DEPOSITIONAL SETTING AND POTENTIAL RESERVOIR FACIES IN THE NANUSHUK FORMATION (ALBIAN-CENOMANIAN), BROOKIAN TOPSET PLAY, NORTH SLOPE, ALASKA

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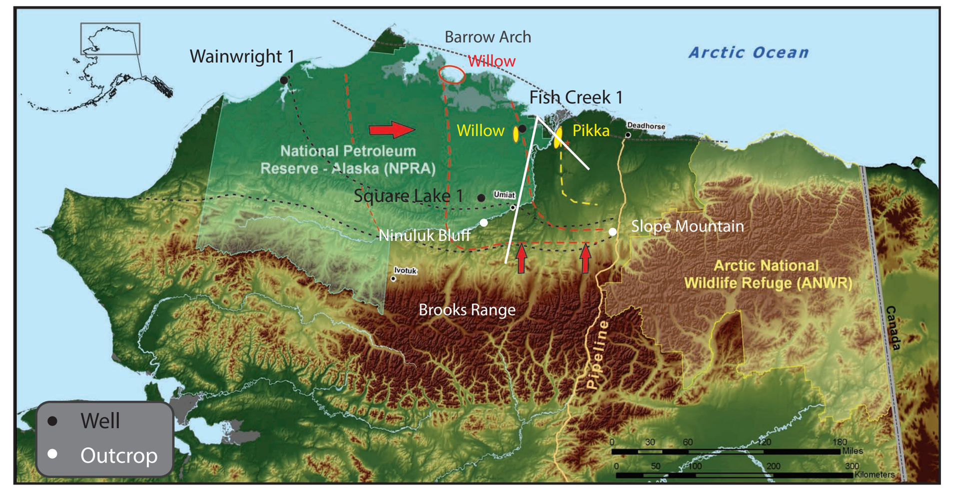
1 ABSTRACT

The Nanushuk Formation is a thick fluvial-deltaic-shelf succession that crops out in the foothills north of the Brooks Range and is present in the subsurface throughout the NPRA and state lands immediately to the east, up to a maximum progradational shelf-edge approximately 30 miles east of the Colville River. Nanushuk strata comprise prominent topsets visible on seismic lines that pass basinward (east) to clinoform reflectors in slope strata of the Torok Formation. Large rivers with headwaters west of the present-day North Slope flowed eastward, down the axis of a foreland basin, and built an extensive delta complex and shelf. Smaller, steeper gradient rivers, with headwaters in the ancestral Brooks Range, flowed north and northeastward and built deltas on the south side of the basin.

Six facies associations are recognized in Nanushuk cores from wells in the eastern NPRA and in outcrops to the south, including: 1. offshore mudstones with minor interbedded fine-grained sandstones; 2. shoreface-delta-front sandstones with minor interbedded mudstones; 3. distributary channel-fill sandstones; 4. bayfill-estuarine mudstones that envelop a variety of fine-grained sandy facies; 5. fluvial channel-fill sandstones; and 6. alluvial floodbasin mudstones. In the eastern NPRA and in outcrops to the south, the offshore and shoreface-delta-front associations are most common. Shoreface-delta-front deposits stack to form coarsening-upward parasequences from 30 feet to over 100 feet thick that are typically bounded by flooding surfaces; amalgamated parasequences with sand-on-sand contacts are common in shoreline proximal settings. Hummocky and swaley cross-stratification, wave ripple cross-lamination (and symmetrical ripple bedforms), mudstone rip-up clasts, and pebble-lined scours are abundant in this association. In the most proximal settings, some shoreface successions are overlain by bayfill-estuarine mudstones. Distributary channel-fill sandstones and bayfill-estuarine mudstones are present locally in the subsurface. The fluvial channel-fill and alluvial floodbasin associations are common in outcrop, but have not been recognized in cores from the eastern NRPA. The abundance of storm wave-generated structures in the shoreface-delta-front and offshore associations indicates powerful storm waves routinely affected Nanushuk deltas and the adjacent shelf in this part of the basin.

Stacked shoreface-delta-front parasequences overlain by flooding surfaces and offshore mudstones, and in proximal settings, parasequences that pinch out updip in mudstones of the bayfill association, represent attractive reservoir targets. Sandstones of this association commonly display visible porosity in core. Toplap relations visible on seismic and sharp-based shoreface successions recognized in Nanushuk outcrops along the Colville River suggest the likely presence of shelf-edge deltas associated with forced regressions, adding to stratigraphic trap potential. Distributary channels encased in bayfill-estuarine mudstones are potentially attractive reservoir targets if effectively sealed updip.



On shaded relief map above selected lowstand shelf margins are shown with dashed red lines. The ultimate Nanushuk shelf margin is shown with a dashed yellow line. Red arrows show sediment dispersal directions. Seismic data indicate dominant easterly sediment dispersal. White line shows approximate location of schematic cross-section at right. Shelf margins are from Houseknecht and Schenk (2001).

The Nanushuk Formation is comprised of fluvial-deltaic and shallow marine deposits.

