[PS]Petroleum Plays in Upper Cenozoic Strata in the Beaufort-Mackenzie Basin, Arctic Canada*

James Dietrich[1], Zhuoheng Chen[1], Gillian Chi[1], Jim Dixon[1], Kezhen Hu[1], and Dave McNeil[1]

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[1]Geological Survey of Canada, Calgary, AB, Canada (jdietric@nrcan.gc.ca)

Abstract

The Upper Cenozoic sedimentary succession in the Beaufort-Mackenzie Basin includes two major depositional sequences: the Pliocene-Pleistocene Iperk Sequence and the latest Pleistocene-Holocene Shallow Bay Sequence. The Iperk and Shallow Bay sequences have a combined thickness of up to 4000 m in the northern Beaufort-Mackenzie Basin. Iperk strata were deposited in delta-plain, shelf and deep-water settings, with Plio-Pleistocene shelf margins prograding northward by distances up to 120 km. The early phase of Iperk sedimentation included widespread lowstand deposition of base-of-slope turbidite fans. In the western part of the basin, deep-water mini-basins developed in the lower Iperk Sequence, adjacent to paleo-seafloor highs above Lower Tertiary fold structures. The Shallow Bay Sequence includes fluvial and marine sediments deposited in a deeply incised paleo-valley system in the Mackenzie Trough area of the western Beaufort-Mackenzie Basin. Potential hydrocarbon reservoirs in the Upper Cenozoic succession include turbidite sandstones deposited in mini-basin and submarine fan settings, and a widespread, thin carbonate-hardground unit at the base of the Iperk Sequence. Upper Cenozoic strata are thermally immature but may contain migrated hydrocarbons from Lower Tertiary or Upper Cretaceous source rocks. Subsidence-maturation modeling indicates hydrocarbon generation occurred from Middle to Late Cenozoic time in northern parts of the basin. One of the Beaufort Sea wells drilled during the early phases of offshore exploration, Nektoralik K-59, provided direct evidence of hydrocarbon charging in a Pliocene reservoir. Natural gas and condensate were recovered from the basal Iperk carbonate unit in a drill-stem test in this well. Indirect evidence of hydrocarbon migration through Upper Cenozoic strata is observed in the Kopanoar M-13 well, where a high temperature anomaly is present in the Iperk Sequence, above an overpressured zone and below a pingo-like feature on the sea floor. The development of pingo-like seafloor features in the Beaufort Sea shelf has been linked to gas venting. Geophysical indications of hydrocarbons in Upper Cenozoic strata include bright spots, flat spots and gas chimneys imaged in seismic reflection profiles. Future petroleum exploration in the unexplored deep-water areas of the northern Beaufort-Mackenzie Basin may include plays and prospects in Upper Cenozoic strata.

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J. Dietrich, Z. Chen, G. Chi, J. Dixon, K. Hu and D. McNeil, Geological Survey of Canada

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The Canadian Beaufort-Mackenzie Basin lies on the continental margin of the Arctic Ocean and contains up to 15 km Upper Cretaceous to Quaternary sediments (Fig. 1). The basin fill consists of a series of basinward-prograding depositional sequences, each one dominated by the formation of delta complexes and their lateral shelf and deep-water (slope and basin plain) equivalents (Fig. 2). The youngest part of the sedimentary succession includes two major sequences: the Middle Pliocene-Pleistocene Iperk Sequence and the late Pleistocene-Holocene Shallow Bay Sequence (Fig. 2).The Iperk Sequence is up to 4000 m thick in the northern Beaufort-Mackenzie Basin (Fig. 3). Plio-Pleistocene sedimentation rates were very high, relative to Miocene and older Tertiary sequences (Fig. 4). Iperk strata were deposited in delta plain, shelf, and deep-water continental slope and rise settings, with Plio-Pleistocene shelf margins prograding northward by distances of up to 100 km (Figs. 5, 6, 7, 16). The early phases of Iperk sedimentation included widespread deposition of a carbonate hardground (K-59 limestone; McNeil et al., 2001) and base-of-slope turbidite fans (Figs. 6, 7). The Iperk Sequence is unconformably overlain by up to 1000 m of Quaternary glaciomarine and fluvio-deltaic sediments in the Shallow Bay Sequence. In the southwestern Beaufort-Mackenzie Basin, Iperk and older strata are eroded beneath a late Pleistocene glacial ice stream channel (Mackenzie Trough, Fig. 16; Blasco et al., 1990).

