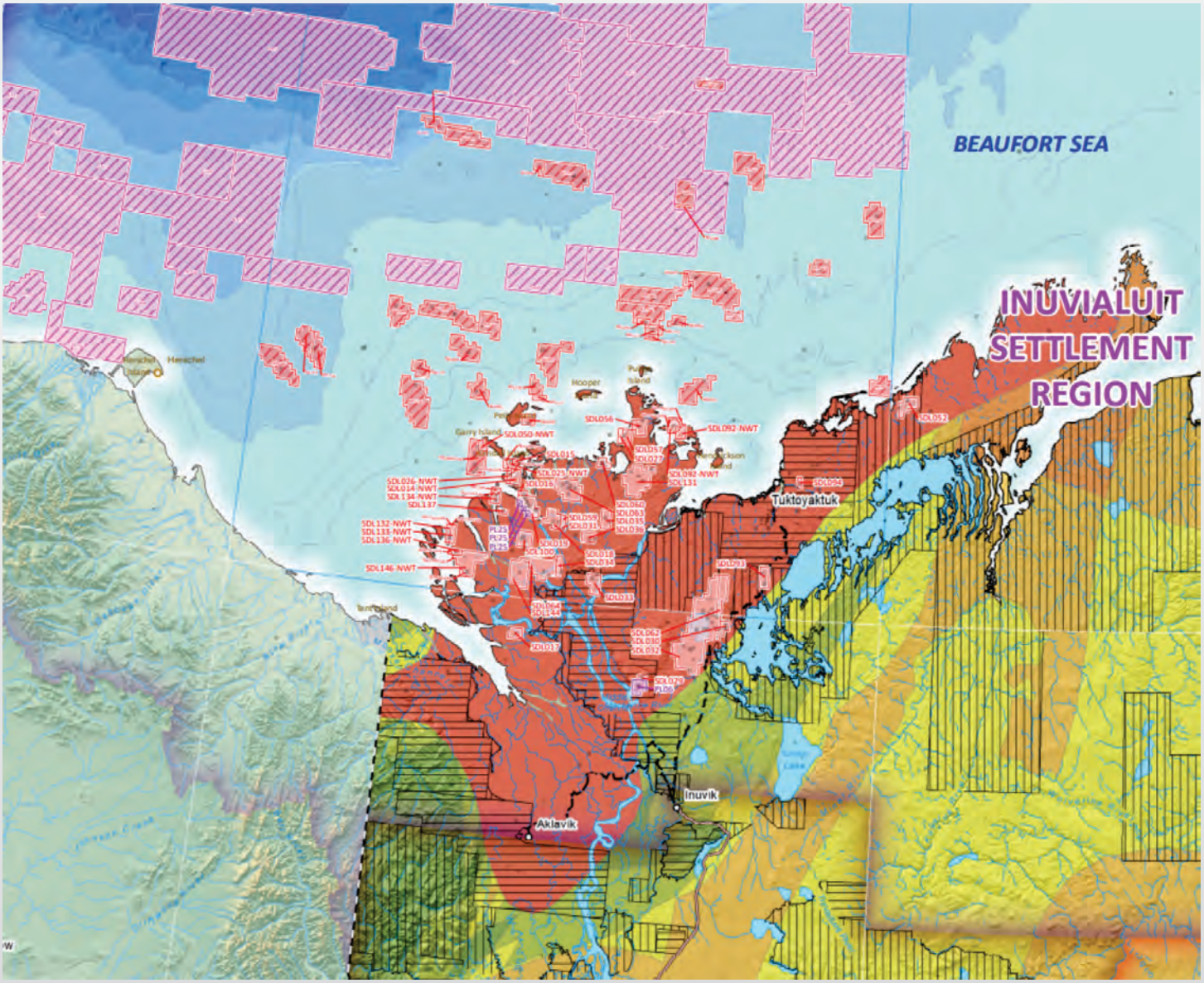
Government of
Northwest Territories

Petroliferous Cenozoic Sequences of the Beaufort-Mackenzie Basin Play Summary

Northwest Territories



Hydrocarbon potential and oil and gas rights in the Mackenzie Delta - Beaufort Sea region of Northern Canada (modified from GNWT-ITI 2021b).

NORTHWEST TERRITORIES
GEOLOGICAL SURVEY

June 2022

Summary

The Beaufort-Mackenzie Basin is a region within the Arctic Circle that hosts a large quantity of petroleum resource. There are 59 oil and gas fields (GNWT-INF, 2012), discovered by 285 exploration wells (Chen et al., 2021; cover page image), including four gas hydrate research wells. Expected petroleum reserves are up to 172.75 x 10^6 cubic metres of recoverable crude oil and condensate and 254.67 x 10^9 cubic metres of marketable conventional gas (Osadetz et al., 2005). Additionally, a potentially large recoverable volume of methane hydrate is present, which represents a possible future contribution to North American energy supply if the gas can be recovered and processed. This document presents an overview of the petroliferous Cenozoic sequences of the Beaufort-Mackenzie Basin with focus on the conventional oil and gas plays and their resource potential based on data from existing scientific and multi-industry studies.

Introduction

The Beaufort-Mackenzie Basin (BMB) is a rifted continental margin basin within the Artic Circle, Northwest Territories, Canada. A significant portion of the Cenozoic basin fill comprises the northward prograding Mackenzie Delta (MD), which extends from the Beaufort Sea's rifted continental margin to the southern permanent pack-ice limit between 128°W and 141°W (Osadetz et al., 2005).

Onshore and nearshore Cenozoic strata are underlain by Mesozoic and Paleozoic strata, whereas more distally offshore the basin floor comprises oceanic crust. Mesozoic and Paleozoic strata are also represented in surface outcrops in the Mackenzie and Richardson Mountains to the south and southwest, and on the Tuktoyaktuk Peninsula (NOGD-INAC, 1995; Wielens, 1992). The Mackenzie Delta's main phase of sedimentation started in the Late Maastrichtian with the deposition of a series of large progradational delta complexes, which migrated northward in the Paleogene to the central part of the basin in the Pliocene in response to the rising Cordilleran orogen in the southwest (Chen et al., 2021; Figure 1).