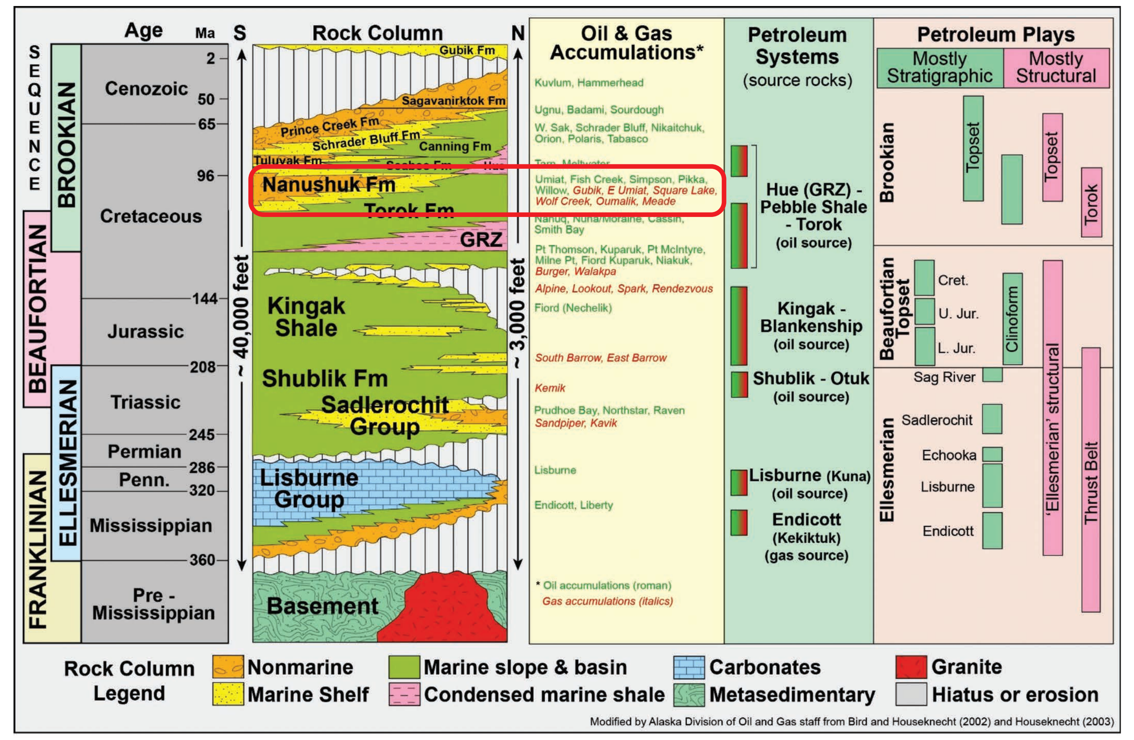
Lower, dominantly marine succession - shelf, shoreface/delta-front parasequences, and distal distributary channel deposits.

Middle, dominantly nonmarine succession - alluvial and delta plain deposits, including fluvial channel and distributary channel-fills, and fine-grained alluvial overbank and interdistributary bayfill successions.

Upper unit capped by transgressive marginal-marine deposits, including estuarine and shoreface successions with retrogradational stacking pattern.

Early work (Huffman et al. 1985) suggested Nanushuk deltas in the western part of the basin were river-dominated and deltas in the central part recorded greater wave influence.

2 REGIONAL SETTING



After Bird and Houseknecht (2002) and Houseknecht (2003)

Brookian sequence comprises the fill of a large east-west-trending foreland basin (see cross-sections below).

Basin bounded by orogenic belt (Brooks Range) on south side and an early Cretaceous rift shoulder (Barrow arch) on north side (see shaded relief map below at left).

Brookian strata include nonmarine, shallow marine, and deep marine clastic rocks, including oil-prone source rocks (see schematic stratigraphic column above).

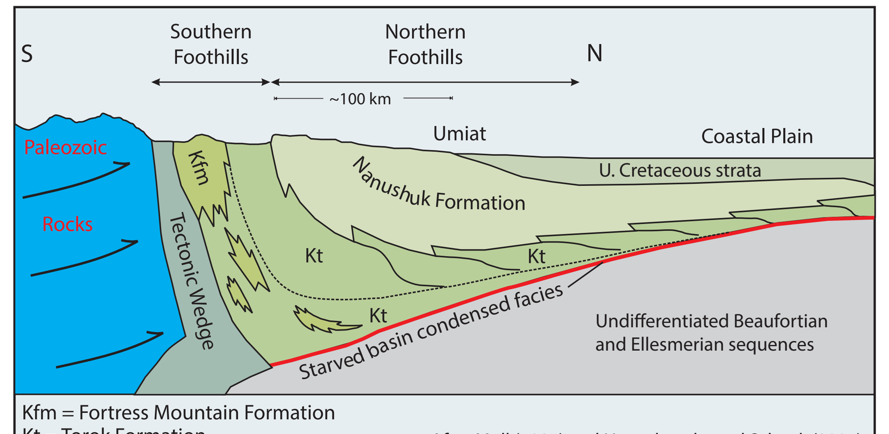
The Nanushuk and Torok Formations are genetically related and fill the western two-thirds of the basin.

Seismic data show a dominant basin-axial dispersal system; seismic and outcrop data show a subordinant transverse dispersal system emanating in the ancestral Brooks Range.

Both systems combined to construct an extensive nonmarine and shallow marine platform imaged as topsets on seismic sections.

