KECK Geology Consortium
Learning Science Through Research
Published by Keck Geology Consortium
Short Contributions
29th Annual Symposium Volume
23rd April, 2016
ISBN: 1528-7491

SEDIMENTOLOGY, STRATIGRAPHY, AND CHEMOSTRATIGRAPHY OF THE ALBIAN-CENOMANIAN TOROK AND NANUSHUK FORMATIONS, NORTH SLOPE, ALASKA

GRANT SHIMER, Whitman College
PAUL MCCARTHY, University of Alaska Fairbanks

INTRODUCTION

Cretaceous Arctic sedimentary strata provide a unique window into a greenhouse world shaped by elevated temperatures, high precipitation rates, near-maximum global sea-levels, and very active sea floor spreading and mountain building. Climatic and tectonic forces certainly had a strong affect on the sedimentology and stratigraphy of Cretaceous sedimentary systems, as well as ocean geochemistry and terrestrial ecology. Through the interpretation of stratigraphic sections, sandstone petrography, and mudstone geochemistry, the six students on this project compiled datasets that enhance our understanding of how the interplay between paleoclimate, orogeny, and autocyclic deltaic processes shape the stratigraphic record of the Albian-Cenomanian Torok and Nanushuk formations.

GEOLOGIC BACKGROUND

The North Slope of Alaska is a physiographic province bordered by the Brooks Range to the south and east and the Chukchi and Beaufort seas to the north (Fig. 1). Brooks Range uplift initiated in response to a Jurassic collision between the Arctic Alaska microplate and an island arc system to the south (Bird and Molenaar, 1992). The Brooks Range foreland basin, known as the Colville basin, is a peripheral foreland basin that formed in response to the stacking of thrust sheets and subsequent loading along the Brooks Range orogenic front and the Herald Arch, a subsurface high beneath the Chukchi Sea (Hubbard et al., 1987; Coakley and Watts, 1991). The basin is unusual in that it has clinoform sequences

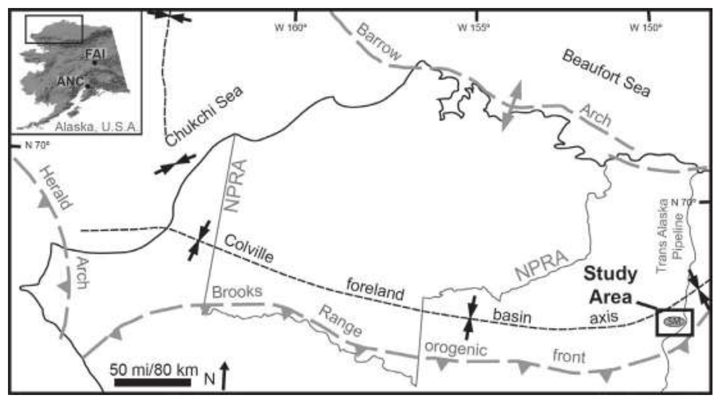

Figure 1. Slope Mountain (SM) lies on the eastern side of the North Slope of Alaska just south of the Colville foreland basin axis on the eastern side of the North Slope, along the Trans Alaska Pipeline. The foreland basin is constrained by the Brooks Range and Barrow Arch. Figure modified from Shimer et al. (2014) from a map originally published in Decker (2007).

with thicknesses of up to 2000 m (Houseknecht et al., 2009), and clinoform heights of up to 700 m (Houseknecht and Wartes, 2013). This unusually deep foreland accumulated a nearly continuous "Brookian" sedimentary record from the Early Cretaceous to the Paleocene (Fig. 2: Mull et al., 2003). Cenozoic deformation and subsequent erosion exposed Cretaceous Brookian sedimentary rocks in a series of anticlines and synclines that make up the Brooks Range foothills, including Slope Mountain (Fig. 3), the surface expression of the northern limb of the Marmot Syncline (Harris et al., 2002).

Bedrock exposures at Slope Mountain include the uppermost Torok Formation and a complete succession of the Nanushuk Formation (Fig. 3).

