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Qualitative petroleum resource assessment of western Hudson Bay, Foxe Channel, and Repulse Bay, Manitoba, Nunavut, Ontario, and Quebec

M.C. Hanna, C.J. Lister, K. Kublik, H.M. King, L.E. Kung, W.M. McCarthy, K.T. McDannell, and Y. Jassim

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EXECUTIVE SUMMARY

Natural Resources Canada (NRCan) has been tasked, under the Marine Conservation Targets[1] (MCT) initiative announced in Budget 2016, with evaluating the petroleum resource potential for areas identified for protection as part of the Government of Canada's commitment to conserve 10% of its marine areas by 2020. As part of this initiative, Parks Canada Agency (PCA) requested that NRCan conduct qualitative petroleum resource assessments of the western Hudson Bay and Repulse Bay areas, within which National Marine Conservation Areas (NMCA) may be evaluated. Also, Fisheries and Oceans Canada (DFO) requested that NRCan conduct a qualitative petroleum resource assessment for an area around Southampton Island within which a Marine Protected Area (MPA) may be evaluated.

The primary objective of this report is to provide a qualitative petroleum resource assessment for the greater Hudson Bay region, including Foxe Channel and Repulse Bay. The Geological Survey of Canada (GSC) interpretation is visually represented by a qualitative petroleum potential map (Figure 1). Data were compiled and assessed for an area that is larger than what was requested based on practical geological considerations (Figure 2). This approach improves the detail and accuracy of GSC predictions.

A brief summary of the geology and petroleum potential of the study area is as follows:

1. **Hudson Bay**. This region is comprised of Paleozoic primarily carbonate and secondary clastic deposits and thin Mesozoic–Cenozoic clastic sediments overlying an Archean to Proterozoic basement of sedimentary, low grade metamorphic, and igneous rocks. Petroleum exploration, including the acquisition of over 40 000 linear km of industry seismic and drilling of five offshore wells, occurred mostly in the centre of Hudson Bay during the 1960s through the 1980s. The petroleum potential of this region is considered low to moderate.
2. **Foxe Channel and Repulse Bay**. North and east of Southampton Island, Repulse Bay and Foxe Channel have minimal seismic data coverage consisting almost entirely of GSC high resolution shallow seismic. These areas are assumed to contain Paleozoic carbonates overlain by Cretaceous sediments deposited in localized grabens, however, no exploration wells were drilled here. The petroleum potential of this region is considered low to moderate.

A secondary objective of this study is to summarize the potential for unconventional energy possibly including: gas hydrates, coal-bed methane, oil shale, and shale gas. Unconventional resource potential is considered very low in offshore parts of the study area. Oil shale and coal-bed methane are not considered to be prospective as an unconventional resource in onshore parts of the study area due to interpreted immature source rock (Appendix A). There are publications that indicate regions of potential methane hydrate stability in the northeast portion of Hudson Bay (Figure 3); however, single-channel and multi-channel seismic data are too limited to conclude strong evidence for presence of gas hydrates.

A tertiary objective of the study is to identify areas with mineral resource potential (Appendix B). This was accomplished through literature review and geologic interpretation over a regional scale. Mineral resources identified onshore, that may extend offshore, include: limestone, lead, zinc, nickel, copper, iron, fluorite, barite, silver, gold, coal, chromite, lithium, gypsum, peat, granite carving stone, and micro-diamonds. Viability of offshore mineral resources requires that a regulatory framework is established allowing offshore mineral mining in Canada. Figure 3 provides information on mineral occurrences and mines near the study area.

[1] The Marine Conservation Targets (MCT) initiative provides targeted funding to Environment and Climate Change Canada (represented by the Parks Canada Agency), Fisheries and Oceans Canada (DFO), and Natural Resources Canada (NRCan) as part of the Government of Canada's commitment to conserve 10% of Canada's marine and coastal waters within the 200 nautical mile limit by 2020.

1. INTRODUCTION

The petroleum potential in the study area was evaluated by a team of GSC geoscientists from September 2017 to May 2018. Objectives were to: a) review, analyze, and integrate data from previous resource assessments, existing scientific literature, and available geoscience databases; b) interpret and map petroleum system elements and regional petroleum plays by applying sound geological principles; and c) provide a qualitative summary of the petroleum potential in the proposed study area. Data were compiled and assessed for an area that is larger than what was requested by PCA and DFO based on practical geological considerations. This approach improves the detail and accuracy of GSC predictions. Results of this qualitative assessment are shown in Figure 1.

2. GEOLOGIC SETTING

Hudson Bay and James Bay are composed of three geologic basins: Hudson Bay, Moose River, and Belcher basins (Figure 3). The Hudson Bay and the Moose River basins contain Phanerozoic (primarily Paleozoic) carbonates while the Belcher Basin contains Proterozoic sediments. The Moose River and Belcher basins have been previously assessed and a qualitative petroleum potential map was created by Hanna et al. (2018) with both basins considered to have low potential for conventional petroleum.