Mapped depositional sequences comprise submarine fan accumulations that are bounded by unconformities (Figure 1). Tectonism is interpreted to be the primary control on the origin of the sequences, deformation, and bounding unconformities, rather than eustatic sea level changes (Dixon et al., 1992).

The Mackenzie River drainage is the second largest in North America and drains into the Arctic Ocean at a rate of 7508 cubic metres per second (Bergquist et al., 2004) and delivers 1.25 × 10^8 tonnes of mainly fine-grained sediment per year (Hill et al., 1991). Thin organic-rich muds were the earliest deposits on the continental margin during the Cenomanian-Early Maastrichtian age and comprise the Boundary Creek, Smoking Hills and Mason River sequences (Figure 1).

At the basin margin, alternating sandstone and shale-dominant successions classified into discrete litho-stratigraphic units are present. Basinward the sedimentary succession is predominantly shale, and conventional litho-stratigraphic units can be less readily identified (Figure 2). Consequently, sequence stratigraphic analysis is used to identify stratigraphic units within the basin fill. Stratigraphic and facies interpretation of reflection seismic, well, and to a lesser extent, outcrop data form the main basis for the identification of sequences, unconformities, maximum flooding surfaces, and internal depositional facies (Figure 3). The regionally extensive stratigraphic units mapped across the lateral extent of the BMB include the Late Cretaceous Boundary Creek, Smoking Hills, and Fish River sequences, the Paleogene Aklak, Taglu, Richards, Kugmallit sequences, and the Neogene Mackenzie Bay, Akpak, Iperk, and Shallow Bay sequences (Figure 1). Chipperfield et al. (2005) provided a summary and grouping of the BMB geological plays based on their geographic location and stratigraphic location (Table 1).

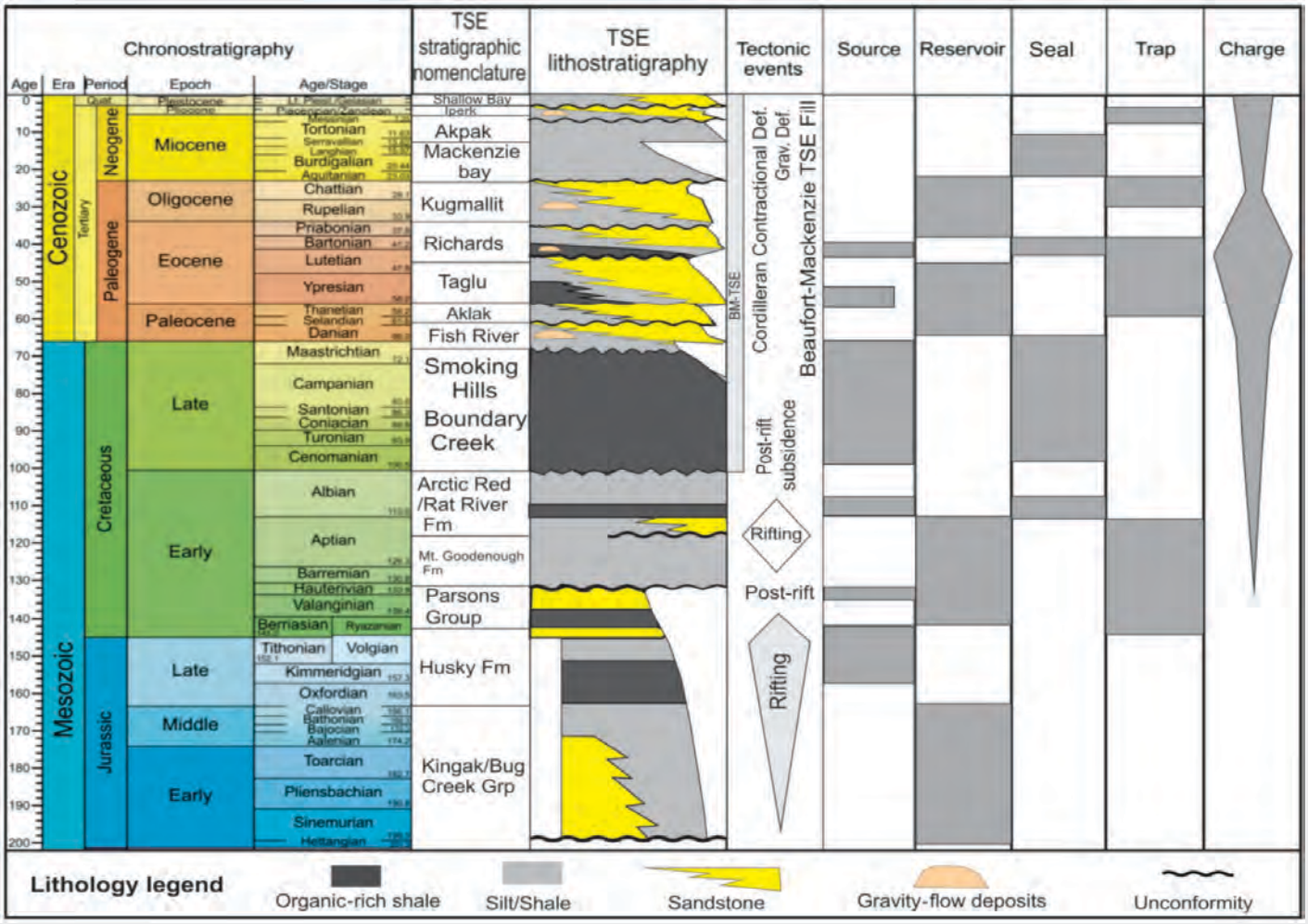


Figure 1: Composite diagram showing the stratigraphy, tectonic history and petroleum system elements in the Beaufort–Mackenzie tectono-sedimentary element (from Chen et al.,2021).

