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CHARACTERISTIC FEATURES OF PRODELTA TO DELTA FRONT SANDSTONES FROM THE CRETACEOUS NANUSHUK AND TOROK FORMATIONS, SLOPE MOUNTAIN, NORTH SLOPE, AK

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INTRODUCTION

The Nanushuk and Torok formations are interfingering deltaic and deep-marine units deposited within the Colville foreland basin of Alaska's Brooks Range during the Albian to Cenomanian ages of the Cretaceous (Mull et al., 2003). The formations dominate the series of anticlines and synclines that define the northern foothills of the Brooks Range, including Slope Mountain (Mull et al., 2003). Previous petrographic work at Slope Mountain focused on the composition of the upper Nanushuk Formation, identifying the sandstones as lithic arenites with primarily metamorphic lithic grains (Bartsch-Winkler, 1985; Johnson and Sokol, 1998). This study examines the petrography of fine-grained sandstones in the transitional strata between the Torok and Nanushuk formations at Slope Mountain, which have not been described extensively in previous work.

METHODS

We collected samples from the Torok and Nanushuk formations at four stratigraphic sections (SM1, SM2, SM6, and SM7) at Slope Mountain (Fig. 3, Shimer and McCarthy, this volume). Samples include resistant sandstone or sandy siltstone layers, 17 of which were selected for petrographic analysis with the goal of an even distribution throughout the measured sections. Samples were cut and made into petrographic thin sections at Smith College. Detailed descriptions were compiled based on field observations, hand samples, and thin sections, with an emphasis on texture and sedimentary structures.

DESCRIPTIONS

Section SM2

SM2, the lowest of the stratigraphic sections, is 60 m thick and consists of medium gray siltstone interbedded with 2-20 cm thick tabular layers of very fine sandstone (Fig. 4, Shimer and McCarthy, this volume). There are mm-scale cross- and planar laminations in the sandstones, and some upper bedding planes are rippled (Fig. 1a). At 4.5 m above the base of the section, a 1 m thick layer of sandstone with a lumpy, pillowy appearance (Fig. 1b), is overlain by 0.5 m thick layer of organic-rich claystone (Fig. 1c). Fossilized plant impressions were abundant in this part of the outcrop. The rest of the outcrop consists of interbedded siltstone and sandstone, with only one other notably thicker sandstone layer just below 20 m from the base of section.

Petrographic examination indicated light bioturbation in the sandstones, with a few thin vertical burrows in a sample 5 m above the base of section (Fig. 1d). The sandstone grain sizes range from coarse silt to fine sand, averaging 130 µm in diameter with moderate sorting and sub-rounded shape. They are classified as lithic wackes, dominated by a nearly equal amount of lithic grains and monocrystalline quartz. The lithic fragments seem to be primarily metamorphic and volcanic in origin. Chert makes up 10-15% of the total framework grains. Chlorite and polycrystalline quartz make up about 5% of each sample, while muscovite and plagioclase feldspar are rare (<1% each).