The Hudson Bay Basin is the largest intracratonic Paleozoic basin in North America. However, contrary to the Williston, Illinois, and Michigan basins, there has been no significant discovery of hydrocarbons in Hudson Bay. The Hudson Bay Basin contains up to 2500 m of preserved Paleozoic sediments (Lavoie et al., 2013), with underlying Proterozoic sediments and Archean igneous and metamorphic rocks. The sedimentary deposits have undergone episodes of burial, uplift, erosion, and structural deformation that may have caused not only petroleum generation and accumulation, but also alteration, migration and/or remigration, and leakage potentially reaching the seabed and sea surface.

Three distinct geologic eras of sedimentary deposition, roughly correlating to mega-sequences, have been identified in the study area: Proterozoic, Paleozoic, and Mesozoic-Cenozoic (Figure 3). Mega-sequences, according to Schlumberger's online dictionary, "The Oilfield Glossary", (http://www.glossary.oilfield.slb.com), are defined as a large group of relatively conformable strata, normally from the same era, that represent cycles of deposition and are bounded by unconformities or correlative conformities (Appendix A and Appendix E). The presence of potential reservoirs, sources, traps, and seals suggests there is potential for a petroleum system or systems in Hudson Bay (Table 1). The Paleozoic sedimentary thickness in Hudson Bay Basin is considered the most prospective sequence from a petroleum exploration perspective. Source rock presence and maturity are historically the overall concern for the study area (Tillement, 1975; Appendix A). Petroleum system elements of the main mega-sequences are described in more detail in Appendix A.

3. DATA

3.1. Literature

The geology of the Hudson Platform and surrounding areas has been the subject of many GSC, National Energy Board of Canada (NEB), provincial, and industry reports, as well as a wide range of academic publications. This GSC/NRCAN study includes interpretation and mapping of petroleum system elements and regional petroleum plays, based on reviews and analyses of previous publications and reports (Appendix D), and available geoscience data, including marine seismic profiles, bedrock geology, well data, RADARSAT data, bathymetric data, new thermal indicators data and identification and evolution of potential reservoirs (Figures 2 and 3). Lavoie et al. (2013) published a comprehensive study characterizing petroleum system elements in the Hudson Platform.

3.2. Geoscience data

GSC's qualitative assessment is based on offshore two-dimensional multichannel and single-channel marine seismic profiles (Figure 2) and their integration with onshore geology, surface slick-like features, bathymetric surveys, well data, surface geology, and potential field data (ship-, aero-, and satellite-borne gravity and magnetic data). Two-dimensional marine multichannel reflection seismic data in the Hudson Bay region were acquired by the petroleum industry in the 1960s through the 1980s (Figure 2).

Five offshore petroleum exploration wells were drilled in the Hudson Bay Basin from 1969 to 1985 (Figure 3). None of these wells encountered significant quantities of producible petroleum. Similarly, no significant hydrocarbons were discovered in onshore petroleum exploration wells in northern Manitoba and northern Ontario. Nonetheless, pore-filling bitumen and dead oil have been reported in reefal carbonate units (Heywood and Sanford, 1976).

3.3. Unpublished analytical data

The Geo-mapping for Energy and Minerals (GEM) program is funded until 2020 for its second phase of technical work (GEM2) to produce publically available regional geoscience knowledge of Canada's North. The GEM2 project is currently underway and collecting data, and therefore, not all data and analyses dependent on new information were available for this report. Available GEM2 data were reviewed.

4. METHODOLOGY

4.1. Scientific Reviews and Workshops

To ensure the sound integration of the geological data, workshops were held with GSC Calgary, GSC Québec, Manitoba and Ontario provincial experts. The qualitative petroleum potential map was generated using a probabilistic assessment method (Lister et al., 2018). Development of workflow, methodology, and mapping have been regularly reviewed by the team and advisors. Poor data coverage and data density for any area leads to higher overall uncertainty when delineating petroleum systems elements (Lister et al., 2018). Results were presented in a draft version of this report to internal GSC advisors and reviewers for comment and thus represented the final stage of qualitative internal technical review.

4.2. Play Mapping

A petroleum potential map was created by combining probabilities of success at the play level for four petroleum systems elements (source, reservoir, trap, and seal) as outlined in Lister et al. (2018). When determining the chance of success for each petroleum systems element, data quality, density, and confirmation of physical data must be considered and incorporated into a value which reflects all information and confidence.

Plays were weighted by a subjective global scale factor to rank their chance of success and a measure of the play's strength compared to other globally competitive exploration targets. Areas with limited data availability should be reassessed after more information has been collected. This iterative process creates more detailed maps with higher confidence. The sum of potential from all plays was calculated to create the overall petroleum potential map (Figure 1).