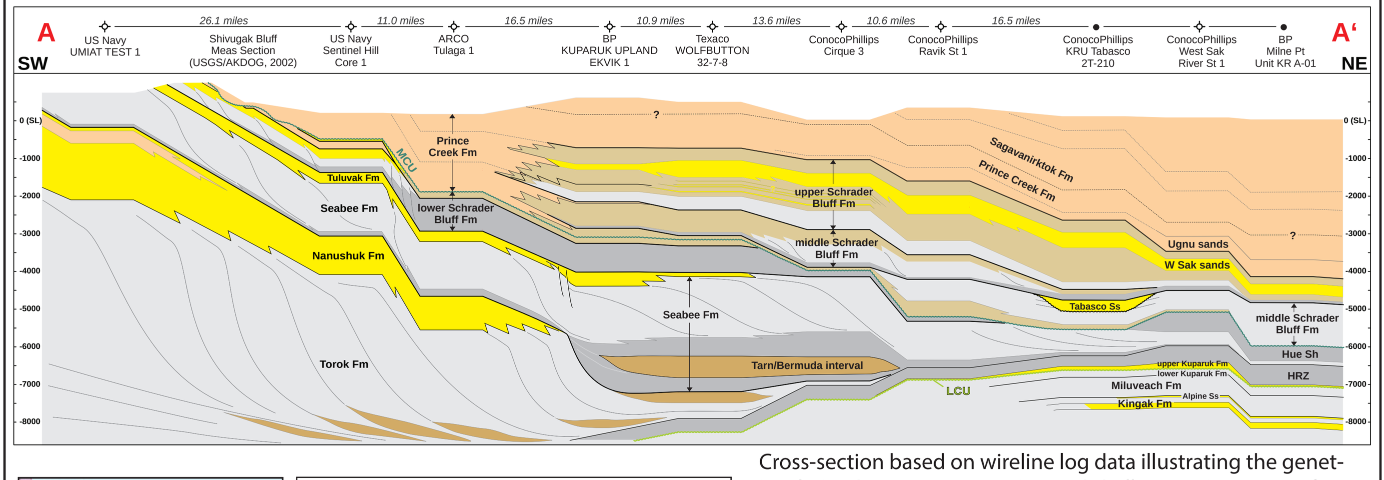
Cartoon at right is a schematic cross-section oriented perpendicular to the axis of the foreland basin. White line on shaded relief map at left shows approximate location of cross-section.

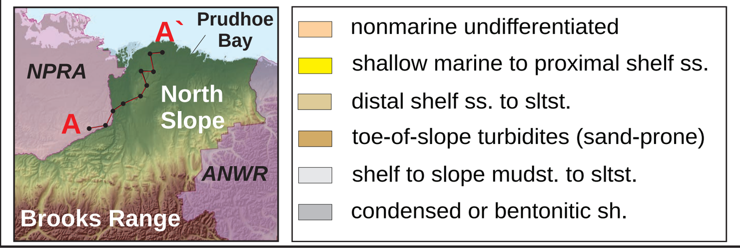
Note the increase in clinoform relief toward the axis of the foredeep. This increase in accommodation is reflected in the thickness of delta-front/shoreface parasequences in the Nanushuk Formation in outcrop.



Kfm = Fortress Mountain Formation
Kt = Torok Formation

After Mull (1985) and Houseknecht and Schenk (2001)





Cross-section based on wireline log data illustrating the genetic relation between nonmarine and shallow marine strata of the Nanushuk Formation and slope and basinal strata of the Torok Formation.

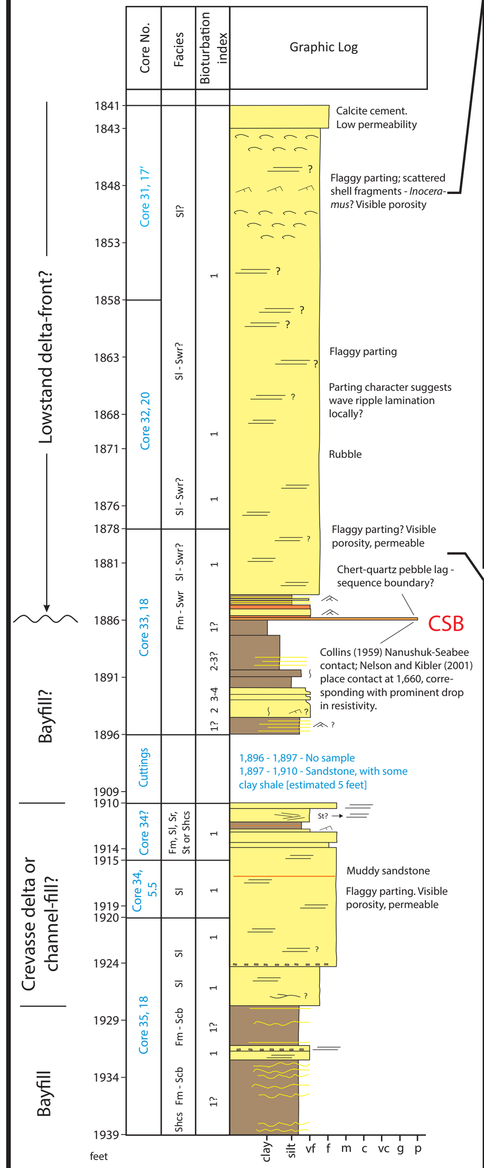
Clinoform sequence thickness (uncorrected for compaction) ranges from 1,968 feet (600 m) near the crest of the Barrow arch to 8,200 feet (2,500 m) near the axis of the foredeep (Houseknecht et al., 2008).

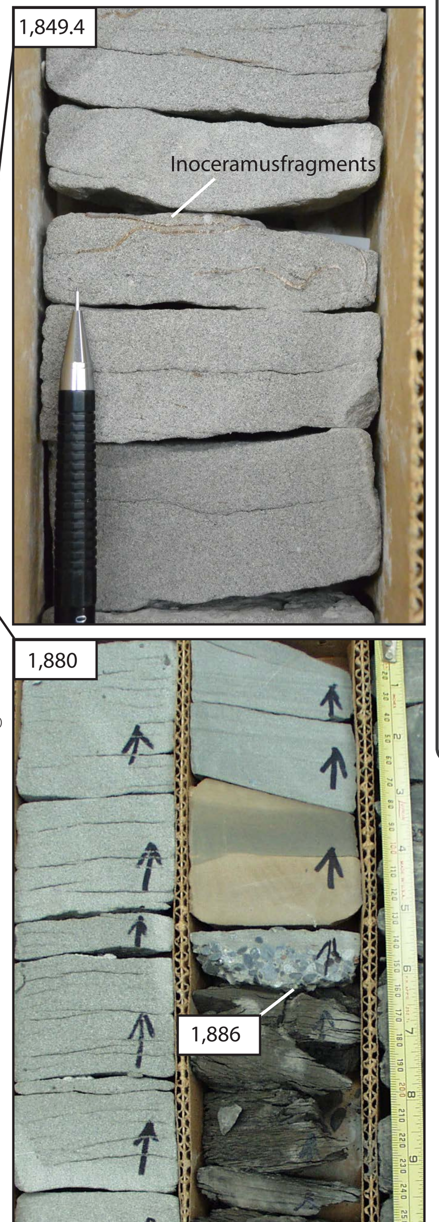
Decker (2007)