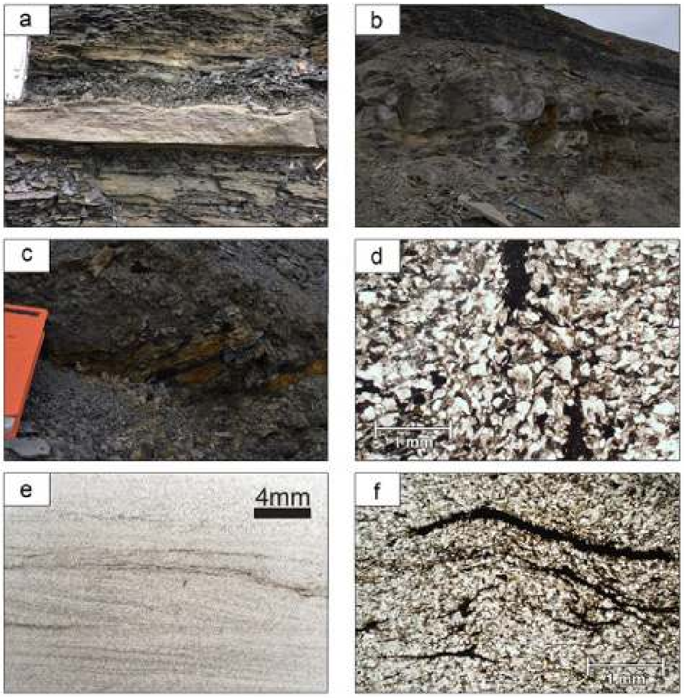

Figure 1. Field photos and photomicrographs from sections SM2 and SM1; (a) characteristic interbedding of shaley siltstone and sandstone from SM2 with ripple marks along the upper bedding plane of sandstone layer; the pocket leatherman is 10 cm long, (b) lumpy, pillowy sandstone bed from SM2; hammer is ~25 cm in length, (c) organic-rich layer containing abundant plant fossils from SM2, orange notebook is ~20 cm long, (d) photomicrograph of a deformed vertical burrow from sample SM2 5.2, (e) and (f) cross-lamination and mud drapes from sample SM1 32.3.

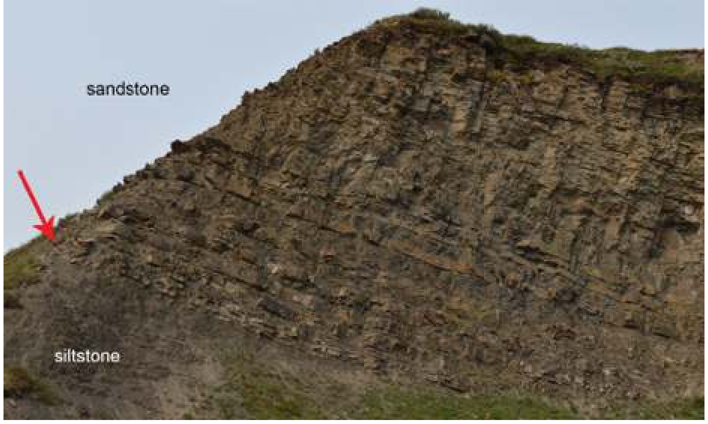

Figure 2. Field photo of the upper half of section SM1; the red arrow points out the prominent contact between siltstone below and the presence of more resistant sandstone layers above.

Section SM1

SM1 section is 58 m thick and it bridges the siltstone-dominated SM2 section with sites SM6 and SM7, which are almost entirely composed of sandstone (Fig. 4, Shimer and McCarthy, this volume). The bottom half of SM1 consists of dark gray, fine-grained, horizontally laminated shaley siltstone interbedded with thin layers of gray sandstone, similar to that of SM2. Resistant beds of fine-grained tabular sandstone interrupt the siltstones at 32 m in section (Fig. 2). The sandstone beds range from 4 cm to just over 1 m in thickness, and are ~0.5 m thick on average with typically sharp contacts. From approximately 32-35 m, sandstone beds are spaced only 0.5 m apart, and even less when the layers are thinner than 10 cm. Above the 40 m mark, the sandstone layers are typically at least 1-2 m apart and at least 1 m thick, until the 50 m mark at which the siltstone disappears and sandstone beds become amalgamated. These sandstones were classified as lithic wackes (50-60% monocrystalline quartz and only 20-30% volcanic and metamorphic lithic fragments). Chlorite and chert constituted around 15-20% of grains in most samples, though a sample from 42.4 m had no chlorite, and chlorite was only an accessory mineral (3-5%) in a sample from 49.2 m. Trace minerals include muscovite and plagioclase feldspar (both < 1%). A sample from 45.2 m also contained glauconite.