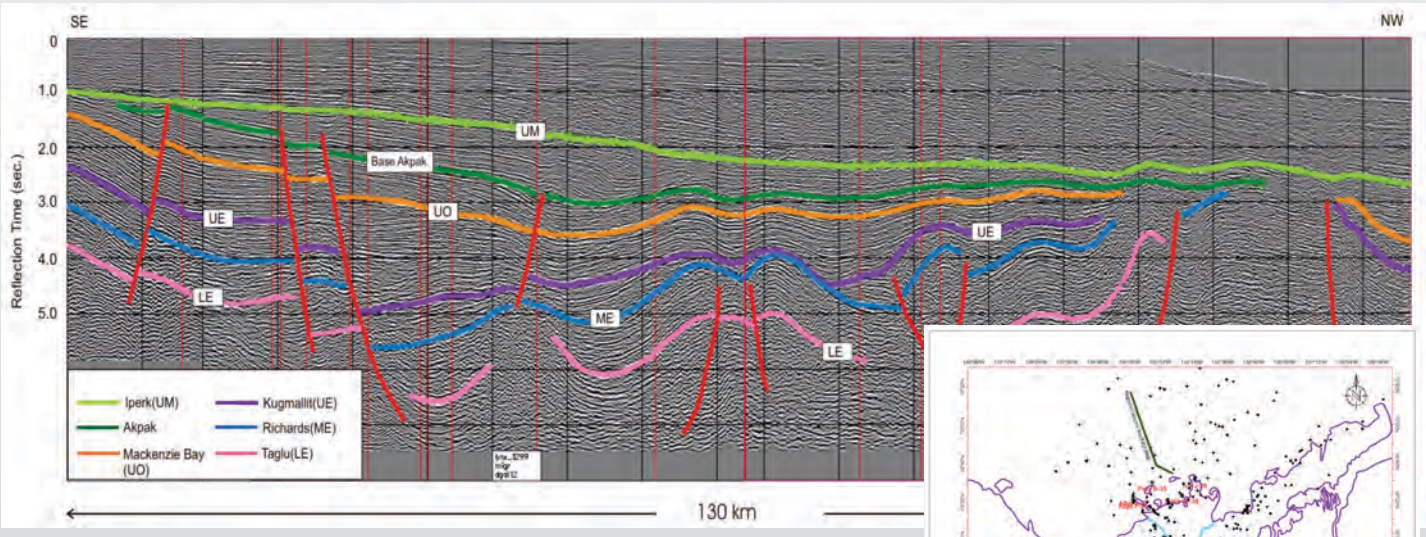


Figure 2: Regional seismic line (84573NW). A NW-SE seismic profile across the eastern and central Beaufort-Mackenzie rifted margin (from Graves et al., 2010).

Table 1: Geological play and discovered gas resources in the Beaufort-Mackenzie Basin (from Chipperfield et al., 2005).

Play Area in Beaufort-Mackenzie Basin	Discovered (Bcf)
Basin Margin Plays:	
Parsons	2,305.0
Tuk	0.0
Mayogiak	0.0
Atkinson Point	0.0
South Delta Parsons	0.0
South Delta Other Mesozoic	33.9
South Delta Paleozoic	3.1
Sub-total	**2,342.0**
Mackenzie Delta Onshore Plays:	
Taglu Onshore	4,002.5
Ivik Onshore	218.0
Sub-total	**4,220.5**
Shallow Offshore Plays:	
Taglu Offshore	173.4
Ivik Offshore	138.7
Netserk	576.8
Tarsiut-Amauligak	2,825.1
Sub-total	**3,714.0**
Deep Water and Other Plays:	
Kopanoar	545.4
Deep Water West	0.0
Adlartok	45.6
Demarcation Basin	0.0
Herschel	0.0
Yukon Coastal Plain	0.0
Sub-total	**591.0**
TOTAL BEAUFORT-MACKENZIE	**10,867.4**

Basin Margin Play Group

The Basin Margin Play Group comprises seven plays that are located either onshore or in the immediately adjacent shallow water, and include the Parsons, Tuk, Mayogiak, Atkinson Point, South Delta Parsons, South Delta Other Mesozoic, and South Delta Paleozoic plays.

Mackenzie Delta Onshore Play Group

The Mackenzie Delta Onshore Play Group comprises the Taglu Onshore and Ivik Onshore plays. The Taglu Onshore play is defined to include all prospects that occur in the Paleocene-Eocene Taglu (Reindeer) sequence onshore in the outer Mackenzie Delta and shallow near-shore areas. The play area is confined by erosion beneath the basal Kugmallit and Iperk unconformities to the southwest (Figure 4), shale-out of deltaic facies to the north and northwest, and by a change in structural style along the flank of the Eskimo Lakes Arch to the southeast. The Ivik play is defined to include all discoveries and prospects in delta-front sandstones of the Upper Richards and Lower Kugmallit sequences present under the onshore areas of the outer Mackenzie Delta (Figure 4).

Shallow Offshore Play Group

The Shallow Offshore Play Group comprises the Taglu Offshore, Ivik Offshore, Netserk and Tarsiut-Amauligak Fault Zone plays that were confined to a narrow fairway located over the conjunction of a series of major listric faults and the front of the Cenozoic deltas, to a water depth of about 30 metres. The Shallow Offshore Play Group comprises a series of stacked deltaic sandstones ranging from upward-coarsening delta front sandstones and overlying distributary mouth bars to distributary channel fill deposits and delta-front sandstones with potential for oil and gas reservoirs.

Deep Water and Other Play Group

The Deep Water and Other Play Group comprises the Kopanoar, Deep Water West, Adlartok, Demarcation Basin, Herschel, and Yukon Coastal Plain plays. These plays are characterized by Cenozoic turbidite sandstones and contain potential hydrocarbon source rocks including Cenozoic shales of the lower Richards and lower Fish River sequences and the oil-prone shales of the Boundary Creek Formation (Figure 1).

Methane Gas Hydrate Play & Resource Potential

Sequestered in the Iperk, Mackenzie Bay, and Kugmallit sequences, methane gas hydrates (GH) have been conclusively identified in the Mallik 2L-38 gas hydrate research well and are inferred to occur in an additional eight industry exploratory wells on Richards Island (Collett and Dallimore, 2002). Based on deterministic GH resource estimates, GH gas in place (GIP) is 8.82×10^{12} m³ in the Beaufort Sea-Mackenzie Delta basin with a probabilistic resource potential of up to 4.2×10^{12} m³ at 50% gas hydrate saturation (Osadetz and Chen, 2010).

