TERTIARY DEPOSITIONAL SYSTEMS IN UPPER COOK INLET, ALASKA: INFLUENCE OF FLUVIAL STYLE ON RESERVOIR GEOMETRIES AND STRATIGRAPHIC TRAP POTENTIAL

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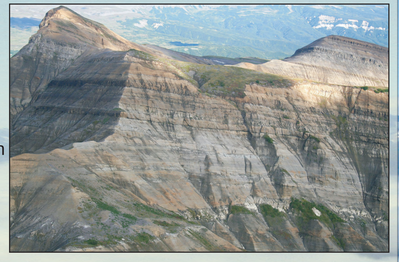
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Abstract

Cook Inlet is part of a large collisional forearc basin with significant petroleum resources. Commercial hydrocarbon production in the basin has been limited to complex Tertiary fluvial reservoirs in structural traps. Recent work in the basin has focused on reconstructing depositional systems in Tertiary strata to improve understanding of stratigraphic trap potential.

Along the mildly deformed eastern basin margin, in the vicinity of Kachemak Bay, gravelly braided fluvial systems occupy incised valleys eroded into deformed pre-Tertiary strata of an accretionary complex. Paleovalley-fills grade up-section and basinward (west) to aerially extensive nonmarine systems that include a variety of fluvial channel styles, each flanked by floodbasin settings. Sand-rich systems deposited tabular sand bodies separated by thin (<10 m thick) coal-bearing mudstone successions. Amalgamated sand bodies typify these systems with composite thicknesses commonly >15 m. Mixed-load systems deposited tabular sand bodies up to 12 m thick with prominent fining-upward trends, but separated by up to 20 m-thick coal-bearing mudstone successions that encase small channelized sand bodies 4-10s of meters wide and 1-5 m thick. Along the deformed western basin margin, in the vicinity of Capps Glacier and the Beluga River, depositional systems include large alluvial fans and a similar variety of lower-gradient alluvial systems away from the margin as recognized in the vicinity of Kachemak Bay.

Depositional systems along both basin margins are characterized by higher gradients, coarser and less mature sediment textures, and little preserved finer-grained material capable of forming reservoir seals. Away from the basin margins, fluvial gradients were lower resulting in a wider range of sediment textures, sand body geometries, and mudstone successions capable of serving as effective reservoir seals.



Regional Geology

Cook Inlet basin is a collisional forearc basin (figs. 1 and 2).

Basin is situated between the Aleutian-Alaska Range volcanic arc to the west and a large, emergent accretionary complex to the east, represented by the Kenai and Chugach Mountains (figs. 1 and 2).

The basin is bounded by major fault systems on the west, north, and east sides (fig. 2).
- -The Border Ranges fault is a subduction-related megathrust that originated in Late Triassic-Early Jurassic that has been progressively rotated toward the west due to growth of the accretionary complex through time.
- -The Bruin Bay fault is a high-angle reverse fault (west side up) that dates back at least to Late Jurassic.
- -The Castle Mountain-Lake Clark fault is a right-lateral strike-slip fault

The Tertiary history of the basin is dominated by nonmarine deposition, including basin margin alluvial fans and incised paleovalley networks, high-gradient gravelly braided fluvial rivers, high-accommodation muddy rivers, and moderate accommodation sandy rivers (fig. 3).

The latter two depositional systems include abundant coal that has sourced biogenic methane reservoired in Tertiary sand bodies.

The accretionary complex and volcanic arc supplied large volumes of chemically unstable detritus to nonmarine depositional systems in the forearc basin.

The dynamic, tectonically active setting of the basin resulted in complex interfingering of alluvial and fluvial facies and syn-depositional deformation.

All producing oil and gas fields in the basin are in faulted anticlinal structures involving Tertiary sandstone reservoirs; no exploration has focused exclusively on the search for stratigraphic traps.

Due to the complex stratigraphy and composition of the Tertiary basin fill, much gas is likely reservoired in low permeability sand bodies.

Pursuing stratigraphic traps and exploiting low permeability reservoirs will benefit from detailed knowledge of Tertiary depositional systems.

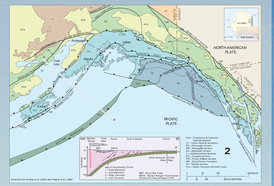


Figure 1 - Generalized plate tectonic setting. Modified from Winkler (2000) and Fisher and Magoon (1978).