Sandstones from the lowermost 2 m of SM1 consist of angular to sub-angular coarse silt to fine sand, averaging about 90 µm in diameter, and exhibiting small-scale coarsening upward patterns. Grain size increases up-section to medium sand, with an average of 150 µm in diameter. Most sandstones from SM1 do not have distinct crossbedding or horizontal lamination, and instead are massive and bioturbated. Samples from layers with horizontal lamination or crossbedding have notably better sorting than samples from massive layers. Soft sediment deformation features are present in the form of distorted, 1-3 µm thick mud drapes (Fig. 1f). Fossilized wood fragments and bivalves are also present, but they are scarce and lack well-defined shapes. In contrast, burrows and other evidence of bioturbation are common. Burrows are horizontal and vertical, and range in diameter from 25-120 µm to very large ones (2-5 cm) found in float samples that are likely from this part of the outcrop.

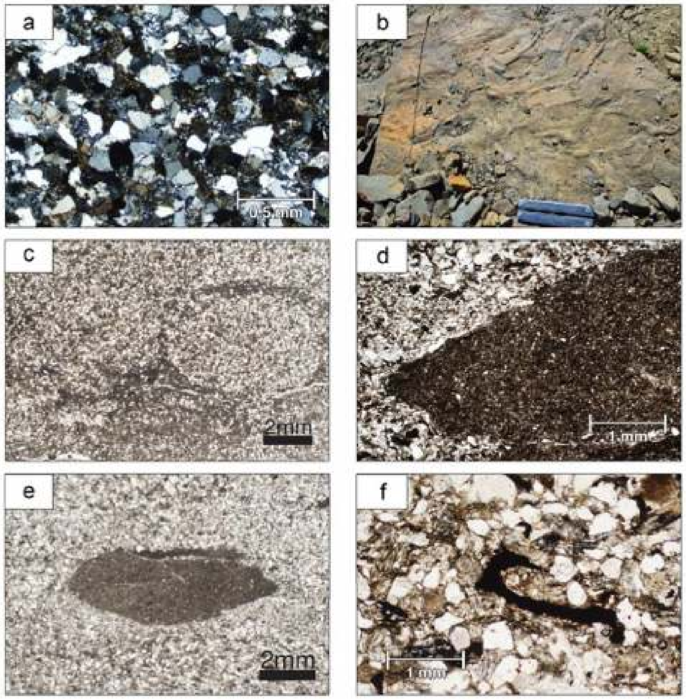

Figure 3. Field photos and photomicrographs from sections SM6 and SM7; (a) photomicrograph of sample SM6 2.5 in XPL classified as lithic arenite and containing primarily quartz, and volcanic and metamorphic lithic fragments, (b) burrow filled in with quartz and ringed with clay from section SM7, (c) burrows along an upper bedding plane of SM7, with a 10-cm long pocket leatherman for scale, (d) and (e) mud-filled burrows from sample SM7 3, and (f) an example of a plant fragment from section SM7.

