GS2017-12

Update on Paleozoic stratigraphic correlations in the Hudson Bay Lowland, northeastern Manitoba and northern Ontario

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In Brief:

- Long distance onshore correlations in the Hudson Bay Basin inform petroleum and mineral exploration and land-use planning
- Stratigraphic correlations of Devonian and Silurian strata are challenging, but resolvable using stable isotopes

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Summary

This work summarizes the continued collaborations between the Manitoba Geological Survey and the Ontario Geological Survey as part of the Hudson-Ungava Project of the Geo-mapping for Energy and Minerals program, Phase 2 (GEM-2; 2013–2020). The objective of this project is to advance the understanding of the sedimentological and stratigraphic framework of the onshore component of the Hudson Bay Basin to support mineral exploration and land-use planning in this underexplored frontier region.

The stratigraphic correlations for the Paleozoic sequence in northeastern Manitoba and northern Ontario have been resolved using a combination of lithostratigraphy, biostratigraphy and chemostratigraphy. This report presents the correlations based on the lithostratigraphic and chemostratigraphic findings in the Silurian and Devonian formations of the onshore extent of the Hudson Bay Basin.

Introduction

The Manitoba Geological Survey (MGS) is a partner in the Geological Survey of Canada's (GSC) Geo-mapping for Energy and Minerals 2 (GEM-2) program, which runs from 2013 to 2020. The MGS is participating in the Hudson-Ungava project (Nicolas et al., 2014), which includes multijurisdictional partners, including Ontario Geological Survey (OGS), Canada–Nunavut Geoscience Office, Laurentian University and University of Manitoba. In Manitoba, the purpose of the project is to enhance the understanding of the stratigraphic and sedimentological framework and structural complexities of the onshore component of the Hudson Bay Basin (HBB) in the Hudson Bay Lowland (HBL) in northeastern Manitoba, and correlate them to the onshore sections in Ontario in order to build a seamless stratigraphic framework for the southern part of the Hudson Platform. The Hudson Platform includes the HBB in northeastern Manitoba and northern Ontario and the Moose River Basin (MRB) in northeastern Ontario. This information will then be integrated with offshore and northern models for the basin to create a basin-wide sedimentological framework, which will form the basis for petroleum potential assessments, exploration in the basin and land-use planning in the region.

A number of cores have been drilled through the onshore Paleozoic sequence of the HBB in northeastern Manitoba and northern Ontario (Figure GS2017-12-1; Nicolas and Lavoie, 2012; Armstrong et al., 2013a). The thickest sections, up to approximately 1000 m, were intersected in two onshore wells, Sogepet Aquitaine Kaskattama Prov. No. 1 (Kaskattama; Oil and gas licence number 2168, Manitoba Growth, Enterprise and Trade, Winnipeg) and Aquitaine Sogepet et al. Pen No. 1 (Pen No. 1; Oil and gas licence number T002784, Ontario Ministry of Natural Resources and Forestry, Peterborough), located in the HBL of northeastern Manitoba and northern Ontario, respectively (Figure GS2017-12-1). These sections have been logged and sampled for biostratigraphy (Nicolas and Lavoie, 2012; Armstrong et al., 2013b) and stable-isotope chemostratigraphy as part of this project. Lithological logs and stable-isotope profiles for other cores in Manitoba, including Kaskattama, Houston Oils et al. Comeault Prov. No. 1 (Comeault; Oil and gas licence number 2337) and Merland et al. Whitebear Creek Prov. (Whitebear; Oil and gas licence number 2454) have been reported on by Nicolas (2016a, b). This report presents the stratigraphy, lithology and stable-isotope profile for the Foran Mining Kaskattama Kimberlite No. 1 (KK1; Assessment File 74223, Manitoba Growth, Enterprise and Trade, Winnipeg) core, and revised Devonian and Silurian stratigraphy for the Kaskattama, Comeault, Whitebear and Pen No. 1 wells. The analysis of the Selco Pennycutaway No. 1 (Pennycutaway; Assessment File 91728) core results were still under evaluation at the time of this writing. Regional correlations of Ordovician strata in the southern HBB are part of an ongoing related study (Hahn et al., 2016).

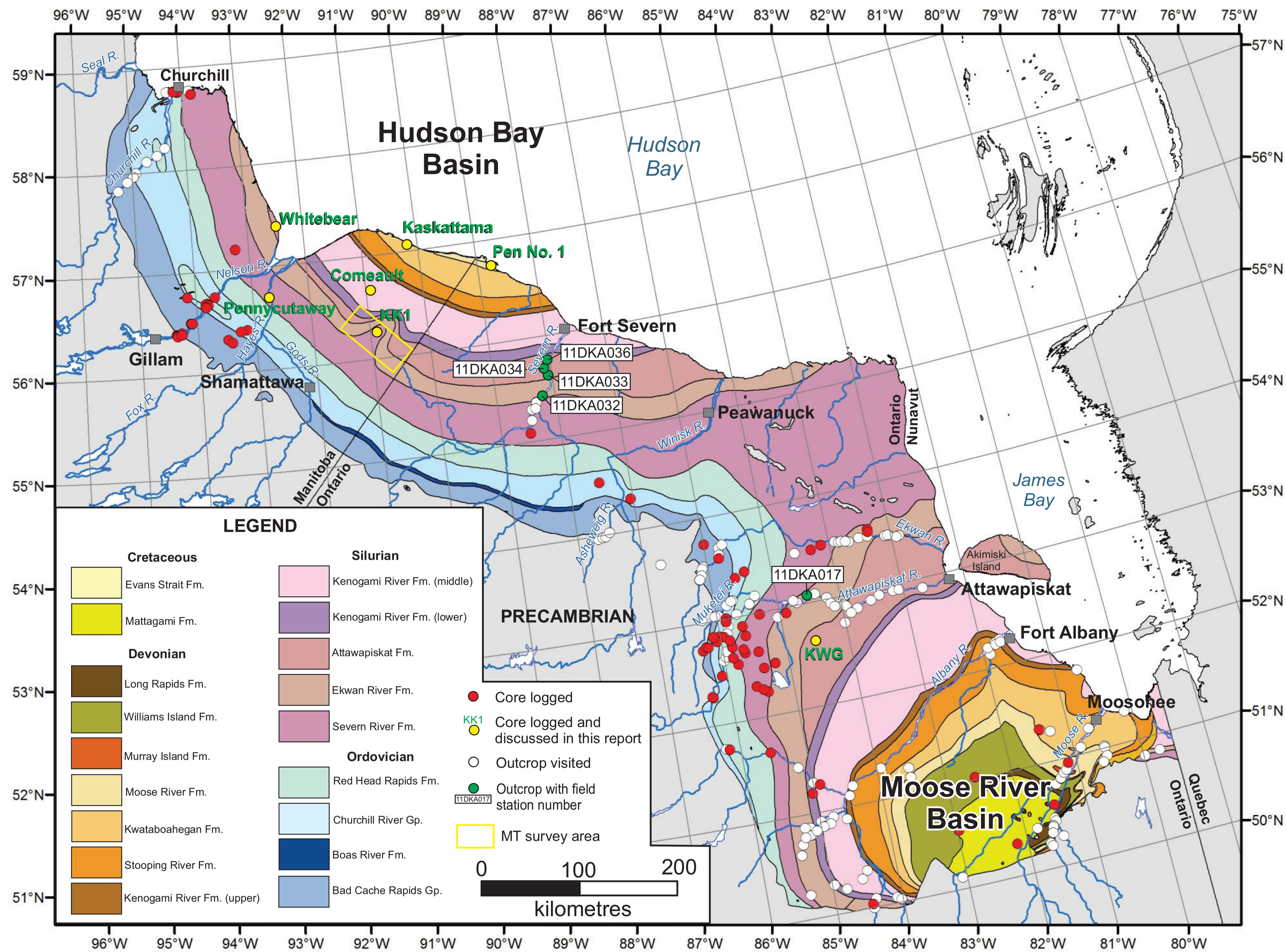

Figure GS2017-12-1: *Regional Phanerozoic geological map of the southern Hudson Platform showing locations of drillholes and outcrops studied for this project. Manitoba geology is modified from Nicolas et al. (2014); Ontario and Nunavut (Akimiski Island) geology is modified from Sanford and Grant (1998) and Ontario Geological Survey (2011). Abbreviations: Comeault, Houston Oils et al. Comeault Prov. No. 1; Kaskattama, Sogepet Aquitaine Kaskattama Prov. No. 1; KK1, Foran Mining Kaskattama Kimberlite No. 1; KWG, KWG-Spider Resources DR-94-19; MT, magnetotelluric; Pen No. 1, Aquitaine Sogepet et al. Pen No. 1; Pennycutaway, Selco Pennycutaway No. 1; Whitebear, Merland et al. Whitebear Creek Prov.*