5. RESULTS, INTERPRETATION, AND CONCLUSIONS

The Hudson Bay Basin contains Paleozoic carbonates similar to those in other producing North American intracratonic analogues such as the Williston, Michigan, and Illinois basins (Figure 4B). Within these Paleozoic rocks, only a few Ordovician units have significant potential as source rocks; some immature Upper Devonian units are also identified (Zhang and Hu, 2013). Pockmarks, bitumen, and slick-like features (which may indicate hydrocarbon seeps) have been identified in Hudson Bay. However, multiple one- and three- dimensional basin models suggest prolific petroleum generation from an Ordovician source rock only when ideal conditions are met (see Appendix C). It is more likely that the source rocks of the Hudson Platform are too thin and were not buried deep enough to generate economic accumulations of conventional petroleum. Additionally, reservoir temperatures have been below 80°C since ~ 300 Ma, so it is likely that some or all generated petroleum has since been biogenically degraded.

Subsurface mapping identified seven plays in the study area (Table 1). These plays were evaluated and combined as described in Section 4.2. The resulting petroleum potential map (Figure 1) shows low to moderate petroleum potential throughout the study area. The highest confidence regions have high data density (e.g. wells, RADARSAT, potential fields, seismic, etc.). The region with the highest potential (light greens in Figure 1) lies just north of the high density data control; therefore, confidence in this petroleum potential is lower. Further north, near Southampton Island, areas of moderate potential exist in Mesozoic-Cenozoic grabens. These grabens may have been buried deeper (more favourable for petroleum generation) and may contain more preserved Paleozoic sediments.

Unconventional resources were investigated for the energy potential possibly including: gas hydrates, coal-bed methane, oil shale, and shale gas. Based on previous publications and provincial reports, unconventional resource potential is considered very low in offshore parts of the study area. Oil shale and coal-bed methane are not considered to be prospective as an unconventional resource in onshore parts of the study area due to interpreted immature source rock (Appendix A). There are publications that indicate regions of potential methane hydrate stability in the northeast portion of Hudson Bay (Figure 3); however, single-channel and multi-channel seismic data are too limited to conclude strong evidence for presence of gas hydrates.

ACKNOWLEDGEMENTS

The GSC Calgary MCT geoscience team sincerely thanks Denis Lavoie, Shunxin Zhang for their expertise and consultation; Michelle Nicolas and Derek Armstrong for their provincial expertise and data; Andy Mort and Keith Dewing for their geological insight; Faizan Shahid for his technical skills; and Tom Brent and Jim Dietrich for their support and guidance during the duration of the study. We would also like to acknowledge Shell Canada for access to their Hudson Bay seismic data. Many other GSC colleagues and emeritus scientists are thanked for pointing to relevant literature, maps, and data resources as well as for sharing their stories and insights about regional geology. Without their generous help, it would have been impossible to complete this project on time. Reprocessing of the Shell Canada seismic data was done internally to the GSC utilizing Halliburton's SeisSpace software and basin modeling was conducted internally to the GSC also, using ZetaWare Inc. software.