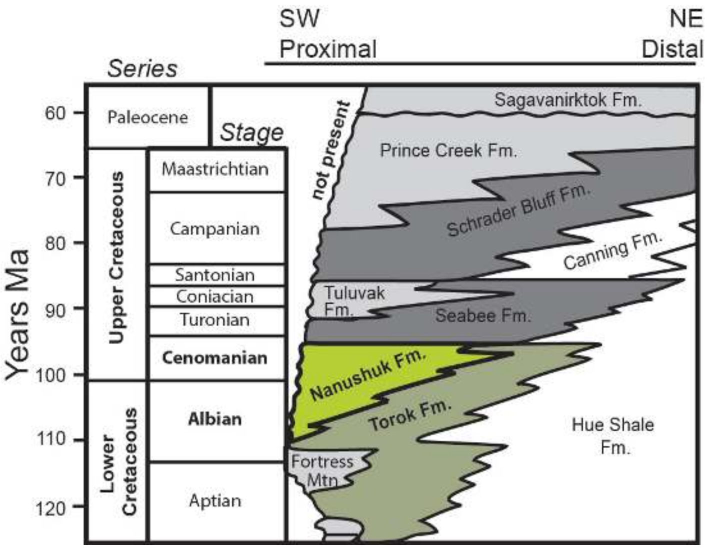

Figure 2. The Nanushuk Formation (bold line, light green) and Torok Formation (dark green) are the primary components of a depositional megasequence that filled much of the Colville foreland basin during the Albian-Cenomanian. A major transgression at the base of the Seabee Formation marked the end of the Nanushuk Formation and the onset of global sea-level rise (LePain et al., 2009). Figure modified from Shimer et al. (2014), from a figure originally published in Mull et al. (2003).

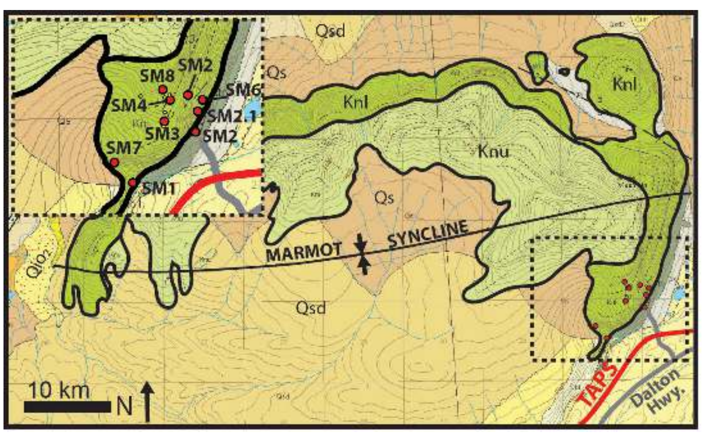

Figure 3. Slope Mountain is the topographic expression of the northern limb of the Marmot Syncline, an exposure of lower (Knl) and upper (Knu) Nanushuk Formation strata (highlighted with bold line) and the Torok Formation adjacent to the Trans-Alaska Pipeline (TAPS). A close-up of the study area (dashed-line and inset box) depicts the eight study sites (SM1-8) for the eleven stratigraphic sections discussed in the text. The base geologic map is modified from Harris et al. (2002).

Previous studies at Slope Mountain include a broad analysis of Nanushuk Formation stratigraphy (LePain et al., 2009) and sandstone petrography (Johnson and Sokol, 1998). The Torok and Nanushuk formations are genetically related basin, slope, and shelf sediments deposited in a thick depositional sequence that largely advanced from west to east along the foreland basin axis during the Albian-Cenomanian, with a south to north component along the orogenic front (Decker, 2007; Houseknecht et al., 2009). Together the deposits display typical topset-foreset-bottomset seismic geometries (Houseknecht and Schenk, 2005). The Torok Formation, which comprises bottomset, foreset, and topset strata, consists of mudstones and rare sandstones deposited in basin, slope, and shelf settings (Mull et al., 2003), while the Nanushuk Formation comprises overlying alluvial, deltaic, and shallow marine facies solely deposited in topset environments (Ahlbrandt et al., 1979; LePain et al., 2009).

