Late Paleocene-Middle Eocene Source Rock Potential in the Arctic Beaufort-Mackenzie Basin

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Summary

The Natsek E-56 oil and gas exploration well from the Arctic Beaufort-Mackenzie Basin (BMB) was selected for a multi-disciplinary study because its strata contain a record of two major Eocene climate events that affected source rock deposition: the Paleocene/Eocene Thermal Maximum (PETM) at ~55.5 Ma and the early mid-Eocene *Azolla* event at ~49 Ma. Rock-Eval data from Natsek E-56 indicates a previously overlooked economically significant interval that occurs just below PETM strata. The pre-PETM unit is an organic rich (~30% TOC) coaly-shale deposit with good source rock potential and marginal thermal maturity. This carbonaceous deposit is characterized by a relatively elevated hydrogen index (HI~149 mgHC/TOC; S2~38 mgHC/g) which suggests increased input of liptinitic-rich material similar to the sapropelic boghead coal formed in lacustrine environments in the vicinity of the modern Beaufort-Mackenzie delta plain.

In recent years, source rock predictions for the Arctic Eocene were postulated from cores on the Lomonosov Ridge, focusing on organic matter (OM) produced during the *Azolla* event. OM associated with the *Azolla* event occurs in the Natsek E-56 (TOC ranges from 1-14%) but reworked terrestrial matter is dominant. The pre-PETM organic rich interval of Natsek E-56 was not recorded from the Lomonosov Ridge, while in Natsek E-56 the interval consists of TOC values double that recorded at any point from the Lomonosov Ridge. Additionally in the BMB, a younger (early Eocene), but similar, TOC-rich interval was recorded from the oil-bearing Immiugak A-06 well. The occurrence of multiple potential source rocks from unique depositional environments in the BMB indicates oil and gas potential in late Paleocene-middle Eocene strata of the Beaufort-Mackenzie region.

Introduction

During the 2000's, demand for natural gas and crude oil in North America and worldwide increased, sparking a renewed interest in the search for additional petroleum resources in circum Arctic regions, including the Beaufort-Mackenzie Basin (BMB) on the northern margin of the Canadian mainland (Bergquist et al., 2003) (Fig.1). The increased interest led to developing and identifying methods to better characterize potential source rocks to aid in targeting areas for future exploration. Using Rock-Eval data Snowdon et al. (2004) in the BMB and Boucsein and Stein (2009) in ACEX (Arctic Coring Expedition - drilled by the IODP Expedition 302 in 2004) both show evidence of high organic matter (OM) accumulation during the late Paleocene and early Eocene. This work demonstrates that Eocene climate events have created hydrocarbon source rock units of economic potential. Uncertainty remains, in the regional extent of these units, their temporal correlation, and thermal maturity. These issues are critical for understanding regional petroleum potential in the circum Arctic region. The Natsek E-56 well was selected for detailed study because it's one of the few wells that preserve a record of terrestrial deltaic and fossiliferous marine strata spanning the PETM and the middle Eocene *Azolla* event, preserved in the Aklak and Taglu sequences respectively.

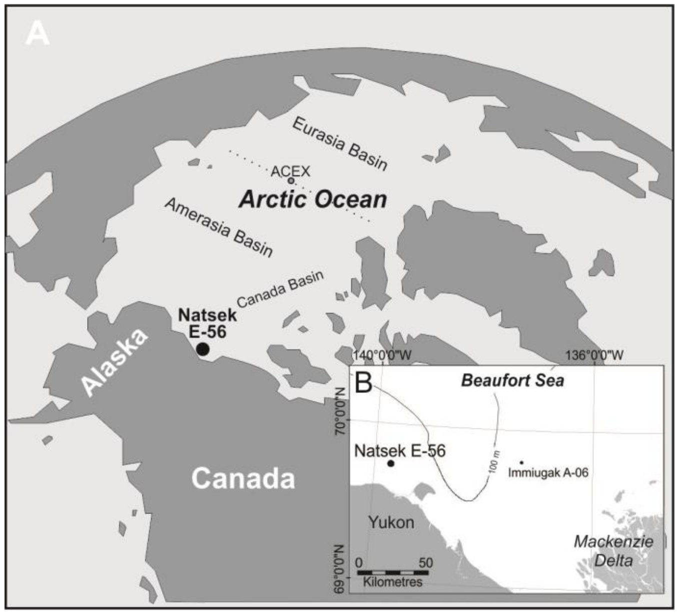

Figure 1: A) location of the study site (Natsek E-56) in comparison to the location of the Arctic Coring Expedition (ACEX) on the Lomonsov Ridge in the Arctic Ocean. The location of the Lomonosov Ridge is indicated by the dashed line; B) location of Natsek E-56 and Immiugak A-06 in the Canadian Beaufort-Mackenzie Basin. Contour line indicates water depth.