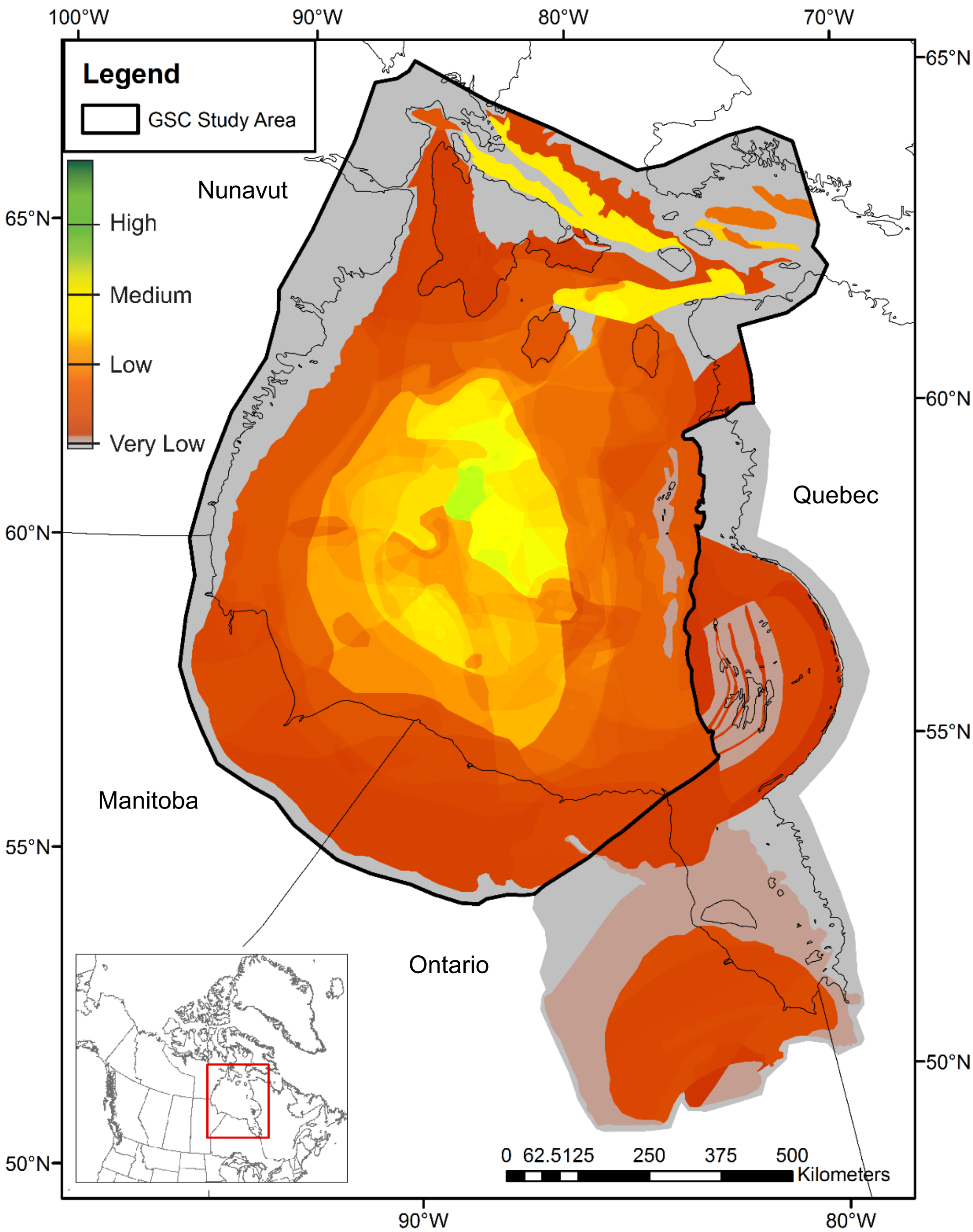

Figure 1. Hudson Bay and James Bay Petroleum Potential Map. Colour code – gradation bar ranges from no potential (grey) and very low potential (pale pink) to low potential (red) to the highest potential (dark green, globally competitive for exploration). The study area (black outline) contains low to medium petroleum potential areas. More interpretive mapping, modern seismic, and potential field data would need to be acquired to generate a more accurate representation of the petroleum potential. The petroleum potential of eastern Hudson Bay and James Bay is discussed in Hanna et al., 2018 (their Figure 1).

