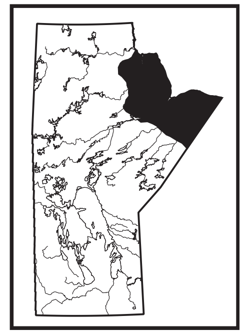
GS-11 Oil shale and reservoir rocks of the Hudson Bay Lowland, northeastern Manitoba (part of NTS 54)

by M.P.B. Nicolas and D. Lavoie[1]



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Summary

The Hudson Bay and Foxe Basins Project is in its fourth and final year. It is part of the Geological Survey of Canada Geo-mapping for Energy and Minerals (GEM) program. In Manitoba, the Hudson Bay Basin is represented by the Paleozoic carbonate succession of the Hudson Bay Lowland in the northeastern corner of the province.

Core samples for biostratigraphical analysis were collected, and conodont and chitinozoan analyses were used to assist in formational assignments. RockEval™ 6 analyses were conducted on 37 samples from Silurian and Ordovician formations to identify potential source rocks in the succession preserved in the Hudson Bay Lowland of Manitoba.

Overall, the RockEval™ 6 analyses resulted in the recognition of a fair number of samples having moderate to good source rock potential, but most of them are considered thermally immature. One sample from the Red Head Rapids Formation yielded a total organic carbon content of 8.44 wt. %, thus it is considered a true oil shale, and confirms the extension of previously found oil shale units in Nunavut and northern Ontario. Two samples of the Red Head Rapids Formation from the Sogepet Aquitaine Kaskattama Prov. No. 1 well are considered thermally mature with excellent oil generation potential.

Previously, the presence of hydrothermal dolomite in core in the Hudson Bay Lowland was confirmed petrographically and with stable isotopes geochemistry. Two more occurrences of potential hydrothermal dolomite in core indicate that this type of feature may be common in the Hudson Bay Lowland. A magnetotelluric survey near the confirmed hydrothermal dolomite occurrence indicated potential porous zones in the subsurface, which is common in hydrothermal dolomite.

This project has demonstrated that the Hudson Bay Basin has all the right elements and conditions for hydrocarbon systems to exist, including mature and diverse source rocks, attractive reservoirs and efficient traps and seals.

Introduction

The Hudson Bay and Foxe Basins Project of the Geo-mapping for Energy and Minerals (GEM) program is in its fourth and final year. The project objective is to document the potential hydrocarbon systems in the successions of the Hudson Bay and Foxe basins by reassessing available geoscience data and acquiring new data in areas or domains that have knowledge gaps (Nicolas and Lavoie, 2009). Led by the Geological Survey of Canada, partners in this project include the National Energy Board, Northern and Indian Affairs Canada, Canadian and international universities, and the Manitoba, Ontario and Nunavut governments. The Manitoba component of the project is located on land in the Hudson Bay Lowland (HBL) of northeastern Manitoba, on the southwestern rim of the Hudson Bay Basin (Figure GS-11-1).

The Hudson Bay Basin is an intracratonic basin consisting of dominantly Paleozoic sedimentary strata with minor overlying Cretaceous and Tertiary strata in places. The Hudson Bay Basin and the adjacent Foxe Basin in the north and Moose River Basin in the south, together cover 25% of Canada's landmass. The modern Hudson Bay sits on the remnant of this ancient basin. The Hudson Bay Basin has offshore areas and onshore exposures in southern Nunavut, with significant onshore strata in northern Ontario and northeastern Manitoba, and minor exposures in northwestern Quebec.

Very little hydrocarbon exploration has been undertaken in the Hudson Bay Basin, with the most recent exploration activities occurring over 25 years ago. Only nine hydrocarbon exploration wells were drilled in the basin: five offshore wells located in the centre of the basin and four onshore wells, including three in Manitoba and one in Ontario. The three Manitoba wells have geophysical logs and fairly continuous core for the length of each well. Mineral exploration drillcore from Manitoba and Ontario have provided additional core for this study. Nicolas and Lavoie (2010) list all of the onshore Paleozoic core available in Manitoba, with the exception of the Foran Mining Kaskattama Kimberlite No. 1 (Foran KK1) core (Zone 15, 0630684E, 6236761N, NAD83). The Foran KK1 core was found in the core library after the publication of Nicolas and Lavoie (2010). The Foran KK1 core was acquired by Foran Mining Corporation in 2004 when exploring for kimberlitic intrusions. The borehole was drilled vertically to a total depth of 332.2 m