Overview of Hudson Bay Basin onshore cores

The HBB Silurian and Devonian sections (Figure GS2017-12-2) in the HBL region have been a challenge to correlate confidently. The Pen No. 1 core in Ontario is continuous through the entire HBB section (217.32–1021.33 m vertical depth), beginning in the Devonian upper member of the Kenogami River Formation through to the Ordovician Bad Cache Rapids Group and Precambrian basement (Armstrong et al., 2013a) and is considered a good reference core for this region. The Kaskattama core intervals begin higher in the section, in the Devonian Kwataboahegan Formation, but have shorter telescoped core intervals rather than continuous core. Both the Pen No. 1 and Kaskattama wells have a small suite of downhole geophysical logs to assist in correlations and help fill in core gaps. In the Kaskattama well, gaps in core recovery or preservation have meant that many formational contacts have not been recovered, resulting in significant gaps in the interpretations. The Comeault core provides a complete view of the section starting in the Silurian lower member of the Kenogami River Formation; however, the upper ~60 m of this core has intermittent poor recovery. The Whitebear core has excellent continuous core recovery but provides only a part of the Silurian section.

Stable-isotope results

This past year, the last of the isotope results for the Manitoba cores were received from the multiwell sampling program conducted in 2014 (for sampling details see Nicolas et al., 2014). Nicolas (2016a, b) presented the data and a preliminary analysis of the first batch of $\delta^{13}C$ and $\delta^{18}O$ stable-isotope results. The latest batch of results covers the middle member of the Kenogami River Formation in the Kaskattama core; short interval samples from the entire KK1 and Pennycutaway cores; and outcrop samples collected in 2014 (Nicolas and Young, 2014) from along the Churchill River and along the coast near the town of Churchill. The new $\delta^{13}C$ and $\delta^{18}O$ stable-isotope results are presented in Nicolas (2017)[2].

[2] MGS Data Repository Item DRI2017002, 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 Growth, Enterprise and Trade, 360–1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

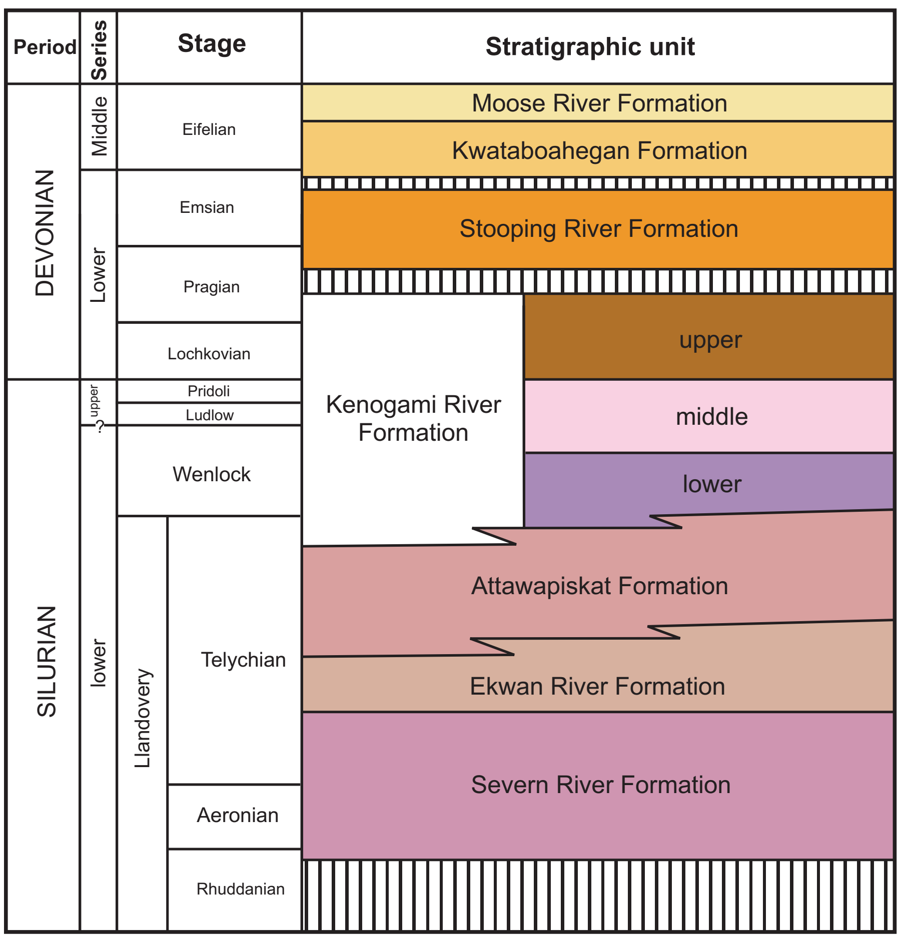

Figure GS2017-12-2: *Time-stratigraphic framework for the Silurian and Devonian succession in the Hudson Bay Basin in northeastern Manitoba and northern Ontario (excludes northeastern Ontario). Series and stages are from the International Commission on Stratigraphy (2017), but their relationships to the formations are based on Norford (1997) and Zhang and Barnes (2007) for the Silurian, and Sanford and Norris (1975) for the Devonian.*

The carbon and oxygen stable-isotope profiles for the Kaskattama core, including the new results for the middle member of the Kenogami River Formation are shown in Figure GS2017-12-3, along with the revised Silurian and Devonian stratigraphic tops (discussed later in this report). The Kaskattama core has intermittent core recovery through the middle member of the Kenogami River Formation, however, the overall trend of the $\delta^{13}C$ profile resembles that of Pen No. 1 (Figure GS2017-12-4), which has a more completely sampled section.

Kaskattama highland and KK1 core

The KK1 drillhole was drilled in 2006 by the Foran Mining Corporation near Bouchard Lake on the Kaskattama highland, northeast of the First Nation community of Shamattawa, northeastern Manitoba (Figure GS2017-12-1). Core was intermittently cut from 16.8 to 332.2 m (Figure GS2017-12-5) and the stratigraphic, lithological/sedimentological and stable-isotope profiles for the Paleozoic core of the KK1 are shown in Figure GS2017-12-5.

This drillhole encountered an unusually thick section of Quaternary sediments (mostly till), overlying a black shale followed by Paleozoic carbonate rocks. The age of the black shale is uncertain, with micropaleontological analyses indicating ages ranging from Cretaceous to Tertiary[3] and Quaternary (McCracken, 2014). The stratigraphic position, lithology and texture of the Kaskattama highland black shale closely resembles Cretaceous black shales in southwestern Manitoba, supporting a more probable age of Cretaceous. In addition to the unusual thickness of sediments overlying the Paleozoic, KK1 is missing a thick section of expected strata as compared to the Comeault core. Preliminary logging of KK1 (Nicolas et al., 2014) reported the Severn River Formation at the top of the Paleozoic bedrock section, rather than the expected (from previous geological maps) Attawapiskat and Ekwan River formations. Biostratigraphy results for KK1 confirmed a Silurian age and Severn River Formation assignment (McCracken, 2014), which is supported by comparing its chemostratigraphic profile to those of nearby cores. This may help in understanding the character and origin of the Kaskattama trough, which is interpreted to run through this area, based on work done by Hobson (1964) and Nelson and Johnson (1966).

A magnetotelluric (MT) ground geophysical survey was undertaken in July 2017 over the Kaskattama highland (Figure GS2017-12-1) as part of the GEM-2 program by J. Craven and B. Roberts from the GSC and I. Ferguson and N. Clark from the University of Manitoba to investigate this anomalous area (for more details see Craven et al., 2017). The MT survey will provide valuable information on the general bedrock composition and structure in the area of the Kaskattama trough. The results from the survey are pending.

