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PETROPHYSICAL CHARACTERISTICS OF POST-2000 SIGNIFICANT CONVENTIONAL DISCOVERY WELLS IN THE BEAUFORT-MACKENZIE BASIN

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ABSTRACT

This study employs an integrated approach to derive reservoir parameters and provides an overview of petrophysical characteristics for post-2000 conventional discovered oil and gas accumulations in the Beaufort-Mackenzie Basin. The evaluated wells include Tuk M-18, Kurk M-15, Paktoa C-60, Olivier H-01, Langley E-07 and K-30 (Langley field), Ellice I-48 and J-27 (Ellice field), Umiak N-05 and N-16 (Umiak field). Petrophysical models are developed for the evaluation of reservoir properties, including lithology, porosity, permeability and water saturation using core-calibrated log data. Potential oil and gas zones are identified using specified porosity and water saturation cut-off values (>10% porosity, <45% Sw).

Most of the log-identified petroleum zones in the ten wells occur primarily in the Paleogene Taglu and Aklak sequences in sandstone reservoirs of good porosity and permeability, or in shaly sandstone and siltstone reservoirs with fair to good porosity and permeability. However, major identified gas zones in the Tuk gas field occur in sandstone of the Lower Cretaceous Kamik Formation. Good quality gas zones in the Tuk M-18 well occur in fine to medium-grained sandstone with good porosity (21% on average), excellent permeability (mainly between 10 and 2000 mD), and high gas saturation (90% on average), and with restricted flow test rates up to 860,000 cubic meter of natural gas per day. In the Paktoa C-60 well, the only significant discovery drilled in the Beaufort Sea since 1990, an oil zone is identified in unconsolidated fine to coarse-grained sandstone of the Taglu Sequence. This zone has good reservoir properties with an average porosity of 25% and maximum permeability of 10 to 100 mD. This log interpretation is consistent with drill stem tests that recovered oil from this interval.

INTRODUCTION

The Beaufort-Mackenzie Basin contains large volumes of discovered oil and natural gas resources and has significant resource potential for future discoveries. The first discovery well, Atkinson H-25, was drilled in the Mackenzie Delta in 1969 and recovered oil, prompting an initial phase of exploration. Offshore drilling in the Beaufort Sea started in 1973 and led to an oil and gas discovery at the Adgo F-28 well in March 1974. Up to 1998, over 250 wells had been drilled, and 53 significant crude oil and gas discoveries had been made, including 20 gas, 13 oil and 20 oil and gas wells (Fig.1), which were estimated to have 161 x 10^9 m^3 (1.01 billion barrels) of recoverable oil and 255 x 10^9 m^3 (9 Tcf) of marketable gas (National Energy Board, 1998). In 1998, the Ikhil J-35 well was drilled in the Ikhil field which entered production in July 1999 to supply natural gas to the local communities in Inuvik.

Since 2000, more than 25 new petroleum exploration wells have been drilled, resulting in ten significant conventional hydrocarbon discoveries that include the following wells: Tuk M-18, Kurk M-15, Paktoa C-60, Olivier H-01, Langley E-07 and K-30 (Langley field), Ellice I-48 and J-27 (Ellice field), Umiak N-05 and N-16 (Umiak field) (Fig.1); Devon and Petro-Canada, 2002; Chevron Texaco, 2003; Oil&Gas Journal, 2007; Hogg et al., 2009; MGM Energy Corp., 2008, 2009; Drummond, 2009; NEB, 2007, 2009, 2013; Northern Oil and Gas Branch, 2009, 2010). In total, 64 significant conventional oil and gas discoveries had been made in the Beaufort-Mackenzie Basin by 2010, among which 54 were made by 1999, and 10 since 2000. Most discovered petroleum resources occur within the Cretaceous to Pleistocene stratigraphic successions and the others occur in Paleozoic carbonates (Fig. 2, modified from Dixon et al., 1994, 2007).