3 POTENTIAL RESERVOIR FACIES: EXAMPLES FROM CORE AND OUTCROP

B. CORE

Square Lake Test Well 1





A prominent erosion surface truncates mudstones interpreted as bayfill deposits at 1,886 feet in Square Lake 1. This surface is overlain by a thin quartz-chert pebble lag which, in turn, is overlain by marginal-marine to marine pelecypod fragment-bearing porous sandstone (shoreface deposits?).

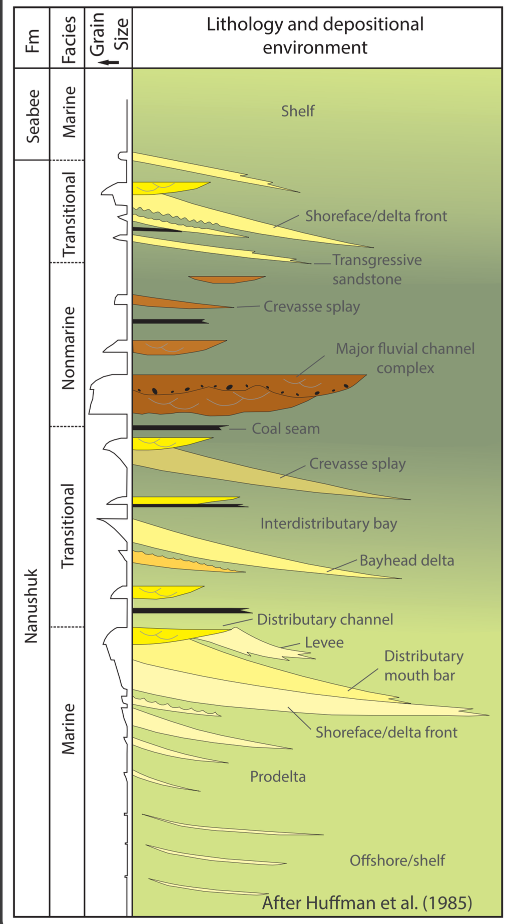
We interpret this surface as a sequence boundary and the overlying sandstone as a transgressive marginal-marine succession (delta-front/beach foreshore?).

Nanushuk shoreface/delta-front parasequences in the Square Lake 1 well are commonly comprised of moderately to well-sorted fine-grained sandstone, and some include visible porosity.

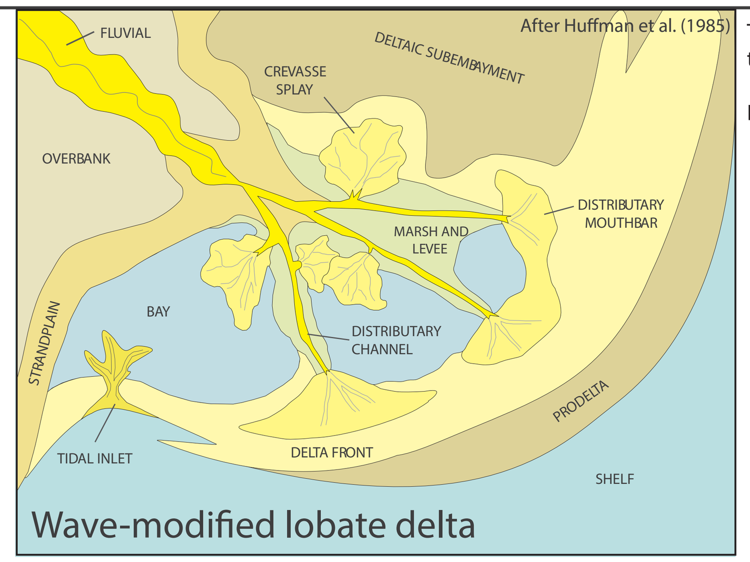
Note: Collins(1959) placed the Nanushuk-Seabee contact at the base of the pebble lag at 1,886 feet in Square Lake 1.

Nelson and Kibler (2001) placed the contact at 1,646 feet corresponding to the base of a prominent decrease (leftward shift) in resistivity.

A. Facies Associations



After Huffman et al. (1985)



After Huffman et al. (1985)

The Nanushuk Formation includes a range of facies associations that record deposition in large, mixed-load rivers that fed a regionally extensive delta complex.

Facies evidence suggest the following:

Nanushuk rivers were moderate to low-sinuosity and flanked by poorly drained overbank areas that supported locally prominent mires.

Large, sandy distributary channels traversed delta plain areas and were flanked by interdistributary bays with brackish to near normal marine water; bayfill mudstones envelope several sandy facies associations, including splay sand sheets, crevasse channels and splays, and sandy bayhead delta lobes.

The Nanushuk coastline included deltaic headlands and interdeltaic areas with strandplains, barrier islands, and associated settings.

Powerful storm waves shaped large sections of the coast that faced the open ocean and delta lobes deposited in this setting were likely wave-modified lobate to wave-dominated cuspate deltas with prominent sandy shorefaces /delta fronts.