Stratigraphic resolutions

Nicolas (2016a) presented the preliminary stratigraphic sections for the Kaskattama, Comeault and Whitebear drillcores along with their $\delta^{13}C$ and $\delta^{18}O$ stable-isotope profiles, and Nicolas and Lavoie (2012) presented the section for the KK1 drillcore. Armstrong et al. (2013b) presented the preliminary section for the Pen No. 1 well. The stable-isotope profiles for these wells were reviewed and compared. Where necessary, cores were re-examined to help resolve stratigraphic inconsistencies. The updated stratigraphic tops for select wells are shown in Table GS2017-12-1, and are displayed graphically in Figures GS2017-12-3 to -7, along with their lithological logs, $\delta^{13}C$ and $\delta^{18}O$ stable-isotope profiles, and spontaneous potential or gamma ray downhole geophysical log traces. These stratigraphic revisions replace those published in Nicolas (2011, 2016a) and Armstrong et al. (2013b). The stratigraphic assignments in the Whitebear and Comeault cores were changed significantly from Nicolas (2011, 2016a), and some adjustments were also made to formation top picks in the Kaskattama core. Revision of formational assignments and top picks was based on comparison of $\delta^{13}C$ and $\delta^{18}O$ stable-isotope profiles among all the cores and review of core descriptions and photographs.

Below is a detailed rationale for formational picks and correlations of the Silurian section in the onshore section of the HBB.

Attawapiskat Formation

The top of the Attawapiskat Formation was intersected in the Pen No. 1, Kaskattama and Comeault cores. The Pen No. 1 core has the best recovery of the Attawapiskat Formation, including the preservation of the upper and lower contacts, and a natural gamma-ray (GR) downhole log and therefore is considered the best reference log for this formation. Kaskattama has intermittent core recovery, but has a GR log, whereas Comeault has variable core recovery and only spontaneous potential (SP) and resistivity logs. All three cores have $\delta^{13}C$ isotope profiles (Figures GS2017-12-3, -4, -6), however, variable recovery through this interval in the Comeault and Kaskattama cores resulted in coarser isotopic profiles for these wells. Accurate formation top picks based on $\delta^{13}C$ may not be reliable, depending on sample frequency (which can in turn be affected by core recovery). Isotopic profiles can, however, corroborate other lines of evidence, such as lithological changes and geophysical responses.

The top of the Attawapiskat Formation in Pen No. 1 (Figure GS2017-12-4) is marked lithologically by a relatively rapid upward transition from porous, granular-looking, dolomitic limestone (including the "Nuia" grainstone reported by Suchy [1992] and Suchy and Stearn [1993]) to massive or laminated, variably argillaceous dolomudstones of the lower Kenogami River Formation. Lithologically, the contact can be picked at a

[3] 'Tertiary' is an historical term. The International Commission on Stratigraphy recommends using 'Paleogene' (comprising the Paleocene to Oligocene epochs) and 'Neogene' (comprising the Miocene and Pliocene epochs). The author used the term 'Tertiary' because it was used in the source material for this report.

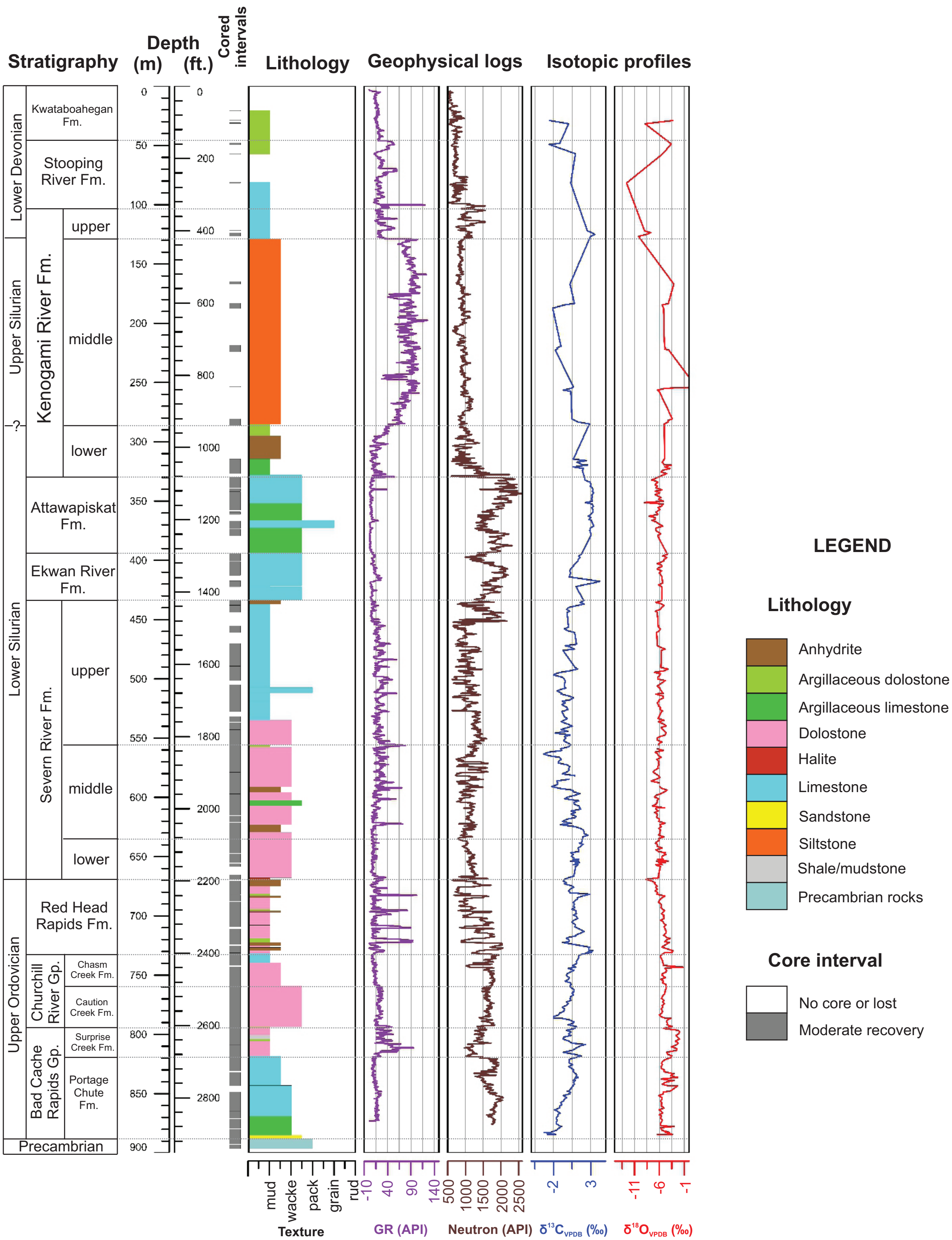

Figure GS2017-12-3: *Profile of the Sogepet Aquitaine Kaskattama Prov. No. 1 core (Oil and gas licence number 2168, Manitoba Growth, Enterprise and Trade, Winnipeg), showing tracks for lithology, geophysical logs, and δ^{13}C and δ^{18}O stable-isotope profiles (modified from Nicolas, 2016a). Abbreviations: grain, grainstone; GR, gamma ray; mud, mudstone; pack, packstone; rud, rudstone; VPDB, Vienna Peedee Belemnite; wacke, wackestone.*