Method

Additional information on Natsek E-56 can be found in Neville et al. (2015).

Rock-Eval Pyrolysis

Total organic carbon (TOC) content and Rock-Eval parameters were determined on bulk ground samples to get information about the source-rock potential, presence of hydrocarbons, and maturity. Rock-Eval 6 pyrolysis was conducted at the Geological Survey of Canada (Calgary) on a Rock-Eval 6 Turbo device following the *Basic Method* as described by Lafrague et al. (1998) and Behar et al. (2001).

Examples

Natsek E-56 archives a relatively complete record of the complex stratigraphic and structural strata of the BMB penetrating the economically significant Taglu Sequence and the less frequently investigated but also potentially economically significance Aklak Sequence (Dixon et al., 1994).

Source rock characterization and hydrocarbon potential

Natsek E-56 is generally characterized by poor to good source rock potential. High S2 values of 1.58-51.64 mg HC/g indicate that most of the organic-rich (TOC ranging from 1.67-34.02 wt.%, avg. 8.14 wt.%) late Paleocene Aklak Sequence sediments have marginal to good source-rock potential (Table 1; Fig. 2). HI values through the entire record, of > 200 mgHC/TOC suggest that the intervals with good source-rock potential are prone to generate a gas to gas/oil mixture when the level of thermal maturity ("oil window") is reached. Based on the range of T_{max} values the level of thermal maturity is estimated to correspond to between 0.49-0.67 % Ro equiv, which indicates immaturity of the OM in the majority of samples.

OM accumulation

The marine and terrestrial deltaic strata deposited during the late Paleocene and early-middle Eocene in Natsek E-56 show significant OC accumulation (TOC 0.35-34.02 wt.%) similar to and higher than that characterized during the same time period in other wells in the BMB and elsewhere in the Arctic.

Early Eocene sediments of fair to good source-rock potential have also been reported at ACEX, on the Lomonosov Ridge. Rock-Eval values reported in ACEX during the early Eocene are similar to Natsek E-56 (TOC 0.35-2.69 wt.%) (Stein, 2007) but Natsek E-56 does not mirror the increase in OC observed in ACEX during the *Azolla* event (a period of time when fresh water is thought to have covered the entire Arctic Ocean). Regional Arctic data suggests that during the restricted marine conditions of the Eocene, the Lomonosov Ridge may have separated the Arctic Ocean into two distinctive bodies of water creating differing depositional environments (Shephard et al., 2013). It is possible that the separation of the basin may have allowed for higher *Azolla* accumulation in the eastern side of the modern-day Arctic Ocean compared to the Beaufort-Mackenzie.