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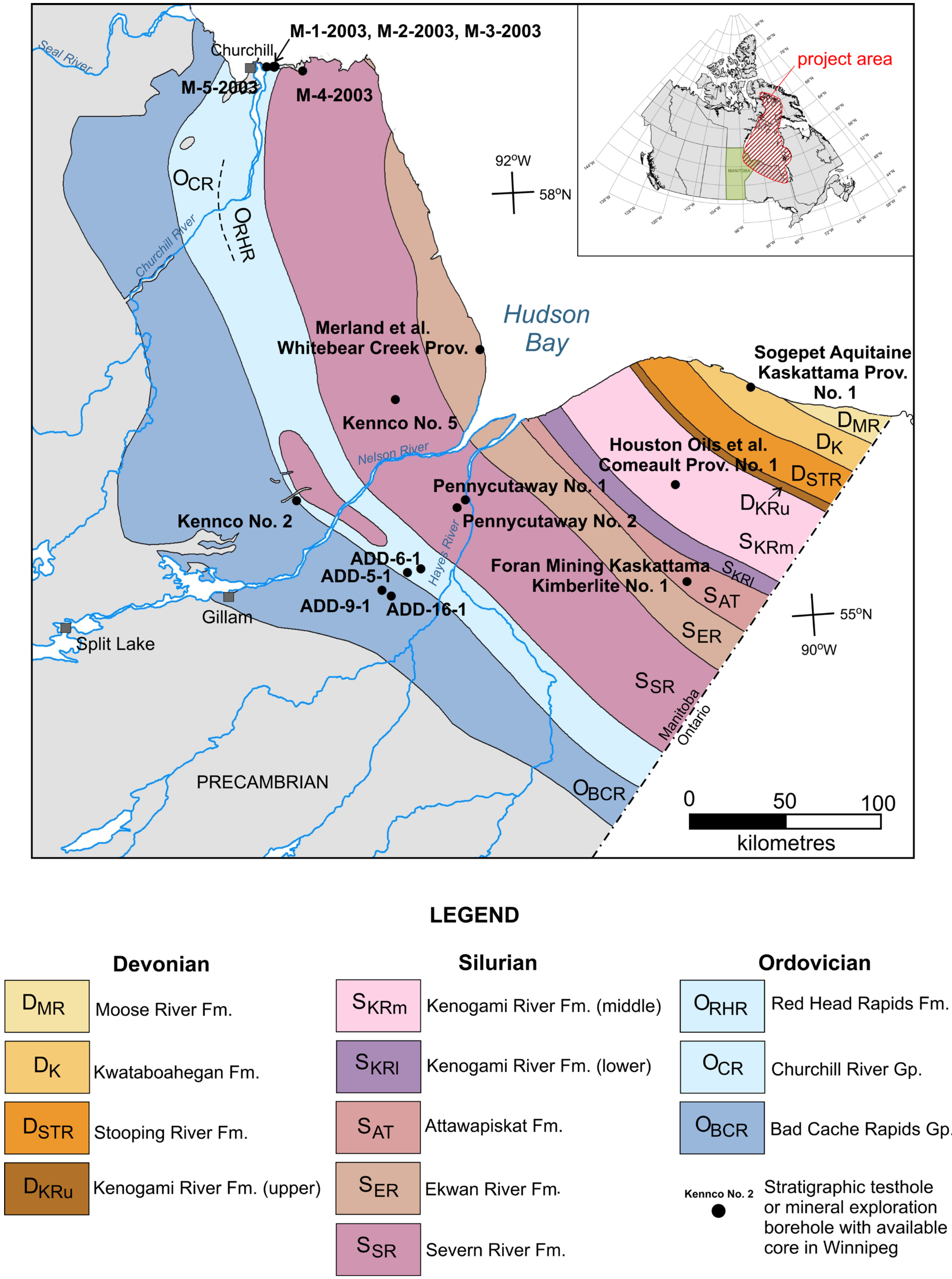

***Figure GS-11-1:** Hudson Bay Lowland in northeastern Manitoba, showing the location of cores available; inset shows the project area for the Geo-mapping for Energy and Minerals' Hudson Bay and Foxe Basins Project.*

and recovered 260.0 m of Quaternary and Tertiary sediment overlying 72.2 m of Paleozoic carbonate rocks. The Paleozoic formations cored represent the section from the uppermost Ordovician Red Head Rapids Formation to the Silurian Severn River Formation.

Over the last two years, sampling of HBL Paleozoic cores was conducted for biostratigraphical and geochemical analysis. The purpose of the biostratigraphical analysis was to assist in the formational assignment of the units seen in the core, with the ultimate purpose to correlate the sedimentary succession observed in Manitoba with the newly erected stratigraphic framework in the central part of Hudson Bay (Hu et al., 2011) and with the framework currently being revised in neighbouring northern Ontario. The geochemical analyses included RockEval™ 6 to test for potential source rock horizons in the lower Paleozoic succession of the HBL in Manitoba as Ordovician source rocks are now identified at numerous localities in the basin (Armstrong and Lavoie, 2010; Zhang, 2010, 2012). In addition, oxygen and carbon stable isotopes of carbonate rocks were analyzed to determine the possibility of fault-controlled, hydrothermal fluid circulation associated with the formation of hydrocarbon reservoirs, which has been recognized and proposed in Manitoba and Nunavut (Lavoie et al., 2011). In parallel with this work, a geophysical magnetotelluric survey was conducted by the Geological Survey of Canada in the Churchill area to investigate the subsurface distribution of porous zones near to a known occurrence of hydrothermal dolomite (HTD).

Sampling results

Biostratigraphy

Core samples of coarse carbonate rocks from the Silurian section of the Merland et al. Whitebear Creek Prov. well (Figure GS-11-2) were sampled for conodont biostratigraphy in order to get a better understanding of the formational boundaries in this well (McCracken, 2011). Ordovician samples were not collected since this section had been previously analyzed by LeFèvre et al. (1976). Of the 11 Silurian samples submitted, five samples were either barren of microfossils or the age was indeterminable, two samples provided only a general age assignment of Middle Ordovician to Middle Devonian, and the remaining four samples yielded enough fossils to assign a probable Llandoverian age (McCracken, 2011). Some of the formation tops for this well (Nicolas, 2011) were assigned using the new conodont biostratigraphy information as a guide, particularly for the Silurian Severn River, Ekwan River and Attawapiskat formations (Figure GS-11-2).

Core samples of shaly limestone, micritic limestone and shale were collected for palynological biostratigraphical analysis (based on chitinozoans) from the Whitebear Creek Prov., Sogepet Aquitaine Kaskattama Prov. No. 1, Houston Oils et al. Comeault Prov. No. 1 and Foran KK1 cores (Figure GS-11-2). Of the 24 samples submitted, only six yielded organic matter and five of those had scolecodonts fossils (Asselin, 2012), which can be used for biostratigraphical dating. Unfortunately, Asselin (2012) reported that the quality and quantity of the scolecodonts were insufficient to make any conclusions on the age of samples or their thermal organic maturation.