The Geological Survey of Canada (GSC) has evaluated the petroleum resource potential for the Beaufort-Mackenzie Basin. Estimates of the total discovered conventional resources (mean values) are 277.3 x 10^9 m^3 (1.744 billion barrels) of recoverable oil and 332.4 x 10^9 m^3 (11.74 Tcf) of recoverable natural gas (Dixon et al., 1994). In 2007 the discovered recoverable oil (mean value) was estimated to be 327 x 10^9 m^3 (2.1 billion barrels) (Chen et al., 2007). Basin-wide appraisals indicate high potential for undiscovered conventional oil and gas (Dixon et al., 1994; Osadetz et al., 2005; Chen et al., 2007). However, no oil and gas resource estimates in conventional reservoirs are publicly available that include the ten recent discoveries since 2000.

This petrophysical study integrates geophysical log data and core analyses for the ten discovery wells; nine of these penetrated Pliocene to Eocene strata; whereas Tuk M-18 well encountered Pliocene to Cretaceous successions (Table 1). The primary objectives are to determine reservoir properties including lithology, porosity, permeability and water saturation, as well as possible hydrocarbon zones, providing key reservoir parameters for further petroleum resource assessments and basin studies.

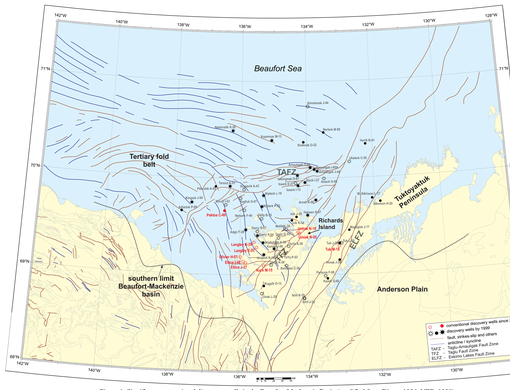

Figure 1. Significant conventional discovery wells in the Beaufort-Mackenzie Basin (modified from Dixon, 1996; NEB, 1998).

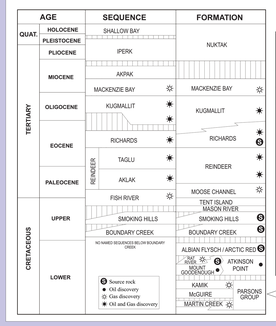

Table 1. Stratigraphic tops and total drilled depths (metres below KB) for the ten wells evaluated in this study
* depth uncertain

Company	Devon and Petro-Canada		Devon Canada	Chevron Texaco & BP Canada Energy			EnCana, Anadarko & ConocoPhillips		MGM Energy Corporation	
Well / Fm. / Seq.	KURK M-15 (2001)	TUK M-18 (2001)	PAKTOA C-60 (2005-2006)	LANGLEY K-30 (2003)	ELLICE I-48 (2003)	OLIVIER H-01 (2004-2005)	UMIAK N-16 (2004)	UMIAK N-05 (2005)	LANGLEY E-07 (2008)	ELLICE J-27 (2008)
Iperk	9.4	9.8	52.3	5.3	9.7	9.7	11.9	9.5	6.2	7.1
Mackenzie Bay			506							
Kugmallit			643		270*	219	237	245		260*
Richards			987	309 (286)	510	742	1938.5	1950	503	572
Taglu	342		1248	533 (458)	2083 (2077)	1764.5 (1752.5)	2818	2863.4 (2860.7)	593	990 (971.5)
Aklak	2700 (2699)	245			2464 (2453)					1764.4 (1688.4)
Fish River										
Mason River		2044								
Smoking Hills		2332 (2326.3)								
Mount Cautereneugh		2519 (2518.5)								
Kamik		2643 (2624)								
McGuire		2719.4 (2719.2)								
Martin Creek		2762 (2758)								
Husky		2792 (2789.6)								
Total Depth (TVD)	3093	2866	2382	1390	3806	3480.5	3101	3549.4	1355	2102
Total Depth (TVD)	3091.8	2833.7	2365.1	1222.3	3751.2	3431.5	3100.8	3437.3	1355	1999.4

Figure 2. Stratigraphic chart, potential reservoirs and source rocks occurring within the Cretaceous to Pleistocene stratigraphic successions of the Beaufort-Mackenzie Basin (modified from Dixon *et al*., 1994, 2007).