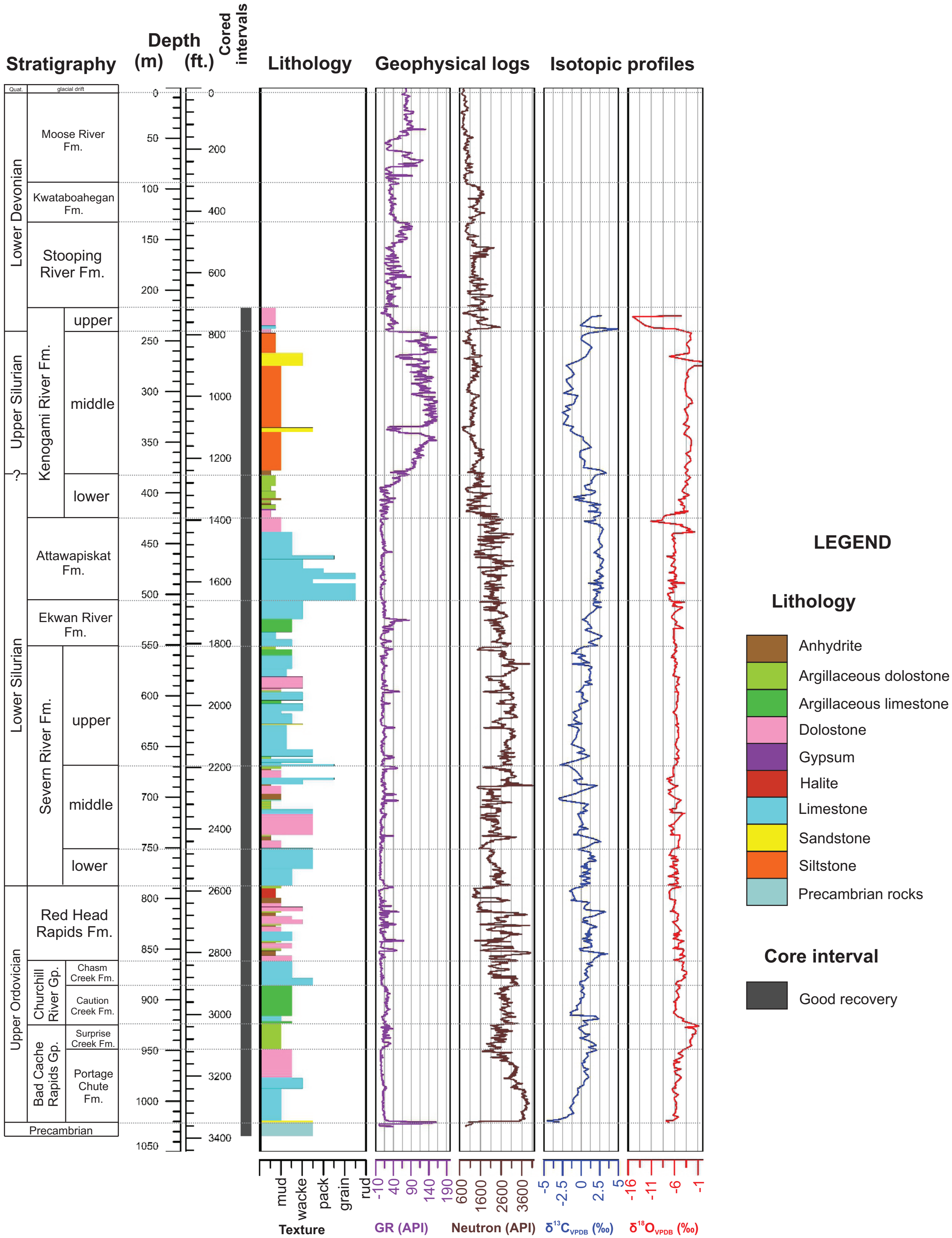

Figure GS2017-12-4: *Profile of the Aquitaine Sogepet et al. Pen No. 1 core (Oil and gas licence number T002784, Ontario Ministry of Natural Resources and Forestry, Peterborough), showing tracks for lithology, geophysical logs, and $\delta^{13}C$ and $\delta^{18}O$ stable-isotope profiles (modified from Armstrong et al., 2013b). Abbreviations: grain, grainstone; GR, gamma ray; mud, mudstone; pack, packstone; rud, rudstone; VPDB, Vienna Peedee Belemnite; wacke, wackestone.*

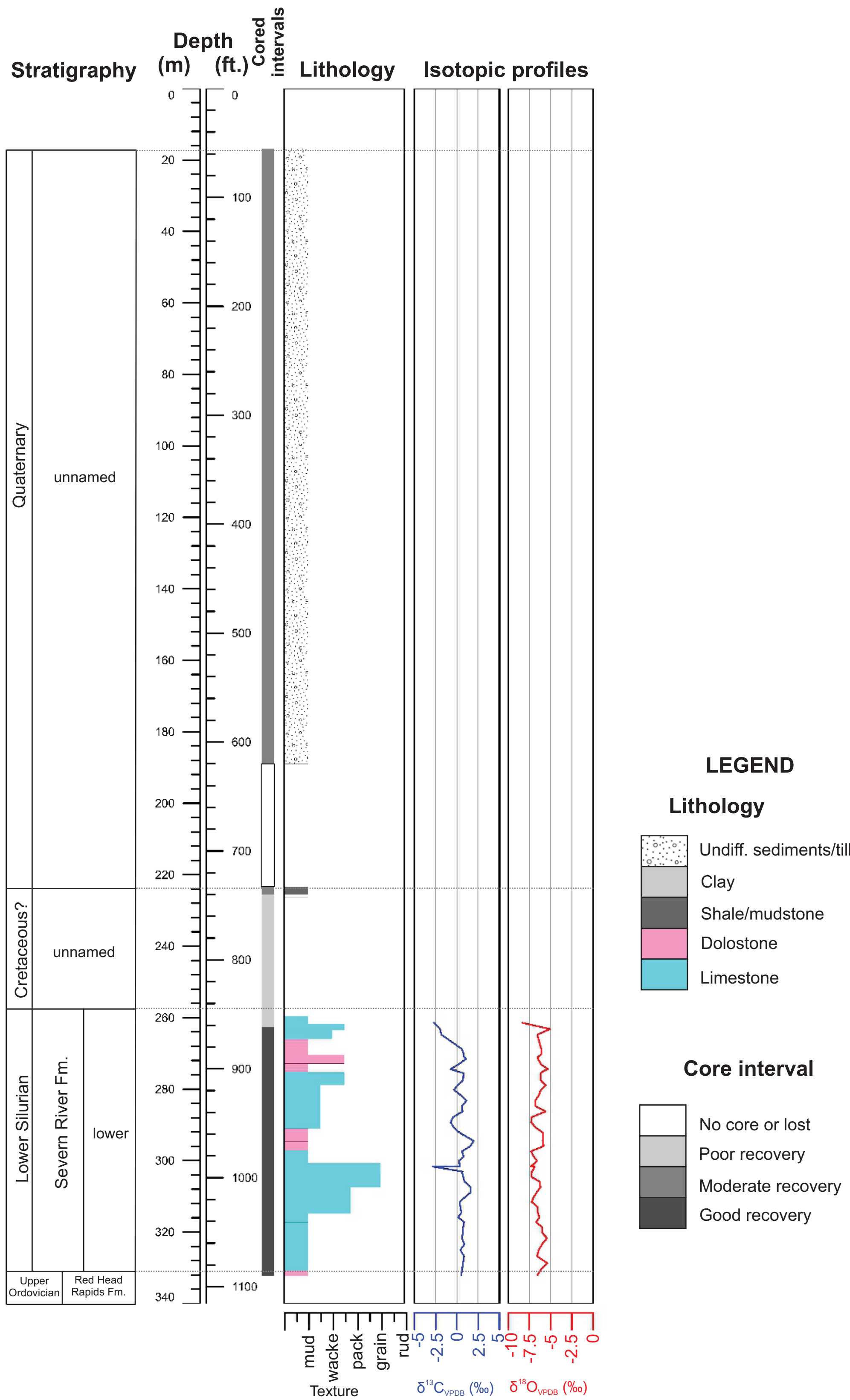

Figure GS2017-12-5: *Profile of the Foran Mining Kaskattama Kimberlite No. 1 (KK1) core (Assessment File 74223, Manitoba Growth, Enterprise and Trade, Winnipeg), showing tracks for the stratigraphy, lithology, and $\delta^{13}C$ and $\delta^{18}O$ stable-isotope profiles. Abbreviations: grain, grainstone; GR, gamma ray; mud, mudstone; pack, packstone; rud, rudstone; Undiff., undifferentiated; VPDB, Vienna Peedee Belemnite; wacke, wackestone.*

Table GS2017-12-1: Stratigraphic tops for select wells in the Hudson Bay Lowland in northeastern Manitoba and northern Ontario. Dashes indicate that stratigraphic unit is not present in the core or could not be picked up from geophysical logs. Abbreviation: Comeault, Houston Oils et al. Comeault Prov. No. 1; Kaskattama, Sogepet Aquitaine Kaskattama Prov. No. 1; KK1, Foran Mining Kaskattama Kimberlite No. 1; n/a, information not available; Pen No. 1, Aquitaine Sogepet et al. Pen No. 1; Whitebear, Merland et al. Whitebear Creek Prov.