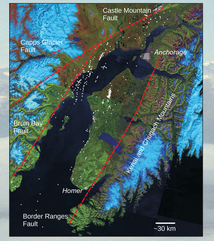
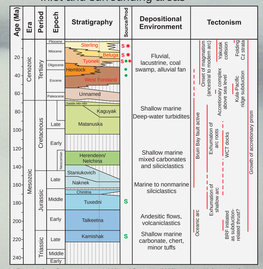


Figure 2 - Landsat image of Cook Inlet and surrounding areas



Redrawn from Curry and others (1993) and Swenson (2003); additional information from Little and Naeser (1989), Pfaffker and others (1989), and Nokleberg and others (1994)

Figure 3 - Generalized stratigraphic column for Cook Inlet

Introduction

Selected measured sections and outcrop photographs are included on the next panel to illustrate nonmarine depositional systems preserved in the Tertiary fill of Cook Inlet basin. Symbols used in measured sections are defined in figure 4 and section locations are shown in figures 5, 6, and 7. Facies codes used in measured sections are defined in table 1. Section locations are shown by white circles on figures 6 and 7.

Table 1 - Facies recognized in nonmarine formations of Cook Inlet basin.

Lithofacies	Code	Description
Gravel-Conglomerate		
Matrix-supported conglomerate	Gmm	Very poorly sorted granule to cobble conglomerate, unstratified, clasts angular to sub-rounded derived from subjacent bedrock and supported by a clayey, silty, sandy matrix
Clast-supported massive conglomerate	Gm	Poor to moderately sorted, disorganized granule to boulder conglomerate, clasts sub-angular to rounded, bedding up to 3+ m, laterally continuous and discontinuous
Clast-supported crudely bedded conglomerate	Gh	Poor to moderately sorted, disorganized to moderately organized granule to boulder conglomerate, clasts sub-angular to well-rounded, crude horizontal bedding up to 1.5 m thick and laterally discontinuous, locally developed clast imbrication
Clast-supported planar cross-bedded conglomerate	Gp	Poor to moderately sorted granule to cobble conglomerate, clasts sub-angular to well-rounded, planar-tangential foresets up to 2.5 m thick and laterally discontinuous over tens of meters
Clast-supported trough cross-bedded conglomerate	Gt	Poor to moderately sorted granule to cobble conglomerate, trough cross-bedded in sets up to 2.5 m thick, log and large plant fragments present locally
Sand-Sandstone		
Massive sandstone	Sm	Poorly sorted, very fine- to very coarse, beds up to 2 m thick, floating pebbles and cobbles locally
Horizontally laminated sandstone	Sh	Very fine- to very coarse, beds from 0.5 cm to 2 m thick, floating pebbles locally, includes some low-angle lamination
Ripple cross-laminated sandstone	Sr	Very fine- to fine-grained, beds to 15 cm thick, locally abundant plant fragments and roots
Planar cross-bedded sandstone	Sp	Very fine- to very coarse-grained, solitary and grouped sets up to 1.5 m thick, locally pebbly
Trough cross-bedded sandstone	St	Fine- to very coarse-grained, in solitary and grouped sets 4 cm to 2 m thick, locally pebbly and pebble line base of some foresets, deformed foresets present locally
Convolute bedded sandstone	Scb	Fine- to medium-grained clayey sands; ubiquitous convolute bedding, trough cross-bedding locally visible within convolute beds
Scour-fill sandstone	Ssf	Very fine- to fine-grained sand with interlaminated mudstone, laminae as form-concordant scour drape, plant fragments and roots locally abundant
Clay/Silt/Mud		
Laminated claystone	Fcl	Light gray to dark brown claystone with undisturbed alternating light and dark millimeter-scale lamination
Massive claystone	Fcm	Light to medium-gray claystone, no visible lamination, minor scattered plant fragments, color mottling locally
Laminated mudstone	Fml	Light gray to brown silt and silt-clay mixtures in undisturbed millimeter- to centimeter-scale laminae, darker laminae commonly finer-grained, locally ripple cross-laminated
Thinly interbedded sandstone and siltstone	Fisl	Interbedded very fine-grained sandstone and siltstone, bed millimeter to multi-centimeters thick, locally ripple cross-laminated
Massive mudstone	Fmm	Light to brown massive silt, silt-clay, and silt-clay-sand mixtures, commonly micromicaceous, no visible internal structures, sideritic concretions locally abundant and commonly with preserved plant fragments, rooted horizons locally
Blocky mudstone	Fmb	Light gray to brown blocky mudstone, common sideritic concretions and rooted horizons; tree stumps in growth position locally
Carbonaceous mudstone	Fcb	Dark brown laminated claystone and mudstone, abundant terrestrial organic material typically preserved as comminuted plant fragments
Coal	C	Dark brown to black, blocky lignitic to sub-bituminous coal, dull and alternating bright and dull layers common, original plant material commonly recognizable; dispersed volcanigenic mineral crystals and disrupted ash layers common