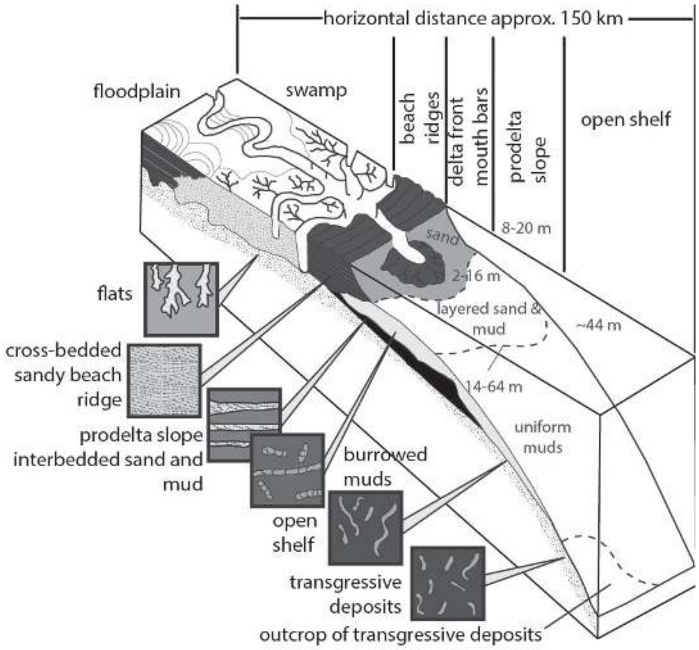

Figure 4. Diagram of a fluvial deltaic sequence, showing typical structures and sediment distribution, modified from a figure adopted from Allen (1970) by Prothero and Schwab (2014). The SM1 and SM2 deposits are interpreted as layered sand and mud deposits of prodelta slope, whereas the overlying SM6 and SM7 represent sandy delta front environments. Common sedimentary structures illustrated here are bioturbation in prodeltaic deposits, and ripple lamination or cross-bedding as sand becomes more common in proximal settings.

Section SM6

The bottom of SM6 is roughly correlative to the uppermost part of section SM1 and is composed of one 6 m thick outcrop of medium light gray lithic arenites in 3-5 cm beds. This sandstone lacks additional identifiable sedimentary structures aside from faint horizontal lamination in the top 20 cm and thin rippled layers spaced about 0.5 m apart. Starting at 2 m above the base of section, there is an alternation of resistant and less resistant sandstone at approximately every half meter, with gradational contacts. Grain sizes range from very fine sand to medium sand (average 130 μm), with a noticeable absence of coarse silt. Sandstones from this section are moderately to well sorted, and the grain shape varies from sub-angular to sub-rounded. There is an even amount of monocrystalline quartz and lithic fragments, each comprising about 40-45% of the framework grains (Fig. 3a). Lithic fragments are volcanic and metamorphic in origin. Remaining framework grains are 5-10% chert, with trace plagioclase feldspar, polycrystalline quartz, and muscovite (< 1% each). Some samples have up to 10% chlorite, but others have none.

Section SM7

Section SM 7 is stratigraphically located approximately 50 m above SM6 and SM1. Similar to SM6, the 12 m thick SM7 section is composed almost entirely of sandstone (Fig. 4, Shimer and McCarthy, this volume). SM7 coarsens up from 1 m of siltstones into medium light gray sandstone, with grain size ranging from very fine sand to medium sand, and an average grain diameter of 180 μm. Sorting is moderate, and grain shape is angular to sub-angular.

Sandstones are classified as lithic wackes and lithic arenites composed of 60-70% monocrystalline quartz, which decreases in abundance upwards to a minimum of 30-40%. Lithic fragments show a reverse trend, from

10-15% to as much as 20-30% at the top of the section. The lithic grains again are primarily volcanic and metamorphic rock fragments. All samples have trace amounts (< 1%) of plagioclase feldspar and muscovite, and typically 3-5% chlorite. One sample from the lower part of the section contains trace amounts of glauconite. Chert and polycrystalline quartz each make up 5-10% of the framework composition.

Tabular layers range from 10 cm to 2 m in thickness (0.5 m average), typically with sharp contacts, although a few are rippled. Field observations revealed mm-scale horizontal lamination, ripple marks, cm-scale crossbedding, including trough cross-stratification. There was one well-preserved example of in situ horizontal burrows along upper bedding planes (Fig. 3b). Petrographic analysis revealed an abundance of trace fossils. Every petrographic thin section had burrows (10-75 µm in diameter) and other evidence of bioturbation (Fig. 3c-e), such as a mottled appearance and destruction of the original sedimentary fabric. Additionally, some of the samples from throughout the section contained small plant fragments (Fig. 3f).