Sand-prone facies associations include:

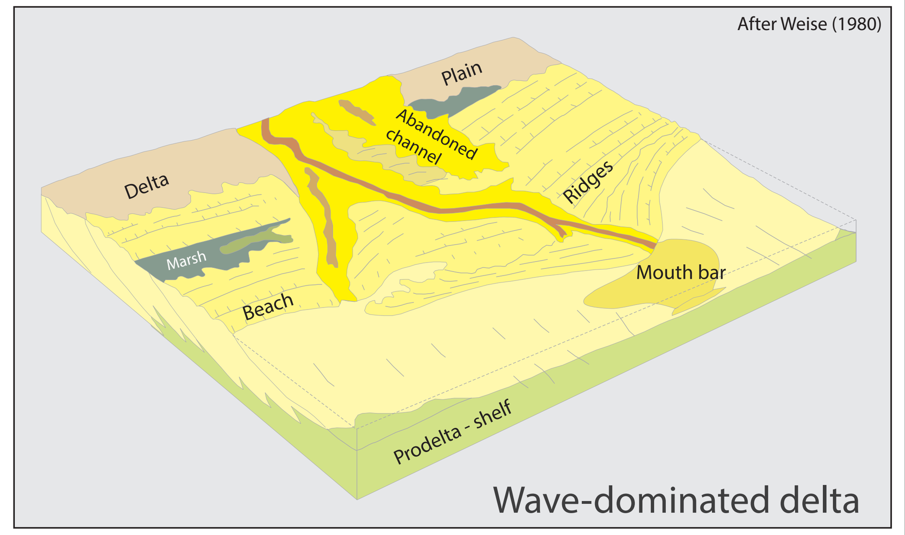
Fluvial channel-fills - broadly lenticular to tabular (not discussed in this poster)

Distributary channel-fills - lenticular to broadly lenticular(?) (Wainwright 1 below)

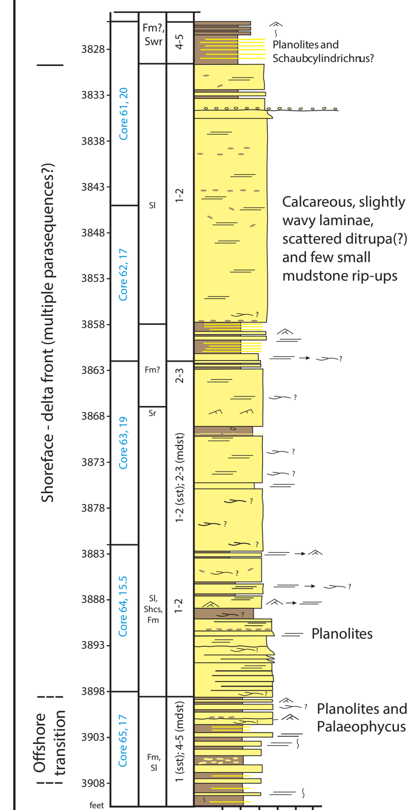
Amalgamated splay sand sheets and crevasse/bayhead deltas encased in interdistributary bayfill mudstones (Square Lake 1 at left and Ninuluk Bluff outcrop below)

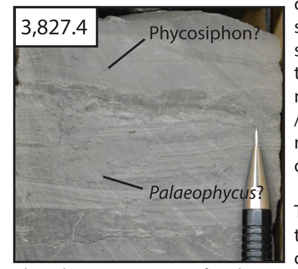
Shoreface and delta-front sand shingles (Square Lake 1 and outcrop analogs below)

The latter are prominent in core and outcrop and display abundant storm-wave-generated features.



Square Lake Test Well 1

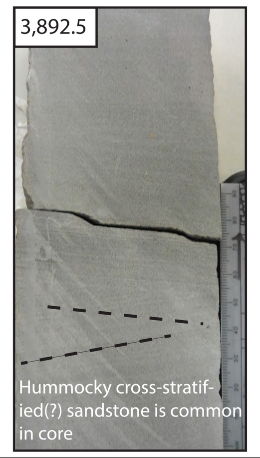




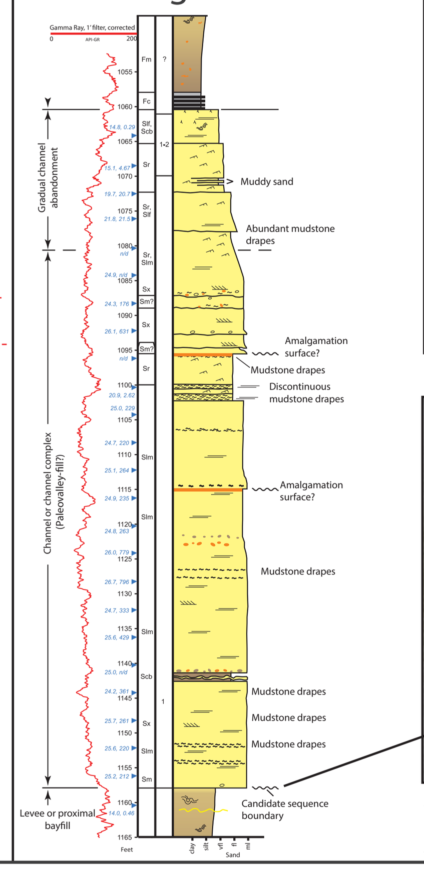
Abundant marine trace fossils in low-energy settings. Assemblage diversity?

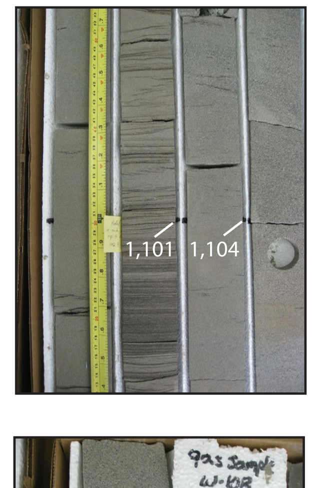
Shoreface/delta-front parasequences in core from Square Lake 1 include abundant structures suggestive of deposition in storm-wave-influenced shallow marine settings. Laminae dipping at low angles commonly change dip angle and direction up-/down section in core suggestive of hummocky cross-stratification. Compare with outcrop photo from Slope Mountain below.

