Natural Resources Canada | Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8321

Report of activities for the ground geophysical survey across the Kaskattama highlands, Manitoba: GEM-2 Hudson-Ungava Project

J.A. Craven, I.J. Ferguson, M.P.B Nicolas, T. Zaprozan, T.J. Hodder, B.R. Roberts, and N. Clarke

2017

Celebrating 175 yrs

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8321

Report of activities for the ground geophysical survey across the Kaskattama highlands, Manitoba: GEM-2 Hudson-Ungava Project

J.A. Craven[1], I.J. Ferguson[2], M.P.B Nicolas[3], T. Zaprozan[2], T.J. Hodder[3], B.R. Roberts[1], and N. Clarke[3]

[1]Geological Survey of Canada, 601 Booth St., Ottawa, ON, K1A 0E8
[2]University of Manitoba, 233 Wallace Bldg., Winnipeg, MB, R3T 2N2
[3]Manitoba Geological Survey, 360-1395 Ellice Ave., Winnipeg, MB, R2G 3P2

2017

Permanent link: https://doi.org/10.4095/306143

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Recommended citation
Craven, J.A., Ferguson, I.J., Nicolas, M.P.B., Zaprozan, T., Hodder, T., Roberts, B.R., and Clarke, N., 2017. Report of activities for the ground geophysical survey across the Kaskattama highlands, Manitoba: GEM-2 Hudson-Ungava Project; Geological Survey of Canada, Open File 8321, 30 p. https://doi.org/10.4095/306143

Table of Contents

Project Summary

This open file presents an overview of pre-survey studies and new ground geophysical data collected in July of 2017 to help determine the origin of the Kaskattama Highlands in northern Manitoba. The region's local topography and possible Cretaceous or Tertiary stratigraphy collected within drill core conflict with the intracratonic basin model for the region used currently as the basis for assessing the hydrocarbon prospectivity of the region. The new data will help constrain possible geological models for the area.

Introduction

The Geo-mapping for Energy and Minerals (GEM) program is laying the foundation for sustainable economic development in the North. The Program provides modern public geoscience that will set the stage for long-term decision making related to responsible land-use and resource development. Geoscience knowledge produced by GEM supports evidence-based exploration for new energy and mineral resources and enables northern communities to make informed decisions about their land, economy and society. Building upon the success of its first five-years, GEM has been renewed until 2020 to continue producing new, publically available, regional-scale geoscience knowledge in Canada's North.

During the 2017 field season, research scientists from the GEM program successfully carried out 27 research activities, 26 of which will produce an activity report and 12 of which included fieldwork (Figure 1). Each activity included geological, geochemical and geophysical surveying. These activities have been undertaken in collaboration with provincial and territorial governments, Northerners and their institutions, academia and the private sector. GEM will continue to work with these key partners as the program advances.

This project activity involves a ground-based magnetotelluric (MT) survey in the Kaskattama Highlands region of northeastern Manitoba to map faults in Paleozoic successions that might explain the origin of the morphology and associated variations in stratigraphy (Figures 2 and 3; Nicolas & Clayton 2015).

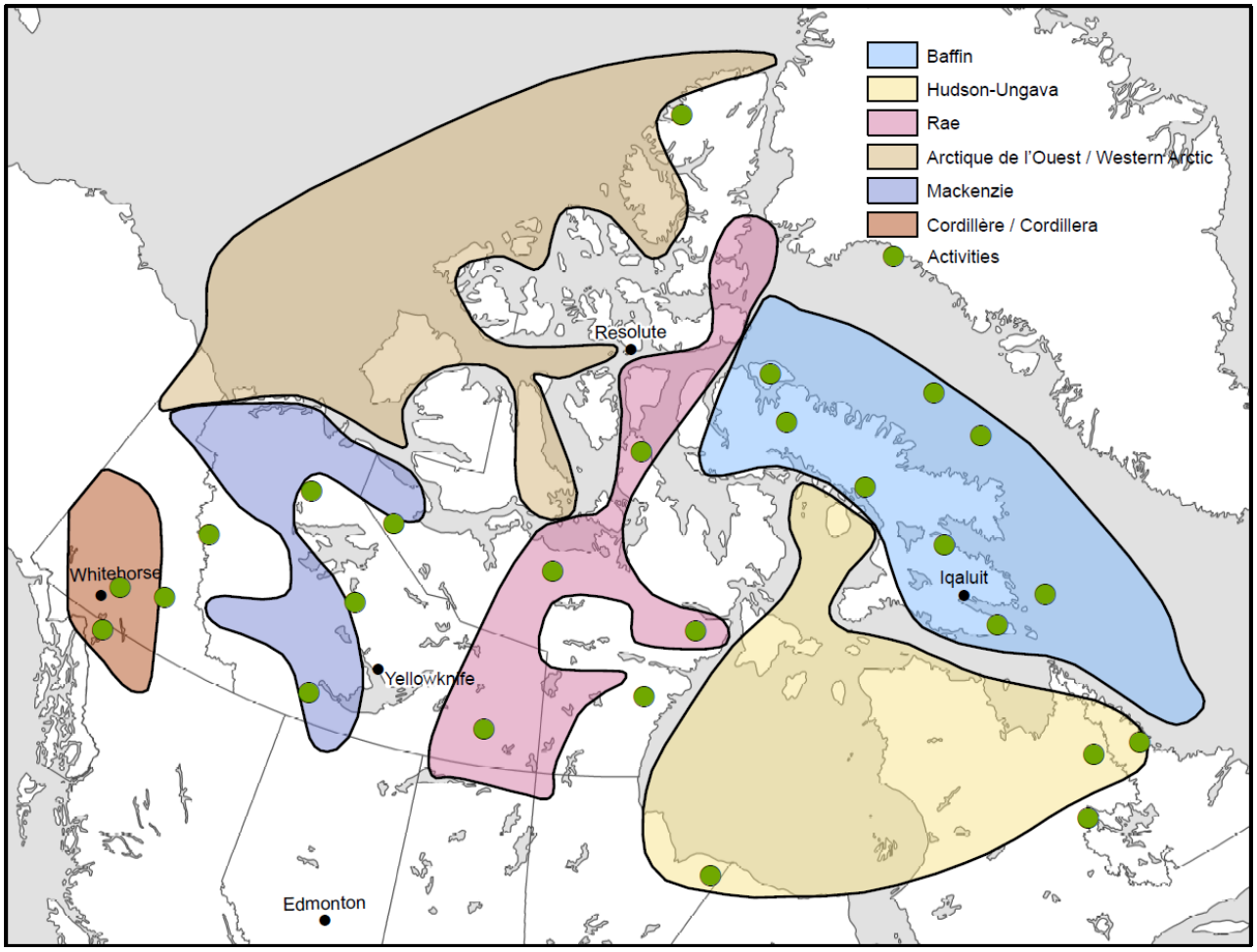

Figure 1 GEM 2017 field activities.

The MT technique is an electromagnetic geophysical technique that provides imaging capabilities to mantle depths at relatively low cost in comparison to other techniques such as seismic reflection. The technique is entirely passive as it utilizes fluctuations in the Earth's natural magnetic field as a virtual transmitter. MT receivers and sensors are portable and low power, and are can be deployed in remote locales with a small crew of two or three persons from a helicopter. Electromagnetic investigations, such as are involved in MT soundings, of sedimentary basins are primarily sensitive to the electrical resistivity of fluids in pores in addition to their connectivity of the pore spaces. Secondarily, EM techniques are sensitive to the host matrix of the rock rock and in sedimentray basins, particularly to the clay content of shale units. As such, MT techniques offer a viable manner to explore for both contrasts in lithology due to layering or faulting, and provide insights into fluid compositions within the pore matrices. For further information about MT soundings the reader is referred to Chave and Jones (2012).

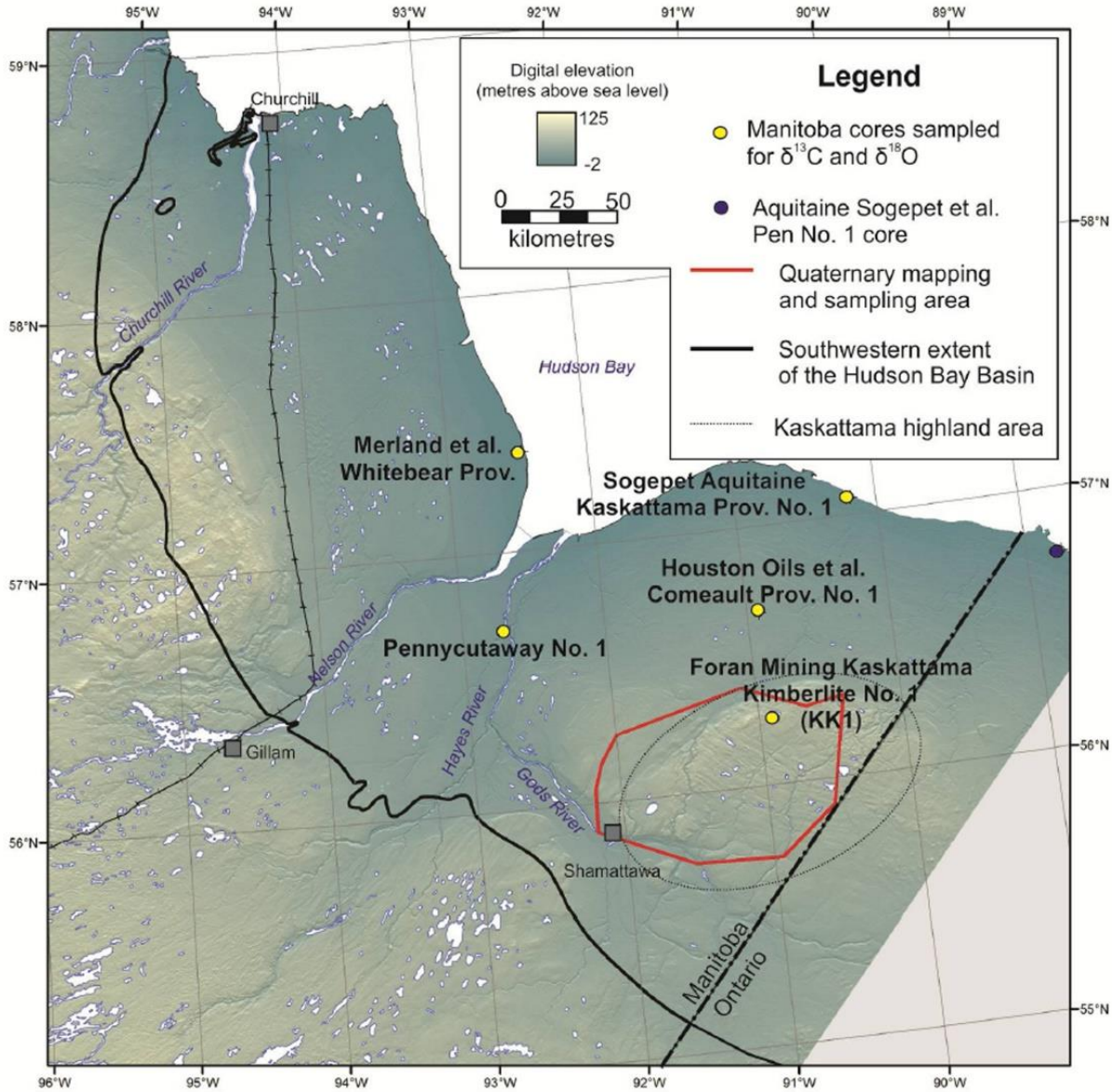

Figure 2. Location of the Kaskattama Highlands area and other scientific investigations (Lavoie et al. 2016). Note the location of drill-holes.

Widely spaced MT soundings have been done in the Hudson Bay Basin (HBB) as part of LITHOPROBE Western Superior (Ferguson et al. 2005, Craven et al. 2001) and Trans Hudson Orogen (THO) transects (Jones et al. 2005), by the GSC under GEM-1 at Churchill (Roberts and Craven 2012), and by Manitoba Hydro in Bipole III planning studies (Adetunji & Ferguson 2013). Local results indicate Ordovician and Silurian units in the basin are more resistive than correlative units in the Williston Basin (e.g., Jones 1988, Gowan et al. 2009) and that overlying Quaternary deposits are relatively conductive (Adetunji & Ferguson 2013). The higher resistivity of the Paleozoic units is likely because of lower pore-water salinity (e.g., Betcher et al. 1995). MT studies of the HBB therefore need careful planning to optimize survey results.