	Core	KK1		Whitebear		Comeault		Kaskattama		Pen No.1	
Era/epoch	**Formation/member**	**Depth (m)**	**Depth (ft.)**	**Depth (m)**	**Depth (ft.)**	**Depth (m)**	**Depth (ft.)**	**Depth (m)**	**Depth (ft.)**	**Depth (m)**	**Depth (ft.)**
Quaternary	Glacial drift (till and gravel)	16.80	55.12	n/a	n/a	n/a	n/a	0	0	3.00	10.00
	Base of glacial drift	223.40	732.94	n/a	n/a	n/a	n/a	7.01	23.00	41.76	137.00
Paleogene/Neogene or Cretaceous	Unnamed	223.40	732.94	-	-	-	-	-	-	-	-
Devonian	Moose River Formation	-	-	-	-	-	-	-	-	41.76	137.00
	Kwataboahegan Formation	-	-	-	-	-	-	7.01	23.00	95.10	312.00
	Stooping River Formation	-	-	-	-	-	-	46.02	151.00	133.50	438.00
	Kenogami River Formation	-	-	-	-	<60.96	<200	103.33	339.00	216.41	710.00
	upper member	-	-	-	-	-	-	103.33	339.00	216.41	710.00
Silurian	middle member	-	-	-	-	-	-	128.93	423.00	240.79	790.00
	lower member	-	-	-	-	<60.96	<200	283.52	930.20	382.40	1254.60
	Attawapiskat Formation	-	-	-	-	122.22	401.00	329.79	1082.00	425.50	1396.00
	Ekwan River Formation	-	-	-	-	158.59	520.30	393.50	1291.00	506.36	1661.30
	Severn River Formation	257.10	843.50	<30.48	<100.00	200.04	656.30	433.43	1422.00	551.66	1809.90
	upper member	-	-	<30.48	<100.00	200.10	656.50	433.43	1422.00	551.66	1809.90
	middle member	-	-	130.15	427.00	323.09	1060.00	555.35	1822.00	669.65	2197.00
	lower member	257.10	843.50	194.77	639.00	382.52	1255.00	634.90	2083.00	750.42	2462.00
Ordovician	Red Head Rapids Formation	330.70	1084.97	220.68	724.00	411.60	1350.40	667.97	2191.50	787.45	2583.50
	Churchill River Group			269.44	884.00	466.88	1531.75	731.89	2401.20	861.91	2827.80
	Chasm Creek Formation			269.44	884.00	466.88	1531.75	731.89	2401.20	861.91	2827.80
	Caution Creek Formation			299.92	984.00	492.80	1616.80	758.95	2490.00	886.05	2907.00
	Bad Cache Rapids Group			328.57	1078.00	529.47	1737.10	793.70	2604.00	924.15	3032.00
	Surprise Creek Formation			328.57	1078.00	529.47	1737.10	793.70	2604.00	924.15	3032.00
	Portage Chute Formation			359.66	1180.00	564.22	1851.12	818.39	2685.00	948.38	3111.50
	member 2			359.66	1180.00	564.22	1851.12	818.39	2685.00	948.38	3111.50
	member 1			391.97	1286.00	614.32	2015.50	884.83	2903.00	1018.95	3343.00
Precambrian	Precambrian (weathered)			396.54	1301.00	616.00	2021.00	887.67	2912.30	1021.38	3351.00
	Precambrian (fresh)					617.22	2025.00	889.41	2918.00		
Total depth of borehole		332.20	1089.90	427.02	1401.00	647.70	2125.00	896.42	2941.00	1034.19	3393.00

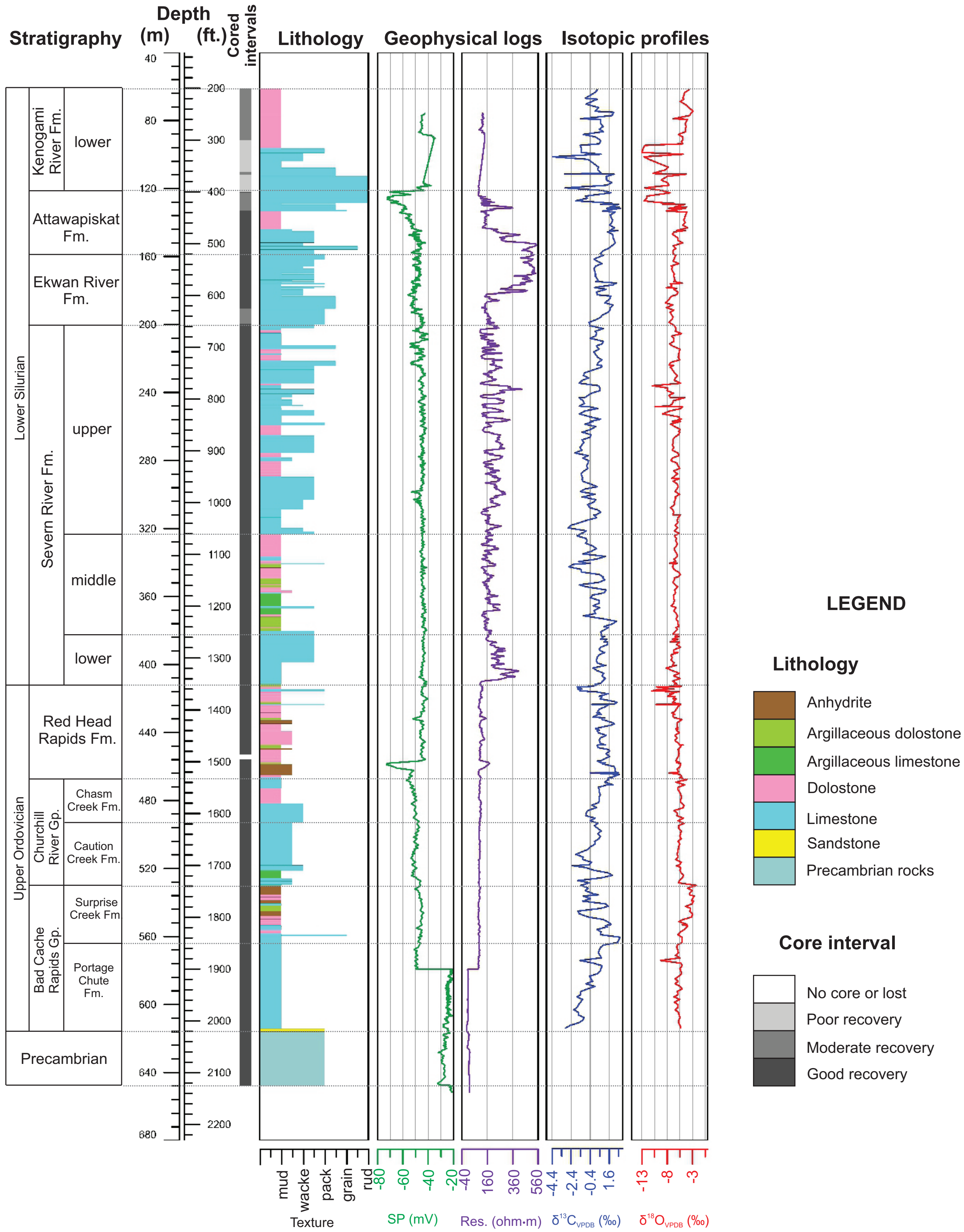

Figure GS2017-12-6: *Profile of the Houston Oils et al. Comeault Prov. No. 1 core (Oil and gas licence number 2337, Manitoba Growth, Enterprise and Trade, Winnipeg), showing tracks for lithology, geophysical logs, and δ^{13}C and δ^{18}O stable-isotope profiles. Abbreviations: grain, grainstone; mud, mudstone; pack, packstone; Res., resistivity; rud, rudstone; SP, spontaneous potential; V, volt; VPDB, Vienna Peedee Belemnite; wacke, wackestone.*