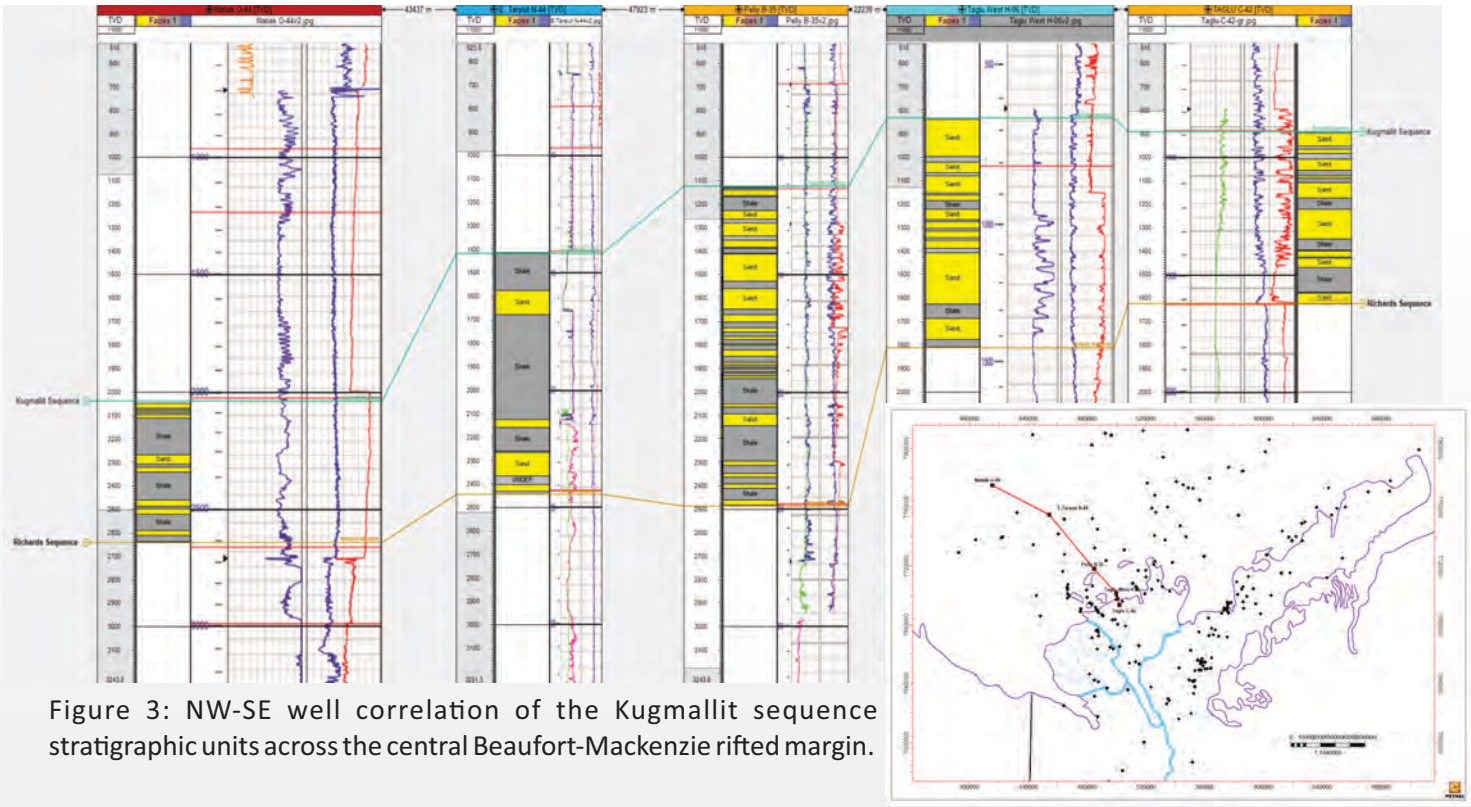


Figure 3: NW-SE well correlation of the Kugmallit sequence stratigraphic units across the central Beaufort-Mackenzie rifted margin.