The Beaufort-Mackenzie Basin contains numerous oil and gas fields in Eocene and Oligocene sandstone reservoirs (Dixon, 1996). Analyses of seismic and well log data indicate there are potential Pliocene hydrocarbon reservoirs in the deep-water (basinal) parts of the Iperk Sequence in the northern basin. Reservoir units include turbidite sandstones deposited in submarine fans and thin carbonates at the base of the succession (Figs. 5, 6, 11; Seismic Profiles 1 to 4). Pliocene deep-water sandstones and carbonates encountered in offshore wells have good reservoir characteristics (Figs. 8 to 11). Pliocene sandstones have measured porosity and permeability values up to 40 % and 300 mD, respectively.

Plio-Pleistocene strata are thermally immature in all parts of the Beaufort-Mackenzie Basin, but may contain migrated hydrocarbons from deeply buried Lower Tertiary or Upper Cretaceous source rocks (Figs. 12, 13, 14). Subsidence-maturation modelling indicates hydrocarbon generation occurred from Middle to Late Cenozoic time in northern parts of the basin. Rapid deposition of a thick Plio-Pleistocene sedimentary wedge in the northern basin produced overpressures and enhanced hydrocarbon generation in Lower Tertiary and Upper Cretaceous strata (Figs. 13, 14).

One of the Beaufort Sea wells drilled during the early phases of offshore exploration, Nektoralik K-59, provided direct evidence of hydrocarbon charging in a Pliocene reservoir (Fig. 10). Natural gas and condensate were recovered from the basal Iperk carbonate unit in a drill-stem test in this well. Indirect evidence of hydrocarbon migration through Upper Cenozoic strata is observed in the Kopanoar M-13 well, where a high temperature anomaly is present in the Iperk Sequence, above an overpressured zone and below a pingo-like feature (mud volcano) on the sea floor (Fig. 15). The development of seafloor mud volcanoes in the Beaufort Sea shelf has been linked to gas venting (Paull et al., 2007). Geophysical indications of hydrocarbons in upper Cenozoic strata include bright spots and flat spots imaged in seismic reflection profiles (e.g., Seismic Profile 5).

Plio-Pleistocene continental slope and rise strata in the northern Beaufort-Mackenzie Basin and adjacent deep-water Canada Basin may have significant petroleum potential. Primary play types are likely associated with thick turbidite sandstones in submarine fan complexes and widespread (thin) marine carbonates. The main play risks are likely related to the timing and pathways of petroleum migration, relative to the deposition and distribution of Plio-Pleistocene reservoir units.

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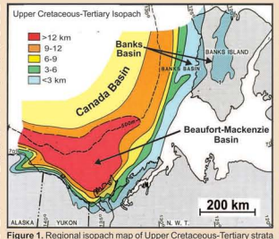


Figure 1. Regional isopach map of Upper Cretaceous-Tertiary strata in the Beaufort-Mackenzie and Banks basins and contiguous deep-water Canada Basin (modified from Dixon and Dietrich, 1990).

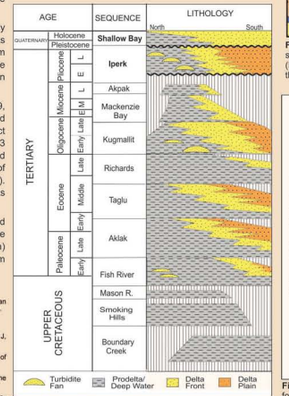


Figure 2. Upper Cretaceous to Quaternary sequence stratigraphy of the Beaufort-Mackenzie Basin, with indicated depositional facies and major Plio-Pleistocene unconformities within the study interval (adapted from Dixon, 2006).