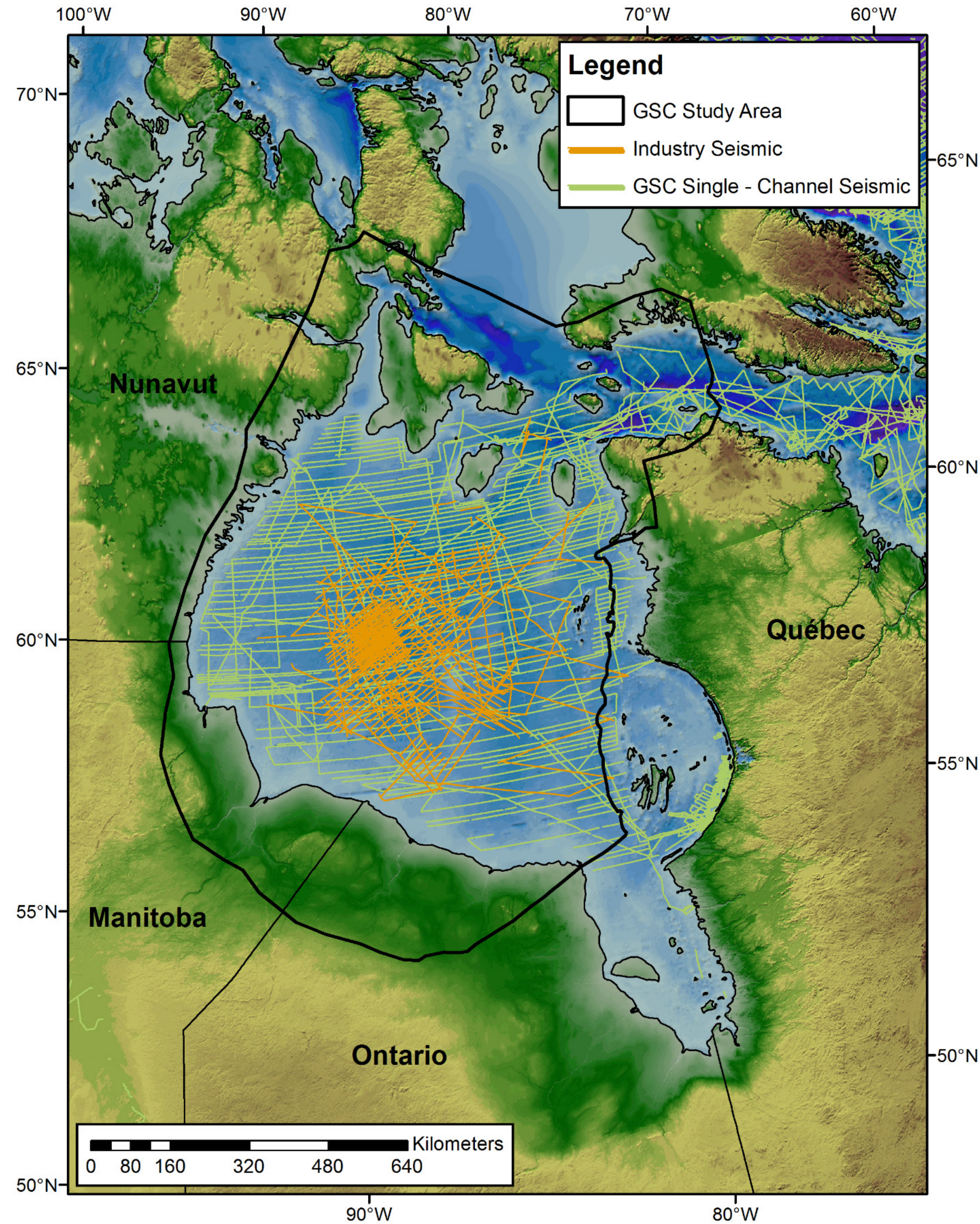

Figure 2. Map showing location of two-dimensional seismic lines in Hudson Bay.

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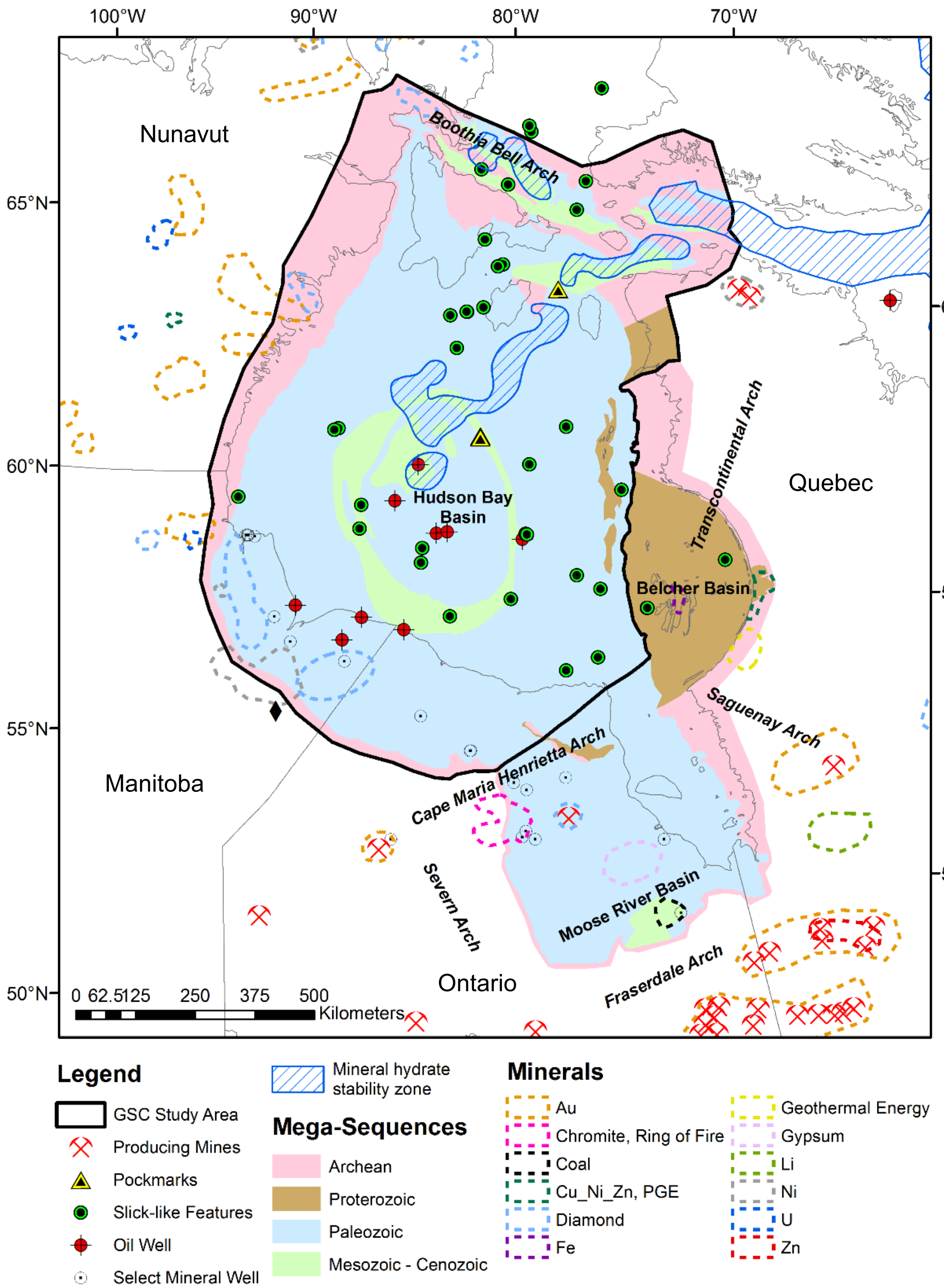

