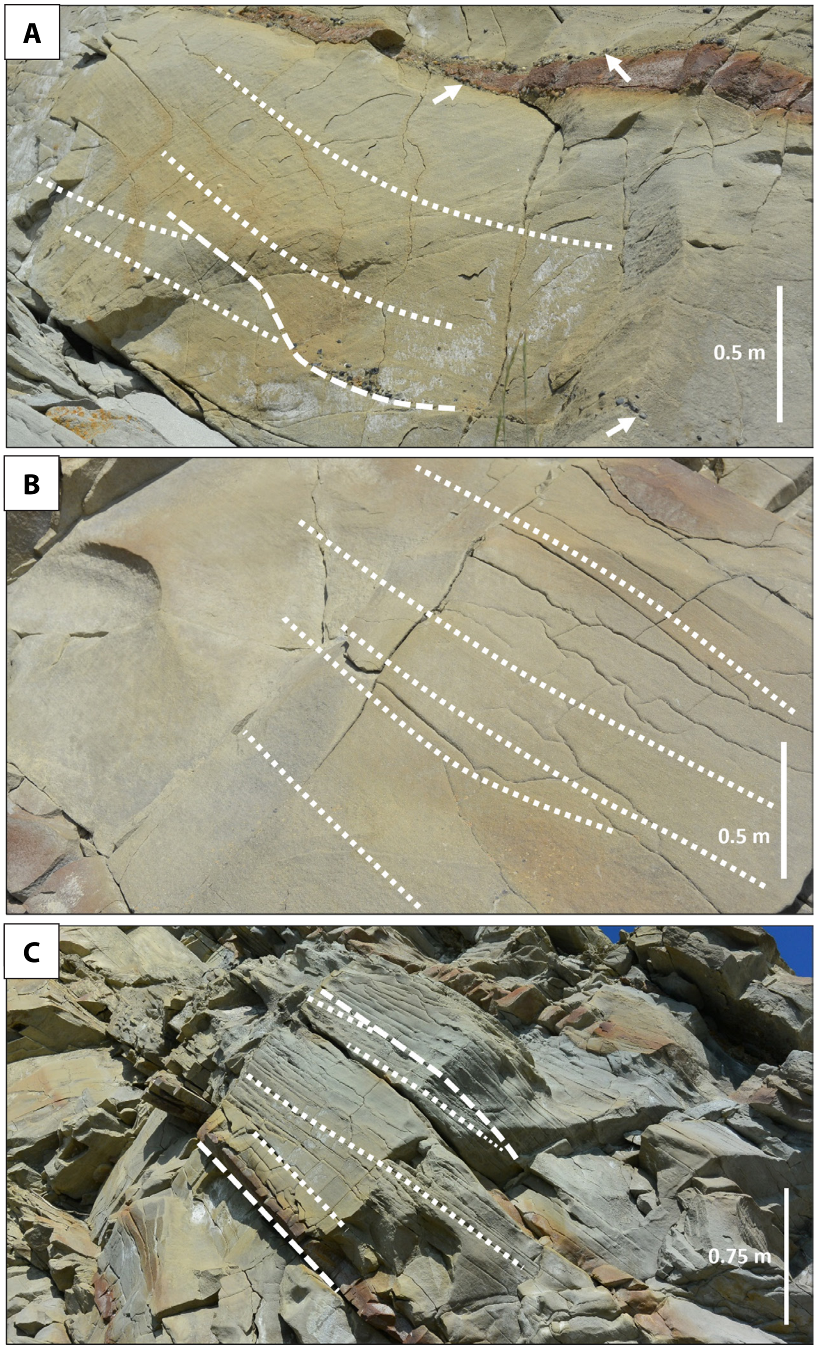

Figure 19. Photographs showing selected features in the thirteenth sandstone body from 166.2 m to 183.6 m. **A.** Amalgamated beds of fine-grained sandstone with prominent chert and quartz pebble-lined scour surfaces (white arrows) between 170 m and 172 m. White dashed line traces a prominent scour surface with approximately 20 cm of relief and chert and quartz pebbles lining the scour pit. The two closely spaced scour surfaces visible near the top of the image (two white arrows) have planar geometries. Sandstones include horizontal, plane-parallel laminae and broad, concave-upward laminae resembling SCS (dotted white lines). Sandstones are unbioturbated (BI 0). **B.** Amalgamated beds of fine-grained sandstone with abundant, faintly visible low-relief concave-up and convex-up surfaces suggesting the presence of HCS at 176 m. Sandstones are unbioturbated (BI 0). **C.** Amalgamated beds of fine-grained sandstone with sets of plane-parallel laminae dipping at low angles. Sandstone body is interpreted to record deposition in a middle to upper shoreface setting and sandstones in the upper 3–4 m are tentatively interpreted as foreshore (beach swash zone) deposits. The relatively sharp contact with underlying mudstones suggests deposition during an episode of falling relative sea level and forced regression.

192.7 m to 246.4 m

The Seabee Formation from approximately 192.7 m to 246.4 m is largely covered by colluvium and vegetation, but local slumps and holes dug by animals indicate the interval is mostly soft clayshale with thin tephra beds (fig. 21A). The weathering character of the colluvium appears to change at approximately 209 m from clayshale without popcorn weathering character below to a distinctive popcorn weathering style above. This change in weathering character is attributed to an increase in the number of tephra beds above 209 m and, possibly, to the mixing of altered volcanogenic material in the background sediment (BI 6?). The succession records deposition in a distal, starved shelf setting (offshore shelf).

246.4 m to 258.8 m

The upper part of the measured section from 246.4 m to 258.8 m is a coarsening-upward succession of clayshale, silty clayshale, and very fine-grained sandstone (fig. 21B). Sandstone beds range from a few centimeters to approximately 50 cm thick and include horizontal plane-parallel laminations and common wave-formed structures, including HCS, wave ripple cross-laminations and wave ripple bedforms. Bioturbation is difficult to assess in clayshale and sandstone appears unbioturbated (BI 0) to sparsely