Sedimentary facies, stacking patterns, and sequence stratigraphic boundaries within the Torok and Nanushuk formations record many episodes of system response to autogenic and allogenic forces (LePain et al., 2009; Shimer et al., 2014). Previous research on the Cretaceous Arctic provides a crucial framework from which to assess allogenic climate forcing within the Torok and Nanushuk formations. Eustatic sea level rise began during the Albian (Hancock and Kauffman, 1978; Müller et al., 2008), but reached its peak during the Cenomanian (Müller et al., 2008). On the North Slope a major Cenomanian transgression marks the contact between the non-marine Nanushuk Formation and overlying deep marine shale of the Seabee Formation (LePain et al., 2009). Transgressive boundaries also separate the upper and lower Nanushuk Formation in the subsurface (Shimer et al., 2014), and were observed in a previous assessment of Slope Mountain (LePain et al., 2009). Gardner (this volume) identifies progradational and retrogradational successions within the Nanushuk Formation at Slope Mountain that we cannot proscribe to allogenic or autocyclic processes at this time.

Paleoclimate records indicate an Albian increase in global temperature that lasted into the Campanian-Maastrichtian (Huber et al., 2002). Analyses from the North Slope and Siberia indicate that Arctic mean annual temperature during the Cenomanian-Turonian ranged from 7.7-14.3ºC (Spicer and Herman, 2010). The widening Late Cretaceous Arctic Ocean reached surface temperatures up to 15ºC (Jenkyns et al., 2004), while siderite $\delta^{18}O$ values from the Nanushuk Formation provide precipitation estimates of 485-626 mm/yr during the Late Albian (Ufnar et al., 2004). Two students (Ratigan, Beninati, this volume) sampled and analyzed the stable isotopic composition of organic carbon deposits and carbonate nodules from the Torok and Nanushuk formations and made new paleoclimate estimates for the Albian-Cenomanian that compare favorably to previous analyses.

Local tectonic forcing was the likely primary factor shaping Torok and Nanushuk formation depositional systems. The Brooks Range fold and thrust belt was very active during the Albian; blueschist facies metamorphic lithic fragments in the Nanushuk Formation are derived from the Brooks Range metamorphic belt to the south (Till, 1992), and phyllitic lithic grains derived from the exhumation of the metamorphic core of the Brooks Range are a major determinant of sandstone reservoir characteristics within the Nanushuk Formation (Fox et al., 1979; Bartsch-Winkler, 1985; Huffman et al., 1985). Petrographic analyses (Dickson, this volume) support previous analyses and emphasize the role of sedimentary facies in determining sandstone composition. Furthermore, geochemical analyses (Ratigan, Beninati, Lewis, this volume) indicate subtle fluctuations in mudstone composition related to influx of inorganic and organic sediment in the prodelta.

Regional volcanism was active during the Cretaceous, particularly in eastern Siberia (Akinin and Miller, 2011). Volcanic deposits in the Nanushuk Formation (Shimer et al., 2016) and smectites in Late Cretaceous paleosols (Salazar Jaramillo et al., 2015) attest to the influence of volcanoclastic sediments on depositional systems in the foreland basin. We identified one potential volcanic ash deposit in the Torok Formation and sampled it for geochemical analyses (Lewis, this volume).