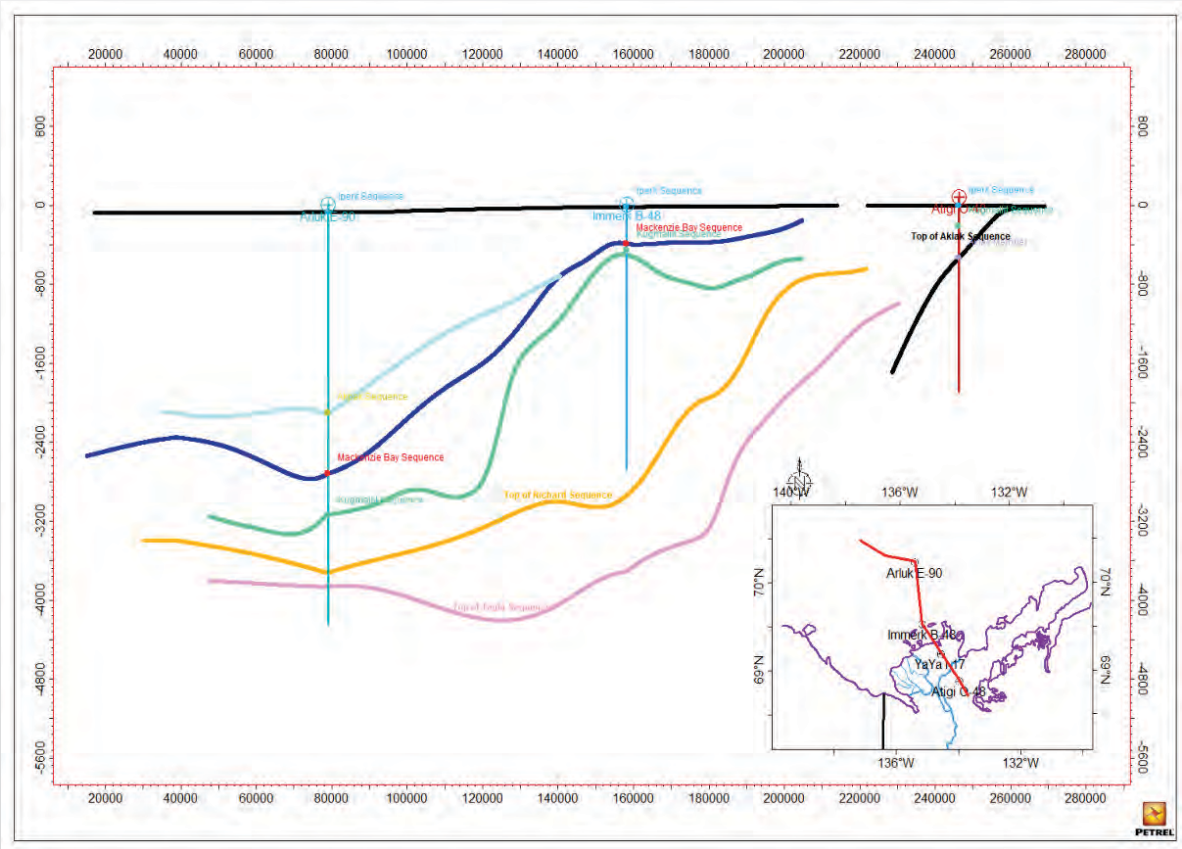


Figure 4: A NW-SW cross section of the interpreted tops of Cenozoic depositional sequences in the Beaufort Sea and Mackenzie Delta.

Source Rocks

Organic rich shale source rocks of the BMB are mapped on regional scale based on seismic interpretations, and sedimentological and stratigraphic analyses. These shale formations are interpreted to have been deposited as sedimentary infill during the Mesozoic syn-rift period and include all stratigraphic successions of the Upper Jurassic and Lower Cretaceous (Graves et al., 2010; Chen et al., 2021; Figure 1). Upper Cretaceous and Cenozoic post-rift sequences also contain organic rich shale source rocks (Figure 1).

Source rocks for most of the discoveries in Cenozoic reservoirs are marine shales in the Upper Cretaceous Smoking Hills and Boundary Creek Formations, and older Jurassic–Lower Cretaceous successions. These marine shales have a total organic carbon (TOC) content of up to 8% (Chen et al., 2007; Chen et al., 2021). There are also Tertiary units considered to be source rock candidates for oil and gas in the basin. McCaffrey et al. (1994) suggested that the deltaic sequences become substantially more oil prone in the distal portions of the delta and generated most of the oils trapped in the Cenozoic sequences (Chen et al., 2021).

More recent studies show that due to their higher maturity, pre-Cenozoic deltaic source rocks are the primary sources of the oil and gas discovered in Cenozoic reservoirs (Snowdon and Powell, 1979; Brooks, 1986a, b; Curiale, 1991; Snowdon, 1995; Snowdon et al., 2004; McCaffrey et al., 1994; Chen et al., 2021). Bergquist et al. (2004) described the Oligocene Kugmallit and the Late Eocene Richards sequences as rich and mature systems with an expanded range of projectivity due to high TOC ranging from 1.5% to 4.5% and hydrogen indices up to 450 kg/t.

The Rock-Eval/TOC study by Jiang et al. (2015) on select core samples obtained from Cenozoic source rock intervals reports TOC content of 0.905%. The Cenozoic organic rich shale and mudstone intervals are immature to marginally mature with a T_{max} in the range of 400 °C to 436 °C and a hydrogen index (HI) mostly below 150 kg/t, indicating that the organic matter in the Cenozoic source rock system is predominantly gas-prone Type III (Jiang et al., 2015).

The deltaic sediments in the Paleogene Aklak, Taglu and Richards sequences of the BMB have molecularly distinctive oil that contains biomarkers indicative of major land plant contribution (Li et al., 2008). Li et al. (2008) also suggest the presence of mixed crude oil from different source rocks as is common in vertically drained petroleum systems.

Oil and Gas Resource Potential

Reservoir Rock Properties

The principal reservoir units in the Cenozoic fill of the BMB are the Paleocene to Eocene Aklak and Taglu sandstones in the west Beaufort region and beneath Richards Island, and the Kugmallit sandstones in the central offshore (NOGD-INAC, 1995). The deltaic Aklak and Taglu sandstone sequences consist of interbedded delta-front and delta-plain sandstones, and prodelta shales. The best reservoir beds in the Aklak sequence have porosity in the range of 20% to 24%, but there also exist finer grained laminated units in which porosity drops to between 15% and 18%. The Taglu sequence comprises a series of stacked deltaic sandstones ranging from upward-coarsening delta front sandstones and overlying distributary mouth bars to distributary channel fill deposits, and exhibits multi-zoned reservoir quality onshore in the outer Mackenzie Delta and shallow near shore area (Chipperfield et al., 2005). Taglu sequence delta plain sandstones and older sequences are known to have higher percentages of volcanic fragments than the younger sequences and are better cemented, and as a consequence have lower porosity between 12% and 20%. Sandstone units from the Taglu field have net pay of 130 m and stacked within 600 m to 700 m gross interval (NOGD-INAC, 1995).

The Kugmallit sequence consists of primarily delta plain to delta front facies across the onshore Mackenzie Delta. Kugmallit oil and gas fields occur primarily offshore and are made up of structural traps in delta plain to delta front sandstones buried at depths greater than 2000 metres. Further offshore, the Kugmallit grades to prodeltaic to basinal facies. The delta-front sequence of the Kugmallit has net pay of 400 m distributed between stacked sandstones separated by shales, over a vertical interval of 1500 m (Figure 3). Average porosity is 24% and is a maximum of 33%.

Oil and Gas Reserves

Although numerous oil and gas fields have been discovered in the BMB, many play types and areas remain under-explored. At time of publication, only the Ikhil gas field is developed for production; it provides back-up gas for power generation to the local community of Inuvik (GNWT-ITI, 2021b; Chen et al., 2021). The volume of discovered marketable resources and reserves for conventional oil and gas in the NWT mainland was estimated by the NEB (2014). These estimates include 160.8 x $10^9 m^3$ (5.7 Tcf) natural gas, 8.3 $10^6 m^3$ (52.0 million barrels) NGLs, and 28.8 $10^6 m^3$ (181.0 million barrels) crude oil. Additional significant discovered reserves exist in the Beaufort Sea and NWT Arctic Islands (NEB, 2014; Table 1; Table 2).

Table 2: Total estimated conventional oil and gas reserves from 59 discovered fields in the Beaufort Sea, onshore Mackenzie Delta, and NWT Arctic Islands (NEB, 2014).