bioturbated (BI 1). A few hundred meters to the southwest thick beds of very fine-grained sandstone with large-scale soft-sediment deformation structures are present in outcrop just above river level (stratigraphically above top of measured section). The coarsening-upward succession records deposition above storm wave base in an offshore transition setting. The deformed beds near river level likely represent delta front deposits or distal distributary channel deposits.

PRELIMINARY SEQUENCE STRATIGRAPHY

Figure 22 summarizes our current interpretation of the upper Nanushuk and lower Seabee at Ninuluk Bluff. The reader is referred to Catuneanu (2019) for definitions of sequence stratigraphic terms used in this report. The succession from 48.3 m and 116.8 m was assigned to a transgressive systems tract by LePain and others (2009). As previously discussed, our recent work has extended the measured section downward to near the base of the exposure and allowed reappraisal of facies changes across the contact at 48.3 m. The succession from crevasse channel or shoreface through foreshore and beach-berm and backshore strata (41.5–48.3 m) overlain by coal and interdistributary bay-lagoon-estuarine deposits suggests a normal progradational succession. The succession from 0 m to 116.8 m is reinterpreted here as a high frequency, fourth- or fifth-order, highstand systems tract (figs 4 and 22, sheet 1; Catuneanu, 2019). More work is needed to better understand the sequence stratigraphic significance of this interval.

The two shoreface sandstone bodies at the top of the Nanushuk at Ninuluk Bluff are each interpreted as the deposits of falling stage systems tracts (FSST) bounded by basal surfaces of forced regression (BSFR). We have not identified the BSFR associated with each FSST but do show regressive surfaces of marine erosion at the base of each sandstone body and candidate sequence boundaries subsequently modified during transgression at their top (fig. 22). Silty clayshale separating the shoreface bodies is interpreted as a transgressive systems tract. A maximum flooding surface (MFS), by definition, bounds the transgressive systems tract recognized in the lower part of the Seabee Formation. Due to poor exposure the MFS cannot be located but, based on facies stacking patterns, an interval containing the surface is identified on fig. 4 and sheet 1 as a maximum flooding zone. The gradual appearance of shallow marine sandstone up-section from this zone records renewed progradation of shallow marine depositional systems and forms the lower part of an HST in the Seabee Formation.