METHODS

We approached Slope Mountain from the east, using a Trans-Alaska Pipeline System (TAPS) access road that intersects with the Dalton Highway (Fig. 3). Over the course of two weeks students measured eleven stratigraphic sections at eight outcrops, with sections (SM) numbered based on the order they were established. Locations include a set of upper Torok Formation and lower Nanushuk Formation sections in transitional shallow marine to marginal marine shelf deposits (Fig. 4) and more widely dispersed sections in marginal marine and non-marine Nanushuk Formation deposits further up the mountain (Fig. 5). Thick intervals of talus and vegetation separate most of the stratigraphic sections (see inset, Fig. 4), but there are correlative relationships between sections SM1, SM2.1, and SM6 based on the lateral extent of the lower-most erosion-resistant Nanushuk Formation sandstone layer. SM3 and SM3.1 are also correlative, as they were measured a short distance from each other at the same sandstone outcrop.

Each measured section is based on field assessments of composition and texture (grain size, sorting), and bed thicknesses. Students also compiled paleocurrent orientations and morphological dimensions for sedimentary structures, and collected mudstones and sandstones for a variety of petrographic and geochemical analyses. Upon return to the University of Alaska Fairbanks, students selected sub-samples for further analysis, and trimmed billets for thin sections. Most samples were shipped to home institutions, while a subset was sent to Spectrum Petrographics (Vancouver, WA) for production of thin sections. Students conducted a variety of processing and analytical procedures at their home institutions with their research advisors. Analytical techniques included stable isotope analysis, X-ray diffraction (XRD), X-ray fluorescence spectroscopy (XRF), and thin section petrography. We also used the Washington State University Stable Isotope Core Laboratory for analysis of organic carbon and nitrogen stable isotopes.

RESEARCH

The six unique student projects included in this volume took shape in the field, as this was our first visit to the Slope Mountain site. We defined workable projects based on the strata encountered and direction of student interest, and we divide our short summaries

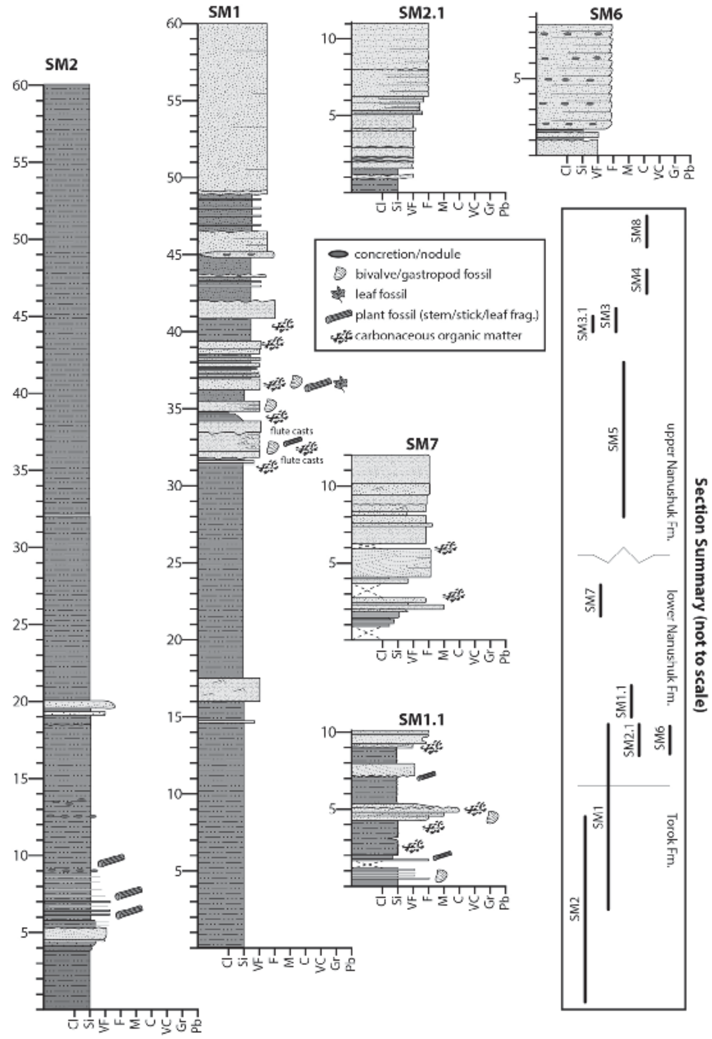

Figure 4. Stratigraphic sections SM1, SM2 and SM2.1, SM6, and SM7 encompass the transition between shelf and prodelta mudstones of the Torok Formation and overlying delta front sandstones of the Nanushuk Formation.