RESERVOIR EVALUATION

Tuk M-18

Tuk M-18 well was drilled by Devon Canada Corporation to a total depth of 2966 m, and was spudded on December 24th, 2001. The well penetrated the Iperk and Aklak sequences, and the Mason River, Smoking Hills, Mount Goodenough, Kamik, McGuire, and Martin Creek formations, and it terminated within the Husky Formation. The primary targets of the well were the potential gas reservoirs in the Cretaceous Kamik sandstone and the shallower Tertiary Aklak section.

Calibrated by core analysis results (Fig. 3), petrophysical parameters are calculated and potential gas zones are identified primarily for the fine to medium-grained sandstone with interbedded siltstone of the Kamik Formation. From log analysis, the effective porosity values predominantly vary from 15 to 20% with the maximum > 25%. The calculated permeability values are mainly between 10 and 2000 mD, showing a similar range to those from core analysis results (Fig. 4). In the identified gas zones, water saturations are very low with indications of significant invasion by resistivity logs. Density-neutron porosity crossover occurs in most of the gas zones, with large separation between Sxo and Sw. Gas peaks also occur in the mud gas log. A laminated siltstone reservoir identified within the Martin Creek Formation has average porosity and permeability values of approximately 11% and 2 mD, respectively, with minor net pay. DST#1 (2681 - 2701.37 m TVD) indicates that the gas rate is 586 x 10^3 m^3/d during the cleanup period, and 290 x 10^3 m^3/d for the main flow period; for DST#2 (2643.2 - 2649.02 m TVD), the final gas rate is 860 x 10^3 m^3/d for the cleanup period and 422 x 10^3 m^3/d during the main flow period, supporting the well log interpretation (Fig.4).

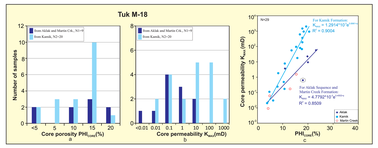

Figure 3. Core porosity and maximum permeability distributions (a and b), and core porosity versus permeability (c) for all core samples from three stratigraphic units; Martin Creek and Kamik formations, and Aklak Sequence of the Tuk M-18 well. The data points can be categorized into two groups by stratigraphy; Group 1 contains samples from Kamik Formation and Group 2 consists of samples from Aklak Sequence and Martin Creek Formation. Most of the porosity values from both groups range primarily from 10 to 20%, with the same peak value. However, big differences are observed in core permeability values between the two groups, which range mainly from 10 to >1000 mD for Kamik Formation, and from 0.01 to 10 mD for Aklak Sequence and Martin Creek Formation. Linear relationships are shown between core permeability and porosity on a semi-logarithmic plot for Kamik sandstone, and siltstones from Aklak Sequence and Martin Creek Formation (one circled shale sample is excluded). N: total number of core samples. N1: total number of core samples from Aklak Sequence and Martin Creek Formation; N2: total number of core samples from Kamik Formation.

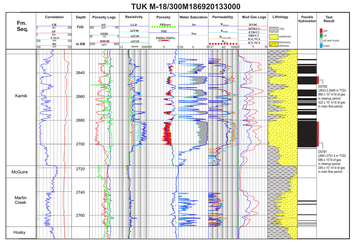

Figure 4. Log analysis results for the Tuk M-18 well. Calculated effective porosity values match the core measurements well. Three permeability models are applied for permeability calculation, including the Timur equation, the core equation from the core-based permeability-porosity correlation (Fig. 3), and the log-core based equation (from core permeability and resistivity logs). Overall, these models give permeability values that are compatible with the core measurements. For the Kamik Formation, the large crossover of density and neutron porosity occurs in all reservoirs except shaly zones. Calculated water saturation (Sw) values are very low in identified sandstone and siltstones. Obvious invasion is indicated by resistivity logs, and large separations occur between Sxo and Sw, showing good mobility and permeability. The gas log also supports most of the potential gas zones interpreted from log analysis.