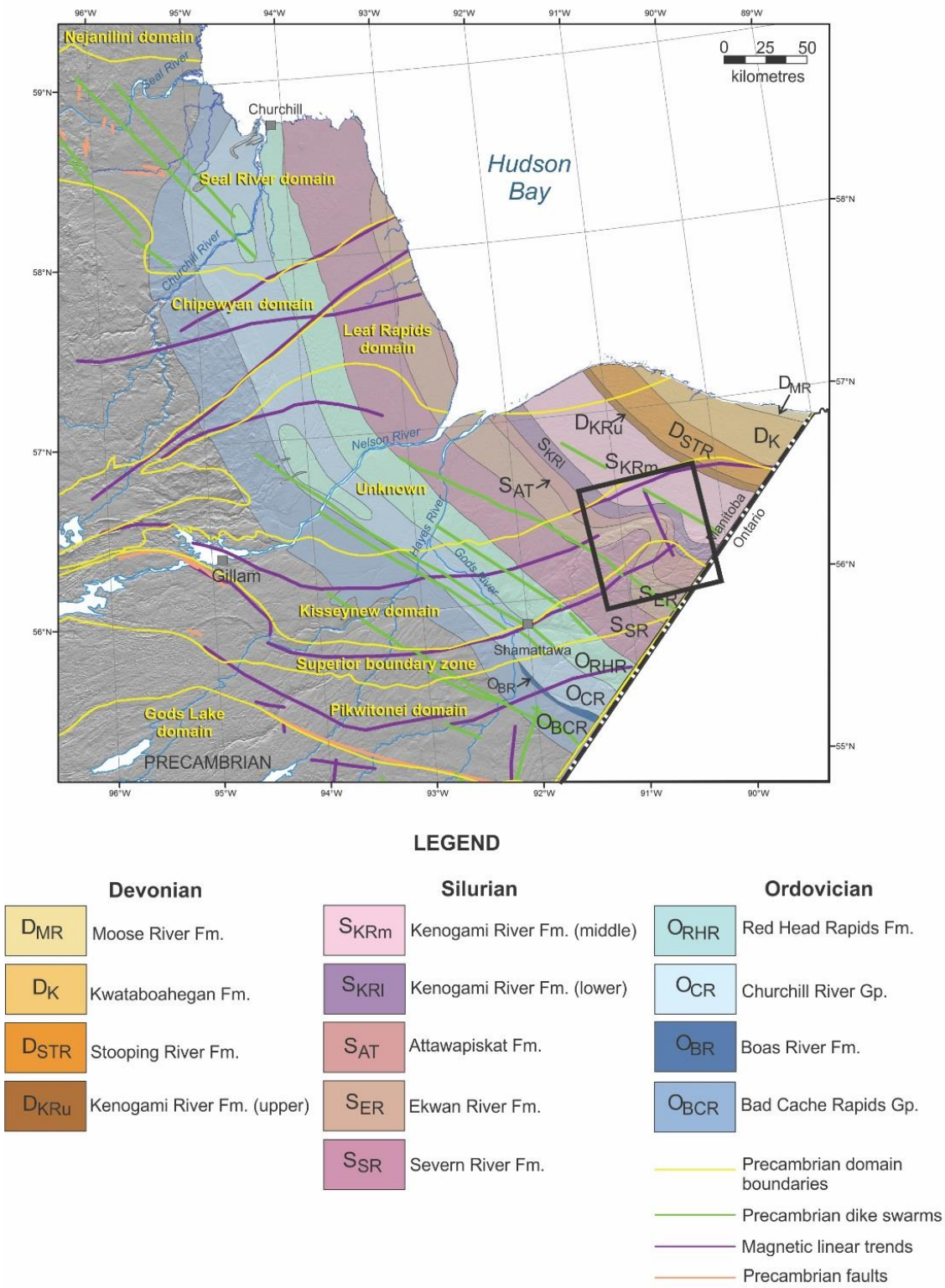

Figure 3. Paleozoic geology of the Hudson Bay Lowlands superimposed on a 90 m pixel-spacing digital elevation model, and overlain with the Precambrian domain boundaries, magnetic linear trends, faults and dike swarms (modified from Nicolas & Clayton 2015). The Kaskattama Highland area lies to the north of Shamattawa. Black rectangle shows the approximate location of the current study area.

In order to assess basement control on the Hudson Bay Basin it is important to characterize the underlying architecture of the Precambrian lithosphere (Figure 3). Basement conductors related to graphitic or other conductive metasedimentary schists can form key markers of Proterozoic continental margins, e.g., flanking the Sask craton in the THO (Jones et al. 2005, Gowan et al. 2009). They can potentially complement potential field data for tracking circum-Superior belts beneath the HBB e.g., resolving the significance of the Fox River Belt and Owl River shear zone, providing an improved framework for studies of tectonic control on basin formation.

The HBB lies over the margin of the Archean Superior craton and the Proterozoic Trans Hudson Orogen (Figure 4 and Figure 4). The western Superior Province, which has been stable since 2.6 Ga, consists of linear, sub-parallel subprovinces including greenstone-granite terranes (Percival et al., 2006). It is hypothesized to have formed through successive formation and accretion of island arcs and accretionary prisms. The Proterozoic THO is interpreted to be analogous to the current Himalayan region (Figure 2). Juvenile Proterozoic and altered Archean rocks of the THO formed during collision of the Archean Superior and Hearne (Figure 4; Ansdell, 2005). Smaller fragments of Archean crust were trapped between the Superior and Hearn cratons (such as the Sask craton in Figure 4) and, along with the shape of the two main cratons, are thought to have prevented the complete convergence of the two Archean cratons. There is some uncertainty as to the tectonic boundaries beneath Hudson Bay itself. Eaton & Darbyshire (2009) propose a model based on interpretation of potential field anomalies in which the southeastern third of the HBB is underlain by Proterozoic crust formed within an oceanic or marginal-basin setting proximal to the Superior craton, the northwestern third is underlain by Archean crust, and the middle third is interpreted to be a continental magmatic arc.

There is also some uncertainties regarding the large-scale 3-D form of the margin of the Superior craton and the Trans Hudson Orogen in the area of the Kaskattama Highlands. The Fox River belt is a low-grade, north-dipping sequence located at the northwest junction of the Superior Province and the THO. It has a width of 20 to 25 km and extends for 152 km (Barager & Scoates 1981, Scoates 1990). It is one of a series of geological units formed at, or near, the boundary of the Superior Province during the development of the THO; this series of geological units is collectively referred to as the Superior Boundary Zone (SBZ) (Minifie et al. 2013). The Thompson Belt is another part of the SBZ.

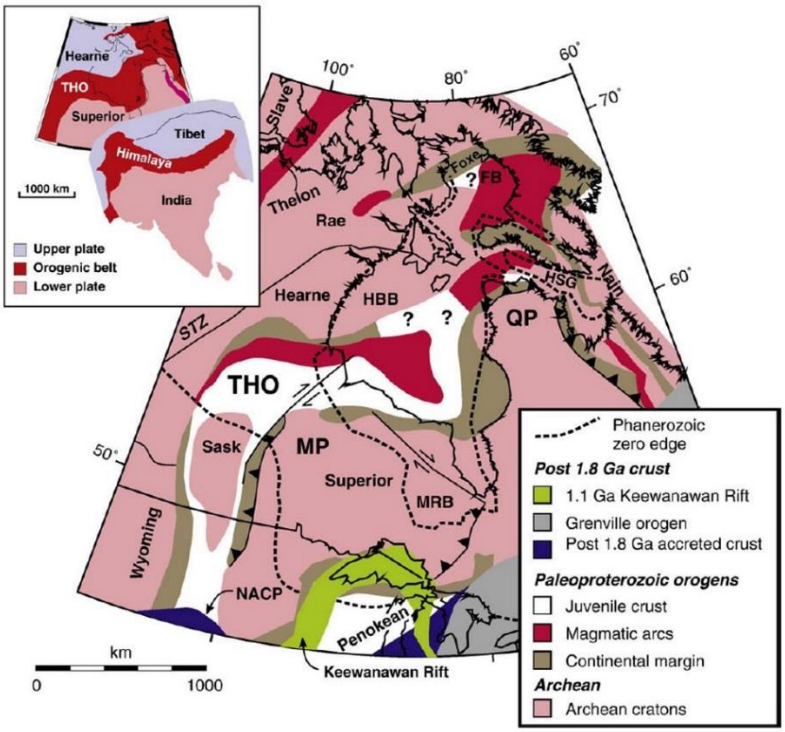

Figure 4. Precambrian geology of the HBB region (Eaton & Darbyshire 2009). THO, Trans-Hudson orogen; MP, Manitoba promontory; QP, Quebec promontory (Ungava Peninsula), HBB, Hudson Bay basin; HSG, Hudson Strait graben; FB, Foxe Basin; MRB, Moose River Basin; NACP, North American Central Plains orogen, STZ, Snowbird Tectonic Zone. Inset compares the shape and extent of the THO with the Himalayan orogen.

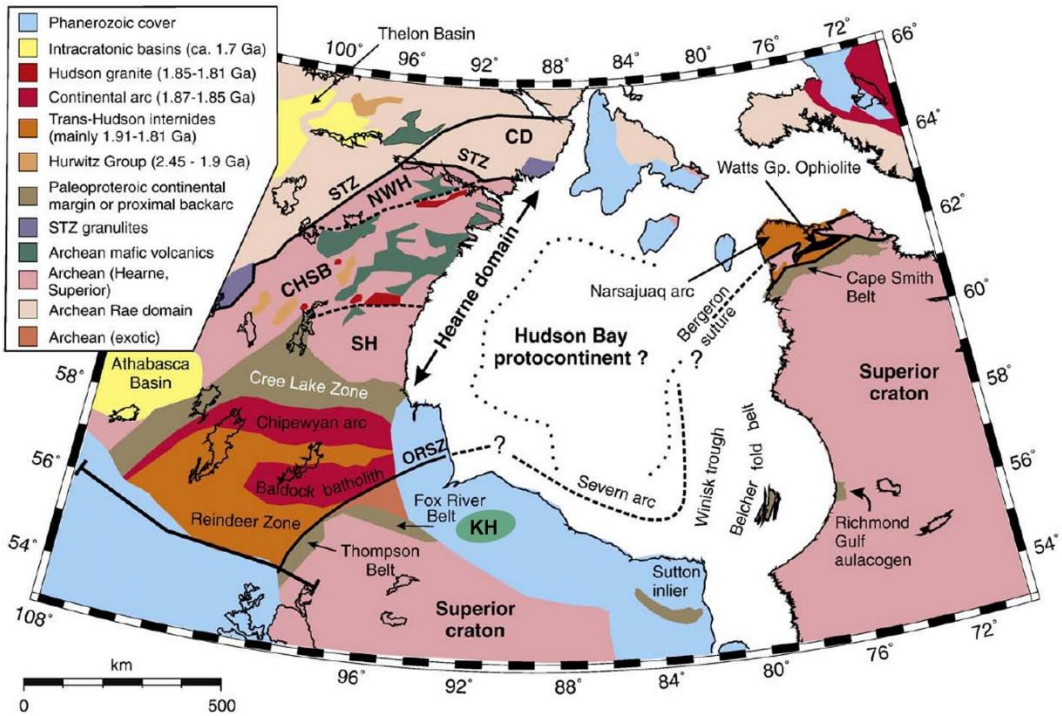

Figure 5. Geological framework of HBB region (Eaton & Darbyshire 2009). Green ellipse labelled KH indicates the area of the Kaskattama Highlands. ORSZ, Owl River shear zone; SH, southern Hearne domain; CHSB, central Hearne supracrustal belt; NWH, northwest Hearne domain, CD, Chesterfield domain; STZ, Snowbird Tectonic Zone.

The Precambrian rocks to the north of the Fox River Belt are exposed at the surface west of the HBB. These rocks are mainly gneisses and are interpreted to be associated with the Kisseynew Domain of the Trans Hudson Orogen. Potential field maps show the gravity and magnetic responses have northwest to southeast trends within the area suggesting that these gneisses extend beneath the Paleozoic HBB. However, there is some uncertainty as to the structure of the deeper parts of the crust (exceeding 10 km) in the study area. There is ongoing debate regarding the exact classification of the geology in this area (e.g., Eaton & Derbyshire 2009), with three possible configurations proposed:

1. In many geological interpretations the Fox River Belt is considered to have formed at the northern margin of the Superior craton (e.g., Barager & Scoates 1981, Hoffman 1990). The whole thickness of the Precambrian crust to the north of the Fox River Belt is interpreted to be part of the Proterozoic Trans Hudson Orogen.
2. In other geological interpretations the Fox River Belt is interpreted to have formed away from the edge of the Superior craton with the younger Proterozoic rocks thrust over the top of the edge of the Superior craton (Figure 6) (Weber 1990). The deeper parts of the crust would consist of Archean rocks of the Superior Province.
3. In studies closer to the Thompson area, an older block of Archean crust has been recognized in rocks previously interpreted to be part of the Trans Hudson Orogen (Böhm et al. 2000). This Archean block does not appear to be associated with the Superior craton and has isotopic age signatures that suggest affiliation with the Sask craton. It is therefore possible that the lower part of the crust in the study area contains Archean rocks from a similar source. In the Böhm et al. (2000) interpretation the Owl River Shear Zone (ORSZ in Figure 5) forms the margin of the Trans Hudson Orogen.

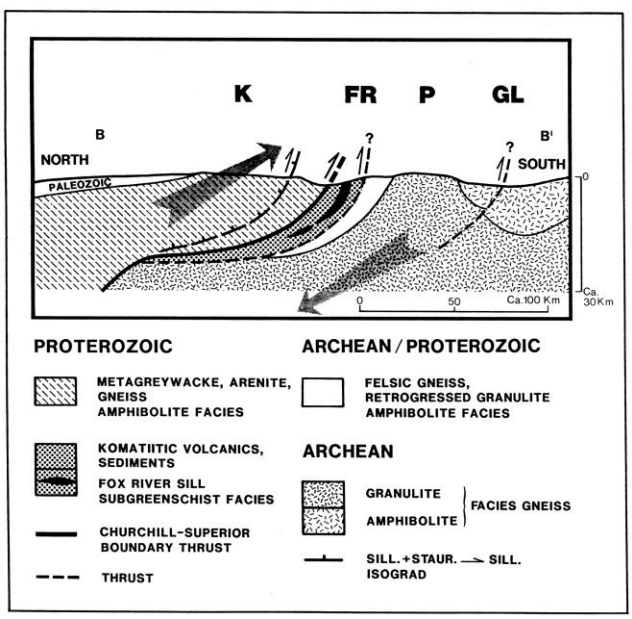

Figure 6. Model of the crustal structure surrounding the Fox River Belt from Weber (1990). The Proterozoic Kisseynew rocks (K) and Fox River (FR) Belt rocks are thrust over the north unit of the Superior Province, the Pikwitonei gneiss (P). GL refers to the Gods Lake Domain of the Superior Province.

The thickness of sedimentary rocks in the Paleozoic Hudson Bay Basin ranges up to around 2500 m (Figure 7 and 8) in the middle of Hudson Bay. Within the current study area, it ranges from around 400 m in the southwest to 1000 m in the northeast. Seismic surveys in marine parts of the basin

have imaged a number of features indicating offset of lowermost units by basement penetrating faults (Figure 8). Figure 9 shows the stratigraphic section for the HBB.