RockEval™ 6 geochemistry

A total of 37 samples was collected from eight wells, covering various Ordovician and Silurian units at different depths; sampled intervals for four of these wells are shown in Figure GS-11-2. Samples were specifically chosen based on their argillaceous shale content and dark colouration. Also included were two samples of dark brown Lower Silurian carbonate rock that were suspected to be oil stained (Figure GS-11-3). The RockEval™ 6 geochemistry results are presented in MGS Data Repository Item DRI2012002[2].

Several dark brown, shaly, finely laminated intervals occur in the Upper Ordovician Red Head Rapids Formation and in the lower part of the Lower Silurian Severn River Formation (Figure GS-11-4). Many of these laminae were sampled but, due to their extreme thinness, sample isolation was difficult and often included sampling of the surrounding mudstone, which resulted in dilution of the sample analysis and affected the total organic carbon (TOC) results (DRI2012002). However, sample number 106-11-HBL-WB-7 from the Red Head Rapids Formation in the Whitebear Creek Prov. core represents the only sample that consists entirely of the dark brown laminae (Figure GS-11-4b), and also yielded the highest TOC value and a high hydrogen index (HI) result (Figure GS-11-5). While the TOC values for laminae in this well ranged from 0.19 to 1.79 wt. %, sample 106-11-HBL-WB-7 yielded a TOC of 8.44 wt. % (Figure GS-11-6). This classifies it as an oil shale and excellent potential hydrocarbon source rock (Peters, 1986), and compares well with values reported for coeval black shales in Nunavut (Zhang, 2010, 2012) and Ontario (Armstrong and Lavoie, 2010). Of particular interest is the fact that if the encasing organic-poor material can dilute TOC values, the HI and S2 (the number of milligrams of hydrocarbons generated by pyrolytic degradation of the kerogen from one gram of

[2] MGS Data Repository Item DRI2012002, containing the data or other information sources used to compile this report, is available online to download free of charge at http://www2.gov.mb.ca/itm-cat/web/freedownloads.html, or on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Innovation, Energy and Mines, 360–1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

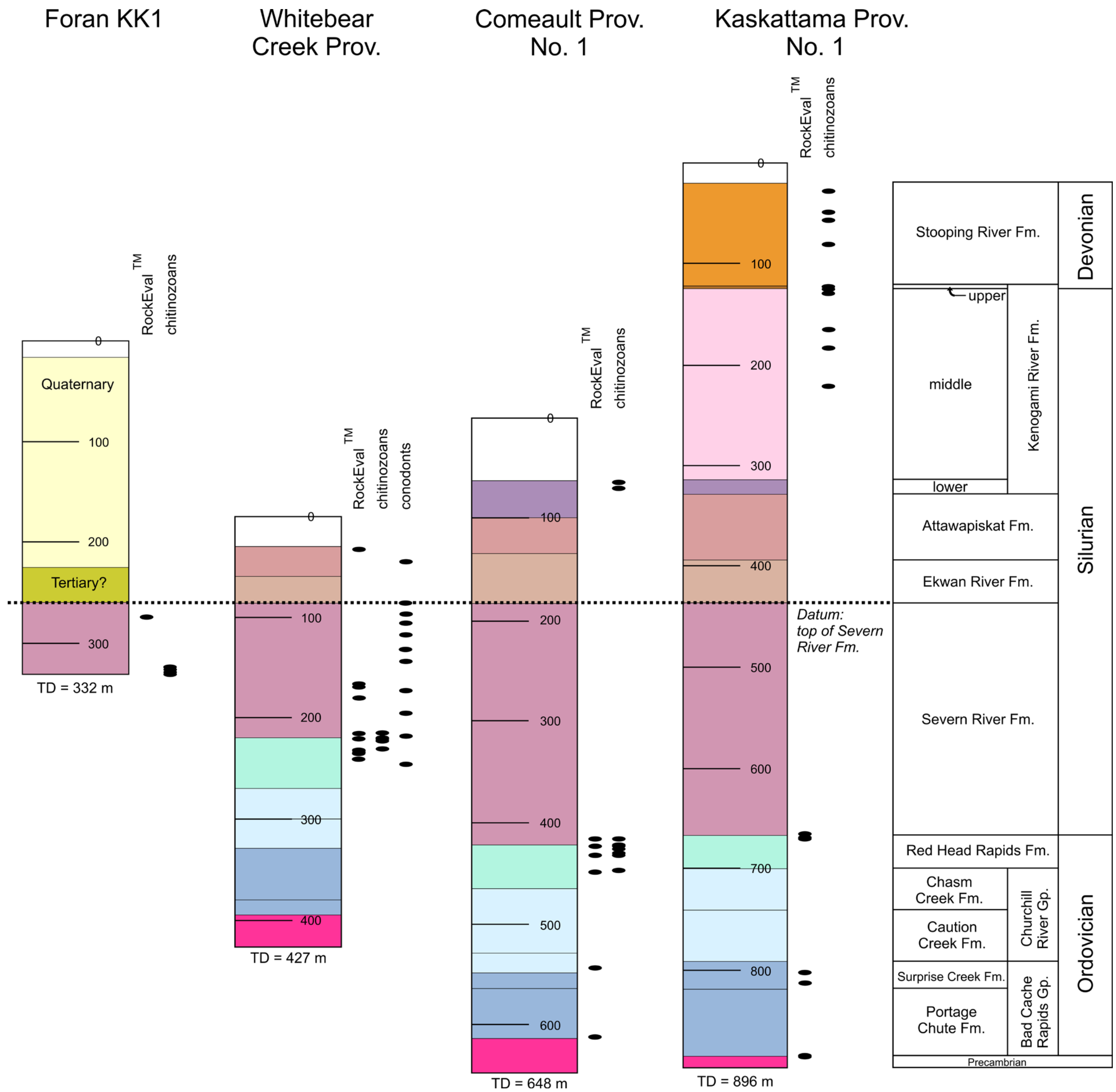

***Figure GS-11-2:** Stratigraphic columns for four of the wells on which sampling was conducted for Rock Eval™6 geochemistry and conodont and chitinozoan biostratigraphy; sampled intervals are shown by the black dots; depths are in metres. Figure GS-11-1 shows the well locations in northeastern Manitoba. Formations are indicated by similar colours used in Figure GS-11-1, with the exception of the Red Head Rapids Formation, which has been separated out from the Churchill River Group in this figure.*