The abundance of features attributable to storm-wave processes suggests the coastline and shallow shelf were shaped by powerful storm waves. We infer delta lobes were storm-wave-modified and, locally, storm-dominated, and generated shoreface shingles oriented parallel to depositional strike. Nanushuk shoreface sands are texturally mature.



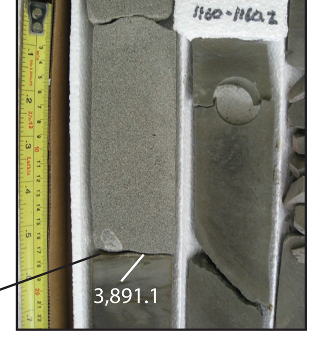
Wainwright 1





Scour surface and abrupt grainsize jump at 1,115 feet? Is this an amalgamation surface juxtaposing two, separate channel-fills or an internal scour surface resulting from an abrupt increase in flow velocity in a single channel?

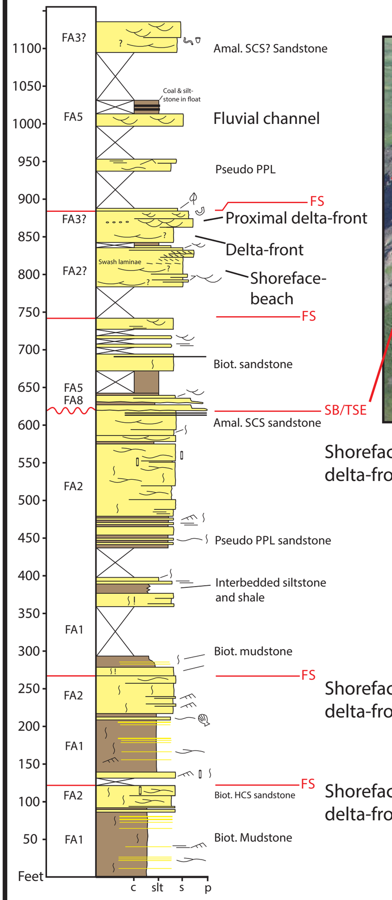
Channel-fill sandstones are fine- to medium-grained and moderately- to well-sorted. This element is encased in mudstones that can function as an effective reservoir seal.

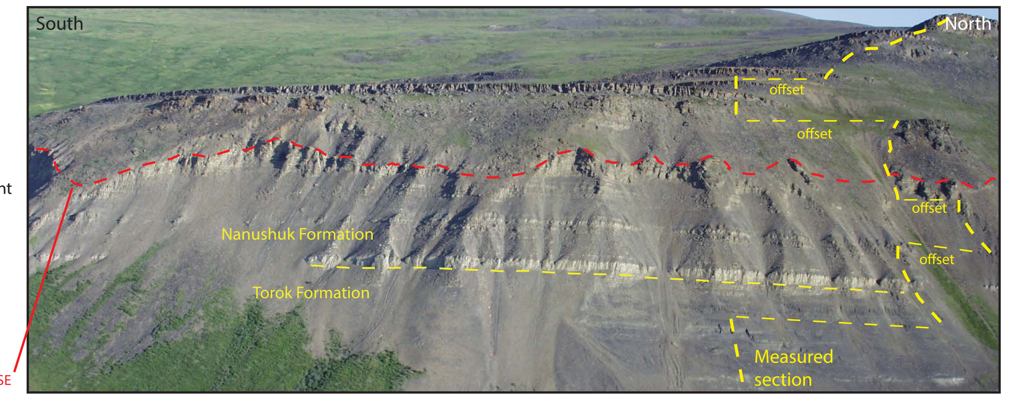


Scour surface at base of channel-fill. Note soft-sediment deformation in siltstones below.

C. OUTCROP ANALOGS

Slope Mountain

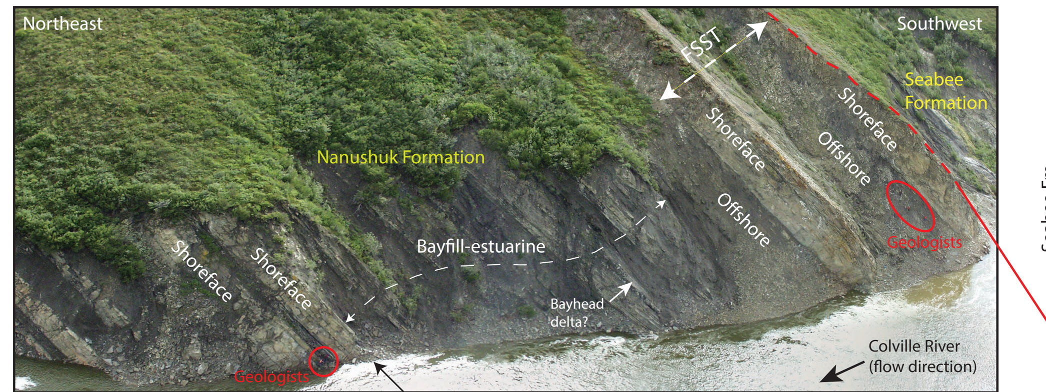




The Nanushuk exposure on the east face of Slope Mountain includes stacked shoreface/delta-front parasequences truncated by a conspicuous unconformity surface at 614 feet (dashed red line in photo above). This surface is overlain by late lowstand/transgressive estuarine facies that are, in turn, overlain by lower shoreface/delta-front deposits.