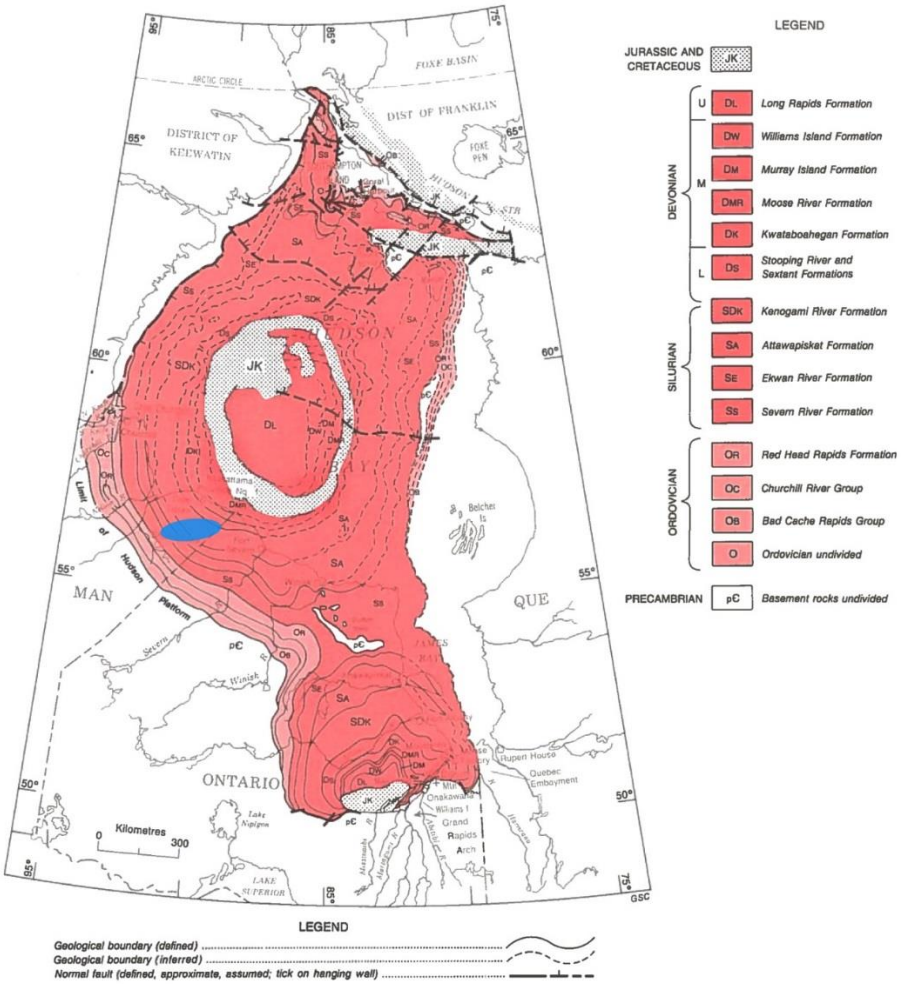

Figure 7. Isopach map of Phanerozoic cover in Hudson Bay and Moose River basins (Norris, 1993). Blue ellipse shows the Kaskattama Highland area.

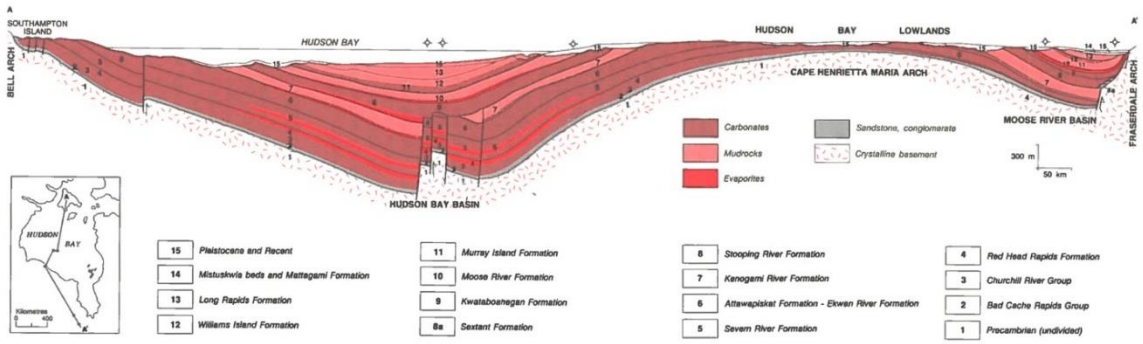

Figure 8. Schematic north-south section of Hudson Bay platform (Norris 1993).

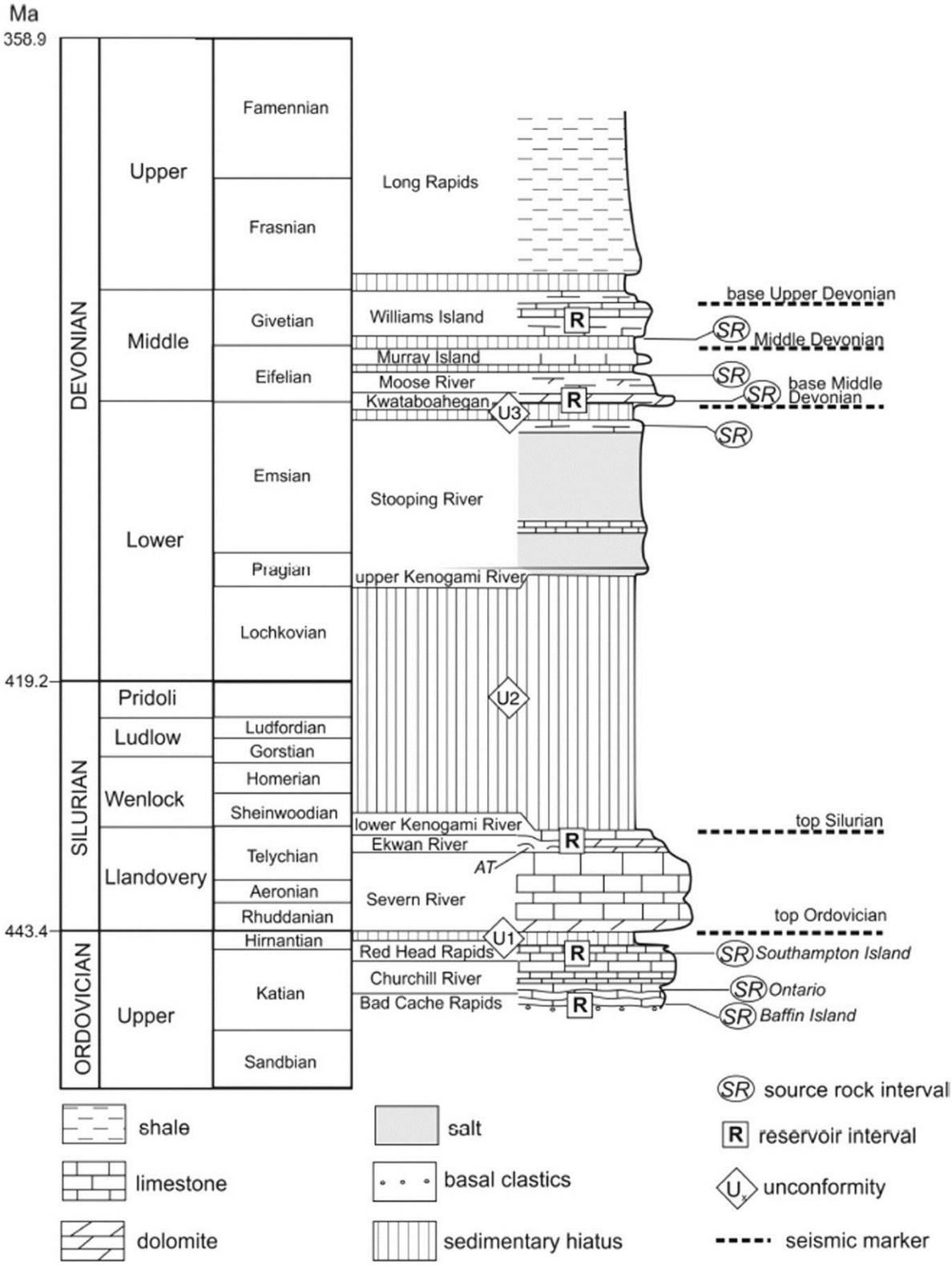

Figure 9. Stratigraphic succession of the Paleozoic rocks in Hudson Bay Basin, with major unconformities (U_1, U_2, and U_3), organic-rich intervals, potential reservoir rocks, source rocks, and major seismic-stratigraphic markers (Lavoie et al. 2015). AT = Attawapiskat reef.

Within the study area, the HBB rocks are Upper Ordovician to Middle Devonian in age (Figure 10). Information on the units comes from sources including a number of stratigraphic testholes, oil and gas industry wells and a drillhole, the Foran Mining Kaskattama Kimberlite No. 1 (KK1) well. Figure 11 shows the thickness of the units observed in four of the wells relative to a datum at the top of the Ordovician Red Head Rapids Formation. The observation of a thickened Quaternary sequence and possible Tertiary or Cretaceous rocks in the Foran Mining Kimberlite No. 1 well has led to a tentative revision of the boundaries of the Paleozoic rocks to the form shown in Figure 33.

The various lithostratigraphic units in the study area can be summarized as follows. The Bad Cache Rapids Group lies unconformably on the Precambrian basement and consists of dominantly carbonate shale and sandstone (Norris 1993; Nicolas 2011). The thickness of the group ranges from 61.97 m to 93.97 m in the current study area (Nicolas and Armstrong, 2017, in press). The group is subdivided into the Portage Chute and the Surprise Creek Formations. The Portage Chute is made up of three layers with sandstone at the base, dolostone in the middle, and limestone on the top while the Surprise Creek consists mainly of dolomitic argillaceous limestone (Norris, 1993; Nicolas 2011). It also contains minor evaporitic cycles (Lavoie et al. 2013). Rocks of the Churchill River Group occur as a narrow outcrop belt that unconformably overlies those of the Bad Cache Rapids Group. This group consists of mainly dolomitic mudstone to wackestone (Lavoie et al. 2013). The unit has been divided into the Caution Creek Formation (wackestone) and the Chasm Creek (mudstone) Formation. The thickness of the Churchill River group ranges from 59.13 m to 62.59 m in the study area (Nicolas and Armstrong, 2017, in press). The Red Head Rapids Formation conformably overlies the Churchill River Group. It is composed dominantly of dolostone and argillaceous dolomite with beds of evaporite (anhydrite with minor halite; Lavoie et al. 2013). It is massive to laminated and has occasional porous beds (Nicolas and Lavoie 2010). The thickness of the Red Head Rapids Formation in the study area ranges from 48.76 m to 63.92 m (Nicolas and Armstrong, 2017, in press). The total thickness of the Ordovician units ranges from 175.86 m to 219.70 m (Nicolas and Armstrong, 2017, in press). The Severn River Formation lies unconformably over the Red Heads Rapid Formation. It consists of fine-grained, thin-bedded limestone and some dolostone (Norris 1993). Within the study area its thickness varies greatly from 73.60 m to 234.54 m (Nicolas and Armstrong, 2017, in press). This increase coincides with a thickening towards the basin center. The Foran Mining Kimberlite No. 1 well terminated 73.6 m below the top of the unit. Within this well the unit is composed predominantly of mudstone with units of calcarenite and packstone. The Ekwan River Formation lies conformably above the Severn River Formation (Norris 1993). It is dominantly composed of mottled wackestone-packstone, dolomitic in places. Within the study area its thickness ranges from 39.93 m to 41.51 m (Nicolas and Armstrong, 2017, in press) but it reaches a thickness of 235 m in the offshore centre of Hudson Bay (Norris 1993). This unit as well as younger Silurian and Devonian units is missing from the Foran Mining Kimberlite No. 1 well where Severn River Formation rocks are overlain by interpreted Tertiary or Cretaceous sedimentary rocks (e.g., Nicolas & Lavoie 2012; (Nicolas and Armstrong, 2017, in press). The Attawapiskat Formation is dominated by reefoid to peloidal and oolitic limestone with local mottling and may be slightly dolomitized. Its thickness ranges from 11.25 to 63.71 m in the study area (Nicolas and Armstrong, 2017, in press). In the Comeault No. 1 and Kaskattama No. 1 exploration wells, the Attawapiskat Formation is overlain by the lower Kenogami River Formation and has a thickness ranging from 46.27 m to 61.91 m (Nicolas and Armstrong, 2017, in press). The member consists of dolomitic mudstone to argillaceous dolomitic mudstone, argillaceous to shaly partings. Some evaporite beds occur near the top of the member. The middle Kenogami River member consists of dolomitic silty shale to shaly siltstone and evaporite. The thickness of this unit in the Kaskattama No. 1 well is 154.59 m (Nicolas and Armstrong, 2017, in press). The upper Kenogami River member is a light brown to tan mudstone, mostly massive with

some mottling and occasional laminations. Its thickness in the Kaskattama No.1 well is 25.60 m. The member is interpreted to be of Lower Devonian age (Figure 9, Lavoie et al. 2013). The Stooping River Formation has a thickness of 57.31 m in the Kaskattama No.1 well. Core recovery from the well is poor but on the basis of the available core the formation has been sub-divided into a lower unit of argillaceous mudstone and an upper unit of dolostone with occasional argillaceous shaly intervals (Lavoie et al. 2013). In the Foran Mining Kimberlite No. 1 well log the Severn River Formation is overlain by a sequence of shaly rocks and clay that is interpreted to be of Tertiary or Cretaceous age (Nicolas and Armstrong, 2017, in press).