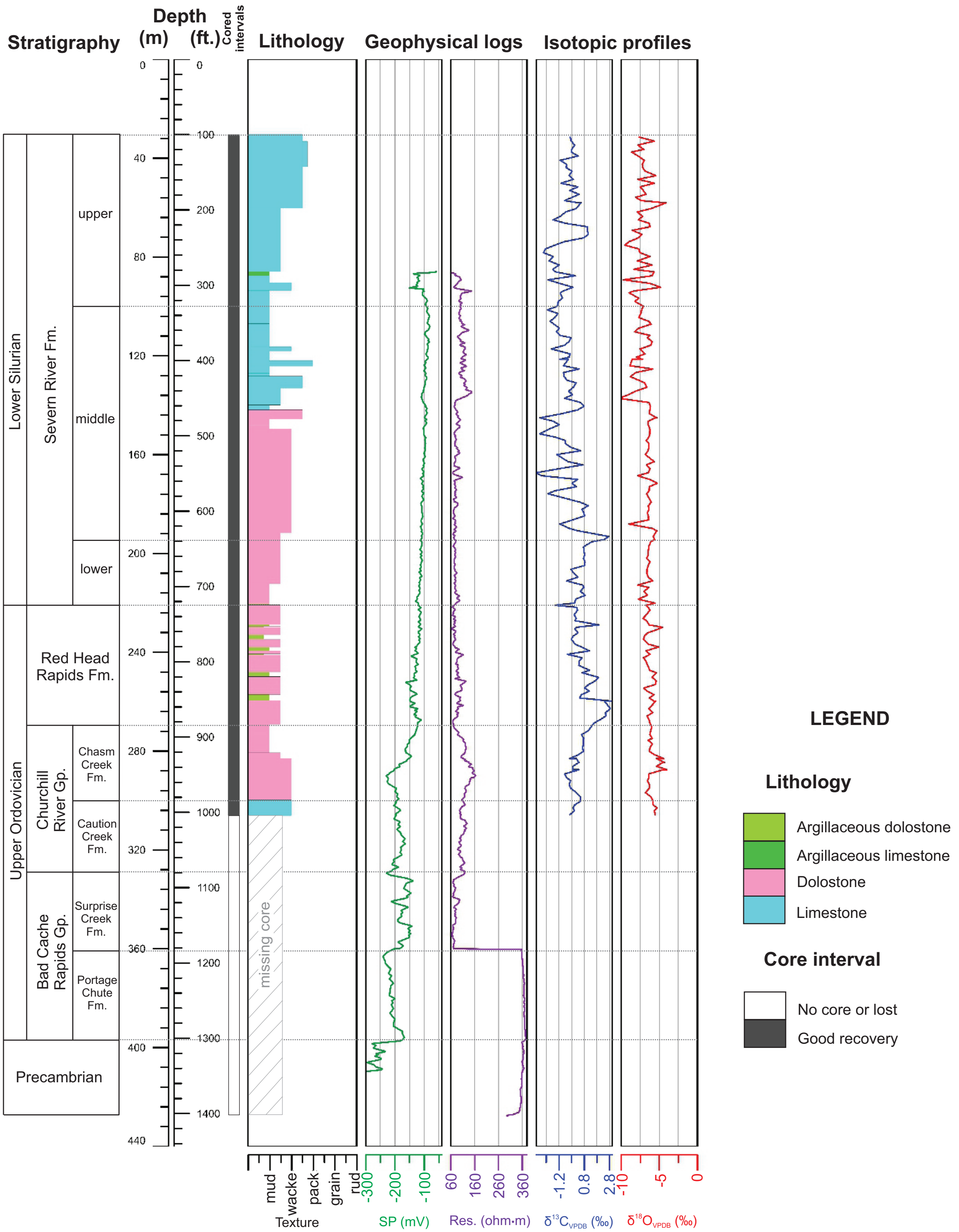

Figure GS2017-12-7: *Profile of the Merland et al. Whitebear Creek Prov. core (Oil and gas licence number 2454, Manitoba Growth, Enterprise and Trade, Winnipeg), showing tracks for lithology, geophysical logs, and $\delta^{13}C$ and $\delta^{18}O$ stable-isotope profiles. Abbreviations: grain, grainstone; mud, mudstone; pack, packstone; Res., resistivity; rud, rudstone; SP, spontaneous potential; V, volt; VPDB, Vienna Peedee Belemnite; wacke, wackestone.*

depth of 424.07 m (1391.3 ft.) in the Pen. No. 1 core, although glauconite (sometimes indicative of slow sedimentation rate and possible disconformity) occurs a few metres deeper at 427.33 m (1402 ft.). The GR log for Pen No. 1 shows a small positive spike at 425.20 m (1395 ft.) followed (downwards) by a drop in the GR baseline. This appears to reflect the transition from the more argillaceous Kenogami River Formation to the cleaner carbonate of the Attawapiskat Formation. Based on this rationale and specifically the GR log signature, the Attawapiskat Formation top contact is picked at 425.50 m (1396 ft.) in Pen No.1.

Using this GR-based pick, the top of the Attawapiskat Formation in the Kaskattama well is picked at 329.79 m (1082 ft.; Figure GS2017-12-3). This fits lithologically as well, although core recovery for this interval of Kaskattama well is poor.

Correlation to the Comeault well is complicated by variable core recovery and lack of a GR log. Correlation is based on the $\delta^{13}C$ profiles among the three wells. In Pen No. 1 (Figure GS2017-12-4), the $\delta^{13}C$ profile for the Kenogami River Formation is erratic, possibly characteristic of an evaporitic intertidal to supratidal environment. The profile for the Attawapiskat Formation in Pen No. 1 is generally smoother and with $\delta^{13}C$ values typically between +2 and +3 ‰. A negative spike (approaching 0 ‰) occurs at 427.88 m (1403.8 ft.), approximately 8 m below the top contact of 425.50 m (1396 ft.). This may indicate diagenesis related to an overlying disconformity, however, until confirmed with more closely spaced sampling, this single-point spike should be considered a possible outlier.

A transect across exposed bedrock in the Severn River in northern Ontario (south of the Pen No. 1 location), showed a similar chemostratigraphic relationship (Figure GS2017-12-8). Samples from the Attawapiskat Formation (biohermal) outcrops (location 11DKA034 in Armstrong, 2011) yielded $\delta^{13}C$ values ranging from +2.27 to +3.28 ‰, and stratigraphically higher, laminated dolostones (location 11DKA036 in Armstrong, 2011) yielded values ranging from +0.93 to +2.17 ‰ (Armstrong et al., 2013a). The latter unit was mapped as uppermost Attawapiskat Formation, but should likely be considered lowermost Kenogami River Formation. In the Kaskattama well, this contact is marked by a similar shift in $\delta^{13}C$ from about +2 ‰ in the lowest portions of the Kenogami River Formation to consistent values of around +3 ‰ in the Attawapiskat Formation.

Lithologically, the Kenogami River–Attawapiskat–Ekwan River formations interval in the Comeault core has significant differences with that observed in the Kaskattama and Pen No. 1 cores. In the Comeault core (Figure GS2017-12-6), a biohermal lithofacies of the Attawapiskat Formation occurs between 122.22 and 133.50 m (401–438 ft.), and represents Norford's (1971) "upper tongue of Attawapiskat Formation". Above 122.22 m (401 ft.) rock types are dominated by dolosiltite, which is characteristic of the lower member of the Kenogami River Formation. From 133.50–145.05 m (438.0–475.9 ft.) the rock types appear more similar to the lower Kenogami River Formation than either the Attawapiskat or Ekwan River formations. The interval from 145.05–153.92 m (475.9–505.0 ft.) consisting of tan to light brown, interbedded wackestones and packstones could, based on lithology alone, be assigned