rock) values are indicative of the nature of the undiluted organic material in the black laminae. The data table in DRI2012002 shows that several samples with relatively fair TOC values (>1%) are characterized by HIs of more than 300, low oxygen indices (OI <50) and S2 values of more than 4 mg/g. The HI versus OI values are indicative of fair Type II organic matter (Figure GS-11-5) whereas the high S2 values (DRI2012002) indicate good source rock potential; the best samples fall in the blue box in Figure GS-11-5. In this dataset, the Ordovician Red Head Rapids and the Silurian Severn River formations have intervals with good source rock potential.

For most samples, the temperatures at maximum release of hydrocarbons (T_{max}) indicate immature rocks (Figure GS-11-6a). The T_{max} values range from 408 to 440°C (T_{max} values below 400°C are disregarded due to the unreliability of this measurement at low temperatures), including two samples from the Red Head Rapids Formation in the Kaskattama Prov. No. 1 well that have values (439 and 440°C, DRI2012002) over the assumed threshold of oil generation (435°C). However, T_{max} values do not increase with depth in this well, and the underlying unit (Bad Cache Rapids Group) has lower T_{max} values (421–428°C); this indicates that T_{max} could

Figure GS-11-3: *Core showing potential oil staining of the Severn River Formation in the Houston Oils et al. Comeault Prov. No. 1 well, northeastern Manitoba (see Figure GS-11-1 for location) at a depth of 415.4 m; scale in centimetres.*

be a somewhat arbitrary indicator of thermal maturation. The T_{max} suppression by kerogen generation from algal-bacterial–rich organic matter is a possibility to partially explain low values in potential oil-prone source rocks (Snowdon, 1995). This potential effect can be seen in the Red Head Rapids Formation of the Whitebear Creek Prov. well in a short 22.5 m interval (220.98–243.53 m), in which T_{max} values should be rather consistent. However, the high TOC and HI sample 106-11-HBL-WB-7 (source rock) has a significantly lower T_{max} value of 420°C compared to almost all of the other samples in this 22.5 m sampling interval (values of between 425 and 429°C, DRI2012002). A similar effect on coeval source rocks in northern Ontario has been reported and the possibility of T_{max} suppression has been proposed based on detailed organic matter reflectance analyses suggesting oil window conditions. Consequently, T_{max} values for high TOC and HI source rocks can be an unreliable indicator of thermal conditions (Armstrong and Lavoie, 2010).

The production index (PI) indicates the capacity of a rock to produce hydrocarbons and measures the in situ hydrocarbon generation. Samples with a PI between approximately 0.1 and 0.4 (oil window) are thermally mature (Peters, 1986), whereas PI values below 0.1 indicate thermal immaturity and lack of oil generation. Figure GS-11-6b shows the PI plotted against depth, with many samples falling within the oil window. While it was stated above that some of the results may be erratic, samples from the Kaskattama Prov. No. 1 well show consistently reliable results. The PI results from this well plot between 0.1 and 0.4. These PI values combined with their depths are good indicators that these rocks have been subjected to conditions favourable for oil generation at one point in their burial history. Of interest here is that while most of the recent research done in the Hudson Bay Basin points towards the Red Head Rapids Formation as the best oil source, other horizons, namely the Severn River Formation, Churchill River Group (Caution Creek Formation) and Bad Cache Rapids Group may also have some hydrocarbon potential. The organic-rich layers in the Bad Cache Rapids Group are restricted to parts of the Surprise Creek Formation and Member 1 (basal sand) of the Portage Chute Formation. The results from the Attawapiskat Formation are also interesting since this formation is dominantly reefal with excellent reservoir potential (Ramdoyal, 2012). However, only one sample from the Attawapiskat Formation was collected, so care must be taken in such interpretations without a larger sampling density to support it.

The TOC results from the sample suite are equally interesting (Figure GS-11-6c). Many of the samples returned values above 0.5 wt. %, which is the minimum threshold to be considered a ‘fair’ source rock (Peters, 1986). Only one sample, 106-11-HBL-WB-7 as indicated above, has a TOC value far exceeding the other samples.

When considering all the applied criteria to classify a rock as having good source rock potential, there are two samples that stand out in Figure GS-11-6: K-2195.8 and 106-10-HBL-Kask-1 (DRI2012002). Both are deep samples, from around 670 m depth, and are from the Red Head Rapids Formation in the Kaskattama Prov. No. 1 well. Their T_{max} and PI fall within the oil window, but their TOC values are quite low (0.34 and 0.55 wt. %). It is possible that the low TOC values resulted from dilution of the source rock zone with sterile, encasing, organically poor facies.