INTERPRETATIONS & DISCUSSION

The transitional strata between the Torok and Nanushuk formations at Slope Mountain demonstrate an upward coarsening trend from siltstone to interbedded siltstone and sandstone, and finally to sandstone-dominated deposits in sections SM6 and SM7. This upward transition represents the progradation of the Torok-Nanushuk deltaic system from a prodelta to delta front setting. Prodelta deposits typically consist of fine siltstones and claystones with weak horizontal lamination and occasional ripple marks and crossbedding in interbedded coarse-grained sandstones (Davis, 1992; Galloway and Hobday, 1983; Prothero and Schwab, 2014). Bioturbation, trace fossils, or invertebrate fossils are common, as well as soft-sediment deformation and slumping. A typical prograding delta sequence coarsens upward as siltstones and mudstones are overtaken by the sandstone-dominated delta front (Fig. 4). A delta front shows similar sedimentary structures to the prodeltaic sandstones, but with more current-generated structures and the addition of "stair-step" slumping (Prothero and Schwab, 2014).

The transition between the Torok Formation and the lower Nanushuk Formation at Slope Mountain follows the described deltaic trends. SM2 is predominantly finely laminated siltstone with rare sandstones that represent deposition during flood conditions or progradation of distal distributary bars. Sandstones exhibit sedimentary structures typical of the prodelta environment, including bioturbation and crossbedding (Davis, 1992; Galloway and Hobday, 1983; Prothero and Schwab, 2014). An organic-rich layer with abundant plant fossils in the lower part of SM2 may signify a storm event or a forced regression. Just below this is a layer that appears to be lumpy and pillowy, which may be interpreted as soft-sediment deformation caused by a storm or seismic event (Hubert and Dutcher 2005, Moretti and Sabato 2007) or erosion and deformation caused by incision during sea-level fall.

Finely laminated prodelta siltstone dominates the lower half of section SM1 until 30 m, where both massive and cross-bedded sandstones begin to take over. These layers vary from massive flood stage deposits with very few sedimentary structures to proximal distributary mouth bars with crossbedding and ripples. Small-scale soft-sediment deformation features are occasionally present throughout SM1, and may indicate slope instability due to high sedimentation rates during storm events (Allen, 1981). Biologic activity is common in the form of bioturbation and fossilized plant fragments. The increased abundance of sandstone and the presence of terrestrially derived organic remains indicate general progradation of the delta system.

In the sandy deposits of sections SM6 and SM7, ripple marks and crossbedding become common, indicating increased supply of sand related to higher current velocity in an upward shallowing transition into delta front sedimentation. Bioturbation is still common, but these sandstones have more intact ripples and horizontal and cross-lamination than those of sections SM2 and SM1. Sorting becomes noticeably poorer with the increase in grain size, another indication of a higher energy environment.

Compositionally, sandstone deposits transition upward from lithic wackes in sections SM2 and SM1 to lithic arenites in SM6 and SM7 in response to