Kurk M-15

Kurk M-15 well, located approximately 150 km north-northwest of Inuvik, was drilled vertically to a final total depth of 3093 metres by Petro-Canada and Devon Canada Corporation (formerly Anderson Exploration Ltd.) in February of 2001. It penetrated the Iperk, Taglu and Aklak sequences. The principal objective of this exploratory well was to evaluate potential gas reserves held in the Taglu Sequence; a secondary objective was the Aklak Sequence. The Kurk M-15 well was reported as a significant discovery (NEB, 2009, 2013; Northern Oil and Gas Branch, 2010).

Figure 5 presents well logs, a gas log, calculated petrophysical parameters, and identified possible hydrocarbon zones. From log analyses results and sample descriptions, the interpreted conventional hydrocarbon zones occur mainly in three intervals. Interval #1 (1342-1554 m) is in the lower Middle Taglu Sequence and includes fine to medium-grained sandstone reservoirs with average values of 22% porosity and 100 mD permeability that decrease at greater depth to 18% porosity and 20 mD permeability in very fine to fine-grained sandstones. Interval #2 (1588.5-1898.6 m) contains very fine to fine-grained sandstone in the top of the Lower Taglu Sequence with an average porosity of 19% and a permeability range mainly from 10 to 100 mD. MDT tests indicate several zones with gas shows, supporting the log analysis results. Interval #3 (2700-2876 m) contains interbedded very fine to fine-grained sandstones with hydrocarbons in the Aklak Sequence that have lower average porosity (15%) and permeability (~10 mD) but higher total gas in mud.

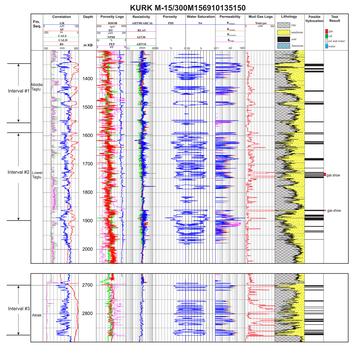

Figure 5. A composite plot showing log analysis results, consisting of lithological interpretation, and calculated petrophysical parameters for the Kurk M-15 well. Potential gas zones are identified in the Middle and Lower Taglu Sequence (upper panel), and Aklak Sequence (lower panel).

GR - gamma ray,
BS - bit size,
CALY - caliper Y,
HCAL - high resolution caliper
RHOB - bulk density
DT - sonic transit time
PEF - photo-electric factor
NPHI - original neutron porosity
RLA5, A40H, AHF90, AHT90, AIT90, M2R9 - deep resistivity log
RLA3/RLA4, P16H/P22H, AHF30, AHT30, AIT30, M2R3 - medium resistivity log
RLA1, P40H, AHF20, AHT20, AIT20/30, M2R2 - shallow resistivity log
PHI - calculated effective porosity
PHI_{CORE} - measured core porosity
$PHIN_C$ - corrected neutron porosity
$PHID_C$ - corrected density porosity
PHIN - uncorrected neutron porosity
PHID - uncorrected density porosity
SP - spontaneous potential
CALX - caliper X
CALS - sonic caliper

S_w - water saturation
S_{xo} - water saturation in the flushed zone
K_{TIMUR} - permeability from Timur equation
K_{TIXEUR} - permeability from Tixier equation
K_{COATES} - permeability from Coates equation
K_{SDR} - permeability from nuclear magnetic resonance log
K_{CORE} - permeability from core equation
K_{MAX} - measured core maximum permeability
$K_{XLOG/MAX}$ - permeability using equation from difference between deep and shallow resistivities