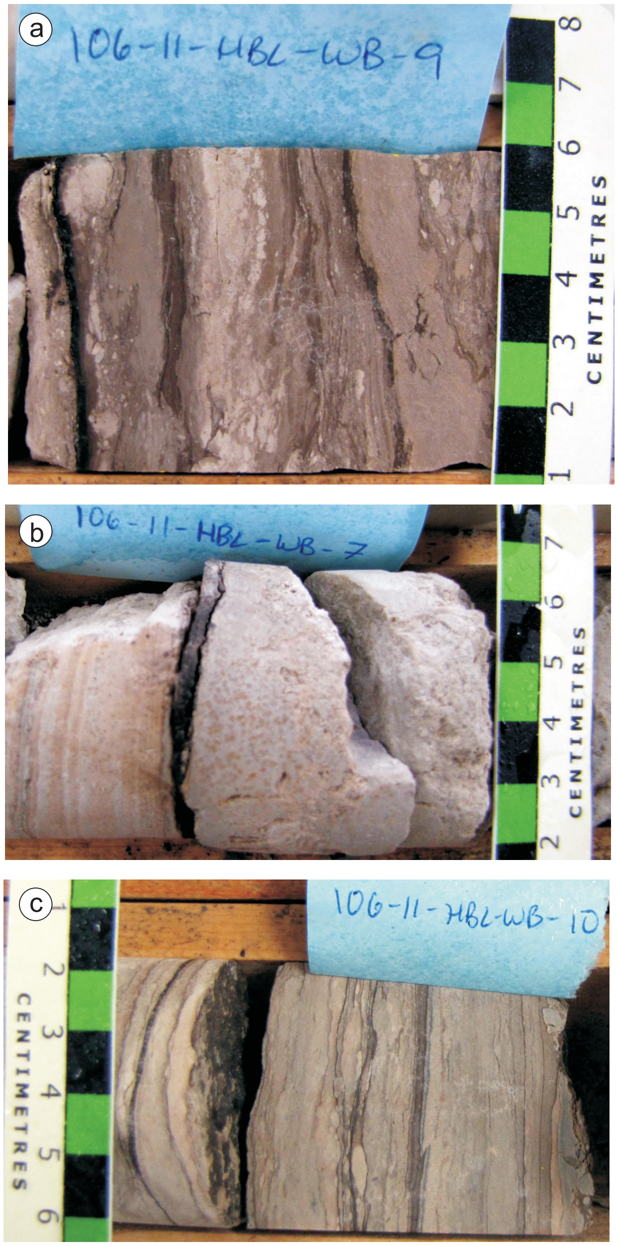

***Figure GS-11-4:** Core of dark brown laminated oil shale from the Merland et al. Whitebear Creek Prov. well, northeastern Manitoba (see Figure GS-11-1 for location). Oil shale in the Red Head Rapids Formation at depths of **a)** 220.98 m and **b)** 221.28 m and in the Severn River Formation at a depth of **c)** 179.98 m. Scale is in centimetres.*

Consequently, two samples were analyzed by RockEval™ 6 to verify suspected oil staining; a sample containing free hydrocarbons (oil) was expected to return unusually high S1 (number of milligrams of hydrocarbons that can be thermally distilled from one gram of rock) values. Both samples were from the Severn River Formation, one from the Comeault Prov. No. 1 well (sample 106-10-HBL-Com-3) and the other from the Kaskattama Prov. No. 1 well (sample 106-10-HBL-Kask-2). Both samples returned very low S1 values of 0.04 and 0.05 mg/g, respectively. It is uncertain if the poor results from these samples are due to organic matter sample dilution or if this analytical method is not the best way to confirm oil staining. In the Kaskattama Prov. No. 1 well, two possible oil-stained intervals were identified in the Severn River Formation (located at approximately 602.43–606.9 m and 651–666 m); only the shallower interval, however, was analyzed using RockEval™ 6. The deeper sample was not analyzed but produced a yellow cut under ultraviolet light when a chip sample was immersed in acetone, suggesting the presence of migrating oil (i.e., live oil) in the sample. In comparison, the oil-stained sample from the Comeault Prov. No. 1 well did not fluoresce under ultraviolet light, and the oil stain is thus considered to be dead oil. Further investigation of the Comeault Prov. No. 1 well potential oil stain is needed for confirmation.

Hydrothermal dolomite

Hydrothermal dolomite is a major hydrocarbon reservoir in intracratonic basins in North America (Lavoie et al., 2011) and the potential occurrence of these porous carbonate features in the Hudson Bay Basin could therefore be significant. Nicolas and Lavoie (2009) reported potential HTD in stratigraphic corehole M-4-03 from the Churchill Northern Studies Centre quarry. This occurrence was confirmed petrographically and isotopically by Lavoie et al. (2011).

A recent magnetotelluric (MT) survey near Churchill (Roberts and Craven, 2012) was designed to test the capacity of MT to map the presence of porous carbonate zones in the shallow subsurface based on variations in the electric conductivity of the rocks. The new MT data identify some conductive zones at relatively shallow depths. Two-dimensional and three-dimensional modelling has provided a consistent image of a high conductivity shallow zone that is interpreted to be related to high porosity layers possibly associated with the hydrothermally altered carbonate rocks identified by Nicolas and Lavoie (2009) in the Ordovician section of the Churchill area. Using the model conductivity, bulk porosities were calculated to reach up to 25% (Roberts and Craven, 2012), which is in line with visual estimates of the core. The more resistive rocks above the porous layer may be Silurian mudstone or limestone rocks from the Severn River Formation.

In the Comeault Prov. No. 1 core, a section of the Severn River Formation showed striking resemblance to the HTD in the M-4-03 core, and is shown in Figure GS-11-7. Analyses on samples collected from the Comeault Prov. No. 1 core are pending.