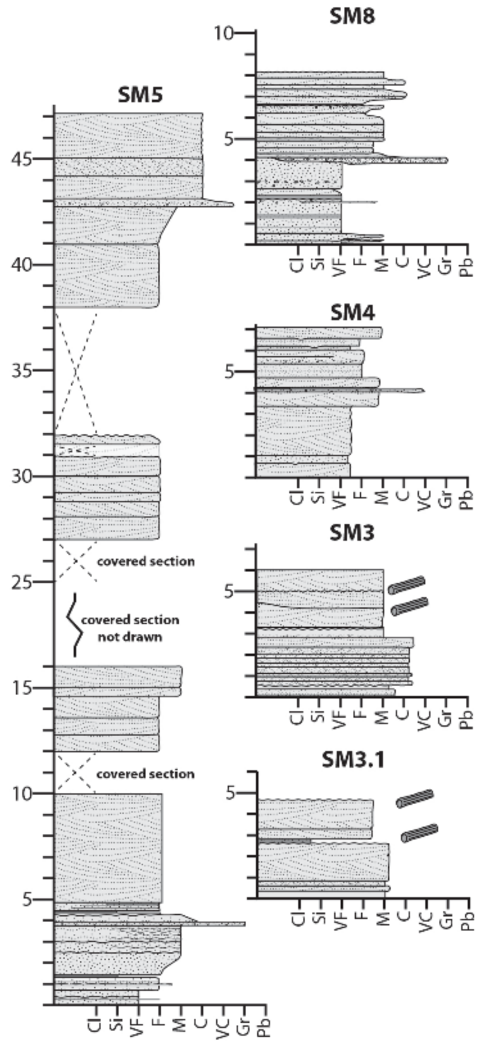

Figure 5. Stratigraphic sections SM3, SM3.1, SM4, SM5, and SM8 fall within the Nanushuk Formation, and represent a variety of depositional environments.

of each project into two broad areas of inquiry; physical analyses of sedimentary structures and sandstone composition, and instrumental analyses of sediment geochemistry.

Facies, Paleocurrents, and Petrology

Sarah Dickson (Smith College) initially set out to characterize bioturbation intensities in the various facies of the transitional strata between the Torok and Nanushuk formations (SM1, SM2, SM2.1, SM6). Sarah described sedimentary structures and ichnofossil abundance in the field, and collected siltstone and sandstone samples to further analyze in the lab. Her project grew to include petrographic analysis of the sandstones and siltstones in that transitional interval, which was largely ignored in previous petrographic analyses at Slope Mountain that focused on coarser-grained sandstones (Johnson and Sokol, 1998). By characterizing the composition and microscopic texture of her samples, Sarah provided a unique insight into the evolution of the Torok-Nanushuk depositional sequence. Her results help pinpoint the transition from suspension- and density flow-dominated prodelta deposition to bed load deposition in the Nanushuk Formation delta front.

Kevin Gardner (Whitman College) conducted a detailed facies analysis of sand-dominated outcrops in the marginal marine to non-marine strata in the

Nanushuk Formation (SM 3, SM3.1, SM5, SM8). Kevin defined twelve facies based on sedimentary textures and observed sedimentary structures. He used the distribution of those facies to determine facies associations, and make depositional environment interpretations. The distribution of these facies associations allowed Kevin to assess changes in relative sea-level over time. He identifies a stratigraphic succession from a regressive, progradational deltaic system (SM5) to transgressive, retrogradational, tide-dominated estuarine system (SM3, SM3.1), followed by a return to a regressive channel-dominated deltaic or fluvial system above a prominent disconformity (SM8). His work supports and expands previous analyses of the stratigraphy at Slope Mountain (LePain et al., 2009).