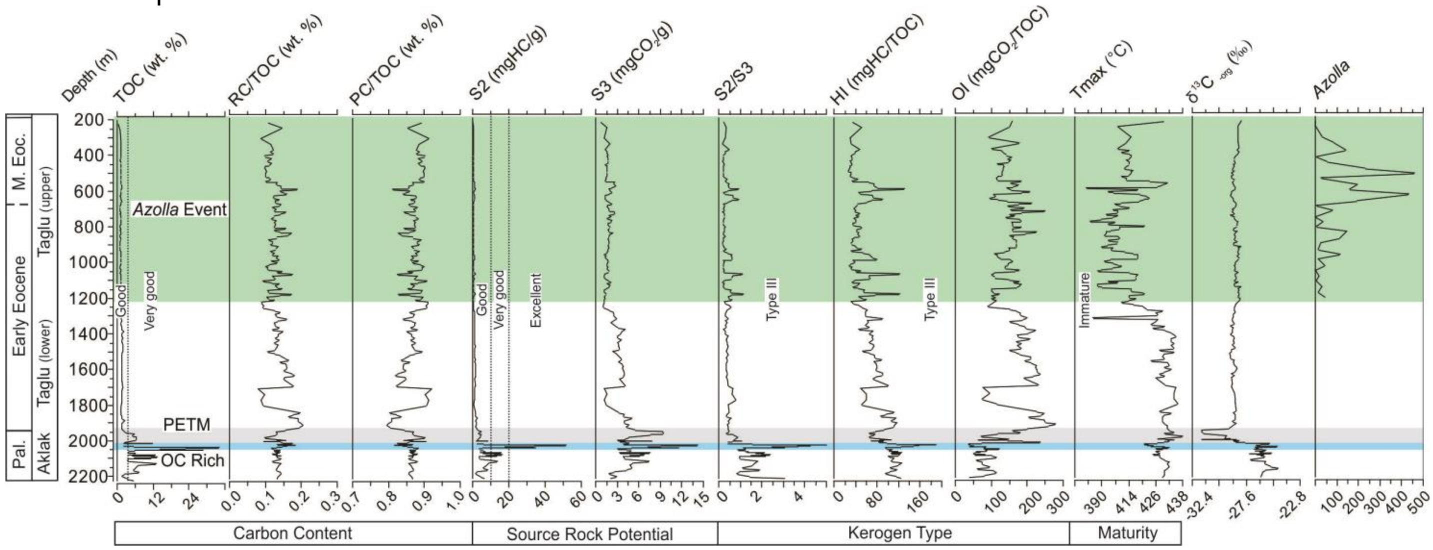

Figure 2: Natsek E-56 stratigraphy, depth (meters below K.B.), Rock Eval results (total organic carbon (TOC); pyrolyzed carbon (PC); residual carbon (RC); mineral carbon (MinC); hydrogen index (S2 x 100/TOC) (HI); oxygen index (S3 x 100/TOC) (OI)) carbon isotope organic carbon ($\delta^{13}C_{-org}$) and *Azolla* abundance.

Table 1: Summary of Natsek E-56 Rock-Eval (production index (PI); pyrolyzed carbon (PC); residual carbon (RC); total organic carbon (TOC); hydrogen index (HI); oxygen index (OI); mineral carbon (MinC)) and carbon isotope organic carbon ($\delta^{13}C_{-org}$) results showing the fluctuation in parameters between stratigraphic units. The results are further subdivided to show additional fluctuations within the sequences. The average of the results for the entire sequence are in bold. The average for the entire section below the PETM is also reported. The section below the PETM was further subdivided to identify the depth of the significant increase in TOC. The full Rock-Eval data set for Natsek E-56 can be found in Neville et al. (2015).

Sequence		Depth m	S2 mgHC/g	S3 $mgCO_2/g$	S2/S3	PI[a]	Tmax °C	TOC wt.%	HI[b] mgHC/TOC	OI[c] $mgCO_2$/TOC	MinC wt.%	PC/TOC wt.%	RC/TOC wt.%
Taglu	**Entire Taglu**	**1950-229**	**0.80**	**2.19**	**0.37**	**0.18**	**417.47**	**1.33**	**57.03**	**161.03**	**0.34**	**0.13**	**0.87**
	Azolla event	1226-229	0.57	1.72	0.35	0.19	411.67	1.17	47.92	148.32	0.34	0.13	0.87
	Lower Taglu	1226-1950	1.22	3.05	0.41	0.16	428.17	1.62	73.85	184.50	0.35	0.14	0.86
Aklak	**Entire Aklak**	**1950-2226**	**10.00**	**5.49**	**1.54**	**0.06**	**428.70**	**8.14**	**108.15**	**93.93**	**0.82**	**0.14**	**0.86**
	PETM	2037-1950	3.55	5.37	0.69	0.08	431.31	4.41	85.23	143.15	0.91	0.14	0.86
	TOC peak	2052-2037	38.06	10.28	3.68	0.02	422.67	25.35	149.00	41.17	0.89	0.15	0.85
	Below TOC peak	2226-2052	6.87	4.48	1.47	0.06	428.78	6.11	110.11	81.96	0.76	0.13	0.87

[a] Production index (S1/(S1+S2)
[b] Hydrogen index (S2 x 100/TOC)
[c] Oxygen index (S3 x 100/TOC)

Aklak – Interval of high source rock potential (TOC peak)

High S2 values of 1.58-51.64 mgHC/g indicate that most of the OC-rich (TOC 1.67-34.02 wt.%, avg. 8.14 wt.%) late Paleocene Aklak Sequence sediments have marginal to good source-rock potential (Powell, 1978) (Table 1; Fig. 2), and HI values (65-189, avg. 108.15 mgHC/g) suggest a source for gas, with some potential for expel liquids when the level of thermal maturity is reached. A follow up study on ACEX conducted by Boucsein and Stein (2009) also report a late Paleocene interval with higher hydrocarbon generation (TOC 0.5-4 wt.%) potential. However, unlike ACEX, Natsek E-56 also contains the “TOC peak” interval below the PETM where TOC reaches an average of 25.35 wt.% (Table 1).