Project findings

The potential for a sedimentary basin to host economic conventional hydrocarbon accumulations is

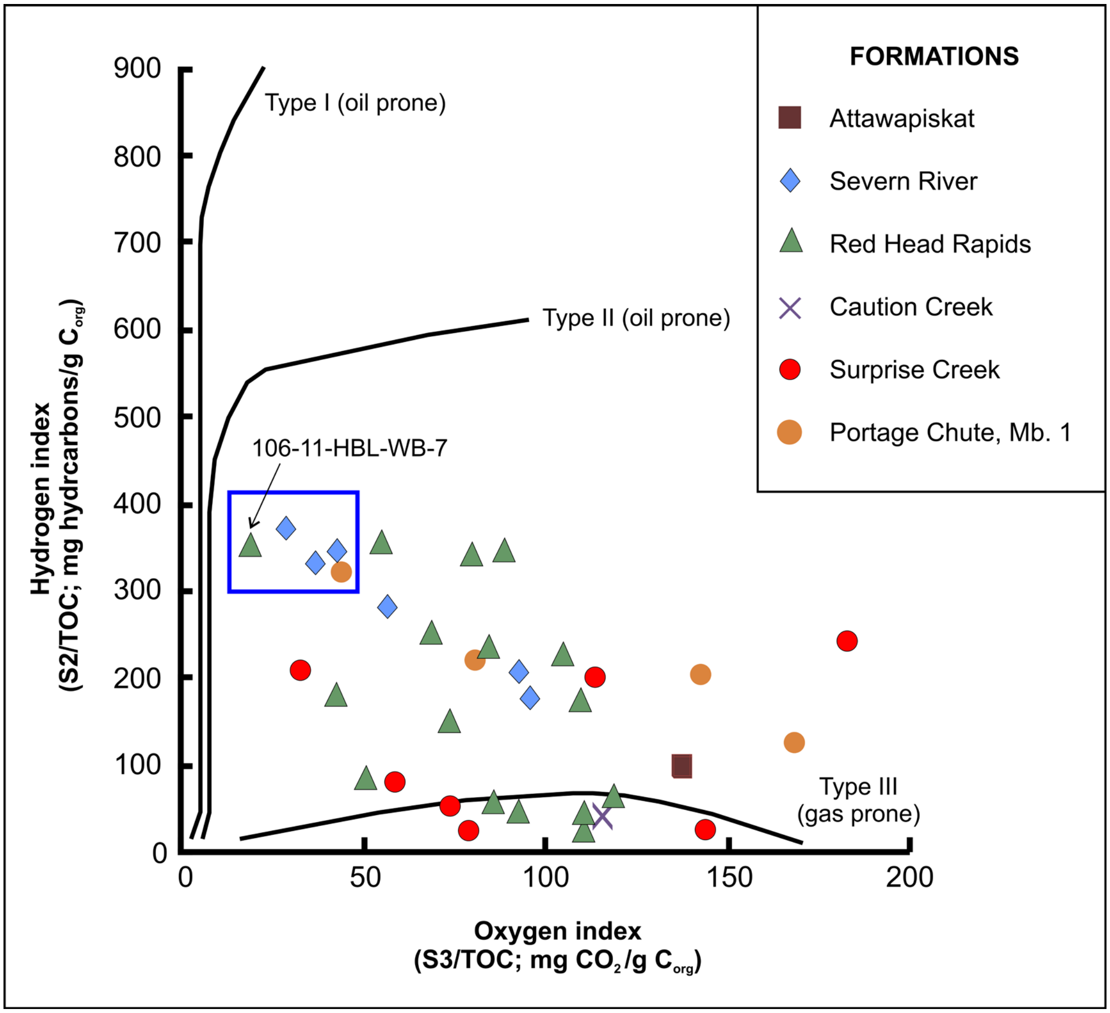

Figure GS-11-5: *Modified van Krevelen diagram of new RockEval™6 data for samples from eight wells in northeastern Manitoba; blue box indicates samples that have a hydrogen index >300 and an oxygen index <50.*

based on the presence of multiple independent elements: a mature source rock rich in organic matter, a porous reservoir capped by a seal and trapping mechanism(s). Over the last four years, the Hudson Bay and Foxe Basins Project has generated new data on these elements for the HBL in northeastern Manitoba.

Source rocks

Upper Ordovician source rocks rich in organic matter were known in Nunavut prior to the start of this project (Macauley, 1986, 1987). Subsequently, new detailed work on these known occurrences has been carried out (Zhang, 2010, 2012) and new localities have been found in northern Ontario (Armstrong and Lavoie, 2010). For the first time, the presence of coeval, organic-matter–rich zones in northeastern Manitoba as well as some potential in younger Silurian shale is being reported. However, it is important to note that all these Upper Ordovician occurrences (except the one in northern Ontario) are relatively thin.

Thermal maturation

In the past, the Hudson Bay Basin was considered to be thermally immature and as such, the Upper Ordovician source rocks were assumed to have never reached the oil window. A recent organic-matter reflectance study of core samples from three Hudson Bay offshore wells (Bertrand and Malo, 2012) and from the thin succession in two northern Ontario onshore mineral exploration boreholes (Armstrong and Lavoie, 2010; Reyes et al., 2011) indicates that, at least for these localities, the Silurian and Ordovician successions are thermally mature and have reached the oil window. This suggests that some significant thickness of strata has been eroded after maximum burial (especially in northern Ontario). For now, the thermal maturation of the northeastern Manitoba sedimentary succession remains poorly constrained. A more detailed evolution of the basin (burial-exhumation history), based on apatite fission tracks (AFT), helium analyses in apatite and thermal maturation indicators, including samples