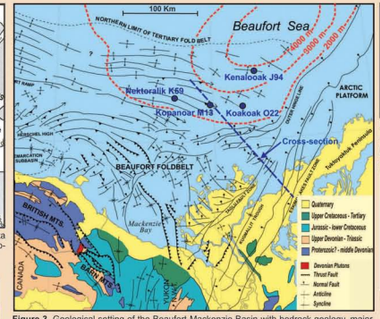


Figure 3. Geological setting of the Beaufort-Mackenzie Basin with bedrock geology, major structural features and trends, and locations of regional cross-section (Fig. 5) and study wells (Fig. 9). Isopach contours (red dashed lines) outline depocentre of Plio-Pleistocene strata in the northern basin (adapted from Lane and Dietrich (1995) and Dixon (1996)).

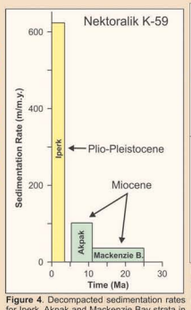


Figure 4. Decompacted sedimentation rates for Iperk, Akpak and Mackenzie Bay strata in the Nektoralik K-59 well (from McNeil et al., 2001). Plio-Pleistocene sedimentation rates were six to ten times higher than Miocene sedimentation rates.

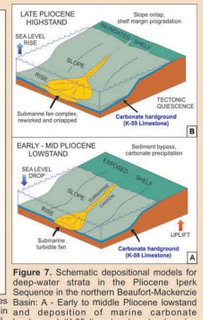


Figure 7. Schematic depositional models for deep-water strata in the Pliocene Iperk Sequence in the northern Beaufort-Mackenzie Basin: A - Early to middle Pliocene lowstand and deposition of marine carbonate hardground (K-59 limestone) and submarine fans; B - Late Pliocene transgression and highstand and deposition of slope and rise sediments (adapted from McNeil et al., 2001).

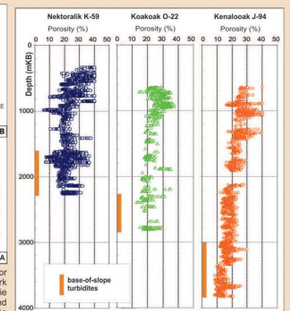


Figure 8. Porosity-depth plots for sandstones in the Iperk Sequence in the Nektoralik, Koakoak and Kenalooak wells. Pliocene turbidite sandstones have high porosity values (up to 25 to 35 %) to depths of 4000 m.

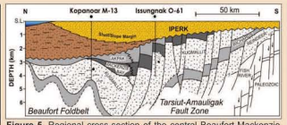


Figure 5. Regional cross-section of the central Beaufort-Mackenzie Basin, highlighting the prograding shelf-margins in the Plio-Pleistocene Iperk Sequence. The base-Iperk sequence boundary is a regional erosional unconformity that truncates older Tertiary and Cretaceous structures.

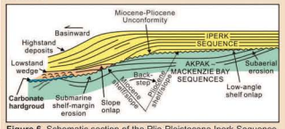


Figure 6. Schematic section of the Plio-Pleistocene Iperk Sequence, illustrating shelf to basinal depositional settings and Miocene-to-Pliocene back-stepping shelf margins. Known and possible petroleum plays include thin carbonates in the basal Iperk (blue unit) draped over lower Tertiary folds, and stratigraphic sandstone traps in lowstand submarine fans (orange unit; adapted from McNeil et al., 2001).