HYDC - total gas
METHC1 - methane
ETHC2 - ethane
PRPC3 - propane
IC4 - IBUT, iso butane
NC4 - NBUT, normal butane
IC5 - IPEN, iso pentane
NC5 - NPEN, normal pentane

Paktoa C-60

Paktoa C-60 well is the only offshore well drilled in the Beaufort-Mackenzie Basin since 1990. It was drilled by Devon Canada Corporation in 2005-06 to a total depth of 2382 m (2365 m TVD), and is located 31 km NW of Garry Island, and 180 km NW of Inuvik (Fig. 1). The well penetrated the Iperk, Mackenzie Bay, Kugmallit, Richards, and Taglu sequences. The primary objective of this well was to evaluate the hydrocarbon potential of the Taglu Sequence in the Paktoa structure; the secondary objective was to evaluate the shallower Kugmallit Sequence. The Paktoa C-60 well was declared as a significant discovery in the Beaufort Sea with 38 x 10^9 m^3 of recoverable oil (240 million barrels) (Oil&gas Journal, 2007; NEB, 2009; Drummond, 2009).

Log analysis results indicate that the identified main reservoir in the Upper Taglu Sequence consists predominantly of unconsolidated fine to coarse-grained sandstone and siltstone with minor carbonaceous minerals. Well testing DST#4 indicates oil was recovered at a flow rate of 190 m^3 per day. Fig. 9 illustrates a composite plot, consisting of well log data and petrophysical analysis results for the well.

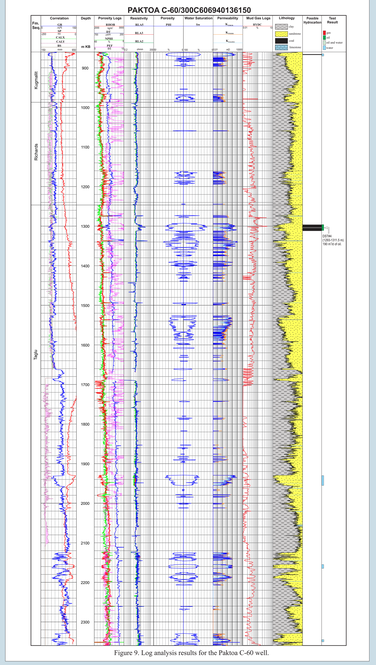

Figure 9. Log analysis results for the Paktoa C-60 well.

Olivier Field

Olivier H-01. Olivier 2H-01 and Olivier 3H-01 wells were drilled by Chevron Texaco with partner BP Energy Canada in the Mackenzie Delta near the edge of the Beaufort-Sea during 2004 and 2005. The objective of the wells was to evaluate the Taglu sandstones to determine the presence of hydrocarbons. The Olivier H-01 well was declared as a significant discovery (NEB, 2009, 2013).

The reservoir characteristics in Olivier H-01 well are evaluated based on core analysis data from the second-leg well Olivier 2H-01 and detailed petrophysical analyses of wireline well logs. Log analyses results indicate that possible hydrocarbon reservoirs occur in the top of Taglu Sequence, which mainly consists of very fine to coarse-grained sandstones. For the identified possible reservoir zones in the Olivier H-01 well, calculated porosity and permeability range predominantly from 15 to 25%, and 1 to 500 mD, respectively, showing similar trends to the core measurements in the Olivier 2H-01 well (Fig. 10). Fig. 11 illustrates well logs, calculated petrophysical parameters, and interpreted possible hydrocarbon zones for the Olivier H-01 well. DST#1 shows that 687 x 10^3 m^3 of gas was produced per day, supporting the well log interpretations.