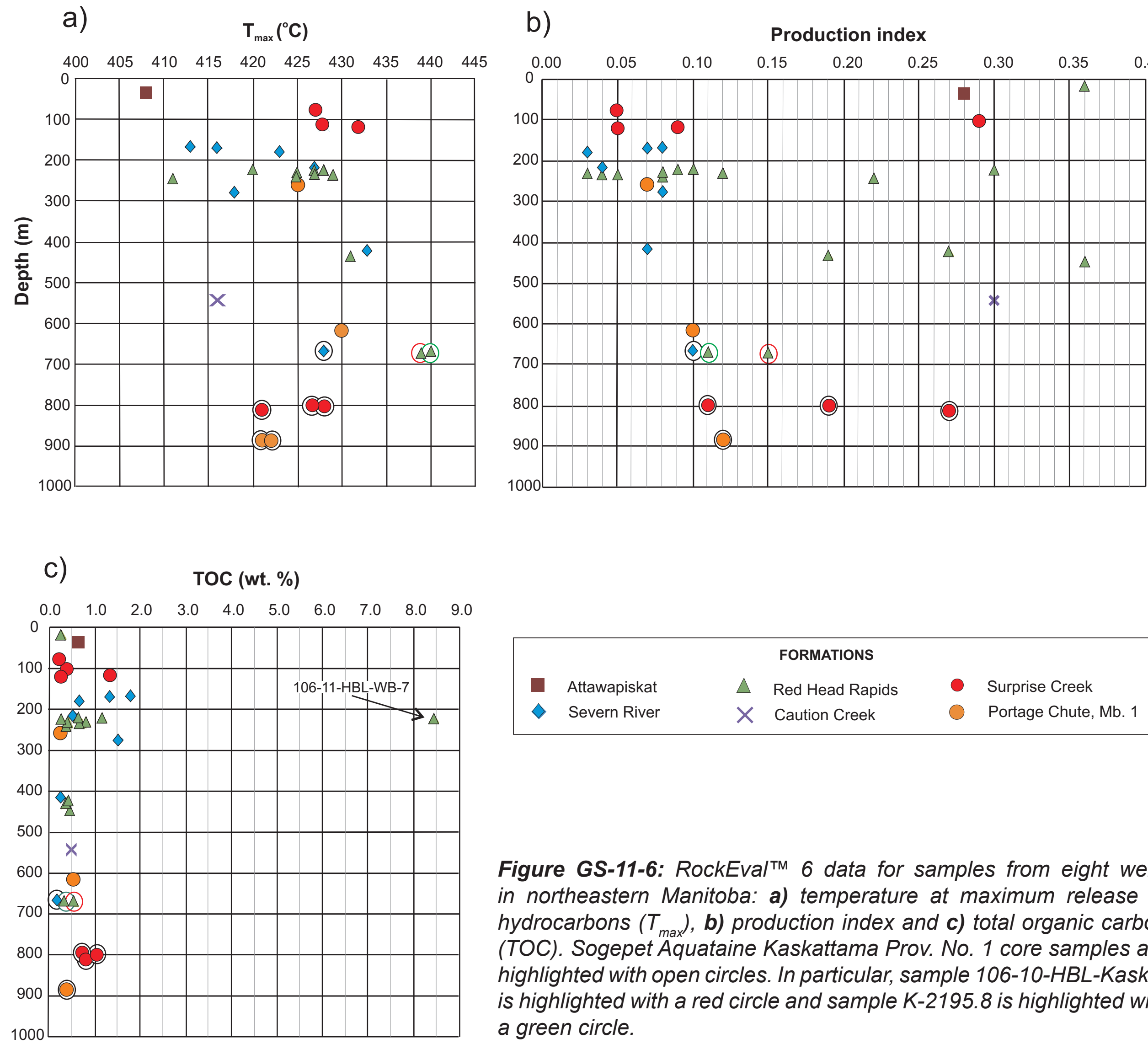

***Figure GS-11-6:** RockEval™ 6 data for samples from eight wells in northeastern Manitoba: **a)** temperature at maximum release of hydrocarbons (T_{max}), **b)** production index and **c)** total organic carbon (TOC). Sogepet Aquataine Kaskattama Prov. No. 1 core samples are highlighted with open circles. In particular, sample 106-10-HBL-Kask-1 is highlighted with a red circle and sample K-2195.8 is highlighted with a green circle.*

from Manitoba, should become available before the end of this project.

Reservoirs

The stratigraphy of the Hudson Bay platform is dominated by carbonate rocks and evaporites, whereas clastic rocks are less prevalent. Previous synthesis on the hydrocarbon potential of the basin (Hamblin, 2008) has proposed that various carbonate facies can be hypothesized as reservoirs in the Hudson Bay platform. For northeastern Manitoba, the bulk of the succession is Upper Ordovician to Lower–Middle Devonian (stratigraphy being revised). In that interval, two main types of reservoirs can be envisaged:

1) HTD documented in the Ordovician succession near Churchill (Nicolas and Lavoie, 2009; Lavoie et al., 2011) and postulated in the Lower Silurian carbonate rocks (this report), and
2) lower Silurian reefs of the Attawapiskat Formation which have only recently been shown to be locally highly porous (Ramdoyal, 2012).

Seals

Hydrothermal dolomites generate their own seal as the fault-controlled dolomite bodies are surrounded by nondolomitized tight limestone facies. For the reef facies of the Attawapiskat Formation, the HTD is encased in tight limestone, which acts as a seal on top of the biogenic structure.

Traps

There are no folds known in the HBL in northeastern Manitoba. The most efficient traps would be produced by fault offsets or generated by primary stratigraphic depositional and erosional features (e.g., pinch out, unconformities).

***Figure GS-11-7:** Core showing potential hydrothermal dolomite in the Severn River Formation in the Houston Oils et al. Comeault Prov. No. 1 well, northeastern Manitoba (see Figure GS-11-1 for location), at a depth of 411.8 m; scale is in centimetres.*

Economic considerations

The results collected to date support an active hydrocarbon system in the Hudson Bay Basin. As detailed in this report, the Hudson Bay Basin has all the required elements for successful hydrocarbon exploration, including confirmed basinal distribution of source rocks, adequate maturation rank of the Silurian and Ordovician succession, HTD and Silurian reefs to provide the reservoirs, and faults and stratigraphic relationships to provide the potential traps.