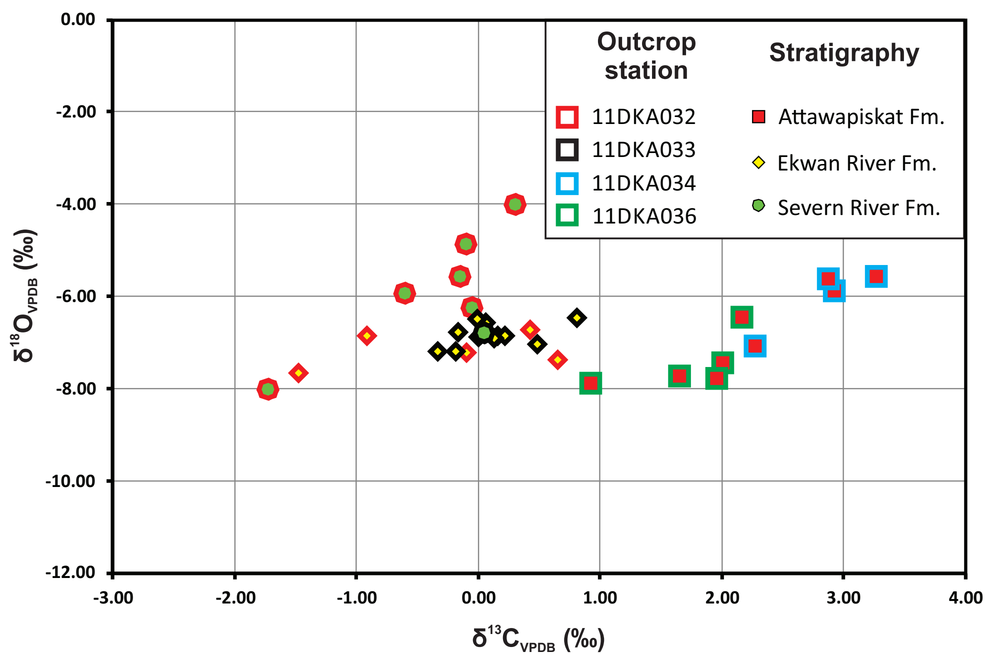

Figure GS2017-12-8: *Plot of* $\delta^{18}O$ *versus* $\delta^{13}C$ *for outcrop samples of the Ekwan and Attawapiskat formations along the Severn River in northern Ontario. Outcrop stations (from Armstrong, 2011), plotted on Figure GS2017-12-1, are 11DKA032 (Ekwan and Severn River formations), 11DKA033 (Ekwan River Formation), 11DKA034 (Attawapiskat Formation), 11DKA036 (upper Attawapiskat Formation or lower Kenogami River Formation). Symbol outline colour is coded according to station number, and symbol shape and fill is coded according to stratigraphic assignment. Abbreviations: VPDB, Vienna Peedee Belemnite.*

to either Ekwan River or Severn River formations. The interval from 153.92–158.59 m (505.0–520.3 ft.) consists of a biohermal lithofacies and corresponds closely to Norford's (1971) "lower tongue of Attawapiskat Formation". The top of the higher biohermal interval (122.22 m) is selected as the official top pick of Attawapiskat Formation in this core.

Nomenclature challenges

The interbedded nature of the formations (or lithofacies characteristics of specific formations) identified in the Comeault core by Norford (1971) comes with its challenges. Traditional lithostratigraphic top selections seldom allow for the recording of the interbedded nature of a section, that is, the occurrence of a formation top more than once in a well that is not structurally disturbed, and so it is seldom recorded that a particular formation occurs more than once in a given location. This is mostly due to the constraints of computer database architecture, and the challenge of handling multiple entries for the same unit. Previous authors (e.g., Lavoie et al., 2015) have acknowledged the complex inter-relationship of these units, and refer to "Attawapiskat reefs" within the Ekwan River Formation, rather than a stand-alone Attawapiskat Formation. The inter-relationship of these formations and their constituent facies remains a subject for further investigation.

Ekwan River Formation

The key lithological difference between the Ekwan River Formation and the overlying Attawapiskat Formation is the former's bedded biostromal nature and the latter's biohermal nature (Savage and Van Tuyl, 1919; Norris, 1993). In the Pen No. 1 core, the Attawapiskat Formation consists of two biohermal zones separated by bedded limestones, which on their own might be interpreted as Ekwan River Formation. As discussed above, the intercalated lithofacies suggest these formations may at least in part be equivalent or, as some have suggested (e.g., Lavoie et al., 2015), the Attawapiskat reef facies should be part of the Ekwan River Formation. For this report, however, the present formational status of these units is retained.

Lithostratigraphically, the top of the Ekwan River Formation is placed at the base of the lowest biohermal limestone (i.e., basal Attawapiskat Formation). In the Pen No. 1 core (Figure GS2017-12-4), this is a sharp contact at 506.36 m (1661.3 ft.). It is also marked by a sharp but small increase (downward) in the average GR response, reflecting the difference between clean carbonate of the Attawapiskat Formation and the slightly higher argillaceous content in the Ekwan River Formation.

Despite the lack of core through this interval in the Kaskattama well (Figure GS2017-12-3), the lithological difference between the Attawapiskat and Ekwan River formations is consistent within Pen No. 1, and is supported by a similar GR log response. The upper contact of the Ekwan River Formation is picked on the GR log at 393.50 m (1291 ft.) in the Kaskattama well.

Isotopically, in these two wells (Figures GS2017-12-3, -4), the top of Ekwan River Formation (identified lithologically) is located near the base of the broad $\delta^{13}C$ high that characterizes the overlying Attawapiskat Formation and immediately above the top of two small positive spikes (albeit more subtle in the Kaskattama core).

The $\delta^{13}C$ isotopic profile for the Ekwan River Formation is best exhibited in the Pen No. 1 core (Figure GS2017-12-4), and generally consists of positive values (+2 to +3 ‰) in the upper part, similar to or slightly lower than values for the overlying Attawapiskat Formation. The middle part of the Ekwan Formation exhibits lower $\delta^{13}C$ values, down to about 0 ‰, but can contain some positive spikes, whereas the lower part of the formation exhibits high values, similar to the top. Below this, passing into the underlying Severn River Formation, average $\delta^{13}C$ values decrease to about 0 ‰.

In the Comeault core (Figure GS2017-12-6), the top of the Ekwan River Formation, based on the $\delta^{13}C$ isotope profile, is at 158.59 m (520.30 ft.), but the lithological change exhibited at this depth is not typical of the Attawapiskat Formation–Ekwan River Formation contact. Lithologically, below 158.59 m (520.30 ft.) and with increasing depth, the rock becomes dominantly a wackestone to wackestone-packstone, greyer in colour, slightly more argillaceous and allochems decrease in abundance. In the isotope profile, the two small positive spikes below 158.59 m (520.30 ft.) in the Comeault core may correlate with similar double spikes that are coincident with the top of the Ekwan River Formation in the Kaskattama and Pen No. 1 wells. The upper unit of the Ekwan River Formation in the Comeault core extends down to 173.77 m (570.0 ft.), and includes some packstone interbeds. Below this, from 173.77 to 182.88 m (570.0–600 ft.), there are variable carbonate rock types, ranging from laminated mudstones to packstones to calcarenites. The allochems (crinoids, brachiopods, horn corals, stromatoporoids, gastropods) between 158.59 and 182.88 m (520.30–600 ft.) are characteristic of the Ekwan River Formation, however, the lithological character of this interval in the Comeault core differs significantly from the Ekwan River Formation in the Kaskattama and Pen No. 1 cores.

Severn River Formation

The Severn River Formation is the thickest Silurian carbonate unit in the southern (onshore) part of the HBB. It has been informally subdivided into three members: lower, middle and upper (LeFèvre et al., 1976; Norris, 1993; Armstrong et al., 2013b).

Although it contains a variety of rock types, the most common lithology of the Severn River Formation is a light tan, burrow-mottled carbonate. Wackestones and packstones dominate the upper and lower members, but can also occur in the middle member. Thin, bioclastic, and locally intraclastic, grainstone beds occur throughout, and appear to be best developed in the lower member, where they occur in association with *Virgiana decussata*-rich limestones. Mudstones, either laminated or massive, also occur throughout but are generally subordinate to the wackestones and packstones, except in the middle member. Dolomudstone and anhydrite beds and nodules characterize the middle member, although mudstones, wackestones and packstones are also present. Nodular and bedded anhydrite is limited to the upper member in the Kaskattama well. These various lithofacies appear to be arranged in sequences that represent shallowing upward cycles. This is especially evident in the middle member where cycles include anhydrite beds capped by greenish, argillaceous, dolomudstone to dolosiltstone beds. These green beds stand out in GR logs as sharp positive spikes. Green argillaceous beds also occur in the upper member but are not as numerous (cycles may not be as well developed). The lower member is defined by its position beneath the evaporative middle member and the occurrence of locally abundant *Virgiana decussata* brachiopods. The lower part of the lower member is marked by a decrease in allochem abundance, grading downwards from *Virgiana*- and coral-bearing grainstones and packstones to wackestones and ultimately lime mudstone (or locally dolomudstone) at its base. The lime mudstone (or dolomudstone) grades rapidly into grey siliciclastic mudstones of the Red Head Rapids Formation.