Lauren Williamson (Colorado College) took detailed paleocurrent measurements on ripple marks, trough cross-bed foresets, flute casts, and scour marks throughout the Torok and Nanushuk formations. Patterns support prior interpretations of the evolution of the Torok-Nanushuk depositional sequence from elsewhere on the North Slope.

Geochemistry and Chemostratigraphy

Evan Lewis (Franklin and Marshall College) sampled mudstones from sections SM1 and SM2 for XRD and XRF analyses and the construction of chemostratigraphic profiles of the Torok Formation. The goal of Evan's project was to identify changes in sedimentation rate, bioproductivity, and paleo-redox conditions in the prodelta environment. To do so, Evan collected major and trace element abundances using XRF, and further converted the trace elemental data to enrichment factors (EF values; Tribovillard et al., 2006) for comparative purposes. Evan's results show that the Torok Formation mudstones largely represent deposition under sub-oxic conditions. The chemostratigraphic profiles also allowed Evan to interpret a potential correlative surface between SM1 and SM2, something very difficult to do in mudstones based on physical observations. Evan also analyzed a curious layer encountered at ≈32 m at SM2. A thorough geochemical investigation of the layer, which initially resembled a volcanic ash deposit, returned a very distinct chemical signature that disproved the preliminary hypothesis.

Ashley Ratigan (Oberlin College) collected carbon-rich mudstones from the Torok and Nanushuk formations for stable isotope analyses of carbon and nitrogen, with the goal of defining the primary source of organic matter and making paleoenvironmental interpretations based on the isotopic results. Her work demonstrates that there is a substantial component of terrestrial plant matter in the prodelta mudstones of the Torok Formation. This information is valuable as it has bearing on the other two geochemistry projects. Ashley was also able to compare her data to other Cretaceous stable isotope analyses and confirm the paleoclimatic interpretations presented in those papers. Her project demonstrated the utility of bulk organic carbon stable isotope analysis and provides motivation for a higher-resolution study of such deposits at Slope Mountain.

Joe Beninati (Washington and Lee University) analyzed the mineralogy and stable isotopic composition of a variety of iron-rich deposits recovered from marine and non-marine facies at Slope Mountain. These deposits, loosely defined as concretions or nodules, were assumed to be iron carbonates ($FeCO_3$), and though often carbonate-rich, XRD analysis demonstrated that many samples lacked a definitive mineral structure. The stable isotope composition of carbon and oxygen in the carbonate-bearing samples returned a series of values that fall within the range of previous studies of both marine carbonates (foraminifera and bivalve shells) and terrestrial sphaerosiderites. This work demonstrated that there is significant promise in the stable isotopic analysis of such deposits for paleoclimatic interpretations, though there is much work to be done in the refinement of sampling strategy, sample composition, and parsing of contributing factors such as terrestrial organic matter input (Ratigan, this volume) to the prodelta system.

CONCLUSIONS

Though limited by time and budget for instrumental analyses, the students compiled a compelling dataset that demonstrates the promise of a thorough investigation of Cretaceous stratigraphy combining traditional facies analysis and field observations with advanced geochemical techniques. Given the overall thickness of the Torok and Nanushuk formations at

Slope Mountain, we were only able to establish a small window into the complexity of high-Arctic deltaic depositional systems during greenhouse conditions. Despite its size, that window provides sufficient insight and motivation for future work at Slope Mountain. Higher resolution geochemical analyses, would improve our ability to recognize climatic effects on sediment influx, bioproductivity, and paleo-redox conditions and their relationships to eustatic sea level and local tectonic uplift. The student projects confirmed that the Slope Mountain location is too accessible and too complete to ignore for paleoclimate studies that may help us understand long-term geologic responses to climate change.