The reassessment of the Hudson Bay Basin using modern technology and viewing old and new data through a modern lens has proven to be a successful venture. What was once thought as a large area without hydrocarbon potential has now been transformed into a highly prospective frontier area worthy of industry investment. Exploration in the north brings significant positive economic impact and development to northern communities, and with Manitoba's coastal location, including a deepwater port at Churchill and rail line to major markets, successful hydrocarbon exploration in the Hudson Bay Basin would benefit all of Manitoba.

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References

Armstrong, D.K. and Lavoie, D. 2010: Re-appraisal of the hydrocarbon resource potential of the Hudson Platform: project introduction and preliminary results from northern Ontario; 49th Ontario Petroleum Institute, Annual Meeting, Program with Abstracts, Niagara Falls.

Asselin, E. 2012: Palynological report on 24 samples provided by Michelle Nicolas (Manitoba Geological Survey) from four wells drilled on the onshore Judson Platform in Manitoba (Merland et al. Whitebear Creek South No. 1; Sogepet Aquitaine Kaskattama Prov. No. 1; Houston Oils et al. Comeault South No. 1; Foran Mining Kaskattama Kimberlite No. 1); Geological Survey of Canada, unpublished Paleontological Report 02-EA-2012, 5 p.

Bertrand, R. and Malo, M. 2012: Dispersed organic matter reflectance and thermal maturation in four hydrocarbon exploration wells in the Hudson Bay Basin: regional implications; Geological Survey of Canada, Open File 7066, 54 p.

Hamblin, A.P. 2008: Hydrocarbon potential of the Paleozoic succession of Hudson/James Bay: preliminary conceptual synthesis of background data; Geological Survey of Canada, Open File 5731, 12 p.

Hu, K., Dietrich, J., Zhang, S., Asselin, E., Pinet, N. and Lavoie, D. 2011: Stratigraphic correlations for five offshore wells in the Hudson Bay Basin, northern Canada; Geological Survey of Canada, Open File 7031, 1 sheet.

Lavoie, D., Zhang, S. and Pinet, N. 2011: Hydrothermal dolomites in Hudson Bay Platform and southeast Arctic Platform: preliminary field and geochemical data; Geological Survey of Canada, Open File 7002, 22 p.

LeFèvre, J.A., Barnes, C.R. and Tixier, M. 1976: Paleoecology of Late Ordovician and Early Silurian conodontophorids, Hudson Bay Basin; *in* Conodont Paleoecology, C.R. Barnes (ed.), Geological Association of Canada, Special Paper, no. 15, p. 69–89.

Macauley, G. 1986: Geochemistry of the Ordovician Boas oil shale, Southampton Island, Northwest Territories; Geological Survey of Canada, Open File 1285, 15 p.

Macauley, G. 1987: Geochemistry of organic-rich Ordovician sediments on Akpatok and Baffin islands, Northwest Territories; Geological Survey of Canada, Open File 1502, 27 p.

McCracken, A.D. 2011: Report on 11 conodont samples from the Silurian Severn River, Ekwan River, Attiwapiskat and Kenogami formations and the Ordovician Red Head Rapids Formation collected from the Merland et al. Whitebear Creek STH #1 well in Manitoba, submitted by Michelle Nicolas (Manitoba Geological Survey) in 2010, Con. No. 1753, HTS 054-F-08; Geological Survey of Canada, unpublished Paleontological Report 2-ADM-2011, 9 p.

Nicolas, M.P.B. 2011: Stratigraphy of three exploratory oil-well cores in the Hudson Bay Lowland, northeastern Manitoba (parts of NTS 54B10, F8, G1); *in* Report of Activities 2011, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 165–170.

Nicolas, M.P.B. and Lavoie, D. 2009: Hudson Bay and Foxe Basins Project: introduction to the Geo-mapping for Energy and Minerals, GEM-Energy initiative, northeastern Manitoba (parts of NTS 54); *in* Report of Activities 2009, Manitoba Science, Innovation, Energy and Mines, Manitoba Geological Survey, p. 160–164.

Nicolas, M.P.B. and Lavoie, D. 2010: Hudson Bay and Foxe Basins Project: update on a Geo-mapping for Energy and Minerals program (GEM) initiative, northeastern Manitoba (part of NTS 54); *in* Report of Activities 2010, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 186–192.

Peters, K.E. 1986: Guidelines for evaluating petroleum source rock using programmed pyrolysis; American Association of Petroleum Geologists, Bulletin, v. 70, no. 3, p. 318–329.

Ramdoyal, A. 2012: Lithofacies analysis, diagenesis and petroleum reservoir potential of the Lower Silurian Attawapiskat Formation, Hudson Bay Basin, northeastern Manitoba; B.Sc. thesis, University of Manitoba, Winnipeg, Manitoba, 124 p.

Reyes, J., Armstrong, D. and Lavoie, D. 2011: The organic facies and thermal maturity of Boas River Formation in cores from the Hudson Platform in northern Ontario, Canada: re-appraisal of the hydrocarbon potential; *in* Proceedings of the 50th Annual Conference, Ontario Petroleum Institute, London, Ontario, Technical Paper 16.

Roberts, B. and Craven, J. 2012: Results of a magnetotelluric survey in Churchill, Manitoba: GEM Energy, Hudson Bay; Geological Survey of Canada, Open File 7151, 24 p.

Snowdon, L.R. 1995: Rock-Eval T_{max} suppression: documentation and amelioration; American Association of Petroleum Geologists, Bulletin, v. 79, p. 1337–1348.

Zhang, S. 2010: Upper Ordovician stratigraphy and oil shales on Southampton Island - field trip guidebook; Geological Survey of Canada, Open File 6668, 44 p.

Zhang, S. 2012: Ordovician stratigraphy and oil shale, southern Baffin Island, Nunavut - preliminary field and post-field data; Geological Survey of Canada, Open File 7199, 25 p.