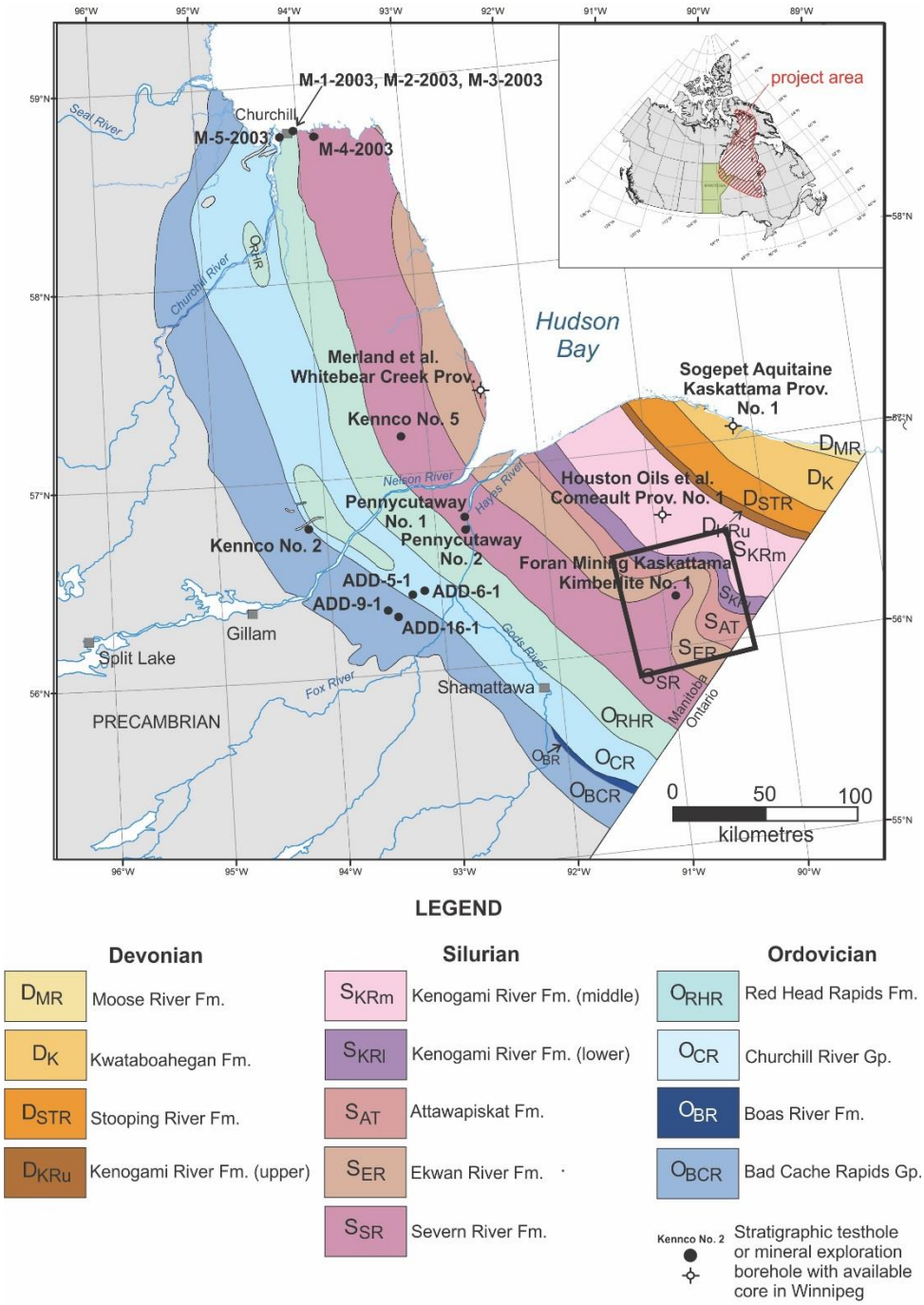

Figure 10. Paleozoic geology of HBB in Manitoba. Black rectangle shows the approximate extent of the Kaskattama Highlands study area. Inset shows the project area for the GEM Hudson Bay and Foxe Basins Project.

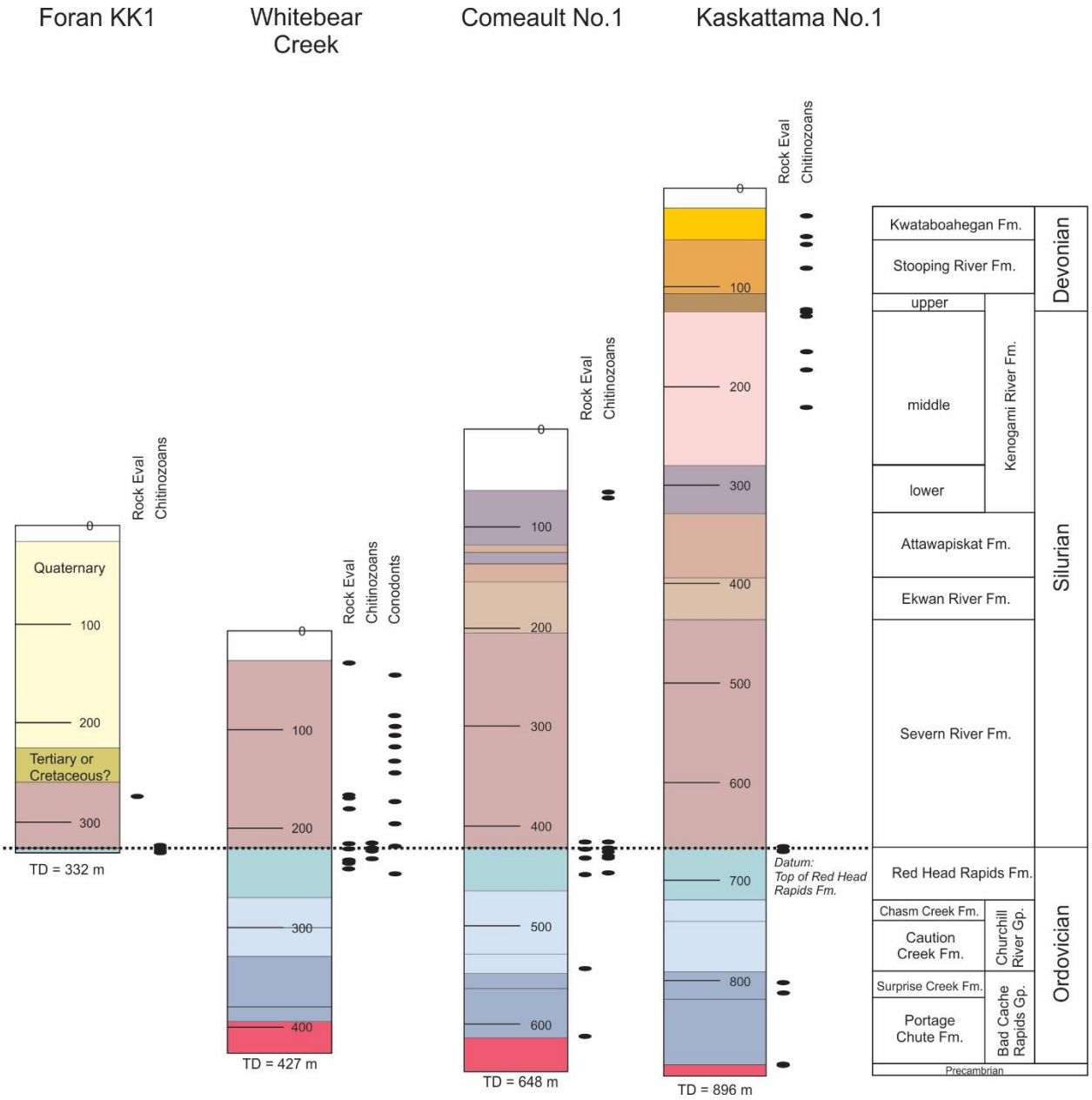

Figure 11. Stratigraphic columns for four from the HBB (modified from Nicolas & Lavoie 2012). Sampling was conducted in these wells for Rock Eval™ geochemistry and conodont and chitinozoan biostratigraphy; sampled intervals are shown by the black dots; depths are in metres. Figure 10 shows the well locations in northeastern Manitoba. Formations are indicated by similar colours as used in 10.

Figure 12 shows the large-scale surficial geology of Manitoba. Across the whole province the near-surface geology is dominated by Quaternary glacial deposits of clay, silt, and sand, with minor deposits of organic detritus. The Hudson Bay Lowland is dominated by offshore glaciomarine silt and clay with minor deposits of marginal glaciomarine clay, silt, and sand. Alluvial sand and gravel, sand, silt clay, and organic detritus occur along the rivers found in this area. The Kaskattama Highlands are very visible on the map and are dominated by silt diamicton derived dominantly from the carbonate rocks of the HBB. There are also smaller areas of offshore glaciomarine clay and silt and very small areas of distal glaciofluvial sediment.

Quaternary deposits in northeastern Manitoba define a long glacial history with evidence of deposition from multiple glacial and interglacial events (Hodder & Kelley 2016). Information on the deeper surficial geology in the Nelson River area is available from lithology logs from an extensive drilling program (at least 17 holes penetrating into the carbonate bedrock) at the Conawapa generating station site. Along the Nelson River, the uppermost 20 m of the surficial sediments consists of silty-clay to clayey-silt, which in some places is overlain by sandy-silt or silty-sand units. Beneath these units a thick layer of till extends to carbonate or shale bedrock, or in some locations, a thin gravel unit overlying the bedrock. The depth to bedrock varies between 45 and 71 m (Adetunji & Ferguson 2013).

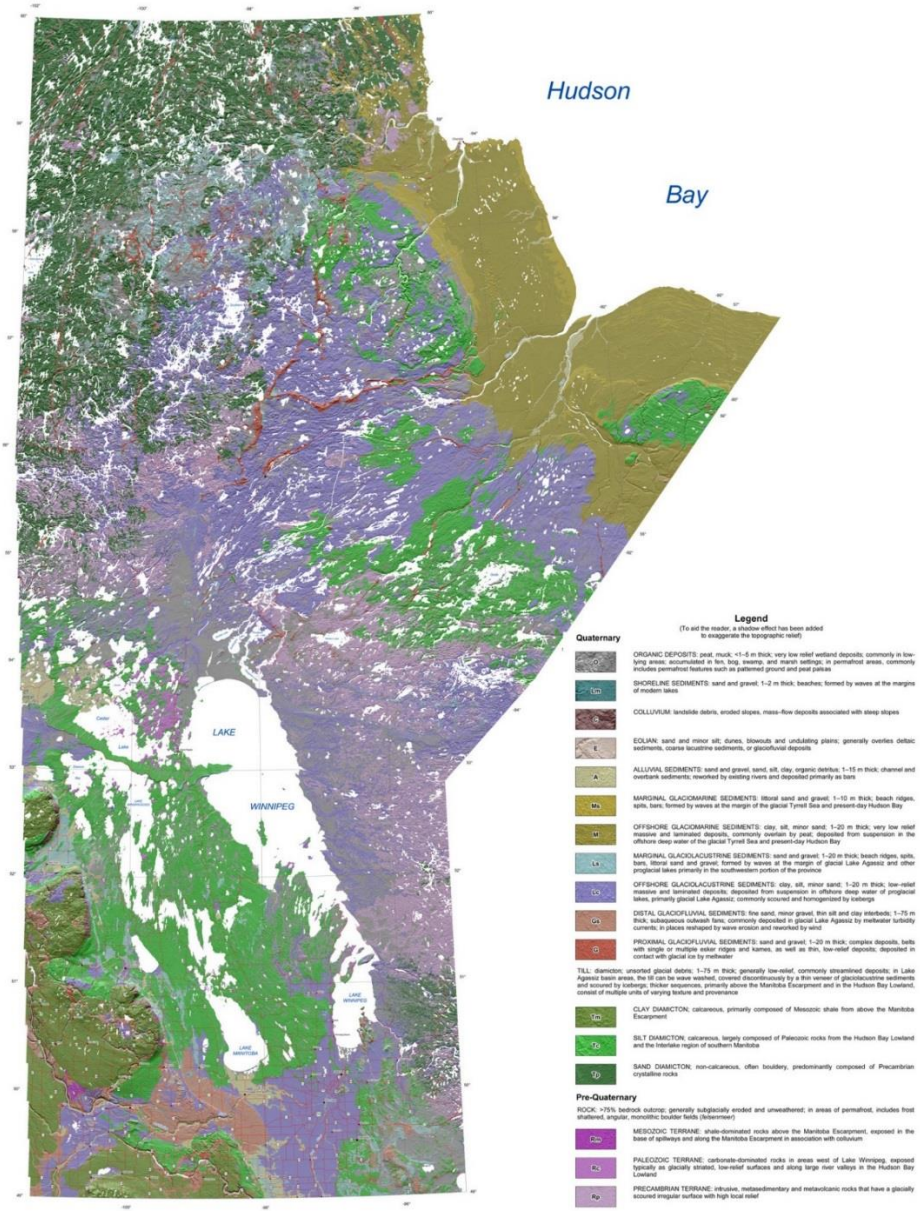

Figure 12. Surficial geology of Manitoba (modified from Matile & Keller 2007). The Kaskattama Highland area is clearly visible adjacent to the Ontario border and centred on latitude at 56º N.

Hodder & Kelley (2016) provide a more detailed analysis of the Quaternary geology of the Kaskattama Highland area. The Foran Mining Kimberlite No. 1 well included an inferred 233 m of Quaternary sediments suggesting the highland area, which rises 150 m above the flat lying Hudson

Bay Lowland, is composed largely of thick Quaternary sediments (Figure 13; Hodder & Kelley 2016). Similar Quaternary successions flank the Sutton Ridge and have been observed in the Attawapiskat area as well.