Study Area	Natural gas billion cubic metres (trillion cubic feet)	Natural gas liquids million cubic metres (million barrels)	Oil million cubic metres (million barrels)
Beaufort Sea	178.0 (6.2)	0.2 (1.2)	106.1 (667.4)
Mackenzie Delta	160.8 (5.7)	8.3 (52.0)	28.8 (181.0)
NWT Arctic Islands	75.2 (2.6)	0	4.9 (31.0)

Gas Hydrate Reserve

Gas hydrates (GH) are crystalline substances composed of water and methane molecules trapped cage-like in a solid water lattice (Englezos, 1993). There are confirmed occurrences of large volumes of sequestered methane in GH both onshore and offshore of the BMB, specifically in sandstones of the Kugmallit, Mackenzie Bay, and Iperk sequences (Dallimore et al., 1999). GH are confirmed in 29% of the BMB wells (Majorowicz and Osadetz, 2001; Figure 5). Osadetz and Chen (2010) deterministically estimate a gas hydrate in-place volume of 8.82 x $10^{12} m^3$.

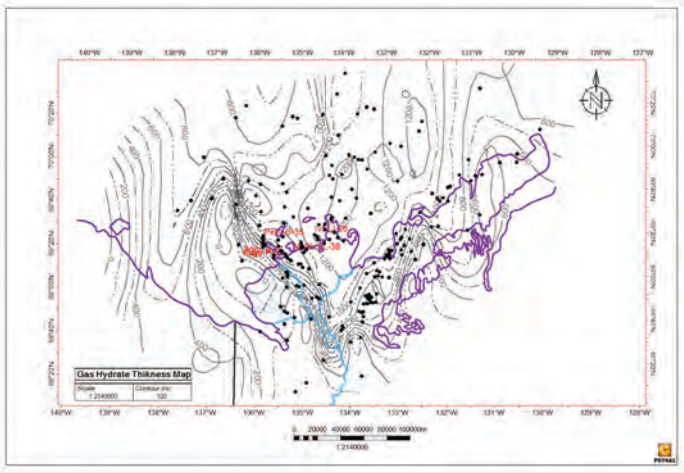
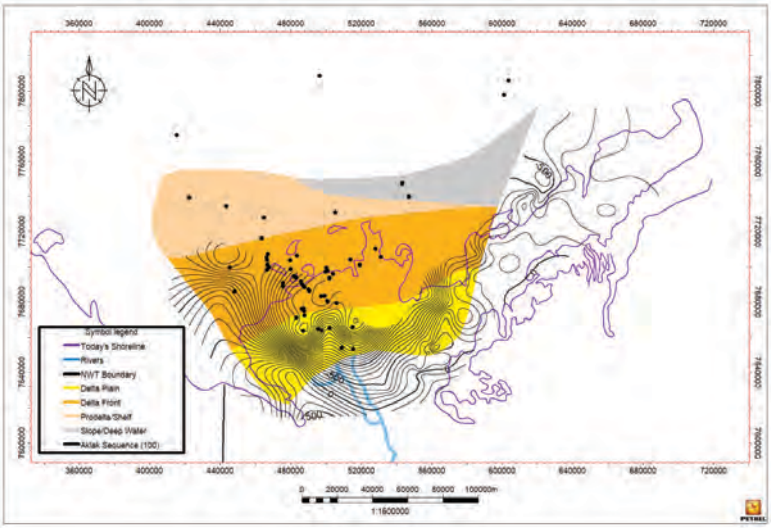


Figure 5: Map showing the depth (in metres) to the base of the methane hydrate stability zone in the Mackenzie Delta-Beaufort Sea region of northern Canada (modified from Judge and Majorowicz, 1992).

Carbon Capture and Sequestration (CCS) Potential

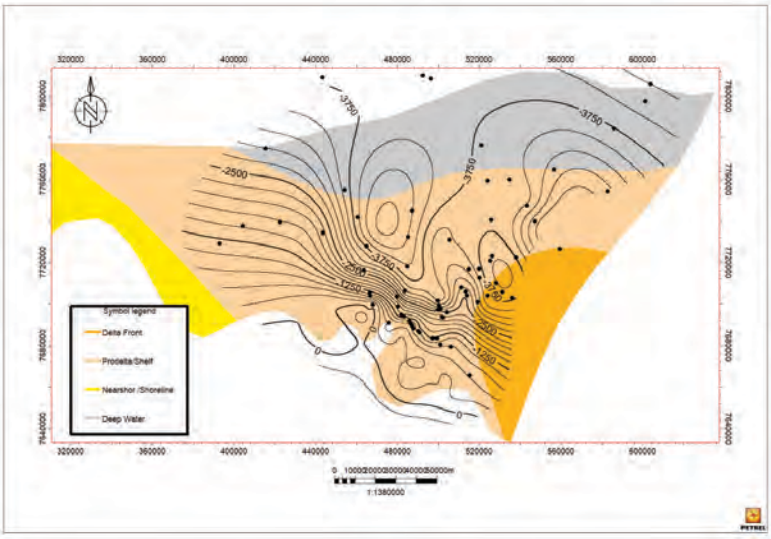
Production and processing of the large natural gas resource for export LNG product will create CO_2 as a by-product. Findings from recent studies have indicated potential for carbon storage within the oil and gas bearing reservoirs of the Mackenzie Delta (PRCL, 2022). Regional geological characterization and mapping demonstrate that the Kamik, Taglu and Kugmallit depositional successions contain reservoir porosity and permeability in the onshore fields for sequestrating the CO_2 volumes that would be generated by LNG operations. Other petroleum system elements such as traps and seals that support gas accumulation occur in the Mackenzie Delta and potentially could accommodate CCS.