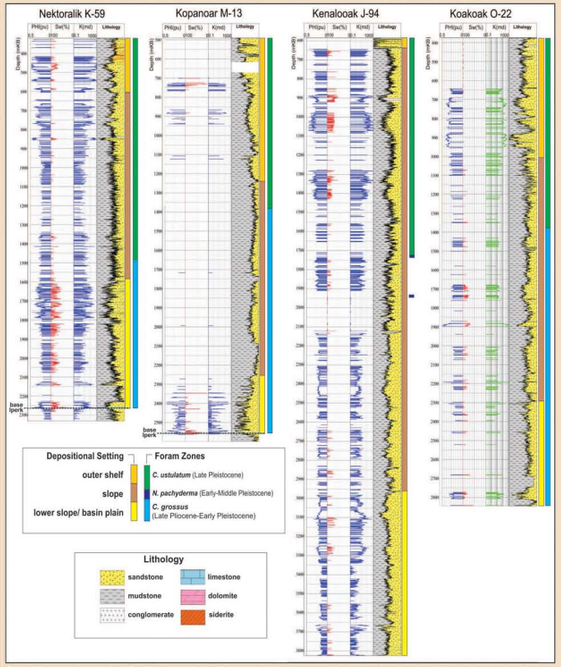


Figure 9. Log analyses of the Plio-Pleistocene Iperk Sequence in the Nektoralik, Kopaonor, Kenalooak and Koakoak wells in the northern Beaufort-Mackenzie Basin. Sections display log-derived lithology, porosity, water saturation and permeability data, interpreted depositional environments (outer shelf to basin plain), and key biostratigraphic zones. Thicker and more abundant sandstone units occur in the outer shelf and lower slope/basin plain settings (particularly in the Nektoralik and Kopanoar wells for the basin-plain deposits). Slope and basin plain turbidite sandstones (overlain by basinal mudstones) are possible petroleum exploration targets.

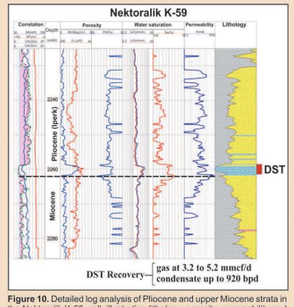


Figure 10. Detailed log analysis of Pliocene and upper Miocene strata in the Nektoralik K-59 well, illustrating lithology, porosity, permeability and water saturations. A drill-stem test of the basal Iperk carbonate unit recovered gas and condensate at significant rates. The tested carbonate unit is a 3 m-thick dolomitic limestone with porosity of 15 % and permeability of 10 to 100 md.

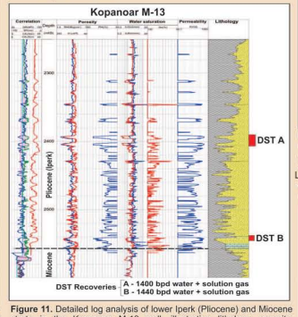


Figure 11. Detailed log analysis of lower Iperk (Pliocene) and Miocene strata in the Kopanoar M-13 well, illustrating lithology, porosity, permeability and water saturation. Two drill-stem tests of Pliocene turbidite sandstones in the lower Iperk recovered water and solution gas. The tested sandstones are 5 to 10 m thick, with porosity of 35 to 40 % and permeability of 200 to 300 mD.

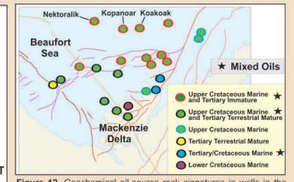


Figure 12. Geochemical oil-source rock signatures in wells in the Beaufort-Mackenzie Basin. Most of the recovered oils from offshore Tertiary reservoirs, including the northernmost fields (Nektoralik, Kopanoar, Koakoak), were derived from Upper Cretaceous marine oil source rocks, with secondary Tertiary source-rock derivations (Li et al., 2008). Basin petroleum potential is enhanced by the widespread occurence of oil-prone Upper Cretaceous source rocks.

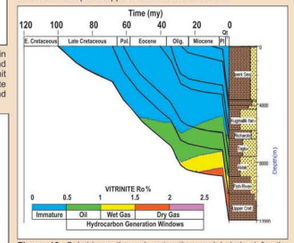


Figure 13. Subsidence-thermal maturation model derived for the northern Beaufort-Mackenzie Basin in the area of the Kenalooak J-94 well (Figs. 3,16). Deep stratigraphy (below ~5000 m) inferred from seismic data. Hydrocarbon source rocks in the Upper Cretaceous and Lower Tertiary sequences are within the oil and gas generation windows in the Middle to Late Tertiary (see hydrocarbon generation models in Fig. 14).