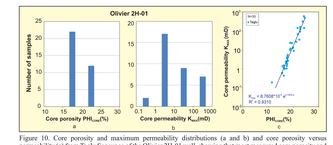

Figure 10. Core porosity and maximum permeability distributions (a and b) and core porosity versus permeability (c) from Taglu Sequence of the Olivier 2H-01 well, showing that most measured core porosity and permeability values range from 15 to 25% and 1 to 490 mD respectively. N: total number of core samples.

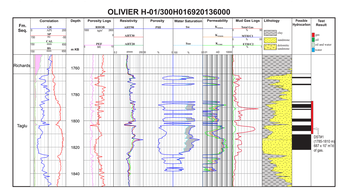

Figure 11. Log analysis results for the Olivier H-01 well. Potential gas zones are identified in the upper Taglu Sequence.

Ellice Field

Ellice I-48 well was drilled by Chevron Canada Resources in 2004 to a total depth of 3806 m (3751 m TVD), and was completed and tested in 2005. The well is located on Ellice Island in the Mackenzie Delta and mainly targeted the Aklak and Taglu sequences. In 2009, NEB confirmed the significant discovery (NEB, 2009). Potential hydrocarbon zones are interpreted from log analysis in Taglu sandstones characterized by good porosity (22% on average) and permeability (~120 mD on average). For DST#2, the maximum gas to surface is 950 x 10^3 m^3 per day, and 52.23 m^3 of condensate was recovered. Fig. 12 illustrates well logs and mud gas log, calculated porosity, permeability and water saturation, and identified potential gas zones, as well as production test results for the Taglu Sequence. No hydrocarbon potential is identified for the Aklak Sequence.

Ellice J-27 well was drilled by MGM Energy Corporation to a depth of 2102 m (1999.4 m TVD) from December of 2008 to January of 2009. The well penetrated the Iperk, Kugmallit, Richards, Taglu and Aklak sequences, and was perforated and tested in both the Aklak and Taglu sequences, yielding gas and demonstrating a significant discovery in Mackenzie Delta (NEB, 2009, 2013), with a contingent resource estimate of 9.3 x 10^9 m^3 of natural gas (Northern Oil and Gas Branch, 2009). Log analysis results indicate four possible hydrocarbon zones. One gas zone occurs in the Taglu medium-grained sandstone characterized by 20% average porosity and 70 mD average permeability. Three potential gas zones mainly occur in the fine to medium-grained sandstones within the Aklak Sequence, with average porosity of 16 to 20% and permeability of 10 to 200 mD, and high gas saturation (80% in average). The production tests indicate that the Aklak gas zone and Taglu gas zone flowed at a maximum rate of 1083 x 10^3 m^3/d and 632 x 10^3 m^3/d, respectively. Fig. 13 shows combined well logs and calculated petrophysical parameters, mud gas log, and production test results.

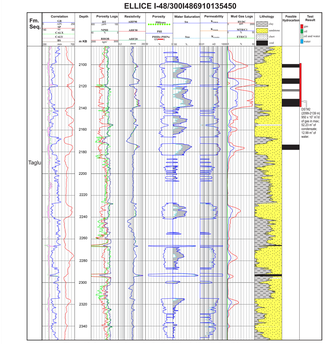

Figure 12. Log analysis results for the Ellice I-48 well. Possible gas zones are identified in the Taglu Sequence.

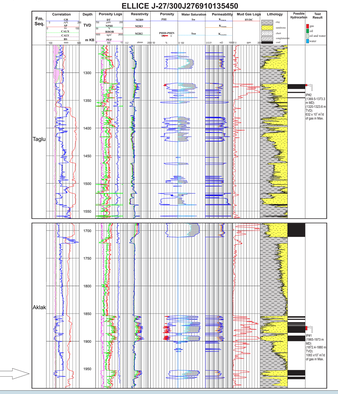

Figure 13. Log analysis results for the Ellice J-27 well. Possible gas zones are identified in the Taglu Sequence (upper panel) and Aklak Sequence (lower panel).