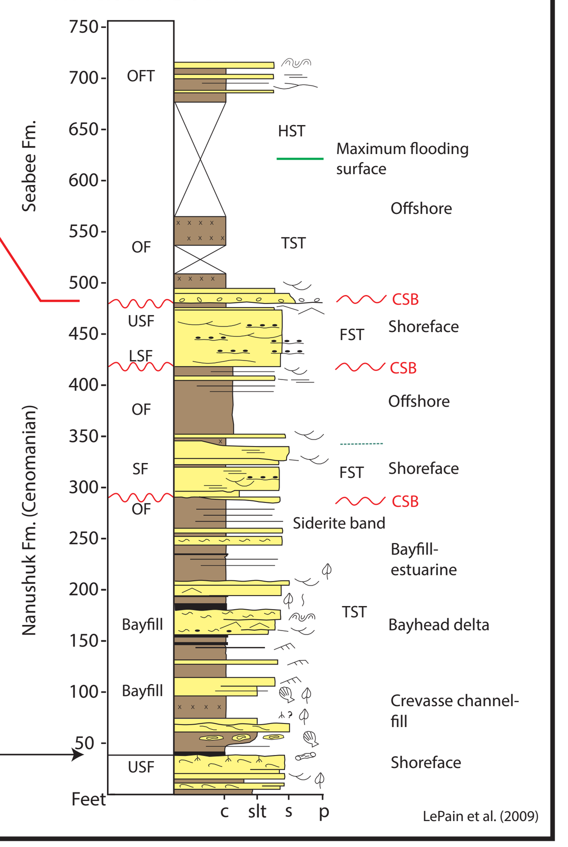
Facies overlying the unconformity at 614 feet may be an outcrop analog for the Nanushuk at some lowstand shelf-edge positions in the subsurface.

Ninuluk Bluff



The Nanushuk Formation at Ninuluk Bluff is a transgressive succession comprised of a retrogradational stack of shoreface (progradational) and estuarine deposits. The succession is capped by two sharp-based shoreface successions interpreted as falling stage systems tract deposits. The contact with the overlying Turonian Seabee Formation is interpreted as a transgressively modified sequence boundary.

Facies associations and stacking pattern may be similar to lowstand and transgressive deposits at shelf-edge locations in the subsurface. These sharp-based shoreface sands are texturally mature.

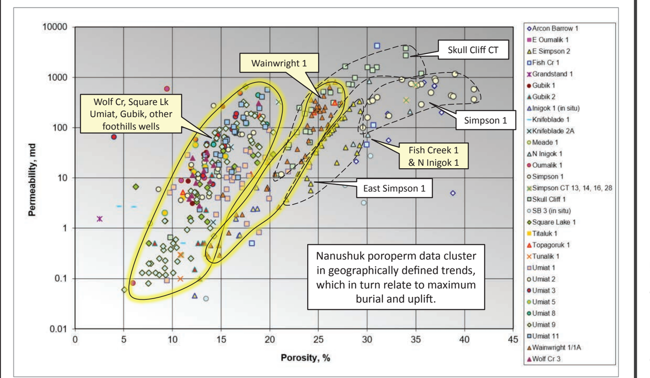


LePain et al. (2009)

4 RESERVOIR QUALITY

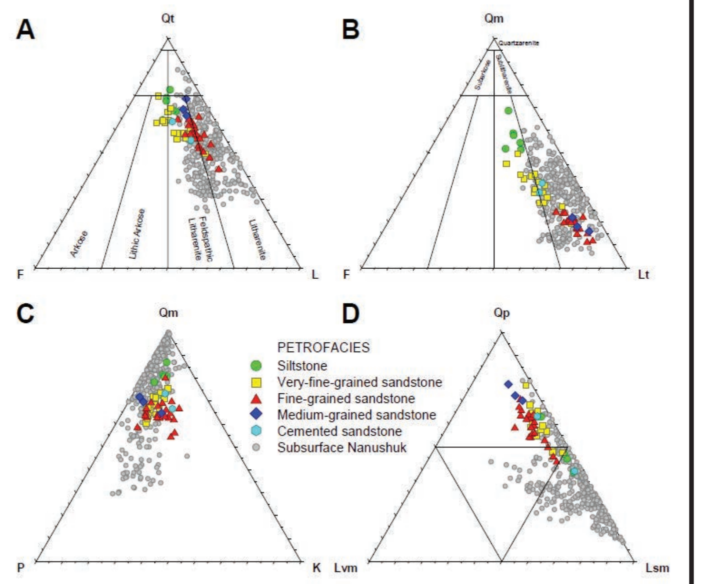
Regionally, compaction is the most signficant control on reservoir quality (porosity and permeability).

Original depositional texture (grainsize and sorting) exerts significant control on sandstone reservoir quality in areas where maximum burial depth is relatively low, such as along the crest of the Barrow arch.

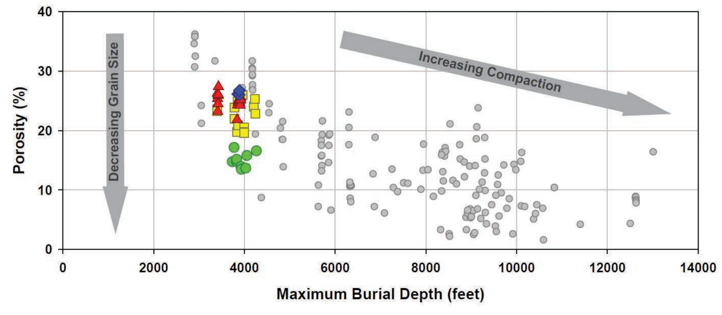


Cross-plot of porosity and permeability of Nanushuk sandstones. After Decker (NAPE 2017).