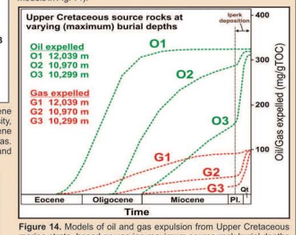


Figure 14. Models of oil and gas expulsion from Upper Cretaceous marine strata, based on varying maximum source-rock burial depths (10 to 12 km) in the northern Beaufort-Mackenzie Basin. Oil and gas generation occurred in the Middle to Late Tertiary, with enhanced phases of hydrocarbon generation (for 10 - 11 km source-rock burial depths: models O3, G2, G3) in the Plio-Pleistocene, coincident with deposition of the Iperk Sequence.

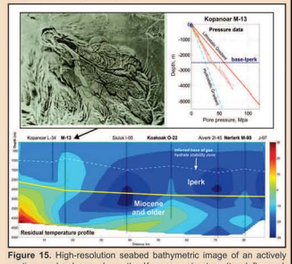


Figure 15. High-resolution seabed bathymetric image of an actively venting mud volcano above the Kopanoar structure (top left panel; image courtesy of S. Blasco) and a pressure-depth profile derived from mud weight data for the Kopanoar M-13 well (top right panel). High pore pressures were encountered in Tertiary strata in the M-13 well, with a pressure-gradient increase below the base-Iperk unconformity. Temperature anomaly profile of 7 wells in the northern Beaufort-Mackenzie Basin (bottom panel) shows relationship between temperature anomalies and petroleum discoveries (Kopanoar M-13, Koakoak O-22 and Nerlerk M-98). Local high-temperature anomalies indicate upward migration of hot fluids from deep to shallow stratigraphic sections. The combined observations of temperature anomalies, high pressures, and active sea-floor venting indicate migration of fluids and gas through Upper Cenozoic strata, with the potential for hydrocarbon charging of Plio-Pleistocene reservoirs and traps.

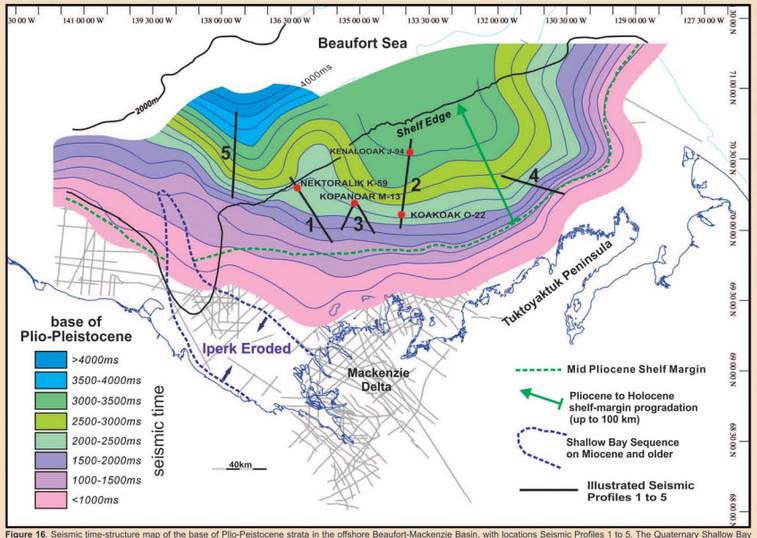
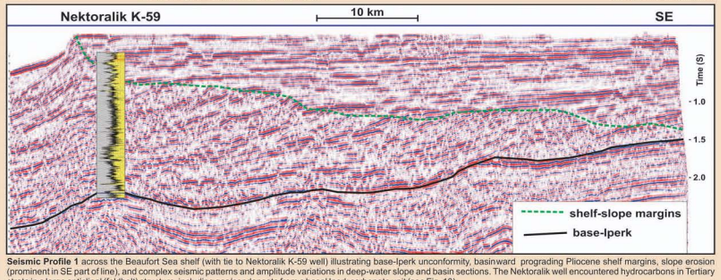
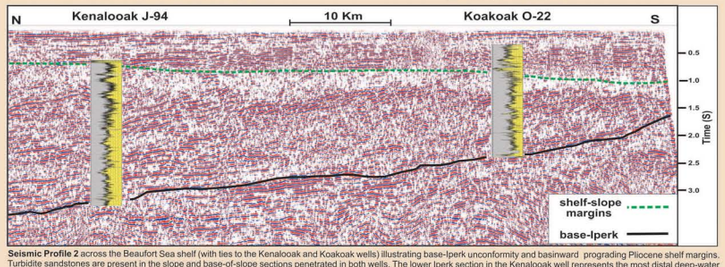