Facies codes and interpretations significantly modified from Miall (1996)

Key to Symbols Used in Measured Sections

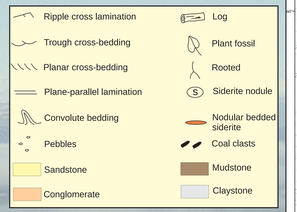


Figure 4

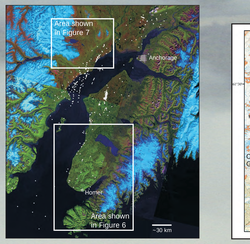


Figure 5 - Lansat image of the Cook Inlet region showing field areas addessed in this poster.

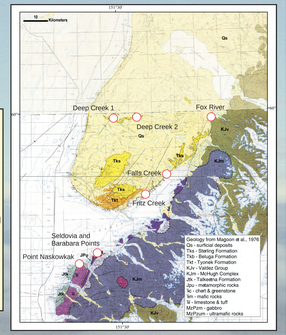


Figure 6 - Geologic map of the southern Kenai Peninsula on the southeast side of the basin. Modified from Magoon and others (1976).

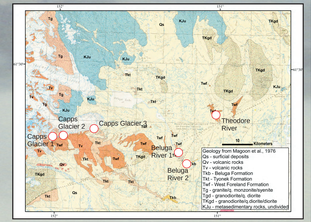


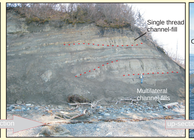
Figure 7 - Geologic map of the Capps Glacier-Beluga River area on the northwest side of the basin. Modified from Magoon and others (1976).

2. Basin Margin to Axial Fluvial Transition: Late Oligocene to Early Miocene

Incised Paleovalleys Cut Into Basinward Side of Accretionary Wedge



- Lenticular conglomerate and sandstone bodies separated by lenticular mudstones.
- Sediment textures suggest flashy discharge and deposition from hyperconcentrated flows
- Sediment derived from local sources in the underlying accretionary wedge.
- Little or no reservoir potential.

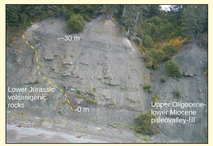


- Tabular sand and lenticular channel-fill sand bodies and thin overbank mudstones.
- Sediment textures suggest traction transport and deposition from "normal" stream flows.
- Mix of local and regional sediment sources from within the accretionary wedge.



- Thick overbank succession truncated by sandy channel-fill of braided fluvial system.
- Regional sediment sources from within the accretionary wedge.
- Organization suggests Tyonek shown here extends beyond the confines of paleovalley.

- Incised paleovalleys were conduits for sediment transport toward the basin axis (west)
- Poorly organized valley fluvial systems grade up-section (and basinward - west) to sandy braided fluvial deposits with thin, discontinuous overbank mudstones.



Margin of incised late Oligocene-early-Miocene paleovalley. Note debrites immediately right of the dashed yellow line (facies Gmm, Table 1).

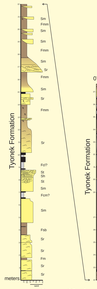


Debrites (facies Gmm, Table 1) along margin of incised paleovalley. Area shown is left of the 30 m mark in the photo at left.

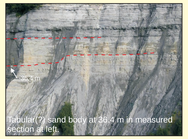


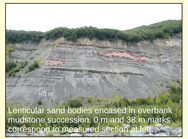
Matrix-supported conglomerate (facies Gmm, Table 1) 2m above the 0 m mark in photo at left.