Sequence Maps and Depositional Environments



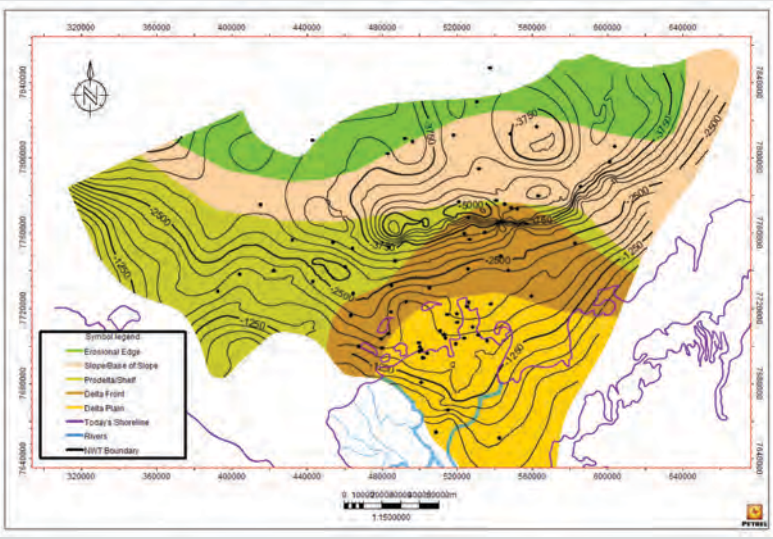
Taglu sequence

Figure 6: Interpreted Taglu sequence depositional environments at time of maximum progradation. Similar to the Aklak sequence, the Taglu sequence is made up of alluvial fluviodeltaic strata deposited on the upper delta plain with occurrence of coal-bearing units (based on Dixon et al., 1992).



Richards sequence

Figure 7: Interpreted Richards sequence depositional environments at time of maximum progradation. The lower boundary presented here by the top of Taglu sequence (base sequence boundary in the contour map, metres below sea level) is an abrupt, conformable contact throughout most of the basin, but is locally a significant erosional unconformity (based on Dixon et al., 1992). The Richards sequence consists mainly of prodelta deposits comprising mostly shale and siltstone.



Kugmallit sequence

Figure 8: Seismic interpretation of the base of Kugmallit (contour map; metres below sea level) draped over the interpreted paleo-environments during Kugmallit progradation (based on Dixon et al., 1992). This map illustrates the geomorphology of the paleo-environment during the Late Eocone - Early Oligocene when the rock units in the Kugmallit sequence were laid down in the basin.

Kugmallit sequence

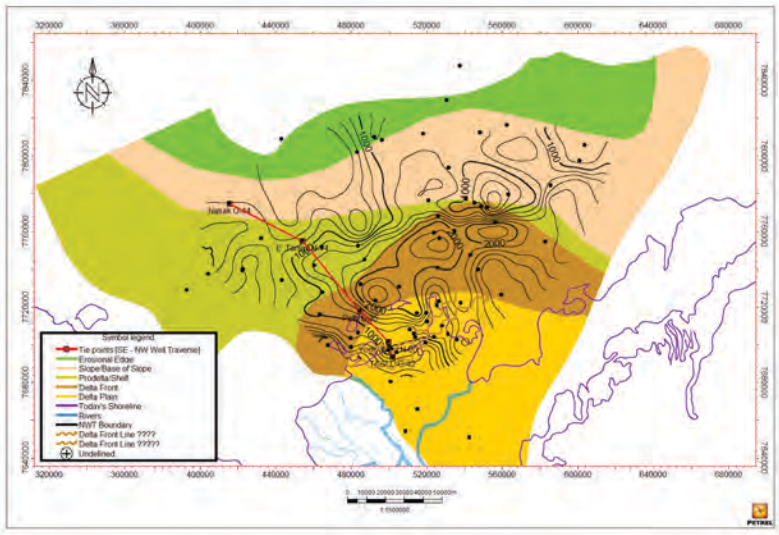


Figure 9: Isopach map of the Kugmallit sequence (contour map; metres) draped over the interpreted paleo-environments during Kugmallit progradation (based on Dixon et al., 1992). This map illustrates that the delta front environment has the thickest sediment deposition.

Kugmallit sequence

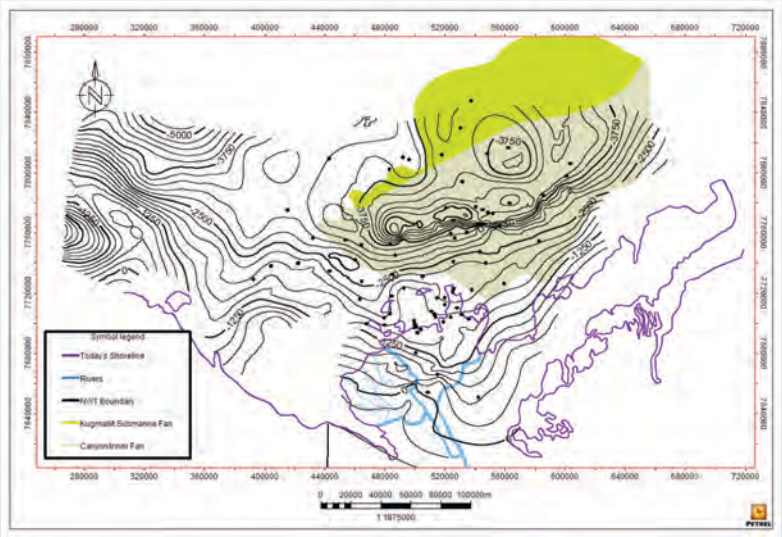


Figure 10: Interpreted depositional environments on the Kugmallit submarine fan (based on Dixon et al., 1992), superimposed on the seismic interpretation of the base of Kugmallit sequence (metres below sea level). This map illustrates the geomorphology of the paleo-environment during the Late Eocone - Oligocene when the Kugmallit submarine fans were deposited distally in the basin. The thickest and most widespread submarine fan successions are in the basal Kugmallit sequence (Dixon et al., 1992).