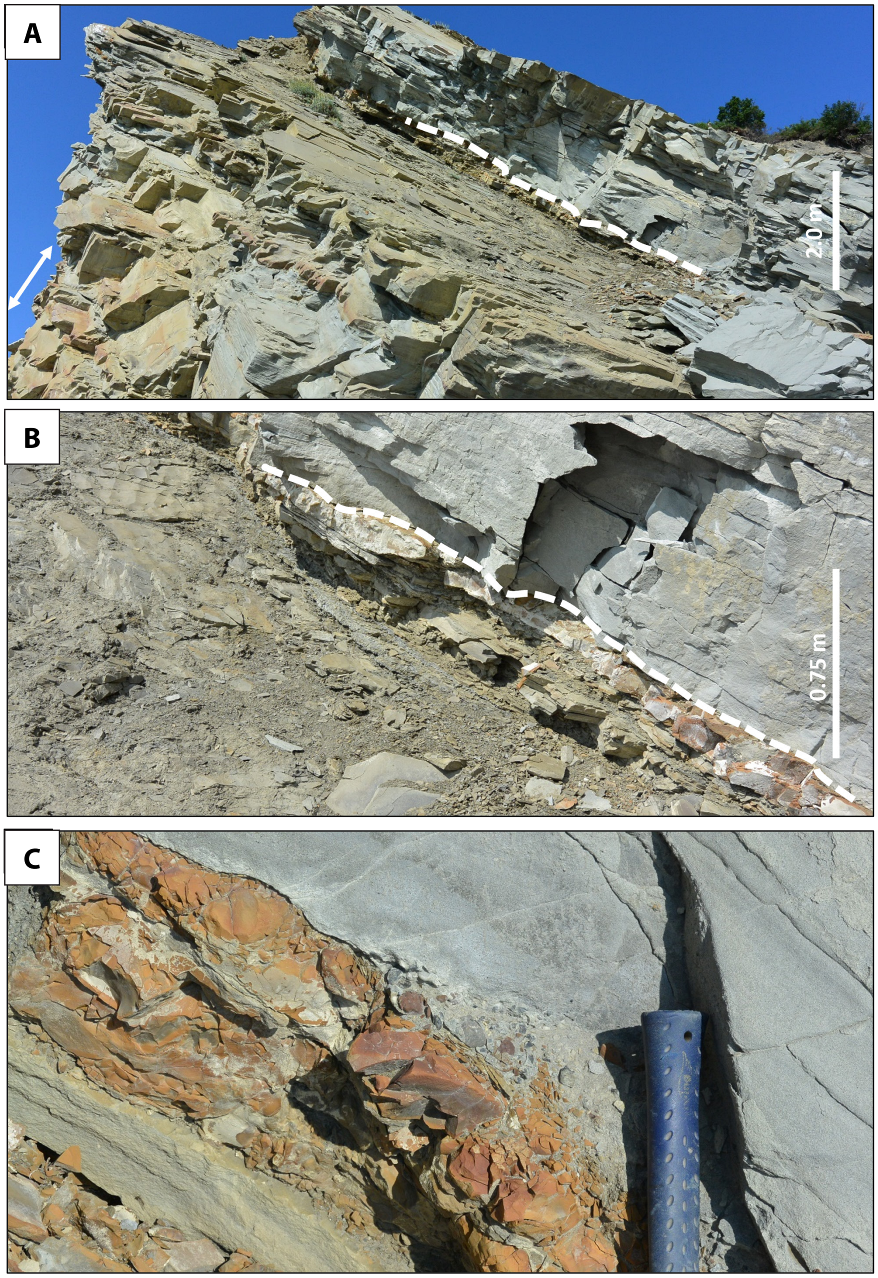

Figure 20. Photographs showing selected features in sandstone beds straddling the Nanushuk–Seabee contact at 183.9 m. **A.** Photograph showing the upper 3–4 m of the Nanushuk Formation (upper part of thirteenth sandstone body) and lower 2 m of the Seabee Formation. Dashed white line marks the contact between the two formations. Double ended white arrow shows approximate location of low-angle laminations interpreted as foreshore deposits. **B–C.** Close-up views of the contact shown in fig. 20A. A thin wedge of very fine-grained sandstone and thinly parting siltstone is present at the top of the Nanushuk and is capped by a discontinuous layer of siderite concretions (orange colored material below dashed white lines in figs. 20 A–B. A discontinuous lag of chert and quartz pebbles overlies the concretions at the base of the Seabee Formation. The package above the pebble lag fines upward from medium- to very fine-grained sandstone. See text for discussion. Visible part of hammer handle in fig. 20C is 16 cm long. The contact is interpreted as a compound surface that first formed as a sequence bounding unconformity subsequently modified during transgression to form a transgressive surface of erosion (CSB and TSE; sheet 1). In this interpretation, the chert and quartz pebbles represent a transgressive lag. An alternative interpretation is possible in which the lag is associated with an unconformity and forms the base of a thin lowstand systems tract. We favor the former.