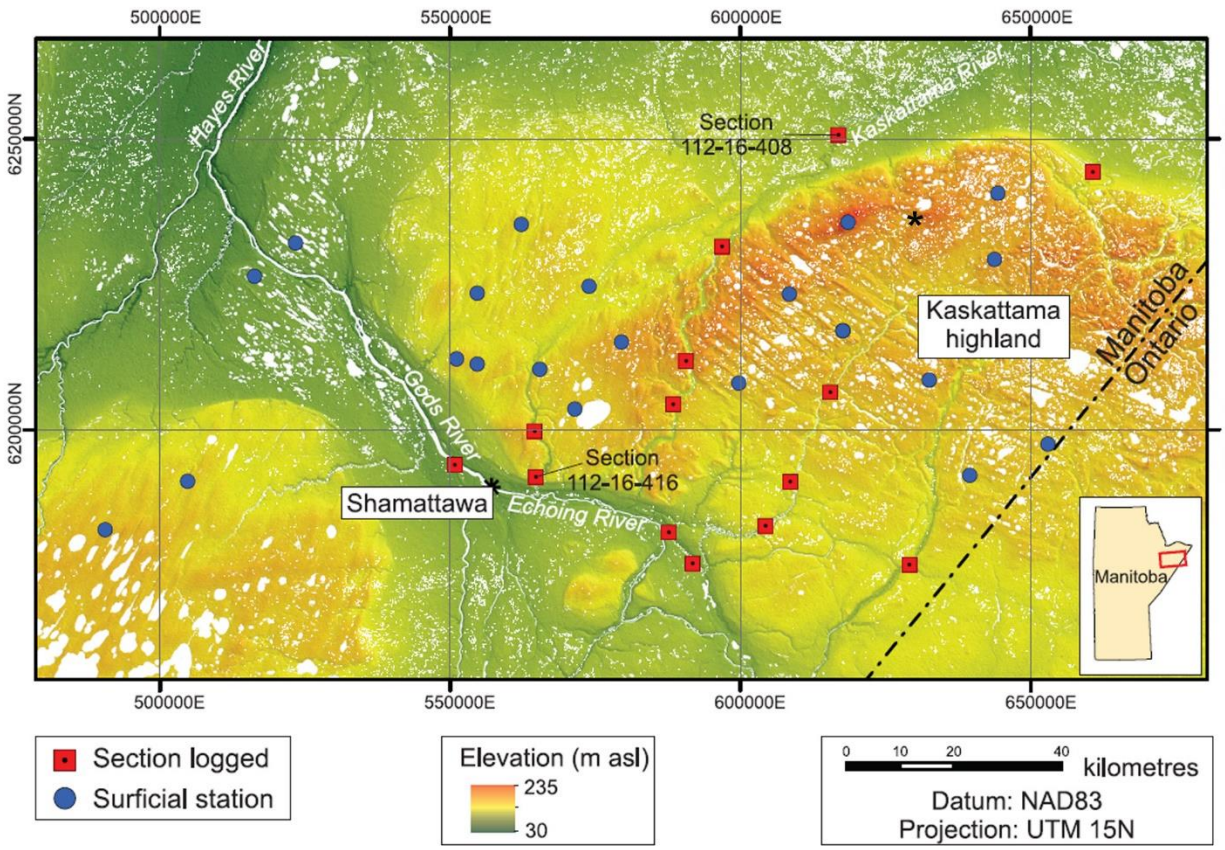

Figure 13. Kaskattama Highland area showing the relief and sample locations for Quaternary studies (modified from Hodder & Kelley 2016). The Foran Mining Kimberlite No. 1 well is located at 630684E 6236761N and is indicated on the map by the black star.

Goal(s) & objective(s)

The primary goal of the MT survey is to map out subsurface faults cutting through the Paleozoic successions that might explain the origin of the structure and the significant variations in the stratigraphy based on cores litho and biostratigraphic re-evaluations. The objective will be to unravel how tectonic factors such as faulting, burial and exhumation influenced the architecture and geological evolution and influenced the petroleum prospectivity of the HBB.

Scientific question(s) addressed

A key question to resolves is the origin of the Kaskattama highlands. Is it a purely a glacio-morphological feature or does it reflect a topographic high created by post-emplacement movement of the stratigraphy? This study seeks also to determine if the late movement related to folding, faulting, or both. Has the faulting led to emplacement and local preservation of stratigraphic units not visible elsewhere in the HBB? How have tectonic factors such as faulting, burial and exhumation influenced the architecture and geological evolution in relation to petroleum prospectivity of the HBB?

Methodology

Our methodology consists of advanced MT modelling of Quaternary, Hudson Bay Basin (HBB), and bedrock resistivity to define response sensitivity of key stratigraphic units. The modelling study (detailed in this section) is then utilized to plan the ground geophysical survey discussed in the next section (Results).

The examination of the ability of MT data to provide information on the geological units of the HBB and the overlying Quaternary deposits requires the development of appropriate simplified resistivity models to represent the different units followed by appropriate 1-D and multi-dimensional modelling, inversion, or sensitivity studies. In this report we develop resistivity models using resistivity ranges observed in surficial conductivity logs from the Nelson River region, geophysical well-logs are available from the Sogepet Aquitaine Kaskattama Prov. No. 1 well, and additional geological information. Unit thickness logged for the Foran Mining Kaskattama Kimberlite No. 1 well are used to represent the structure in the Kaskattama Highland area and thickness values from the Merland et al. Whitebear Creek Prov. well are used to represent the structure in surrounding areas.

The resistivity values for Quaternary and younger units are based on the observation from the conductivity logs in the Nelson River area. The values correspond closely with the clay content of the different units and range from 12.5 Ω.m (80 $mS.m^{-1}$) for clay-rich units to 66 Ω.m (15 $mS.m^{-1}$) for sand and gravel deposits. Silt-rich units are assigned an intermediate value.

Inspection of the electrical logs from the Sogepet Aquitaine Kaskattama Prov. No. 1 well showed a moderate consistency of the resistivity and its variation in each geological unit (Figure 14) and suggested that it would be reasonable to divide the resistivity section according to these units at least for the modelling in the current project. There was no strong justification evident for division of any of the defined geological units into sub-sections based on the observed resistivity values.

The MT method is based primarily on horizontal electric current flow so the well log data were combined into single values for each geological unit by appropriate averaging of conductivity (cf. resistivity) values. Representing the well log data in each unit as a series of a sub-layers with thickness h_i and resistivity ρ_i the average values were calculated using a longitudinally-averaged value:

$$\rho_{\sigma}^{av} = \left[\sum_i h_i\right] \cdot \left[\sum_i \frac{h_i}{\rho_i}\right]^{-1} \qquad \text{Eq. 1}$$

This formula was also applied when combining the resistivity of multiple layers into a single composite layer. In order to provide a comparison, we also computed a transverse-averaged value

$$\rho_{\rho}^{av} = \left[\sum_i h_i \rho_i\right] \cdot \left[\sum_i h_i\right]^{-1} \qquad \text{Eq. 2}$$

The ratio of the transverse to the longitudinal resistivity defines the amount of anisotropy present in the geological unit. The coefficient of anisotropy is:

$$\lambda = \left(\frac{\rho_{\sigma}^{av}}{\rho_{\rho}^{av}}\right)^{1/2} \qquad \text{Eq. 3}$$

Equations 1 and 2 simplify for the case of equal thickness layers (i.e., equally-spaced well log values). In the case of equal thickness values we also calculated a geometric mean value for the resistivity using:

$$\rho_{gm}^{av} = \left[\prod_{i=1}^{N} \rho_i\right]^{1/N} = \exp\left(\left[\sum_{i=1}^{N} \ln \rho_i\right] / N\right) \text{Eq. 4}$$

Table 1 shows the averaged resistivity of each of the geological units in the Sogepet Aquitaine Kaskattama Prov. No. 1 well calculated using the three methods and Figure 14 shows the results. As required by the theory, the longitudinal resistivity values are the smallest and the transverse resistivity values are the highest. The coefficients of anisotropy are mostly in the moderate range. Lower values in the Stooping River Formation and Upper Kenogami member are due in large part to the limited amount of data in these units.

Table 1. Detailed unit thickness and resistivity measurements from Kaskattama Kaskattama Prov. No. 1 well log data. Estimated thickness values are from previous interpretations (Nicolas & Lavoie 2012). This is not expected to change the results presented nor is it the primary source of uncertainty in our calculations, namely the resistivity of the units.

Age	Unit	Thickness (m)	Resistivity Average (Ω.m)			Coeff Anisotr.
			Transverse Resistivity	***Longitudinal Resistivity***	***Geometric Mean Resist.***	
Devonian	Stooping River	24.92	22.37	19.08	20.53	1.083
Devonian	Upper Kenogami R.	3.66	31.54	29.23	30.42	1.039
Silurian	Middle Kenogami R.	185.62	50.19	17.47	26.14	1.695
Silurian	Lower Kenogami R.	13.41	117.94	83.26	99.45	1.417
Silurian	Attawapiskat	65.53	121.15	34.84	62.77	1.865
Silurian	Ekwan River	42.37	23.80	15.23	18.89	1.250
Silurian	Severn River	231.65	24.40	16.16	19.81	1.510
Ordovician	Red Head	32.0	106.14	33.93	57.88	1.769

	Rapids					
Ordovician	Churchill River	92.05	357.49	238.74	301.12	1.497
Ordovician	Bad Cache Rapids	79.48	479.55	245.93	362.27	1.396

The next step in the development of a resistivity model for the Kaskattama Highland area included using the depth and lithology information from the Foran Mining Kaskattama Kimberlite No. 1 well for the Severn River Formation and younger rocks and from the Kaskattama Kaskattama Prov. No. 1 for older units. The information from the Foran Mining Kaskattama Kimberlite No. 1 well was taken from the core logs of M. Nicolas along with the notes of R. Bezys and G. Matile (M. Nicolas, Manitoba Geological Survey, personal communication 2016).

Table 2 lists the parameters of the detailed resistivity model that was derived and Figure 15 shows the model.

a) The Precambrian bedrock was assigned a resistivity of 5000 Ω.m based on the expectation that the rocks were likely low porosity crystalline rocks.
b) The Paleozoic rocks were assigned longitudinal resistivity values as determined above and listed in Table 1 and thickness from the Foran Mining Kaskattama Kimberlite No. 1 well. The youngest Paleozoic unit in the Foran Mining Kimberlite No. 1 well is the Severn River Formation so the younger Silurian and Devonian units intersected in the Kaskattama Prov. No. 1 are not included in the resistivity model.
c) There was no definitive local information available on the resistivity of the interpreted Cretaceous to Tertiary shale and clay unit. The clay unit was assigned a resistivity of 14 Ω.m based on the conductivity log results. However, depending on the exact nature of the clay deposit, the true resistivity may be a little higher than this value. TEM soundings of kaolinite deposits in the Lower Cretaceous Swan River Formation at Sylvan, Manitoba yielded resistivity values of 40 Ω.m (Ferguson et al. 1999b). The resistivity of the shale was assigned to be 8 Ω.m based on results from elsewhere in Manitoba. Well logs through Cretaceous shales on the Manitoba Escarpment yield typical resistivity values of 3-10 Ω.m (e.g., McNeil & Caldwell 1981). Surface TEM measurements in the Killarney area of central south Manitoba yield values of 3-6 Ω.m for the Cretaceous Odanah shale and ~2 Ω.m for the Millwood shale (Zaporozan 2012).
d) The detailed information on the surficial geological units was used to group the units into 8 main units and these were then assigned a resistivity based on the conductivity logging results from the Nelson River area (see Section 6.1.1). The surficial peat deposits are relatively resistive (Adetunji & Ferguson 2013) and are excluded from the resistivity models.

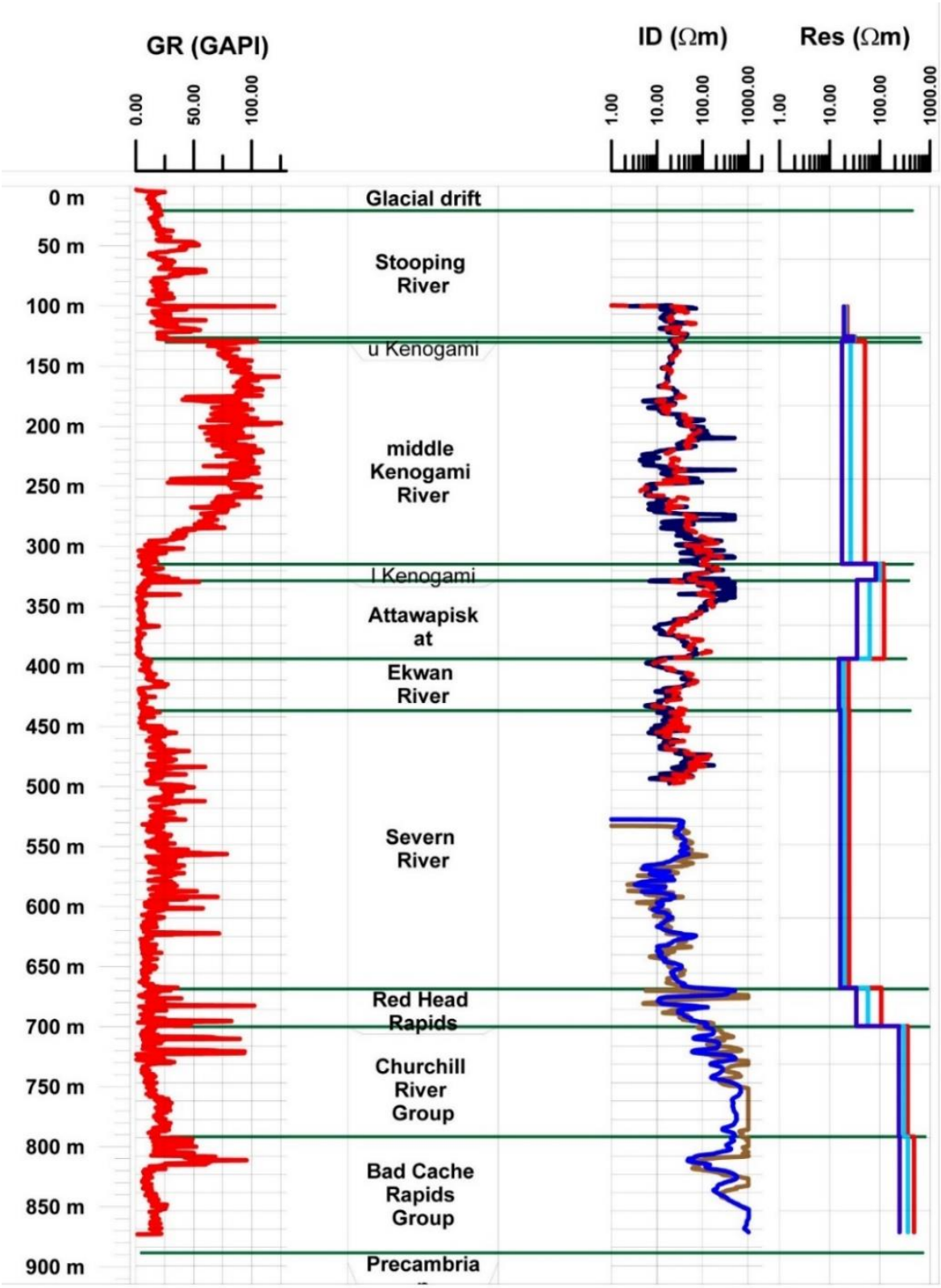

Figure 14. Sogepet Aquitaine Kaskattama Prov. No. 1 well comparing electrical logs with averaged resistivity values: longitudinal-resistivity average (dark blue), geometric average resistivity (cyan), and transverse-resistivity average (red). The separation of the blue and red curves increases with increasing formation anisotropy.