Langley Field

Langley K-30 well was drilled by Chevron Canada Resources in 2003 to a total depth of 1390 m (1222.3 m TVD) in the Mackenzie Delta on the edge of the Beaufort Sea, and it penetrated the Iperk, Richards and Taglu sequences. The main target of the well was the Taglu Sequence. Chevron Canada reported that the Langley K-30 well had encountered commercial quantities of natural gas (Chevron Texaco, 2003; Daily Oil Bulletin, 2003). NEB declared it a significant discovery (NEB, 2007, 2009, 2013). Gas zones are identified from log analysis in shallow part of the Taglu Sequence. The reservoir section consists predominantly of fine to coarse-grained sandstone and grey claystone, with quartz, chert and lithic grains (Datalog Canada Ltd., 2003). Log analysis results indicate that the average porosity is about 25%, estimated permeability values range mainly from 100 to 1000 mD, and the average water saturation is < 20%. Gas peaks on the mud gas log and a production test with 508 x 10^3 m^3 of gas per day support log interpretations. Fig. 14 shows a composite plot, consisting of well logs, calculated petrophysical parameters, interpreted lithology and potential hydrocarbon zones, as well production results.

Langley E-07, a vertical well, was drilled by MGM Energy Corporation during the 2007-2008 winter program in the Mackenzie Delta, with a total depth of 1355 m. The Langley E-07 well penetrated the Iperk, Richards and Taglu sequences, and it is located approximately 15 km southeast of the existing Langley K-30 discovery. The primary target of the well was the Taglu Sequence. MGM Energy Corporation announced the discovery (MGM Energy Corp., 2008). A possible gas reservoir is identified in the Taglu sandstone from log analysis and it has over 30% of porosity, over 1000 mD of permeability, and 30% of water saturation on average. The well test result indicates that gas was recovered at restricted flow rates of 388 x 10^3 m^3/d on a 2-inch choke (MGM Energy Corp., 2008). Fig. 15 illustrates well logs, calculated petrophysical parameters, a gas log and a well production test result.

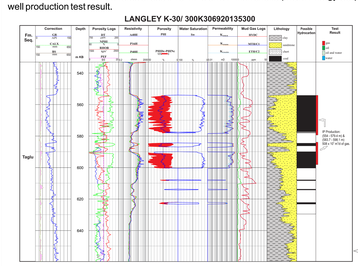

Figure 14. A composite plot showing log analysis results, consisting of lithological interpretations, calculated petrophysical parameters, and identified potential gas zones for the Langley K-30 well.

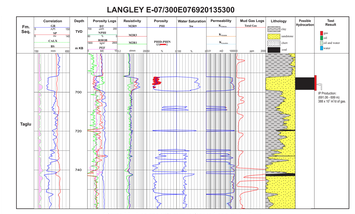

Figure 15. Log analysis results for the Langley E-07 well.

Umiak Field

The Umiak field lies onshore in the Mackenzie Delta portion of the Beaufort–Mackenzie Basin (Fig. 1). A partnership of EnCana, Anadarko and ConocoPhillips drilled the Umiak N-16 well in 2004 which led to the discovery of oil and gas in Eocene Taglu shoreface and delta front sands (Hogg et al., 2009). In 2005 the extent of the Umiak field was confirmed by the Umiak N-05 appraisal well. Together these two wells have delineated the fourth largest onshore gas accumulation on the Mackenzie Delta. NEB declared the two wells as significant discoveries (NEB, 2007, 2009, 2013). Core porosity and maximum permeability distributions from Taglu samples of the two wells are illustrated in Figure 6.