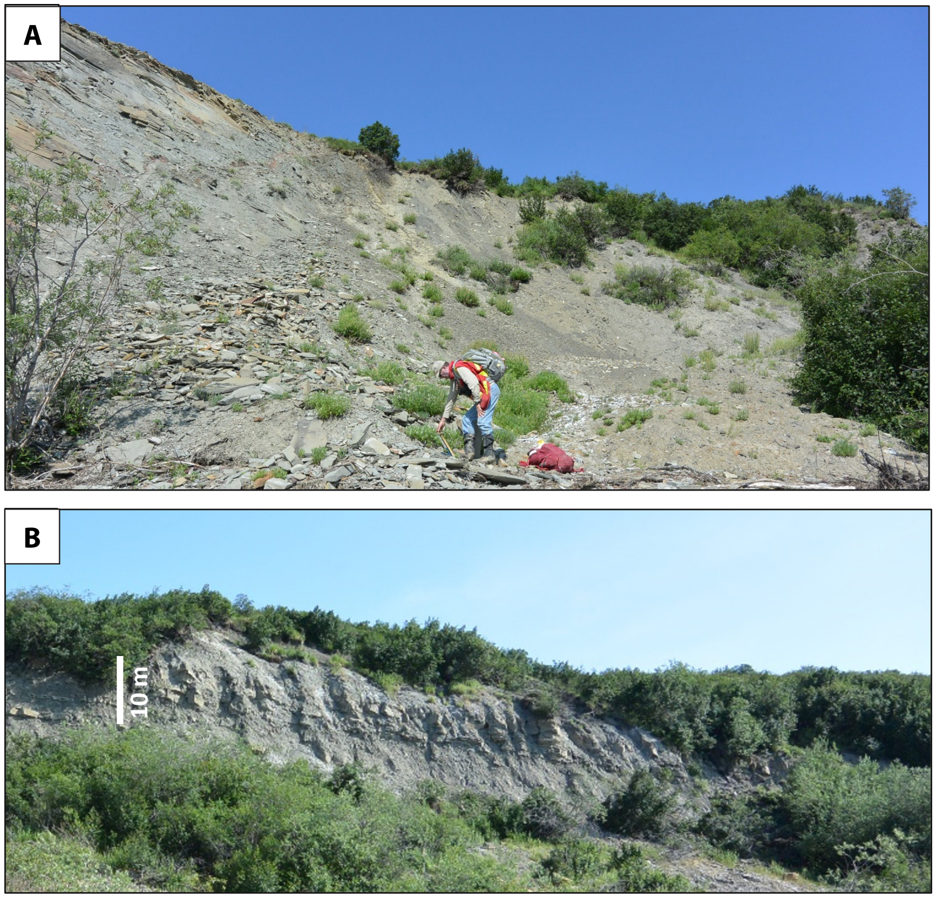

Figure 21. Photographs showing the lower Seabee Formation from approximately 187.5 m to the top of the measured section at 258.8 m. **A.** View toward the southwest showing the Seabee Formation from the dip slope at approximately 187.5 m to the vegetated area corresponding to the covered interval shown on sheet 1 between 209.5 m and 246.3 m. The lower 21 m of shale includes discrete, thin tephras ranging in thickness from a few millimeters to a centimeter or more. Above approximately 209 m clayshale has a distinctive popcorn weathering character due to admixed clay and bentonite (altered tephras). **B.** View toward the southwest showing top of the measured section from approximately 246 m to 258.8 m. Note the gradual appearance of thin to medium beds of very fine-grained sandstone. Several sandstone beds have well-developed HCS that grades upward to wave ripple cross-lamination, and some beds are capped with wave ripple bedforms. These structures appear in a predictable vertical sequence in individual sandstone beds (±horizontal, plane-parallel lamination →±HCS→±wave ripple cross-lamination→±wave ripple bedforms). The plus-minus symbols indicates that each structure is not always present in every bed. The sequence of sedimentary structures in sandstone beds records deposition from long-period storm waves in a shallow marine setting, followed by waning energy conditions and reworking of the upper part of the sand bed by shoaling waves (classic tempestite; Walker and others, 1983; Duke and others, 1991).

Figure 22, next page. Sequence stratigraphic interpretation of the upper Nanushuk and lower Seabee at Ninuluk Bluff. Line drawings to the right of the simplified measured section summarize our interpretation of the two shoreface sandstone bodies (12 and 13, sheet 1) between 126.9 m and 183.6 m. Both bodies have a sharp contact with underlying mudstone. Mudstone is interpreted to record deposition in offshore transition settings. The sandstone bodies are interpreted to record deposition in shoreface settings during falling stage systems tracts (forced regression). Numbers next to black leader lines on line drawing denote meters above base of measured section. Note a basal surface of forced regression associated with each falling stage systems tract has not been identified. This surface, by definition, marks the base of a falling stage systems tract (Catuneanu, 2019). Key to abbreviations: CSBU, candidate sequence bounding unconformity; CSBCC, candidate sequence boundary correlative conformity; RSME, regressive surface of marine erosion; TSE, transgressive surface of erosion; TS, transgressive surface; FSST, falling stage systems tract; TST, transgressive systems tract; HST, highstand systems tract.