Table 2. Detailed resistivity model for the Kaskattama highlands. Estimated thickness values are from previous interpretations (Nicolas & Lavoie 2012). This is not expected to change the results presented nor is it the primary source of uncertainty in our calculations, namely the resistivity of the units.

Unit	Formation/Group	Lithology	Thickness (m)	Resistivity (Ω.m)	Conductivity ($mS.m^{-1}$)	Conductance (S)
Pleistocene	Glacial Drift	peat	1.83	-	-	-
Pleistocene	Glacial Drift	sand/sandy gravel	9.14	66.7	15	0.14
Pleistocene	Glacial Drift	silty clay	12.19	25	40	0.49
Pleistocene	Glacial Drift	clay	2.74	12.5	80	0.16
Pleistocene/ Quaternary	Glacial Drift	silt till	3.35	28.6	35	0.12
Quaternary		medium-fine sand/sand gravel	50.60	66.7	15	0.76
Quaternary		silt till	90.14	28.6	35	3.15
Quaternary		unknown	53.42	28.6	35	1.87
Quaternary Total			**194.16**			**5.78**
Cretaceous-Tertiary?		clay	2.13	14.3	70	0.13
Cretaceous-Tertiary?		Shale	31.55	8	125	3.94
Cretaceous-Tertiary? Total			**33.68**			**4.07**
Silurian	Severn River	Mudstone	73.60	16.2	61.90	4.56
Silurian Total			**73.60**			**4.56**
Ordovician	Red Head Rapids	Dolomitic Limestone	33.1	33.9	29.47	0.98
Ordovician	Churchill River	Wackestone/ Mudstone	84.15	238.7	4.19	0.35
Ordovician	Bad Cache Rapids	Limestone/ Sandstone	66.24	245.7	4.07	0.27
Ordovician Total			**183.49**			**1.60**
Precambrian	Precambrian		-	5000	0.2	-

Table 2 also lists the total conductance of the larger-scale geological divisions of the model. The Quaternary, Cretaceous-Tertiary, and Silurian intervals all have a conductance of around 4-5 S suggesting that significant changes to any of these units (e.g., thickening or thinning by 20% or more) should cause a significant change to the MT response. In contrast, the Ordovician units have a combined conductance of only 1.6 S indicating that the MT response will be only very weakly sensitive to changes in these units.

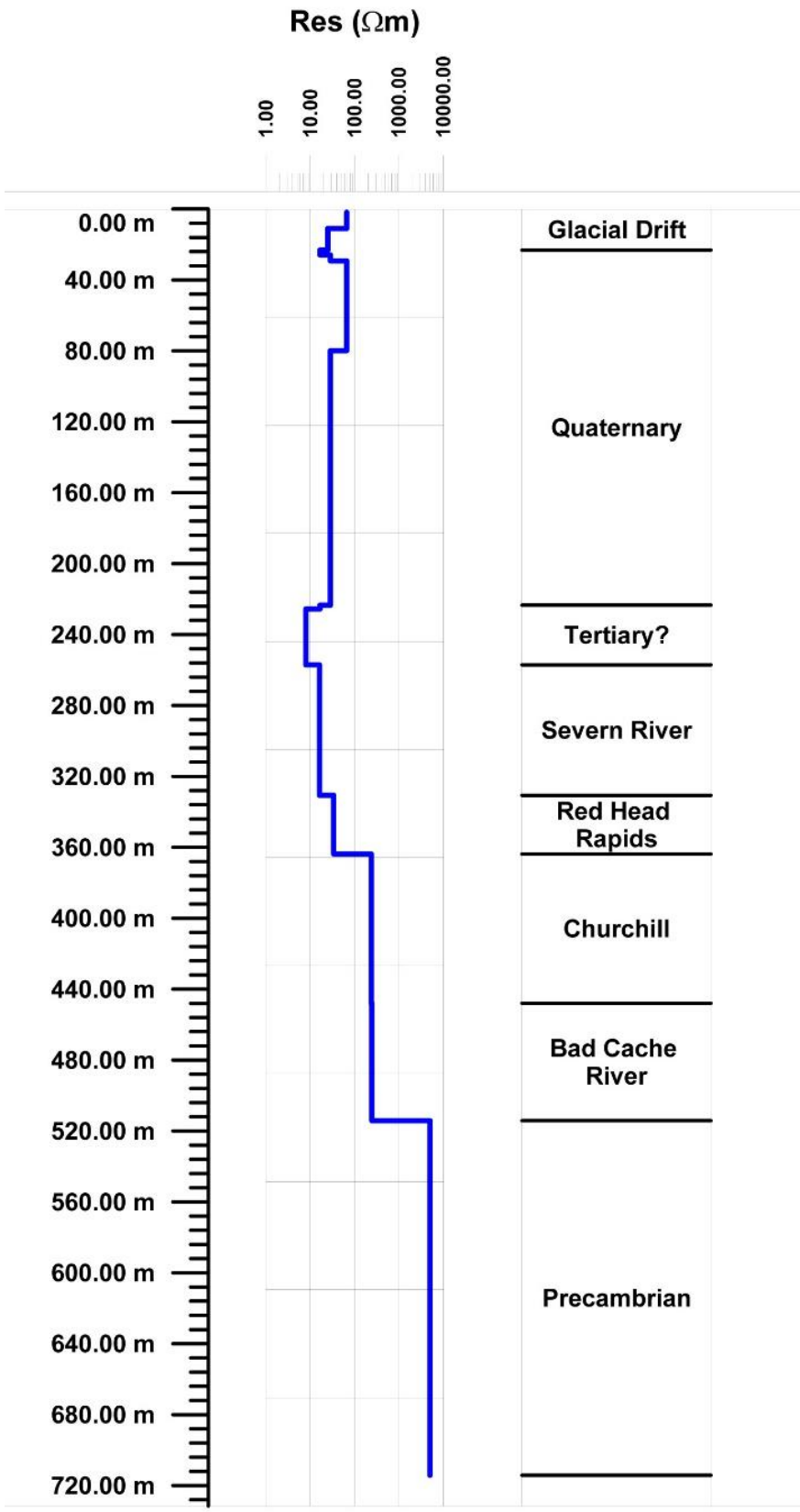

Figure 15. Detailed synthetic resistivity model for the Kaskattama Highland area. See table 2 for values.

Table 3. Simplified six-layer models for the Kaskattama highland area and for surrounding areas.

Unit	Thickness (m)	Resistivity (Ω.m)	Thickness (m)	Resistivity (Ω.m)
	Kaskattama Highland area		***Surrounding area***	
Quaternary	194.16	33.60	30.48	33.6
Tertiary	33.68	8.30	-	-
Ekwan-Attawapiskat	-	-	55.37	42.4
Severn	7.36	16.16	135.00	16.1
Red Head Rapids	33.10	33.8	48.53	33.8
Ordovician	150.39	242.2	127.18	242.2
Precambrian	-	5000	-	5000

The resistivity model for the Kaskattama highland area was further simplified into a six layer structure in order to facilitate modelling. The layers used corresponded to Precambrian, deeper Ordovician (Bad Cache Rapids and Churchill River), more shallow Ordovician (Red Head Rapids), Silurian, (Severn River), Cretaceous-Tertiary, and Quaternary-Pleistocene. Resistivity values for the composite units were obtained using the longitudinal resistivity average (which is equivalent to the total thickness divided by the conductance in Table 2). Table 3 shows the composite unit thicknesses and resistivities for the simplified model and Figure 15 shows the model.

In order to fully examine the sensitivity of MT responses to different geological units it is useful to also consider responses from outside the Kaskattama highland area. The geological unit thicknesses for the background model were taken from those in Merland et al. Whitebear Creek Prov. well since this well lies in a similar stratigraphic position to the Kaskattama Highland area (Figure 10). The resistivity values were taken to be the same as those for the Kaskattama model. However, it was necessary to include an additional unit corresponding to the Silurian Ekwan River and Attawapiskat formations (with the resistivity determined using a longitudinal-resistivity average of the values for the two individual units shown in Table 1). The Cretaceous-Tertiary units is also absent from the background model. Table 3 shows the thickness and resistivity values for the background model and Figure 16 shows the model.

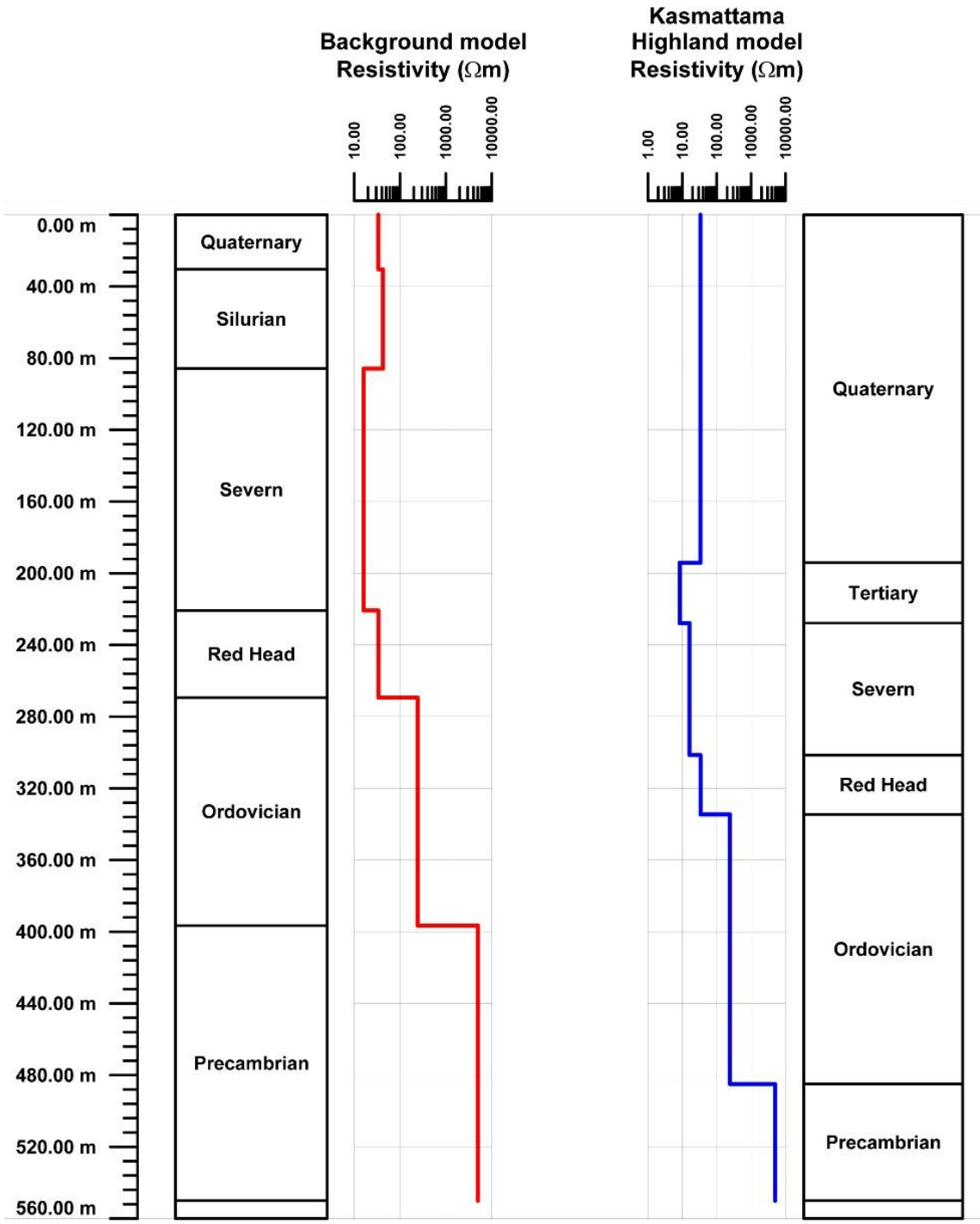

Figure 16. Simplified six-layer models for the Kaskattama highland area and for background areas.

To examine the resolution of the major Hudson Bay Basin units in the Kaskattama highlands, the MT response of the main model was compared with the response of models in which the various layers were perturbed. In particular, we examined the effects of doubling and halving the thickness of each later and of doubling the resistivity. The responses were all calculated using IX1D software (Interpex, Colorado) and exported and plotted in the following section using GRAPHER (Golden Software, Colorado).