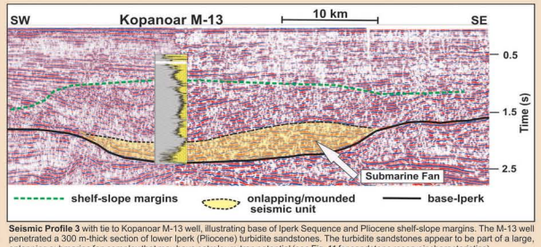
Figure 16. Seismic time-structure map of the base of Plio-Peistocene strata in the offshore Beaufort-Mackenzie Basin, with locations Seismic Profiles 1 to 5. The Quaternary Shallow Bay Sequence directly overlies Miocene and older strata in the Mackenzie Trough area of the southwestern Beaufort-Mackenzie Basin (blue dashed line). Late Pliocene to Holocene shelf margins prograded seaward by distances of up to 100 km (green arrow) from the position of the Mid Pliocene shelf margins (green dashed line).



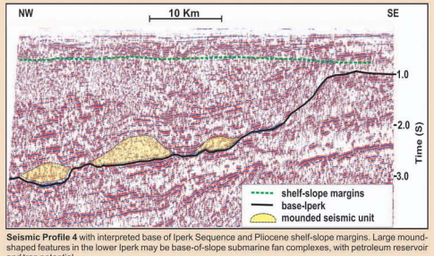
Seismic Profile 1 across the Beaufort Sea shelf (with tie to Nektoralik K-59 well) illustrating base-Iperk unconformity, basinward prograding Pliocene shelf margins, slope erosion (prominent in SE part of line), and complex seismic patterns and amplitude variations in deep-water slope and basin sections. The Nektoralik well encountered hydrocarbons in Tertiary strata in a large anticlinal (foldbelt) structure, including gas/condensate from a basal Iperk carbonate unit (see Fig. 10).



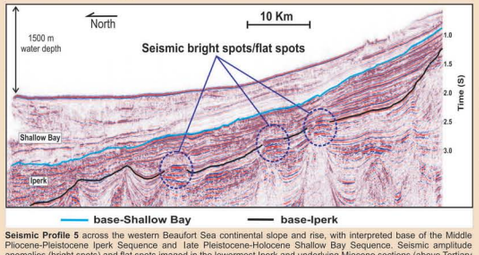
Seismic Profile 2 across the Beaufort Sea shelf (with ties to the Kenalooak and Koakoak wells) illustrating base-Iperk unconformity and basinward prograding Pliocene shelf margins. Turbidite sandstones are present in the slope and base-of-slope sections penetrated in both wells. The lower Iperk section in the Kenalooak well represents the most distal deep-water section encountered in the basin wells drilled to date, 70 to 80 km basinward of paleo-shelf margin positions.



Seismic Profile 3 with tie to Kopanoar M-13 well, illustrating base of Iperk Sequence and Pliocene shelf-slope margins. The M-13 well penetrated a 300 m-thick section of lower Iperk (Pliocene) turbidite sandstones. The turbidite sandstones appear to be part of a large, onlapping submarine fan complex that may have petroleum-trap potential (see Fig. 11 for sandstone reservoir characteristics).



Seismic Profile 4 with interpreted base of Iperk Sequence and Pliocene shelf-slope margins. Large mound-shaped features in the lower Iperk may be base-of-slope submarine fan complexes, with petroleum reservoir and trap potential.



Seismic Profile 5 across the western Beaufort Sea continental slope and rise, with interpreted base of the Middle Pliocene-Pleistocene Iperk Sequence and late Pleistocene-Holocene Shallow Bay Sequence. Seismic amplitude anomalies (bright spots) and flat spots imaged in the lowermost Iperk and underlying Miocene sections (above Tertiary fold structures) may be direct hydrocarbon indicators.