The top of the upper member of the Severn River Formation is exposed in two outcrops, map station 11DKA032 on the Severn River (Armstrong, 2011) and map station 11DKA017 (Armstrong, 2011; same as map station 15DKA063 in Armstrong, 2015) on the Attawapiskat River (Figure GS2017-12-9), and in numerous cores (e.g., Comeault, Kaskattama, Pen No. 1, KWG-Spider Resources DR-94-19 [KWG; Ratcliffe and Armstrong, 2013]). Despite these numerous occurrences, the top of the upper member of the Severn River Formation is difficult to pick in the subsurface.

Outcrop exposures on the Severn and Attawapiskat rivers reveal a sharp disconformable contact; although the uppermost lithofacies of the Severn River Formation differs in each case (Figure GS2017-12-9). In the Severn River outcrop (11DKA032; Armstrong, 2011), the uppermost Severn River Formation lithofacies is a thin-platy bedded, greenish (weathering to yellowish), argillaceous dolosiltstone, similar to the uppermost Severn River Formation in the Pen No. 1 core. Farther to the east in Ontario, in the MRB, on the Attawapiskat River (at outcrop 11DKA017; Armstrong, 2011) the uppermost Severn River Formation is a very fine-grained, burrow-mottled wackestone with thin packstone beds. It looks similar to the basal beds of the overlying Ekwan River Formation, except that the latter have a coarser grained matrix. The disconformable nature of the contact is obvious at this locality and was described by Suchy (1992).

In core from the MRB, such as core KWG (also map station 13LMR004 in Ratcliffe and Armstrong, 2013), the contact is subtle and hard to pick. Many of the thin grainstone beds in the upper Severn River Formation have sharp bases, which can easily be mistaken for the contact. Key lithological indicators to recognizing this contact include an increase in matrix grainsize in the Ekwan River Formation, as well as the occurrence and abundance of stromatoporoids, tabulate corals and crinoidal fragments. Chert also tends to be more prevalent in the Ekwan River Formation, where it is locally very abundant (especially in the lower half of the formation). In the KWG core, there is an interval (67.5–70.22 m) of creamy tan to light grey lime mudstone-siltite in the middle of the formation, which could be interpreted as the uppermost Severn River Formation. Below this, however, there is an interval (72.8–79.33 m) of grey, wackestone-packstone-grainstone beds with abundant stromatoporoids, tabulate corals and chert—classic Ekwan River Formation lithofacies. The lowest bed is intraclastic overlying a disconformity. Underlying it is a grey-tan, burrow-mottled, lime

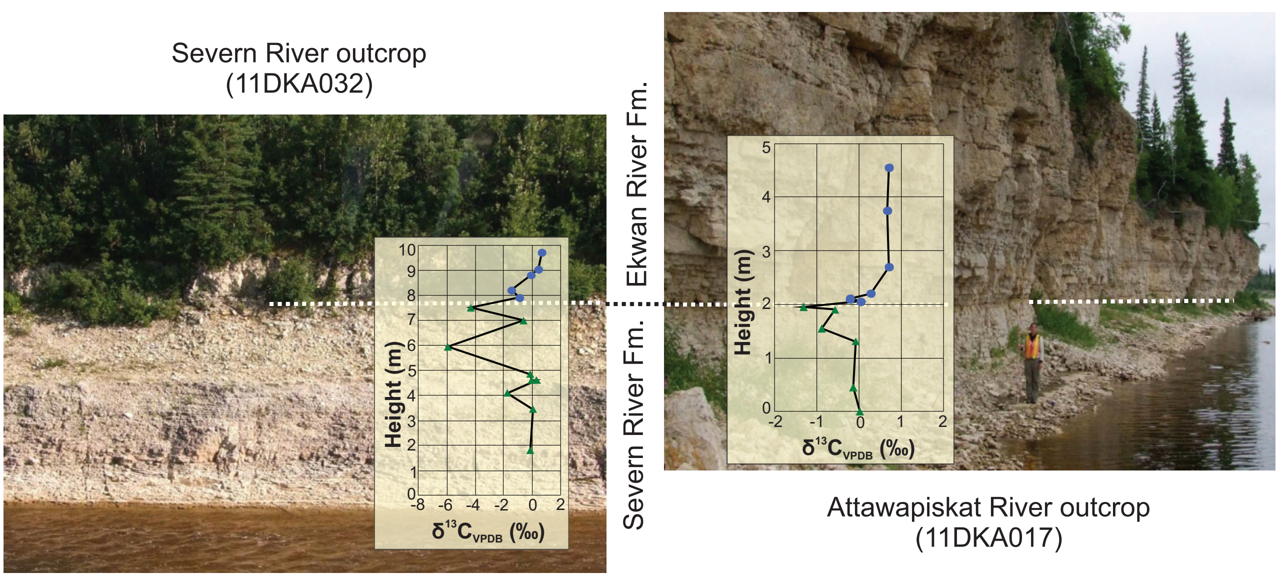

Figure GS2017-12-9: *Outcrops showing the disconformable contact between the Ekwan River and Severn River formations, on the Severn River (left; station 11DKA032 from Armstrong, 2011) and 365 km to the southeast on the Attawapiskat River (right; station 11DKA017 from Armstrong, 2011). Outcrop photographs are overlain with their respective $\delta^{13}C$ isotopic profiles. Data points are colour coded to formations: blue dots are Ekwan River Formation and green triangles are Severn River Formation.*

mudstone to sparsely fossiliferous wackestone, similar to the uppermost Severn River Formation in the Attawapiskat River outcrop. These key lithological indicators are also present in the Comeault core.

Isotopically, the top of the Severn River Formation is marked by a downward decrease in $\delta^{13}C$ from values around +2 ‰ in the lower Ekwan River Formation to values typically ranging from –1 to +1 ‰ in the upper Severn River Formation. In Ontario, the isotopic profile across the contact is consistent among cores and outcrops in both the HBB (Severn River outcrops and Pen No.1 core) and MRB (Attawapiskat River outcrops and KWG core; Figure GS2017-12-9; Armstrong et al., 2013b; Ratcliffe and Armstrong, 2013). In most cases, the contact is marked by a negative $\delta^{13}C$ spike in the uppermost Severn River Formation, possibly related to the overlying disconformity. In Pen No. 1, the spike occurs at 558.79 m (1833.3 ft.; Figure GS2017-12-4), and at 441.96 m (1450 ft.) in Kaskattama (Figure GS2017-12-3) and 200.04 m (656.3 ft.) in Comeault (Figure GS2017-12-6).

The top of the Severn River Formation in Pen No. 1 (Figure GS2017-12-4), as defined lithologically and isotopically, occurs in a GR low between two moderate GR positive spikes and at the top of a negative shift in the neutron log. This corresponds to a depth of about 438.91 m (1440 ft.) in the Kaskattama well (Figure GS2017-12-3), with both the GR log and isotopic profiles in agreement. This is, however, in conflict with the top of the Severn River Formation in the Kaskattama well being picked lithologically at the top of the anhydrite at 433.43 m (1422 ft.). The discrepancy between the lithological pick, isotopic signature and GR logs for this well is likely due to intermittent core recovery.

In the Whitebear core (Figure GS2017-12-7), the isotopic signature between 30.48 and 220.68 m (100.0–724.0 ft.) follows the pattern typical of the Severn River Formation in Comeault, thus confirming the absence of the Attawapiskat and Ekwan River formations in this core.

Economic considerations

The Hudson Bay Lowland in Manitoba is a large frontier area with good potential for local hydrocarbon accumulations. The stratigraphic information described here guides the long-distance correlations of rock units, as well as predictability of the depositional environment that formed the rocks. This provides a basic geological framework for the sedimentary basin including its structure and lithologies, which is required to attract exploration investment. Geographic predictability, particularly in a large basin like the HBB, helps a company identify focus areas for exploration. The information gathered from this project supports exploration of natural resources and informs decisions on land-use planning that balance conservation and responsible resource development.

Economic benefits from collaborative programs such as GEM-2 can be measured in terms of industry attraction and investments over the long term. The program also provides access for the MGS to expertise and services from world-class GSC laboratories, as well as training opportunities for students to develop themselves as new geoscience experts in Manitoba, benefits that can be applied to other projects in the future.

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