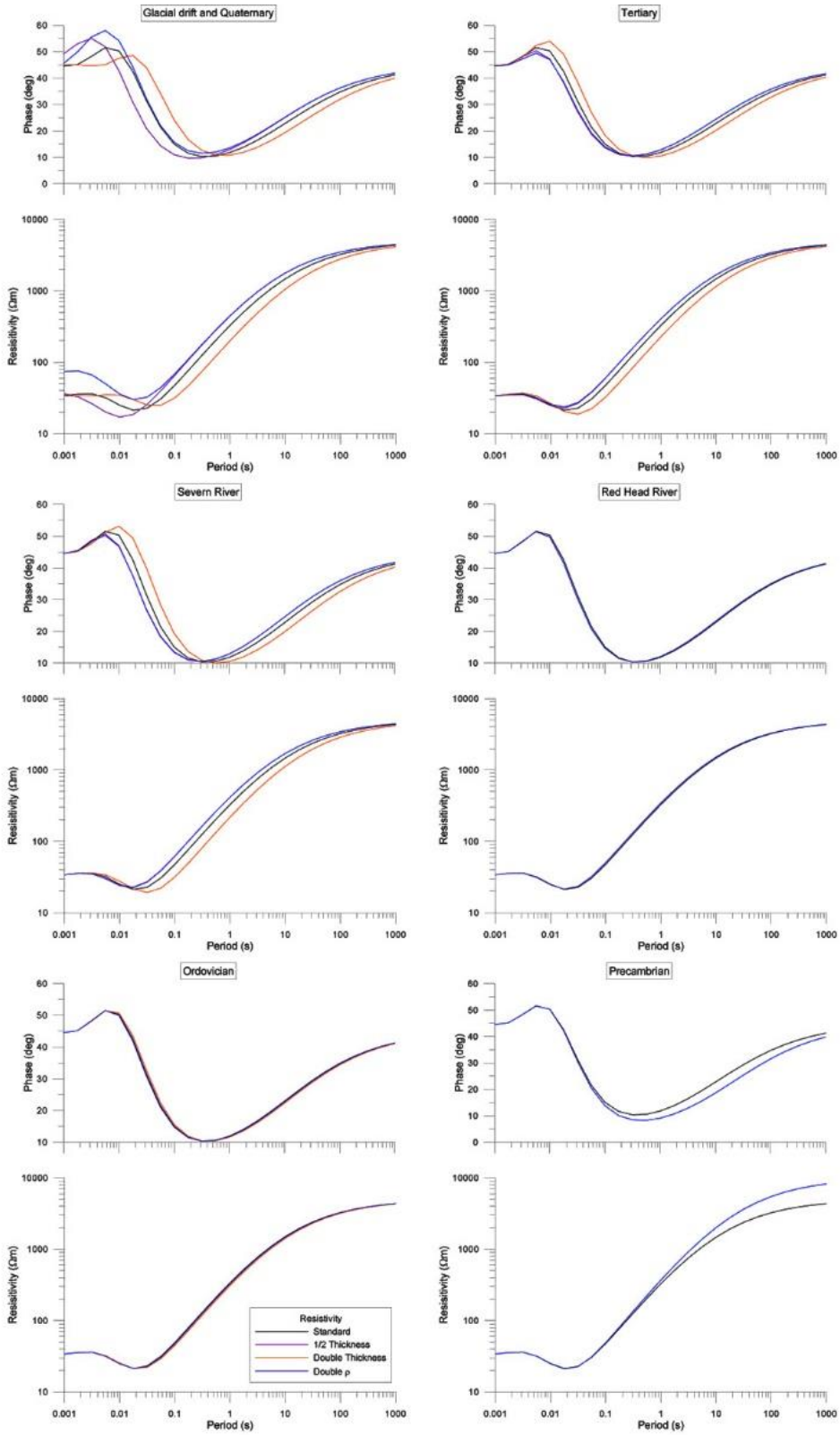

Figure 17. Sensitivity of MT responses to changes in the six composite units in the Kaskattama Highland synthetic resistivity model.

Results (achieved or forecasted)

Figure 17 shows the results of these computations for the Kaskattama highland area. The 1-D modelling results show that the MT response is sensitive to large changes to both the overall thickness and resistivity of the Quaternary unit. Changing either of these parameters produced changes in the MT response of at least 0.3 decades in apparent resistivity and 15° in phase. The effects of half the thickness of the layer and doubling the resistivity are different indicating separate sensitivity to both thickness and resistivity. The sensitivity is changes in the model parameters is strong over the period range from 0.001 to 1 s. However, the sensitivity to the individual changes in resistivity and thickness becomes negligible at periods exceeding 0.01 s indicating the effects of equivalence in the MT response of conductive layers. At longer period the response is sensitive to only the conductance, the produce of the thickness and conductivity of the layer. As the changes to resistivity or thickness become smaller, the effect on the MT response will also decrease and would require increasingly accurate MT responses in order to be resolved. In addition, if resistivity changes occur to only part of the composite Quaternary unit, particularly lower parts, the changes will also become increasingly difficult to resolve.

The 1-D modelling results also reveal reasonable sensitivity of the MT response to large changes in either the resistivity or the thickness of the Cretaceous-Tertiary or Severn River units. This result was expected based on the similar conductance of the upper three units in the model. Because of equivalence, the resistivity and the thickness cannot be derived independently. The MT response has negligible sensitivity to the Red Head Rapids Formation and to the deeper composite Ordovician unit. The conductance of each of these units is too low to cause any significant change to the MT response. The modelling results suggest that the MT response is sensitive to the resistivity of the Precambrian bedrock at periods exceeding 1 s. However, this result is because of the infinite thickness of this unit in the model. In reality, the MT response usually has very low sensitivity to resistive upper crust underlying sedimentary rocks but does provide reasonable resolution of more conductive regions of the mid to deep crust.

Figure 18 shows the sensitivity of the MT responses in background areas around the Kaskattama highlands In the background areas the Quaternary sequence is much thinner than in the highlands and has lower conductance. Based on the depth of surficial sediments at the location of the Merland et al. Whitebear Creek Prov. well the integrated conductance of this unit is only 0.9 S. As a result, the effects of the Quaternary unit are seen in the MT response only at periods of less than 0.01 s. The MT responses are sensitive to thickness and resistivity of the composite Ekwan River-Attawapiskat unit (conductance 1.3 S) and to the underlying Severn River Formation. However, independent resolution of the thickness and resistivity would only be possible with high quality MT responses at period of less than 0.03 s. In this period range it may also be difficult to differentiate the effects of the Quaternary sediments from the response of the underlying Paleozoic rocks. The MT resolution of the Red Head Rapids, composite deeper Ordovician unit, and Precambrian rocks is similar for background areas as it is for the Kaskattama Highlands.

The modelling results depend on the accuracy of the synthetic resistivity model. Significant changes to this model would yield different results. For example, a factor of 4 decrease in the resistivity of the deeper Ordovician units would mean that these units have a conductance comparable to overlying units and therefore greater responses sensitivity. None the less, the modelling shown provided useful

guidance into the frequency response expected on site and was utilized to plan equipment shipped to the field and deployed. Preliminary 2-D modelling sensitivity studies (not shown) also provided useful guidance of station spacing Zaprozan & Ferguson, 2017). These parameters were subsequently utilized in a survey based out of Gillam, MB (Figure 3).

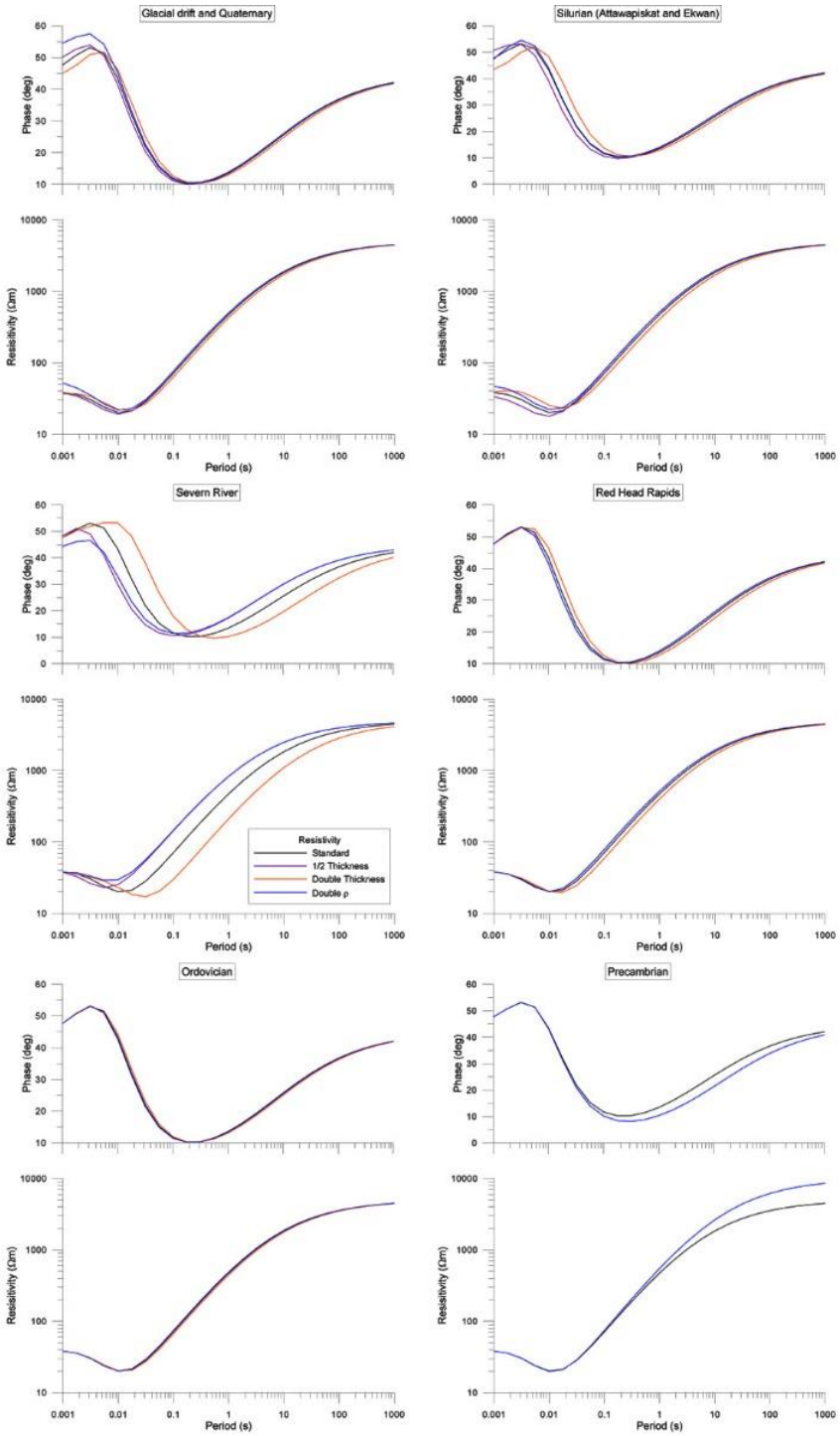

Figure 18. Sensitivity of MT responses to changes in the six composite units in the background area synthetic resistivity model.

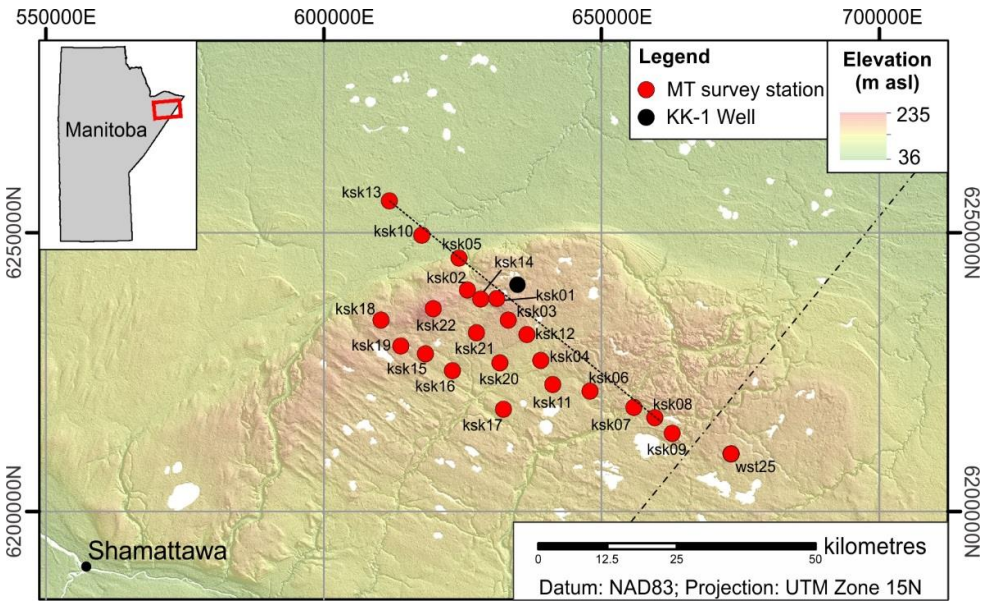

Figure 19. Location of MT sites sounded during summer field work 2017 (ksk??). Site wst25 is from an earlier Lithoprobe MT survey. The profile location for Figure 21 is also shown with a dashed line. The KK-1 well refers to the Foran Mining Kaskattama Kimberlite No. 1 well.

The 22 site locations occupied in the summer of 2017 are shown in Figure 19. Site locations were chosen to provide a high-resolution 2-D line accompanied by less dense 3-D coverage. The main survey line was located to pass close to the Foran Mining Kaskattama Kimberlite No. 1 well and to span the Kaskattama highland area. The time series collected at each site were processed to apparent resistivity and phases using robust, remote reference algorithms similar to methods discussed in Roberts and Craven (2012). Each MT site consisted of a combination of high frequency (10 k Hz – 1 Hz) and lower frequency (400 Hz to 1000 s) measurements, the so-called audio-band MT and broadband MT soundings respectively, to enable response estimation across the full spectrum the modelling study indicated was required to investigate the region.

Pre-survey calibrations are necessary both to verify equipment integrity and to document their frequency response for removal from the measured response and resultant identification of the desired earth response. Calibrations were conducted as required in the field in order to avoid adverse electromagnetic noise associated with the hydro dams and large transmission networks near Gillam. However, even with a calibration site a few hundred km from Gillam MB (Figure 3) at MT site KSK01 (Figure 19), it became apparent that a spurious noise source existed in the field. The noise was quickly determined to be associated with particular installations where the magnetic induction coils were placed in peat or other soft ground and were oscillating due to the wind or perhaps to motions related to thawing of the discontinuous permafrost.