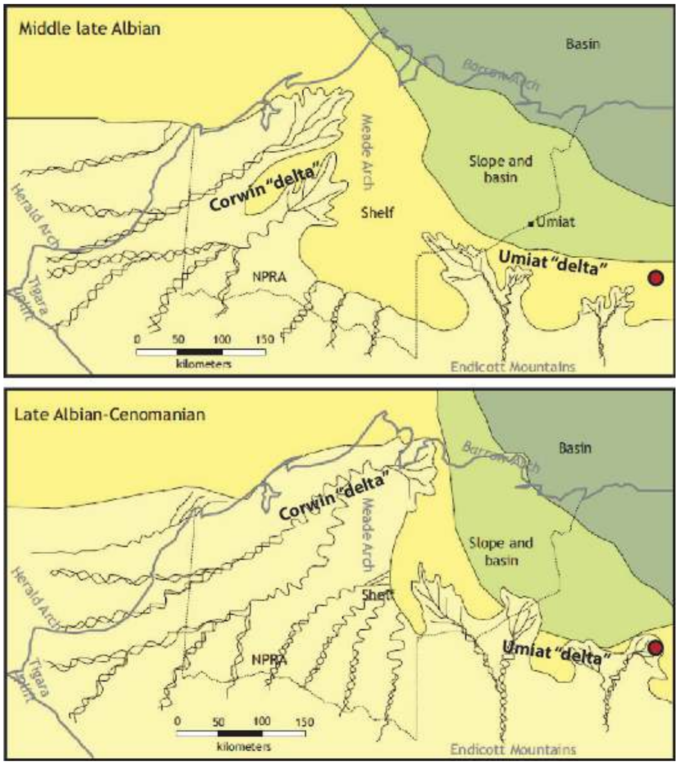

Figure 5. Paleogeogeographic reconstructions showing the progression of the Corwin and Umiat delta systems throughout the Albian to Cenomanian, with the approximate present-day location of Slope Mountain represented by a red dot showing the transition from marine shelf to fluvial sedimentation during this time period. Modified from LePain et al., (2009).

increased energy during the transition from prodelta to delta front environments. The lack of significant compositional differences among samples from the four outcrops suggests that the entire succession most likely originated from the same delta system. Huffman et al. (1988) described two deltas in northern Alaska during the Cretaceous (Albian) that contributed to the deposition of the Nanushuk Formation: the Corwin delta and the Umiat delta (Fig. 5). The Corwin delta is distinguished by sedimentary lithic fragments and high sedimentation rates, whereas the Umiat delta is dominated by metamorphic lithics and better fossil preservation (Bartsch-Winkler, 1985, Huffman et al., 1988). The sedimentary structures of the Umiat delta include crossbedding and ripple cross-laminations (Huffman et al., 1988), represented at Slope Mountain by the sandstone deposits of sections SM1, SM6, and SM7.

Previous petrographic studies that focused on outcrops just above SM6 and SM7 described the lithic fragments as primarily metamorphic and volcanic in origin, with some less abundant sedimentary grains (Johnson and Sokol, 1998). The lower Nanushuk Formation also appears to have lithic grains primarily composed of metamorphic and volcanic fragments, which confirm that the Nanushuk Formation at Slope Mountain originated from the Umiat delta. This hypothesis is further supported by the relative abundance of trace fossils in float and in situ in the lower Nanushuk Formation. Huffman et al. (1988) stated that trace fossils are nearly absent from the Corwin delta deposits, but prolific in the Umiat deltaic sequence.

When the transition from the Torok to Nanushuk Formation at Slope Mountain is compared with other descriptions of the Nanushuk Formation a few subtle differences illustrate changing paleoenvironmental conditions as the Umiat delta prograded into the Colville Basin. Previous descriptions of the Nanushuk Formation include prolific bioturbation and invertebrate fossils, which were not observed in abundance at Slope Mountain. This may indicate one of two things: either (1) sedimentation rates were slightly higher in the Umiat delta at Slope Mountain than in other areas of the delta, or (2) the deep marine environment of the Torok Formation saw lower oxygen levels that carried over into the transition period, negatively affecting the abundance of invertebrates and their preservation. The occurrence of glauconite in some samples from SM1 and SM7 supports the presence of local oxygen-poor conditions (Mullins et al., 1985). The results of this study generally support and build upon previous work on the Torok and Nanushuk formations both at Slope Mountain and elsewhere in the North Slope of Alaska.

CONCLUSIONS

The Mid-Cretaceous deltaic deposits of the lower Nanushuk Formation at Slope Mountain illustrate the transition between the deep marine deposits of the Torok Formation and the fluvial deposits of the upper Nanushuk Formation. These transitional deposits are initially dominated by siltstones interbedded with resistant sandstone layers in a typical prodelta succession, but as the Umiat delta prograded northward there is a gradual shift to sandstones deposited in a delta front environment.

The horizontal lamination of predominantly finer-grained and better sorted lithic wackes that dominates the lower sections is replaced by crossbedding and ripple marks of coarse-grained, more poorly sorted lithic arenites, which indicates the transition to current generated sedimentary structures and a higher energy depositional system. The Slope Mountain deposits do differ from other descriptions of the Nanushuk Formation in that bioturbation is less prolific, which may suggest lower oxygen levels or more rapid sedimentation in this particular area of the Colville Basin.

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