Kugmallit sequence

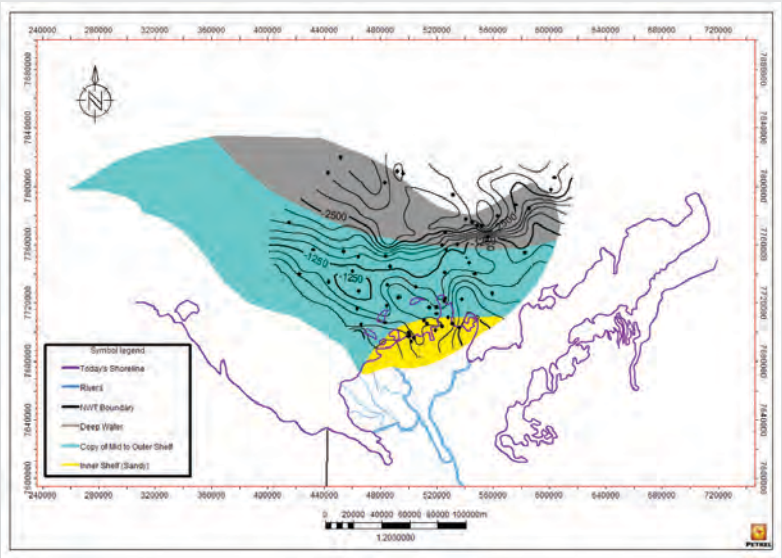
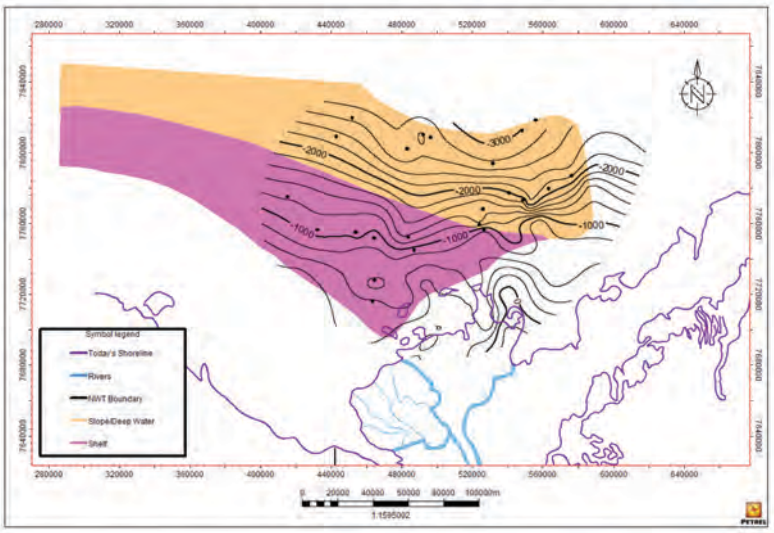
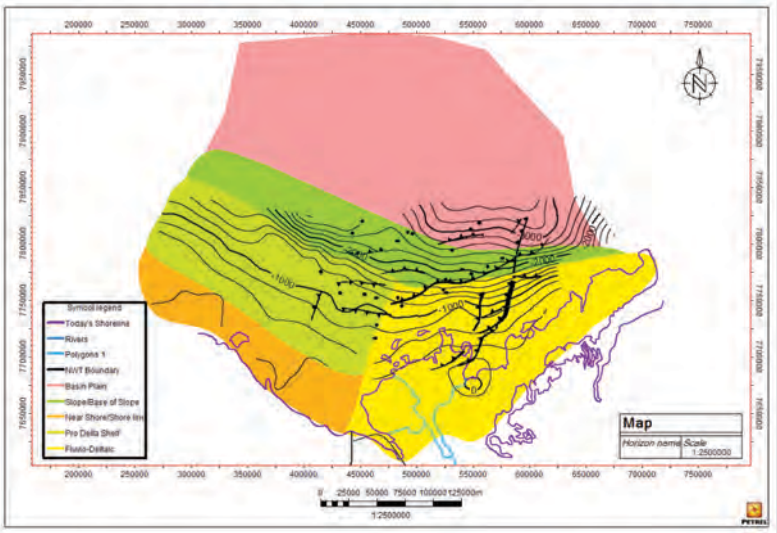


Figure 11: Interpreted map of the top of the Oligocene Kugmallit sequence (contour map, metres below sea level) draped over the interpreted Mackenzie Bay Sequence depositional environments at time of maximum progradation (based on Dixon et al., 1992). Shale dominated Mackenzie Bay sequence clinoforms are predominantly outer shelf and deep water deposits.



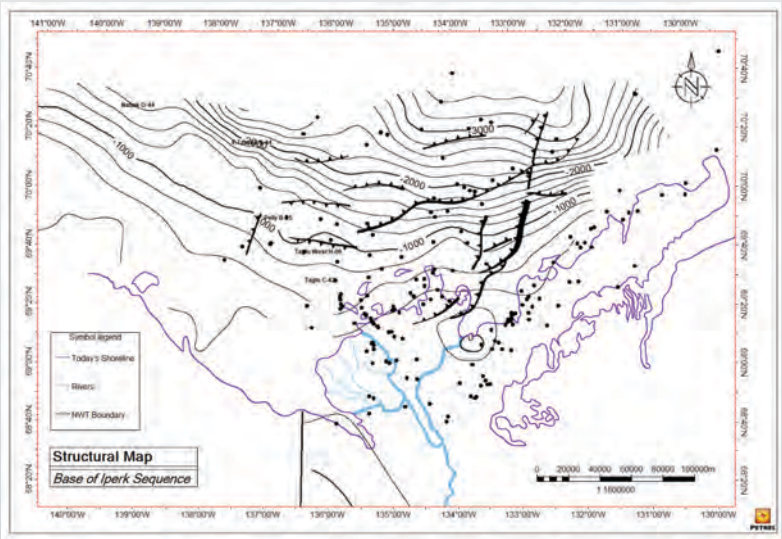
Akpak sequence

Figure 12: Interpreted Akpak sequence depositional environments at time of maximum progradation (based on Dixon et al., 1992). The Akpak sequence is superimposed on the top of Mackenzie Bay sequence. The Akpak Sequence consists mainly of silty prodelta/shelf, slope, and basinal deposits (Dixon et al., 1992).



Iperk sequence

Figure 13: Seismically interpreted map of the base of Iperk sequence (metres below sea level; remapped from Graves et al., 2010) draped over interpreted Iperk sequence depositional environments (based on Dixon et al., 1992). The interpreted base is a major erosional unconformity that can be traced throughout the Beaufort-Mackenzie and Banks-Beaufort basins. Iperk strata consist of near-shore to slope facies of weakly consolidated to unconsolidated sand and conglomerate at the basin margins, grading laterally into a succession with more shale (Dixon et al., 1992).



Iperk sequence

Figure 14: Structural map of the base of Iperk sequence interpreted to represent the geomorphology of the Pliocene sequence boundary (based on Dixon et al., 1992).

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