Data quality overall was excellent (Figure 20). Magnetic field variations are very similar (i.e. the fields are planar) across the survey area. Therefore, if the installation of a magnetic coil at a site was observed to be leading to poor response estimation, then data from nearby magnetic coils firmly buried in glacial till could be used to provide a more robust response. A detailed examination of the data processing will be presented in a follow-up report, but one feature of note is present within the phase response at frequencies the modelling study identified as associated with the HBB. This relatively

high phase feature is denoted with an arrow in Figure 20. It is clearly visible in both the phase curves (XY and YX) that are derived from MT data and is a robust feature of the data. Increasing phase values are associated with transitions to more conductive electrical units at depth. Figure 21 is a contoured section of the average phases observed at each site across the northeastern profile (location shown in Figure 19). The frequencies associated with the till response and deeper portions of the crust and upper mantle have been omitted. The high phase zone is isolated to those sites near the Foran Mining Kaskattama Kimberlite No. 1 well (just north of site KSK01) with the interpreted presence of Cretaceous or Tertiary sediments. We have further interpreted the lower phases values at lower frequencies (labelled HBB in Figure 21) to represent undifferentiated Ordovician and Silurian strata. These units appear to be dipping (and faulted?) in the section, but such interpretations are speculative. Further work discussed below will enable more reliable images that can be used to infer geometries and fault offsets.

Conclusions

The 1-D modelling results suggest that MT soundings in the Kaskattama highland and surrounding areas can place constraints on the resistivity structure of the underlying Mesozoic and Paleozoic rocks. In the highlands area, major changes in the thickness of the Quaternary sequence, the Cretaceous-Tertiary unit, or the Severn River Formation should affect the MT response. In the background area the response may also be sensitive to major changes in the composite Ekwan River-Attawapiskat unit. However, the resolution is limited, especially in the Kaskattama highlands because of the conductive Quaternary rocks at the surface. Inversions will require a constrained approach in which either the resistivity or the thickness is constrained. The modelling study also identified the frequency ranges of characteristic features in the subsurface. We have utilized this information to plan and successfully execute a MT survey across the Highlands and preliminary analysis indicates that the survey data has clear signatures related to subsurface structure. The data suggest a significant lateral extent, ca. 25-30 km, of possible Cretaceous or Tertiary sediments (from the vicinity of site 10 to site 6 in Figure 21) in this region.

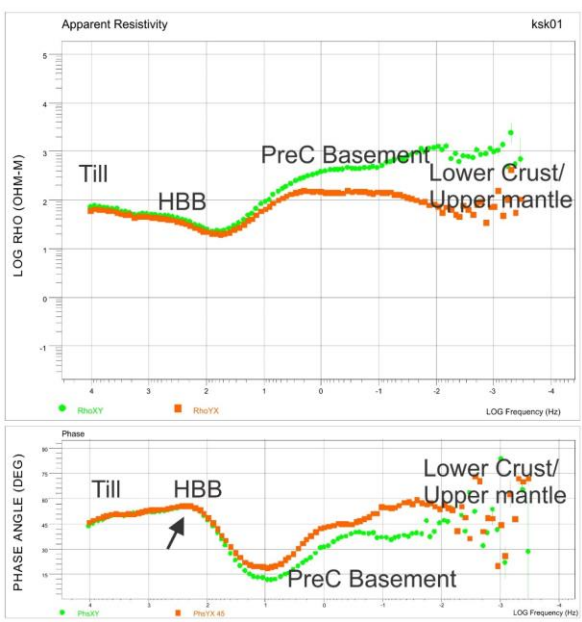

Figure 20. MT data from site ksk01 nearest the well. The responses associated with the spectrum we know from the synthetic study for the till, HBB and Precambrian basement are well determined. Only the data at the longest periods that are penetrating the lower crust or upper mantle are poorly determined. The arrow identifies a high phase response.

Future works/next steps

Samples from the Foran Mining Kimberlite No. 1 well have been sent to the petrophysics lab at GSC-Pacific for analysis. The results will enable a firmer understanding of the electric structure of the subsurface (see for example, Bancroft et al, 2014). Unconstrained 1-, 2- and 3-D inversion to generate earth models will be performed to help derive key features within the subsurface that control the local topography and geometry of the HBB in this area. The inversions will feed back to a better interpretation of the phase pseudosection presented in Figure 21. The inversions will also be performed using the geological control derived from the rock properties and electrical logs from nearby wells. At various stages interpretations of the models and images will be rendered and published and implications for the origins of the Highlands and the potential impact for hydrocarbon prospectivity will be identified.

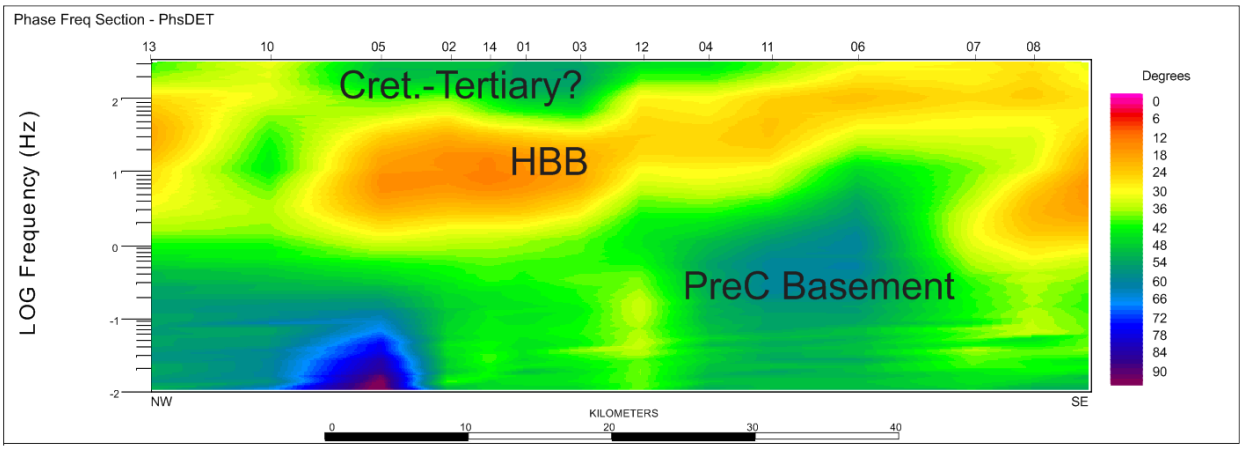

Figure 21. Contoured phase section along northern profile (dashed line in Figure 19). The frequency band utilized is isolated primarily to the structure below till and within uppermost crust where the data estimates were the most reliable.

Acknowledgements

Custom Helicopter provided courteous and safe transport to and from the field sites. Bernard Giroux is thanked for use of his MTUs. Neil Brandson at MGS provided reliable logistical support, and Guy Buller helped load our GIS maps onto our field computer, which proved very helpful to locate sites accurately.

References

Adetunji, A. & Ferguson, I.J., 2013. Manitoba Hydro Bipole III HVDC Converter Project, Site Selection and Design of Bipole III DC Land Electrodes: Earth Electrical Resistivity at Bipole III North Candidate Electrode Site. 83 pp. and Appendices. Report prepared for Teshmont Consultants LP, Winnipeg, Manitoba, submitted to Manitoba Hydro.

Ansdell, K.M. 2005. Tectonic evolution of the Manitoba-Saskatchewan segment of the Paleoproterozoic Trans-Hudson Orogen, Canada; *Canadian Journal of Earth Sciences*, **42,** 741-754.

Bancroft, B., Craven, J.A., Enkin, R.J., Nicolas, M.P.B. & Roberts, B. 2014. Results from a magnetotelluric and rock property study near Churchill, Manitoba. *Geological Survey of Canada, Open File* 7549, 21 p.

Barager, W.R.A., Scoates, R.F.J., 1981. The Circum-Superior belt: a Proterozoic plate margin? *In*: Kröner, A. *Ed.*, Precambrian Plate Tectonics. Elsevier, Amsterdam, pp. 297–330.

Betcher, R. N., Pupp, C., & Grove, G. 1995. Groundwater in Manitoba: hydrogeology, quality concerns, management. Environment Canada, National Hydrology Research Institute.

Böhm, C.O., Heaman, L.M., Creaser, R.A. & Corkery, M.T., 2000. Discovery of pre-3.5 Ga exotic crust at the northwestern Superior Province margin, Manitoba. *Geology*, **28,** 75-78.

Chave, A.D. and Jones, A.G.(Eds.),2012, The Magnetotelluric Method: Theory and Practice, Cambridge Univ. Press., 552pp.

Craven, J.A., Kurtz, R.D., Boerner, D.E., Skulski, T., Spratt, J., Ferguson, I.J., Wu, X., & Bailey, R.C., 2001. Conductivity of Western Superior upper mantle in northwestern Ontario, *Current Research*, 2001, Geological Survey of Canada.

Eaton, D.W. & Darbyshire, F. 2009. Lithospheric architecture and tectonic evolution of the Hudson Bay region; *Tectonophysics*, **109,** 1-22, doi: 10.1016/j.tecto.2009.006.

Ferguson, I.J., Craven, J.A, Kurtz, R.D., Boerner, D.E. Bailey, R.C., Wu, X., Orellana, M.R., Spratt, J., Wennberg, G. & Norton, M. 2005. Geoelectric responses of Archean lithosphere in the western Superior Province, central Canada. *Physics of the Earth and Planetary Interiors,* 150, 123-143. doi: 10.1016/j.pepi.2004.08.025

Ferguson, I.J., Ristau, J.P., Maris, V.G., & Hosain, I., 1999. Geophysical imaging of a kaolinite deposit at Sylvan, Manitoba, Canada, *Journal of Applied Geophysics*, 41**,** 105-129. doi: 10.1016/S0926-9851(98)00051-2.

Gowan, E.J., Ferguson, I.J., Jones, A.G. & Craven, J.A., 2009. Geoelectric structure of the northeastern Williston basin and underlying Precambrian lithosphere. *Canadian Journal of Earth Sciences,* 46**,** 441-464. doi:10.1139/E09-028

Hodder, T.J. & Kelley, S.E., 2016. Quaternary stratigraphy and till sampling in the Kaskattama highland region, northeastern Manitoba (parts of NTS 53N, O, 54B, C) ; *in* Report of Activities 2016, Manitoba Innovation, Energy and Mines, *Manitoba Geological Survey,* pp. 187-195.

Hoffman, P.F., 1990. Subdivision of the Churchill Province and extent of the Trans-Hudson Orogen. In: Lewry, J.F., Stauffer, M.R. (Eds.), The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada Special Paper, 37, 15–40.

Jones, A.G., 1988. Static shift of magnetotelluric data and its removal in a sedimentary basin environment. *Geophysics*, 53, 967-978.

Jones, A.G., Ledo, J., & Ferguson, I.J., 2005. Electromagnetic images of the Trans-Hudson orogen: The North American Central Plains (NACP) anomaly revealed. *Canadian Journal of Earth Sciences,* 42**,** 457-478. doi: 10.1139/e05-018

Lavoie, D., Armstrong, D., Nicolas, M. & Zhang, S., 2015. *Geological Survey of Canada, Open File* 7713(10.4095), p.295547.

Lavoie, D., Pinet, N., Dietrich, J., Zhang, S., Hu, K., Asselin, E., Chen, Z., Bertrand, R., Galloway, J., Decker, V. and Budkewitsch, P., 2013. Geological framework, basin evolution, hydrocarbon system data and conceptual hydrocarbon plays for the Hudson Bay and Foxe basins, Canadian Arctic. *Geological Survey of Canada, Open File Report, 7363*, 213 p.

McNeil, D. H. & Caldwell, W.G.E. 1981. *Cretaceous Rocks and Their Foraminifera in the Manitoba Escarpment.* The Geological Association of Canada, Special paper number 21.

Matile, G.L.D. and Keller, G.R. 2007. Surficial Geology of Manitoba. Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Surficial Geology Compilation Map Series, SG-MB, scale 1: 1 000 000.

Minifie, J.M., Kerr, A.C., Ernst, R.E, Hasite, A.R., Ciborowski, T.J.R., Desharnais, G. & Millar, I.L. 2013. The northern and southern sections of the western ca. 1880 Ma Circum-Superior Large Igneous Province, North America: The Pickle Crow dyke connection? *Lithos*, 174, 217-235.

Nicolas, M.P.B., 2011. Stratigraphy of the 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*, pp. 165-170.

Nicolas, M.P.B., and Armstrong, D.K. 2017 (in press). Update on Paleozoic stratigraphic correlations in the Hudson Bay Lowland, northeastern Manitoba and norther Ontario; *in* Report of Activities 2017, Manitoba Growth, Enterprise and Trace, Manitoba Geological Survey.

Nicolas, M.P.B., & Clayton, B.W., 2015. Manitoba Geological Survey, *Report of Activities*, 89-96.

Nicolas, M.P.B. & Lavoie, D. 2012. Oil shale reservoir rocks of the Hudson Bay Lowland, northeastern Manitoba (part of NTS 54); *in* Report of Activities 2012, Manitoba Innovation, Energy and Mines, *Manitoba Geological Survey*, pp. 124-133.

Nicolas, M.P.B. & 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*, pp. 186-192.

Norris, A.W., 1993, Hudson platform – Geology; Chapter 8 in Sedimentary Cover of the Craton in Canada, eds. D.F. Stott and J.D. Aitken, Geological Survey of Canada, Geology of Canada, n5, 653-700.

Percival, J.A., Sanborn-Barrie, M., Skulski, T., Stott, G.M., Helmstaedt, H. & White, D.J., 2006. Tectonic evolution of the western Superior Province from NATMAP and Lithoprobe studies. *Canadian Journal of Earth Sciences*, 43, 1085-1117.

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.

Scoates, R.F.J. 1990. The Fox River Sill, Northeastern Manitoba – a major stratiform intrusion. Geological Report GR82-3, Manitoba Energy & Mines, Geological Services

Weber, W., 1990. The Churchill–Superior Boundary Zone, southeast margin of the Trans-Hudson orogen; a review. *In:* Lewry, J.F., Stauffer, M.R. *Eds.*, The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada Special Paper, 37, 41–55.

Zaporazan, T., 2012. Electromagnetic and magnetic imaging of the Spiritwood Valley buried aquifer near Cartwright, Manitoba. B.Sc. (Hons.) Thesis, U. Manitoba, Winnipeg, Canada.

Zaporozan, T., & Ferguson, I., 2017. Synthesis of magnetotelluric results from the Hudson Bay Basin and examination of magnetotelluric resolution. Report submitted to the Geological Survey of Canada, GEM2 Ungava project, 57 pp.