ACKNOWLEDGEMENTS

We thank research advisors Lisa Greer (Washington and Lee), Bosiljka Glumac (Smith College), Carol de Wet and Stan Mertzmann (Franklin and Marshall), Karla Hubbard (Oberlin), and Paul Myrow (Colorado College). The advisors' experience and lab facilities greatly expanded analytical opportunities for the students. Outside laboratory support came from the Washington State University Stable Isotope Core Laboratory and Spectrum Petrographics. Thanks to the University of Alaska Fairbanks for access to research space, vehicles, bear safety training, and student housing. Logistical support from the Toolik Field Research Station (NSF) was invaluable. Thanks to Tom Gillispie of the Alaska Office of History and Archaeology for field research permits, and Alyeska Pipeline Company for access to pipeline property. Tony Fiorillo and Beth Hook of the Perot Museum and Yoshitsugu Kobayashi of the University of Hokkaido provided field support and introduced the students to vertebrate field paleontology. Special thanks to Tana Park, Patti Moss, and Debi Morehead of Whitman College for their assistance with grant expenses, and to the Whitman College Geology Department for general support and guidance. Finally, thanks to Bob Varga, the Keck Geology Consortium, the National Science Foundation, and ExxonMobil for this research opportunity.

REFERENCES

Ahlbrandt, T.S., Huffman, A.C., Fox, J.E., and Pasternack, I., 1979, Depositional Framework and reservoir quality studies of selected Nanushuk Group outcrops, in T.S. Ahlbrandt, ed., Preliminary Geologic, Petrologic, and Paleontologic Results of the Study of Nanushuk Group Rocks, North Slope Alaska, U.S. Geological Survey Circular 794, p. 14-31.

Akinin, V.V., and Miller, E.L., 2011, Evolution of calc-alkaline magmas of the Okhotsk-Chukotka Volcanic Belt: Petrology, v. 19, p. 237-277.

Bartsch-Winkler, S. B., 1985, Petrography of sandstones of the Nanushuk Group from four measured sections, central North Slope, Alaska, *in* A. C. Huffman, ed., Geology of the Nanushuk Group and Related Rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 75-97.

Coakley, B.J., and Watts, A.B., 1991, Tectonic controls on the development of unconformities: the North Slope, Alaska: Tectonics, v. 10, p. 101-130.

Decker, P.L., 2007, Brookian sequence stratigraphic correlations, Umiat field to Milne Point field, west-central North Slope, Alaska: Alaska Division of Geological and Geophysical Surveys Preliminary Interpretive Report 2007-2, 21 p.

Fox, J.E., Lambert, P.W., Pitman, J.K., and Wu, C.H., 1979, A study of reservoir characteristics of the Nanushuk and Colville Groups, Umiat Test Well 11, National Petroleum Reserve in Alaska: U.S. Geological Survey Circular 820, 47 p.

Hancock, J.M., and Kauffman, E.G., 1978, The great transgressions of the Late Cretaceous: Journal of the Geological Society, v. 136, p. 175-186.

Harris, E.E., Mull, C.G., Reifenstuhl, R.R., and Montayne, S., 2002, Geologic Map of the Dalton Highway (Atigun Gorge to Slope Mountain) Area, Southern Arctic Foothills, Alaska. Alaska Division of Geological and Geophysical Surveys Preliminary Interpretive Reports, 2002-2. 1 sheet.

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

Houseknecht, D. W., K. J. Bird, and C. J. Schenk, 2009, Seismic analysis of clinoform depositional sequences and shelf-margin trajectories in Lower Cretaceous (Albian) strata, Alaska North Slope: Basin Research, v. 21, p. 644-654.

Houseknecht, D.W., and Wartes, M.A., 2013, Clinoform deposition across a boundary between orogenic front and foredeep – an example from the Lower Cretaceous in Arctic Alaska: Terra Nova, v. 25, p. 206-211.

Hubbard, R. J., S. P. Edrich, and P. Rattey, 1987, Geologic evolution and hydrocarbon habitat of the 'Arctic Alaska microplate': Marine and Petroleum Geology, v. 4, p. 2-34.