Within the Aklak Sequence, just prior to the PETM (2052-2037 m), Natsek E-56 records the “TOC peak” interval (Table 1), a layer not yet observed, but likely present, elsewhere in the BMB. This interval consists of organic rich (TOC 14.49-34.02, avg. 25.35 wt.%), black oil shale coaly deposits with “good” source rock potential (Powell, 1978), characterized by elevated hydrogen-rich (S2 18.09 - 51.64, avg. 38.06 mgHC/g) material associated with increased input of algal matter. The high OC values recorded in the ‘TOC peak” are similar to values from the Barents Sea and the northern North Atlantic off Norway, where black shales are characterized by OC contents typically between 15-25 wt.% with peak values of ~30 wt.% (Leith et al., 1992; Langrock et al., 2003; Langrock and Stein, 2004).

Conclusions

Conditions in the BMB during the late Paleocene were favorable to TOC accumulation as TOC values recorded here are ~2% higher than those recorded on the Lomonosov Ridge during the same time interval. Within the already high potential late Paleocene sediments, is an organic rich interval reported exclusively in Natsek E-56; the “TOC peak” (HI values avg. 149 mgHC/g, S2 values avg. 38.06 mgHC/g and TOC avg. 25.23 wt.%). The unique depositional characteristics of the BMB (autochthonous boghead lacustrine environment) were favorable to the accumulation and preservation of OC with good hydrocarbon generation potential. The overall high TOC and extremely organic rich “TOC Peak” interval suggest the late Paleocene to early Eocene rocks of the BMB are of higher economic value than those from the Lomonosov Ridge. The difference in potential is related to the significant difference in depositional environment between the two locations (terrestrial bog versus marine).

Acknowledgements

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References

Behar, F., Beaumont, V., De B. Penteado, H.L., 2001. Rock-Eval 6 technology: performances and developments. Oil and Gas Science and technology – Rev. IFP 56, 11–134.

Bergquist, C.I., Graham, P.P., Johnston, D.H., Rawlinson, K.R., 2003. Canada’s Mackenzie Delta: fresh look at an emerging basin. Oil and Gas Journal 101, 42-46.

Boucsein, B., Stein, R., 2009. Black shale formation in the late Paleocene/early Eocene Arctic Ocean and paleoenvironmental conditions: New results from a detailed organic petrological study. Marine and Petroleum Geology 26, 416-426.

Dixon, J., Morrel, G.R., Dietrich, J.R., Taylor, G.C., Procter, R.M., Conn, R.F., Dallaire, S.M., Christie, J.A., 1994. Petroleum resources of the Mackenzie Delta and Beaufort Sea Geological Survey of Canada, Bulletin 474, pp 64.

Lafargue, E., Marquis, F., Pillot, D., 1998. Rock-Eval 6 Applications in Hydrocarbon Exploration, Production and Soil Contamination Studies. Oil & Gas Science and Technology– Revue de l’Institut Français du Pétrole 53, 421-437.

Langrock, U., Stein, R., 2004. Origin of marine petroleum source rocks from the late Jurassic/Early Cretaceous Norwegian Greenland Seaway-evidence for stagnation and upwelling. Marine and Petroleum Geology 21, 157–176.

Langrock, U., Stein, R., Lipinski, M., Brumsack, H., 2003. Late Jurassic to Early Cretaceous black shale formation and paleoenvironment in high northern latitudes-examples from the Norwegian-Greenland- Seaway. Paleoceanography.

Leith, T.L., Weiss, H.M., Mørk, A., Arhus, N., Elvebakk, G., Embry, A.F., Brooks, P.W., Stewart, K.R., Pchelina, T.M., Bro, E.G., Verba, M.L., Danyushevskaya, A., Borisov, A.V., 1992. Mesozoic hydrocarbon source-rocks of the Arctic region. In: Vorren, T.O., et al. (Eds.), Arctic Geology and Petroleum Potential, NPF Special Publications 2, pp. 1–25.

Neville, L.A., McNeil, D.H., Grasby, S.E, Galloway, J.G., Sanei, H., Dewing, K., 2015. Rock-Eval Pyrolysis results for cuttings samples from the Natsek E-56 well, Beaufort-Mackenzie Basin, Canada. Geological Survey of Canada, Open File Report 7949.

Powell, T.G., 1978. An assessment of the hydrocarbon source rock potential of the Canadian Arctic Islands. Geological Survey of Canada Paper 78-12, pp. 82.

Shephard G.E., Müller, R.D., Seton, M., 2013. The tectonic evolution of the Arctic since Pangea breakup: Integrating constraints from surface geology and geophysics with mantle structure. Earth-Science Reviews 124, 148-183.

Stein, R., 2007. Upper Cretaceous/lower Tertiary black shales near the North Pole: organic-carbon origin and source-rock potential. Marine and Petroleum Geology 24, 67–73.