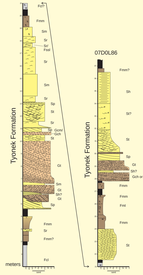
Axial Fluvial Depositional Systems



Capps Glacier



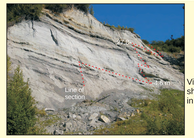










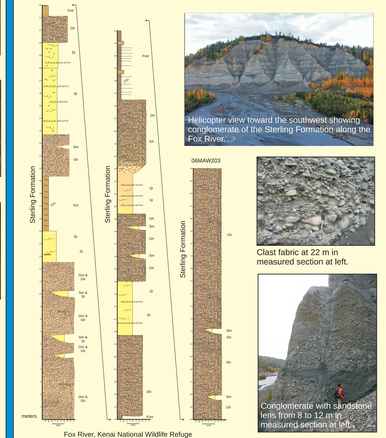


View toward the north showing two fluvial cycles in the Tyonek Formation.

- Axial fluvial systems included mixed-load muddy rivers.
- Meandering plan-form geometries are inferred for trunk channels.
- Single thread channels associated with overbank areas represent splay channels that stripped sediment from trunk channels.
- Sand bodies of inferred trunk channels have tabular geometries; splay channel sand bodies are lenticular.

4. Basin Margin to Axial Fluvial Transition: Latest Miocene to Early Pliocene

Alluvial Fan to High-Gradient River Systems



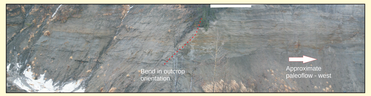
Moderate Accommodation Sandy River Systems Basinward from Eastern Basin Margin

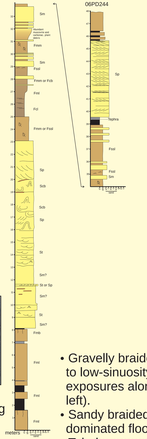




Tabular sand bodies in the uppermost Beluga-lower Sterling formation along the west shore Kachemak Bay.

Phtomosaic image below shows a tabular sand body in the Sterling Formation along Deep Creek. Two outcrop faces are oriented at 90° to each other. The left panel is characterized by relatively few through-going scour surfaces separating sand packages with numerous concave-upward scour surfaces; the right panel is characterized by the same few through-going scour surfaces. These surfaces separate sand packages with planar-tangential foresets dipping toward the right (west). Left panel is oriented close to depositional strike and the right panel nearly parallel to the paleoflow direction. Contrasting organization in intersectiong panels is thought to be characteristic of sandy braided fluvial settings (Adams and Bhattacharya, 2005).







Exposure of the Sterling Formation along Deep Creek where the section at left was measured.



Cross-bedded sandstone at 9 m. Note mudstone exposed at level of sample bags.

- Alluvial fans and/or high-gradient gravelly braided stream systems were present along the western basin margin.
- Gravelly braided streams may have been situated immediately basinward (west) of alluvial fans. Facies documented in the measured section at left include large-scale foresets in conglomerate, which do not suggest deposition in an alluvial fan setting (e.g Blair and McPherson, 1994).
- Gravelly braided streams graded basinward (westward) to low-sinuosity sandy braided streams exemplified by exposures along Deep Creek (measured section above left).
- Sandy braided streams were flanked by mud-dominated floodplains.
- Tabular geometries are inferred for most thicker sand bodies, such as the sand between 8 and 23 m in measured section above left).

1. Basin Margin to Axial Fluvial Transition: Late Paleocene to Early Eocene

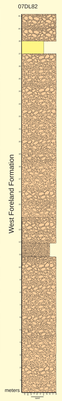
Syn-Tectonic Alluvial Fan Deposition at Western Basin Margin and Transition to High-Gradient Rivers Toward Basin Axis



View south at ~500 m of cobble and boulder conglomerates with minor lenses of coarse-grained poorly sorted sandstone.



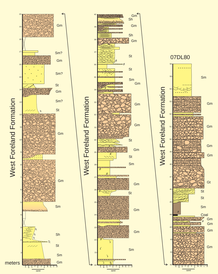
View north from where geologist in photo above is standing (to his right).





Tightly packed, clast-supported cobble conglomerate. Note felsic plutonic and mafic metavolcanic clasts.

- Measured section at left shows the lower 30+m of a 450-500 m-thick alluvial fan succession.
- Measured section at right is located ~4 km east of the section at left and is interpreted to record interfingering between distal alluvial fan and sandy interfan low deposits.
- Conglomerate bodies are tabular to broadly lenticular in outcrop; sandstones are lenticular.