Figure 3. Geology map of the Hudson Bay Area. Hudson Bay and James Bay geologic mega sequences, select petroleum system indicators (sea surface slick-like features, and sea floor pockmarks) and well locations. Wells shown are both petroleum and mineral wells drilled in the Hudson Bay Basin and surrounding onshore areas.

Hudson Bay Basin study area petroleum potential chance of success summary							
Age (Ma)	**Play**	**Reservoir**	**Trap**	**Source**	**Seal**	**Highest uncertainty**	**Global Scale factor (0-1)**
359	Devonian structural	Carbonates, Clastics	Small offset faults	Upper Ordovician black shales	Tight Carbonates, Shales - Long Rapids Fm.	Source	0.30
411	Silurian / Devonian unconfomity	Carbonates, Clastics	Stratigraphic	Upper Ordovician black shales	Tight Carbonates, Shales	Source	0.30
416	Silurian / Devonian reef	Williams Island, Kwataboahegan and Attawapiskat Fms.	Stratigraphic	Upper Ordovician black shales	Tight Carbonates, Shales	Source	0.50
416	Paleozoic Hydrothermal Dolomite	Carbonates	Stratigraphic	Upper Ordovician black shales	Tight Carbonates, Shales	Source	0.50
419	Silurian structural	Carbonates, Clastics	Primarily small offset faults	Upper Ordovician black shales	Tight Carbonates, Shales	Source	0.50
450	Ordovician reef	Red Head Rapids Fm.	Stratigraphic	Upper Ordovician black shales	Tight Carbonates, Shales	Source	0.50
450	Ordovician structural	Carbonates, Clastics	Primarily small offset faults	Upper Ordovician black shales	Tight Carbonates, Shales	Source	0.50
999	Proterozoic structural	Clastics	Folds, Subcrop	Proterozoic source	Tight Carbonates, Shales	Source/ Preservation	0.45
Presence and Quality		High	Med	Low			

Table 1. Hudson Bay petroleum play elements. Hudson Bay petroleum plays include petroleum systems elements, elements of highest uncertainty, and a global scale factor (Section 4.2 of this report). Play ages are approximations of time of reservoir formation. Proterozoic plays are given the age '999' to ensure functionality and order in file structure. In the Belcher Basin, sediments are 1.8 Ga (billion years) and sediments of similar age may exist within the study area but are still undocumented.