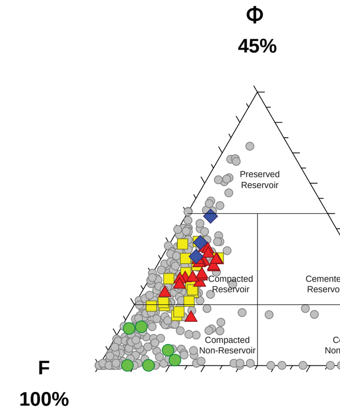
Sandstone Composition



Most Nanushuk sandstones are litharenites, feldspathic litharenites, and lithic arkoses. Quartz and chert are abundant, the lithic population is dominantly sedimentary rock fragments, and plagioclase is more abundant that potassium feldspar. Qt=total quartz (includes chert); F-feldspar; L=lithics; Qm=monocrystalline quartz; F=feldspar; Lt=total lithic grains (lithics plus polycrystalline quartz and chert); Qm=monocrystalline quartz; P=plagioclase; K=potassium feldspar; Qp=polycrystalline quartz (including chert); Lvm=volcanic and metavolcanic rock fragments; Lsm=sedimentary and metasedimentary rock fragments. After Helmold (2016).

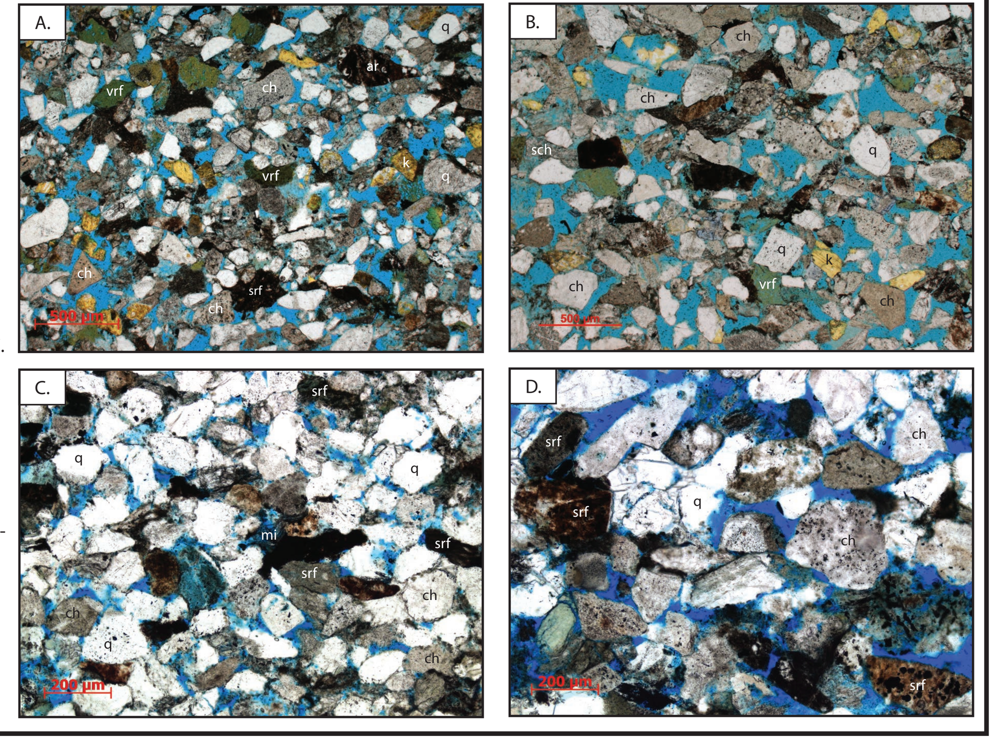


Cross-plot of porosity versus maximum burial depth of siltstones and sandstones. Colored data points correspond to samples from the Wainwright well and the gray points are regional subsurface Nanushuk sandstones. At a given value of Dmax, reservoir quality is largely controlled by grainsize. Helmold (2016).



Porosity-framework-cement ternary diagram showing reservoir quality of Wainwright and regional sandstones and siltstones (colored and gray points, respectively). Most sandstones plot in the compacted reservoir and compacted non-reservoir fields. Helmold (2016).

Photomicrographs of selected sandstones from the Square Lake 1 and Wainwright 1 wells. Blue areas in all images correspond to porosity. All are in plane light. A-B. Distributary channel sandstone at 1,088 and 1,148 feet, respectively, in the Wainwright 1 well (magnification in both images 5x). C. Bioturbated shoreface sandstone at 3,027 feet in Square Lake 1 (magnification 10x). D. Bioturbated sandstone from offshore transition/prodelta setting at 1,818 feet in Square Lake 1. Key to abbreviations: q = quartz, ch = chert, k = potassium feldspar, p = plagioclase, mi = mica, srf = sedimentary rock fragment, vrf = volcanic rock fragment. All photomicrographs taken by Helmold.



SUMMARY

o The Nanushuk coastline and shallow shelf were shaped by powerful storm waves and deltas were wave-modified to wave-dominated.

o The delta-front setting was commonly a shoreface with strike-elongate sand bodies with high textural maturity. Shoreface successions range from a few 10s of feet to well over 100 feet in thickness; amalgamated shoreface sandbodies are common.

o Distributary channel sand bodies are dip oriented (east-west in NPRA subsurface), relatively thick, with moderate to high textural maturity. Composite distributary channel sand bodies can be up to 100 feet thick.

o Outcrop analogs provide insight regarding possible facies associations to be expected at lowstand shelf-edge positions in the subsurface.
Slope Mountain (Albian, lower, dominantly marine Nanushuk) - Complex unconformity surface is well exposed that truncates shoreface/delta-front deposits and is overlain by late lowstand and/or transgressive estuarine and bioturbated lower shoreface deposits.
Ninuluk Bluff (Cenomanian, upper, transgressive marginal-marine to marine Nanushuk) - Sharp-based shoreface sand bodies deposited during falling stage systems tract are encased in offshore mudstones. A variety of estuarine facies are well-exposed.

o Reservoir quality is ultimately controlled by maximum burial depth; depositional texture (mainly grainsize) is secondary control.

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