- Basin margin depositional systems are related to motion on the Capps Glacier fault and are syn-tectonic (figs. 2 and 7, first panel).
- Thick alluvial fan deposits are exposed immediately south of the Capps Glacier fault and were sourced from Tertiary felsic plutons in the hanging wall of the fault and form subjacent metavolcanics in the footwall and up depositional dip to the north and west.
- Alluval fan deposits grade toward the basin axis (south and east) to high-gradient braided fluvial deposits.

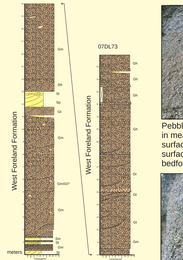


Lenticular to tabular pebble conglomerate and interbedded lenses of sandstone between 22 and 28 m in measured section at left.



Pebble conglomerate at 26 m in measured section at left.









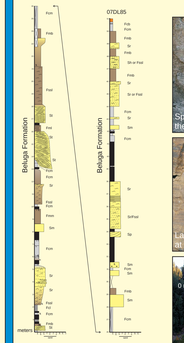
Sandstone lens at 11 m in measured at left.

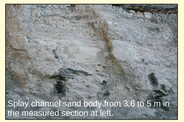


- Measured section above includes facies suggestive of deposition in high-gradient gravelly braided streams.
- Braided stream systems were located basinward of syn-tectonic alluvial fans shown in the measured section at far left.
- The extent of gravelly braided streams away from the faulted basin margin is poorly constrained - basinwide?
- Conglomerate bodies are tabular and extend for 10s of meters along local strike in outcrop; sandstones are lenticular and extend for meters to 10s of meters along local strike.

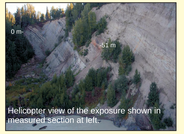
3. Axial Fluvial System: Late

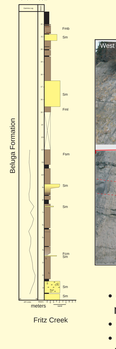
High-Accommodation Muddy River Systems



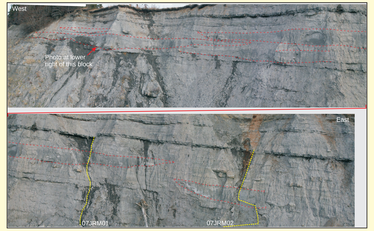


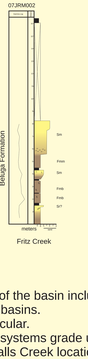






- The photomosaic image at left shows sand body geometries in a muddy fluvial system exposed along the west shore of Kachemak Bay.
- Note broadly lenticular sand bodies encased within coal-bearing mudstone successions.
- Laterally continuous mudstones with abundant lignitic coal seams represent potential reservoir seals.





- Axial fluvial depositional systems near the west and east sides of the basin included muddy mixed-load rivers flanked by broad, poorly drained flood basins.
- Sand body geometries are dominantly lenticular to broadly lenticular.
- In the Kachemak Bay region, late Miocene muddy depositional systems grade up-section to latest Miocene-early Pliocene sandy depositional systems (Falls Creek location, shown in block above and in fig. 6 on first panel).
- The nature of depositional systems at the basin margin during this time interval are unknown.



Contact between overbank mudstone succession (~20 cm above flag left of geologist) and broadly lenticular argillaceous sand body. This location is 2 km northeast of the outcrop shown in photomosaic at left.



Contact between argillaceous sand body and underlying mudstone (red arrow on photomosaic at left).

Mercury Injection Capillary Pressure Data

Homer-Kachemak Bay Area:

Samples tied to measured sections shown on panel 2 are enclosed by a red rectangle (sample number).

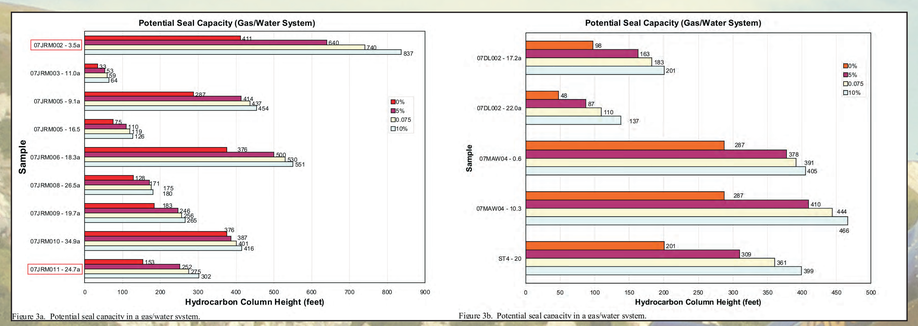


Figure 3a. Potential seal capacity in a gas/water system.