Umiak N-16 well was drilled in the Burnt Lake area in 2004 to a total depth of 3101 m. The well penetrated the Iperk, Kugmallit, Richards, and Taglu sequences; the main objective was to test the gas potential of the Taglu Sequence, and the Lower Richards Sequence. Log analysis indicates that possible gas zones occur from the top to lower section of the Taglu Sequence, which consists mainly of very fine to fine, and fine to coarse-grained sandstone, interbedded with siltstone and coal beds. The sandstones can be slightly dolomitic, partly with chert, and with minor carbonaceous material and pyrite (Datalog Canada Ltd., 2004). The identified gas reservoirs show 10 to 20% porosity and calculated permeability values are mainly from 20 to 200 mD. From thin section petrographic analysis (at depth of 2829.5 m), microporosity associated with kaolinite may affect effective porosity and reduce permeability (Core Laboratories, 2004). Three clean up/flow tests were performed, confirming two gas production zones (Fig. 7), supporting the log analysis results.

Umiak N-05 well was drilled about 2 km SE of the Umiak N-16 well in 2005 to a total depth of 3549 m, and it penetrated the Iperk, Kugmallit, Richards and Taglu sequences. The well targeted reservoirs in the Tertiary-aged lower Richards and Taglu Sequences on the Umiak structural anticline, and it is a significant discovery (NEB, 2007, 2009, 2013).

From log analysis, possible hydrocarbon reservoirs are identified in both the lower Richards and Taglu sequences. The lower Richards sandstones are generally very fine to medium-grained, and contain chert and quartz with occasional feldspar (Datalog Canada Ltd., 2005). The Richards sandstone reservoirs range from 10% to 25% in porosity, and 20 to 1000 mD in permeability. Taglu sandstones are typically very fine to medium-grained with occasional coarser interbeds. The sands are composed of chert and quartz grains with occasional feldspar grains and sedimentary rock fragments. Log analysis indicates that three hydrocarbon zones occur in the Taglu Sequence. In the upper and middle potential hydrocarbon zones, most porosity values are between 10 and 18%, and their permeability values range from 20-200 mD. The log- calculated hydrocarbon saturations may be lower than real values in some intervals due to poor borehole conditions. Gas and oil were recovered in two DSTs, supporting the log interpretations. The lower hydrocarbon zone in the Taglu Sequence shows better reservoir quality, with an average porosity of 18% and a wide permeability range mainly from 20 to 2000 mD, similar to the core measurements (Fig. 8).

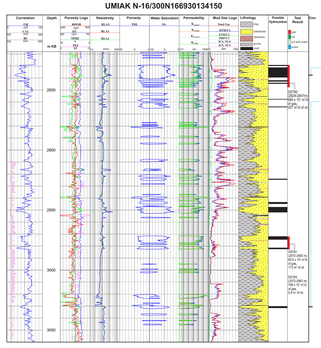

Figure 7. Log analysis results for the Taglu Sequence of the Umiak N-16 well.

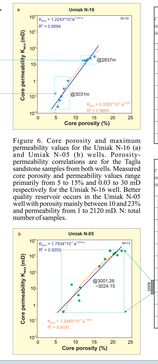

Figure 6. Core porosity and maximum permeability values for the Umiak N-16 (a) and Umiak N-05 (b) wells. Porosity-permeability correlations are for the Taglu sandstone samples from wells. Measured core porosity and permeability values range primarily from 5 to 15% and 0.03 to 30 mD respectively for the Umiak N-16 well. Better quality reservoir occurs in the Umiak N-05 well with porosity mainly between 10 and 23% and permeability from 1 to 2120 mD. N: total number of samples.

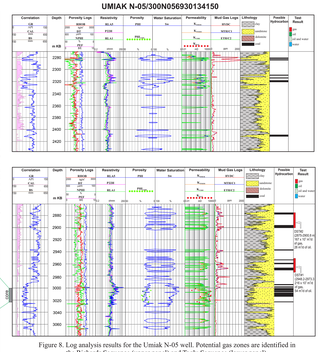

Figure 8. Log analysis results for the Umiak N-05 well. Potential gas zones are identified in the Richards Sequence (upper panel) and Taglu Sequence (lower panel).

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