Huber, B.T., Norris, R.D., and MacLeod, K.G., 2002, Deep-sea paleotemperature record of extreme warmth during the Cretaceous: Geology, v. 30, p. 123-126.

Huffman Jr., A. C., T. S. Ahlbrandt, I. Pasternack, G. D. Stricker, and J. E. Fox, 1985, Depositional and sedimentologic factors affecting the reservoir potential of the Cretaceous Nanushuk Group, central North Slope, Alaska, *in* A. C. Huffman, ed., Geology of the Nanushuk Group and Related Rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 61-74.

Jenkyns, H.C., Forseter, A., Schouten, S., and Sinninghe Damsté, J.S., 2004, High temperatures in the Late Cretaceous Arctic Ocean: Nature, v. 432, p. 888-892.

Johnson, Mark J., and Sokol, Nikolas K., 2000, Stratigraphic variation in petrographic composition of Nanushuk Group sandstones at Slope Mountain, North Slope, Alaska *in* Karen D. Kelley and Larry P. Gough, eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1998: U.S. Geological Survey Professional Paper 1615, p. 83-100.

LePain, D.L., McCarthy, P.J., and Kirkham, R., 2009, Sedimentology, stacking patterns, and depositional systems in the middle Albian-Cenomanian Nanushuk Formation in outcrop, central North Slope, Alaska: Alaska Division of Geological and Geophysical Surveys Report on Investigations 2009-1, 86 p.

Mull, C.G., Houseknecht, D.W., and Bird, K.J., 2003, Revised Cretaceous and Tertiary stratigraphic nomenclature in the Colville Basin, northern Alaska: U.S. Geological Survey Professional Paper 173, 51 p.

Müller, R.D., Sdrolias, M., Gaina, C., Roest, W.R., 2008, Age, spreading rates, and spreading asymmetry of the world's ocean crust: Geochemistry, Geophysics. Geosystems, v. 9, doi: 10.1029/2007GC001743.

Salazar Jaramillo, S., McCarthy, P.J., Trainor, T., Fowell, S.J., and Fiorillo, A.R., 2015. Origin of clay minerals in alluvial paleosols, Prince Creek Formation, North Slope, Alaska: Influence of volcanic ash on pedogenesis in the Late Cretaceous Arctic. Journal of Sedimentary Research, v. 85, p. 192-208.

Shimer, G.T., McCarthy, P.J., and Hanks, C.L., 2014, Sedimentology, stratigraphy, and reservoir properties of an unconventional, shallow, frozen reservoir in the Cretaceous Nanushuk Formation at Umiat Field, North Slope, Alaska: AAPG Bulletin, v. 98, p. 631-661.

Shimer, G.T., Benowitz, J.A., Layer, P.L., McCarthy, P.J., Hanks, C.L., and Wartes, M., 2016. $^{40}Ar/^{39}Ar$ ages and geochemical characterization of Cretaceous bentonites in the Nanushuk, Seabee, Tuluvak and Schrader Bluff formations, North Slope, Alaska. Cretaceous Research, v.57, p. 325-341.

Spicer, R.A., and Herman, A.B., 2010, The Late Cretaceous environment of the Arctic: A quantitative reassessment based on plant fossils: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 295, p. 423-442.

Till, A.B., 1992, Detrital blueschist-facies metamorphic mineral assemblages in Early Cretaceous sediments of the foreland basin of the Brooks Range, Alaska, and implications for orogenic evolution: Tectonics, v. 11, p. 1207-1223.

Tribovillard, N., Algeo, T.J., Lyons, T., and Riboulleau, A., 2006, Trace metals as paleoredox and paleoproductivity proxies: an update: Chemical Geology,v. 232, p. 12-32.

Ufnar, D.F., Ludvigson, G.A., González, L.A., Brenner, R.L., and Witzke, B.J., 2004, High latitude meteoric $\delta^{18}O$ compositions: Paleosol siderite in the Middle Cretaceous Nanushuk Formation, North Slope, Alaska: Geological Society of America Bulletin, v. 116, p. 463-473.