Figure 3b. Potential seal capacity in a gas/water system.

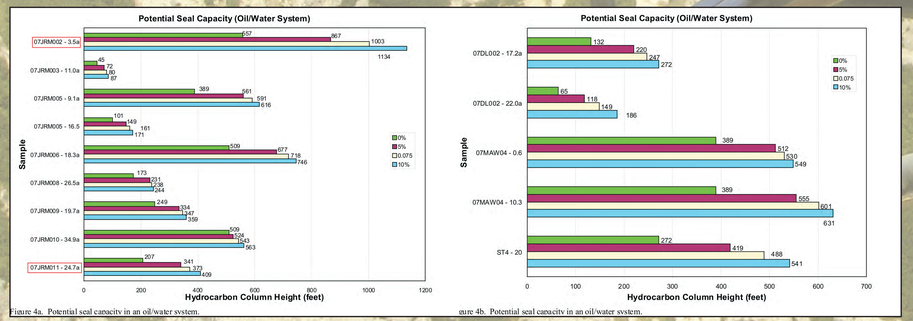


Figure 4a. Potential seal capacity in an oil/water system.

ure 4b. Potential seal capacity in an oil/water system.

Capps Glacier-Beluga River Area:

Samples tied to measured sections shown on panel 2 are enclosed by a red rectangle (sample number).

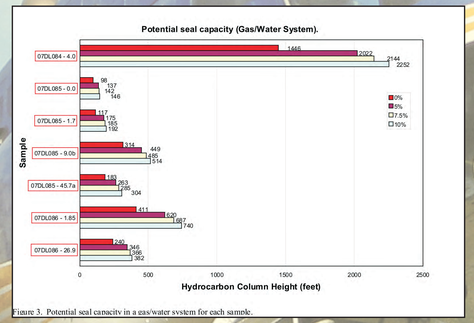


Figure 3. Potential seal capacity in a gas/water system for each sample.

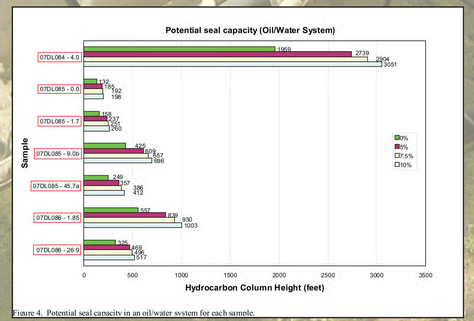


Figure 4. Potential seal capacity in an oil/water system for each sample.

Conclusions Regarding Stratigraphic Trap Potential

Muddy and sandy river systems preserved in Tertiary strata of Cook Inlet basin include lenticular, broadly lenticular and tabular sand body geometries; alluvial fan and gravelly river deposits include tabular and broadly lenticular conglomerate bodies and broadly lenticular sand bodies.

The late Oligocene-early Miocene Tyonek Formation and late Miocene lower Beluga Formation include thick overbank mudstone successions that encase lenticular crevasse splay sand bodies (shoe-string sands); thicker tabular sand bodies in both formations represent the deposits of larger trunk channels.

Lenticular crevasse splay channel sand bodies are commonly argillaceous and would likely be characterized by low permeability. These types of sand bodies and associated siltstone bodies in overbank successions represent potential tight sand gas reservoirs.

The latest Miocene upper Beluga and early Pliocene Sterling formations include thick (>8 m) tabular sand bodies separated by moderately thick (5-15 m) overbank successions.

Repetive successions of overbank mudstones and tabular sandstones in all Tyonek, Beluga, and Sterling formations stack to form multiple potential reservoir zones.

Inferred tabular and lenticular geometries for conglomerate and sandstone in the late Paleocene-Eocene West Foreland Formation stack to form thick potential reservoir intervals; absent to thin, discontinuous mudstones suggest effective reservoir seals may be lacking in these depositional systems. We do not know the aerial extent of these coarse-grained facies and it is possible they grade toward the basin axis to finer-grained deposits capable of forming reservoir seals.

Mercury injection capillary pressure data for mudstone samples collected from overbank facies iindicate their ability to serve as reservoir seals for both oil and gas.

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