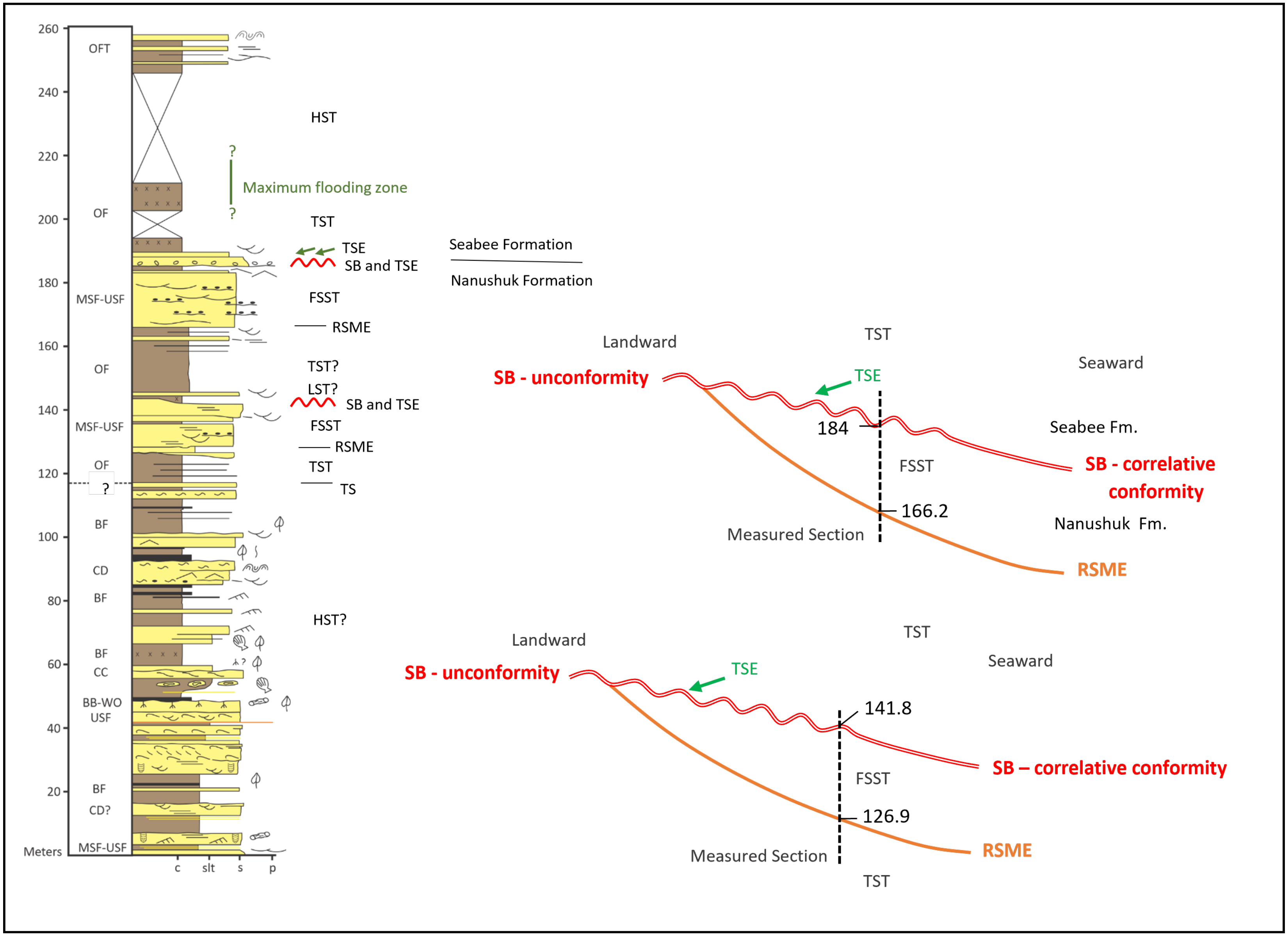

Figure 22, see caption on previous page. Sequence stratigraphic interpretation of the upper Nanushuk and lower Seabee at Ninuluk Bluff.

DISCUSSION

Despite differences in stratigraphic position and thickness, the facies organization documented in this report for the Nanushuk and basal Seabee Formations at Ninuluk Bluff provide a useful outcrop analogue to help understand reservoir-scale facies in recent discoveries in the northeastern NPRA and on state lands east of the Colville River. The Ninuluk Bluff exposure includes several shoreface-delta front sand bodies encased in mudstone-dominated successions. The two sharp-based shoreface bodies at the top of the formation are associated with FSSTs, include good potential for effective reservoir top seals, and are situated in close stratigraphic proximity to offshore deposits in the lower part of the Seabee formation which, in the east-central Colville basin, includes rich oil-prone petroleum source rocks. This stratigraphic arrangement provides potential access to petroleum charge and is similar to Nanushuk lowstand shelf margin sand bodies located up-dip from oil-prone source rocks in the Torok Formation and Hue Shale (Houseknecht, 2019). These same facies stacking patterns also have useful analogue value for shoreface and delta front deposits in younger Upper Cretaceous strata east of the Nanushuk maximum progradational limit.

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