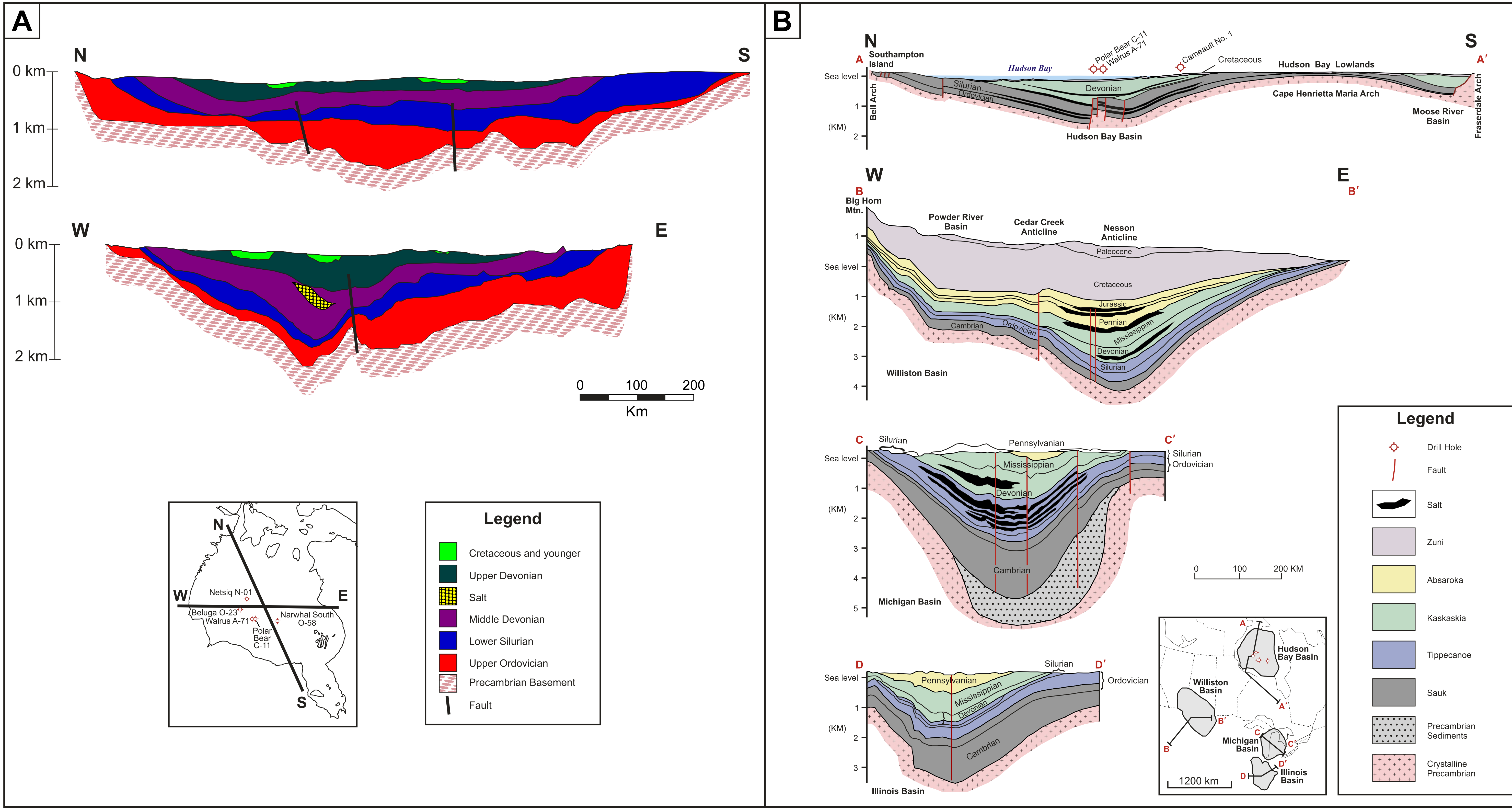

Figure 4. Hudson Bay geologic cross-sections. A) North-South and East-West cross-sections through Hudson Bay based on basin model (Appendix C). This section was generated using logged well tops, and three dimensional model surfaces derived and depth converted from seismically mapped horizons. B) Paleozoic sediments in Hudson Bay are much thinner than those in other intracratonic basins in North America *(modified from* Burgess, 2008 and Zhang, 2010).

APPENDIX A. MEGA-SEQUENCE PETROLEUM SYSTEMS

This summary is primarily derived from Lavoie et al. (2013) and Lavoie et al. (2015) who previously evaluated the petroleum system elements in the Hudson Bay Basin. A more detailed system element analysis can be found in the aforementioned citations and references therein.

Mega-sequence 1 – Proterozoic Era

There is little to no information about the offshore Hudson Bay Basin petroleum systems and potential in this mega-sequence. The extent of Proterozoic sediments under Hudson Bay is unknown; therefore, the Proterozoic stratigraphy and early structural evolution is inferred from adjacent basins. The Proterozoic stratigraphy thought to be present includes clastic, carbonate, low grade metamorphic, and igneous rocks mapped in outcrops on the Belcher Islands, in Northern Ontario (Sutton Inlier), and in the Richmond Gulf Graben (Chandler, 1988 and Jackson, 2013). Anticline-Syncline pairs mapped in outcrop on the Belcher Islands and seismically in the Winisk basin (Lavoie et al., 2013) may extend further westward into Hudson Bay. For all wells drilled in the central part of Hudson Bay, the basement consists of metamorphosed gneisses most likely Archean in age. There is no direct evidence of Proterozoic low metamorphic sediments west of the Belcher other than some poor seismic in the Winisk Basin. The presence of Proterozoic underneath most of Hudson Bay basin is quite equivocal.

The following descriptions are adapted from Appendix A of Hanna et al. (2018). Note that formations described are specific to the Belcher Basin; however, presence of time- and lithological- equivalent units are proposed to possibly exist within the study area. Where relevant, comments are made on elements specific to Hudson Bay.

Source Rock

Based on the work of Jackson (2013) the most prospective source interval in the Belcher Islands is the Omarolluk Formation: a 5-20 m thick basal black shale of Proterozoic age. This unit is seen on the Gilmour Peninsula and Young Point and is thought to represent turbidite deposition in a deep-water restricted basin. The authors have not found Rock Eval analyses or other tests to indicate the total organic carbon (TOC) content of the Lower Omarolluk shale, but it is equivocally considered to be the best candidate for a regional source rock. Circumstantial evidence of petroleum generation and migration comes from sea-surface slick-like features near the Belcher Islands (Decker et al., 2013) and from dark staining (potential oil staining) recorded in the Loaf sandstone (Jackson, 2013).

Reservoir

Potential reservoir units in the Belcher Islands and Richmond Gulf Graben include underlying (relative to source) sandstones of the McLeary (Belchers) and Pachi formations (Richmond Gulf, Chandler, 1988), and sandstones within the overlying Loaf and Omarolluk formations (Belcher Islands, Jackson, 2013). The formations may have low porosity due to greywacke lithology (Jackson, 2013) and mineralogical changes during diagenesis and subsequent metamorphism.

Trap

Deformation caused by the Trans-Hudson Orogeny buried, folded, and faulted the Belcher Basin sediments as well as sediments in the Winisk Basin within Hudson Bay. Evidence of this deformation has been interpreted on seismic data west of the Belcher Islands (Lavoie et al., 2013). Although the Loaf and Omarolluk sandstones have been eroded from the crests of anticlines, the McLeary Formation may exist in anticlines in the subsurface. Since the McLeary Formation underlies potential source rocks, it would require unusual, yet not impossible, geologic processes for hydrocarbon charge.

Seal

Regional seals would have been formed by shales and siltstones of the Upper Member of the Loaf Formation and a number of localized seals could exist within cemented zones of sandstone or carbonate.

Mega-sequence 2 – Paleozoic Era

The Paleozoic section in the Hudson Bay itself has a maximum preserved thickness of ~2500 m and consists primarily of Ordovician to Devonian carbonates, clastics, and locally thick Devonian evaporites (Hu et al., 2011; Lavoie et al., 2013). Exact or approximate thickness of preserved successions in the northern part of the Bay and in Foxe channel is unknown. Literature on Hudson Bay Basin stratigraphy and source rock organic geochemistry (Lavoie et al., 2013), tectonics (Pinet et al., 2013a), and slick-like features (Decker et al., 2013) suggests that Hudson Bay Basin may contain all necessary elements for petroleum generation. Although similar Paleozoic carbonates and shales produce oil and gas throughout North America, the sediments in the Hudson Bay Basin have low to medium potential, mainly due to questions on the extent and thermal maturity of potential source rock(s). Figure A-1 illustrates the Paleozoic (Ordovician to Devonian) mega-sequence stratigraphic column.

Source

Source is the highest uncertainty element in mega-sequence 2. Three distinct Upper Ordovician shale intervals with source rock potential are identified in the Hudson Bay Platform: Amadjuak Fm., Boas River Fm., and the Read Head Rapids Fm. (Lavoie et al., 2013); the stratigraphic assignment of these units has recently being revised (Armstrong et al., 2018; Zhang and Riva, 2018). For the purposes of this report, these calcareous black shale units are treated as a single, amalgamated Upper Ordovician source. Source rocks of Ordovician age are present (Zhang and Lavoie, 2012) with evidence of oil staining and bitumen/pyro-bitumen. However, source rock maturity is a realistic uncertainty when compared to other analog intracratonic basins in North America (Nicolas and Lavoie, 2012, Reyes et al., 2016). Onshore source rock samples are immature (Reyes et al., 2016; Jiang et al., 2018) although limited samples from the offshore indicate that they are mature (lower oil window conditions; Zhang, 2008; Lavoie et al., 2015; Pinet et al., 2016). See Appendix C for further details.

Reservoir

Regionally, reservoir units in mega-sequence 2 are primarily Ordovician to Devonian carbonates which exist in the Hudson Bay Basin. Carbonate reservoir distribution is highly variable and affected by numerous lithologic and diagenetic influences (Ahr, 2008). Major reservoir facies identified in Lavoie et al. (2013) are Paleozoic reefs (Ordovician, Silurian, and Devonian) and hydrothermal dolomite (Upper Ordovician). Hydrothermal dolomite occurs when hot fluids intrude a carbonate facies, dissolving primary calcite and potentially creating secondary porosity more or less imperfectly filled by secondary high temperature carbonate cements. This type of reservoir is a prolific hydrocarbon producer in North America (Davies and Smith, 2006). Reefs and hydrothermal dolomite features have been seismically imaged and mapped in the subsurface and in surface outcrops of the Hudson Bay Basin (Hu and Dietrich, 2012; Lavoie et al., 2011; Castagner et al., 2016; Lavoie et al., 2018; M. Nicolas and D. Armstrong, pers. comm.).

Trap

Lavoie et al. (2013) identified five different potential trap types in Hudson Bay: tilted fault blocks, reefs, hydrothermal dolomite, unconformities, and salt dissolution folds. Paleozoic reefs (Hu and Dietrich, 2012), hydrothermal dolomite, unconformity traps (Dietrich et al., 2013), and large basement faults and other small-offset faults (Figure A-2) have been seismically mapped in the study area. Salt dissolution plays were not considered in this study.

Seal

Seals in the study area are varied and can include tight carbonates, evaporates, and shales. Hydrothermal dolomites could have been sealed by overlying carbonates; however, carbonates are brittle and may have fractured during post hydrocarbon generation deformation. Pressure-depth profiles indicating overpressure (Hu and Dietrich, 2012) provide evidence for effective seals.

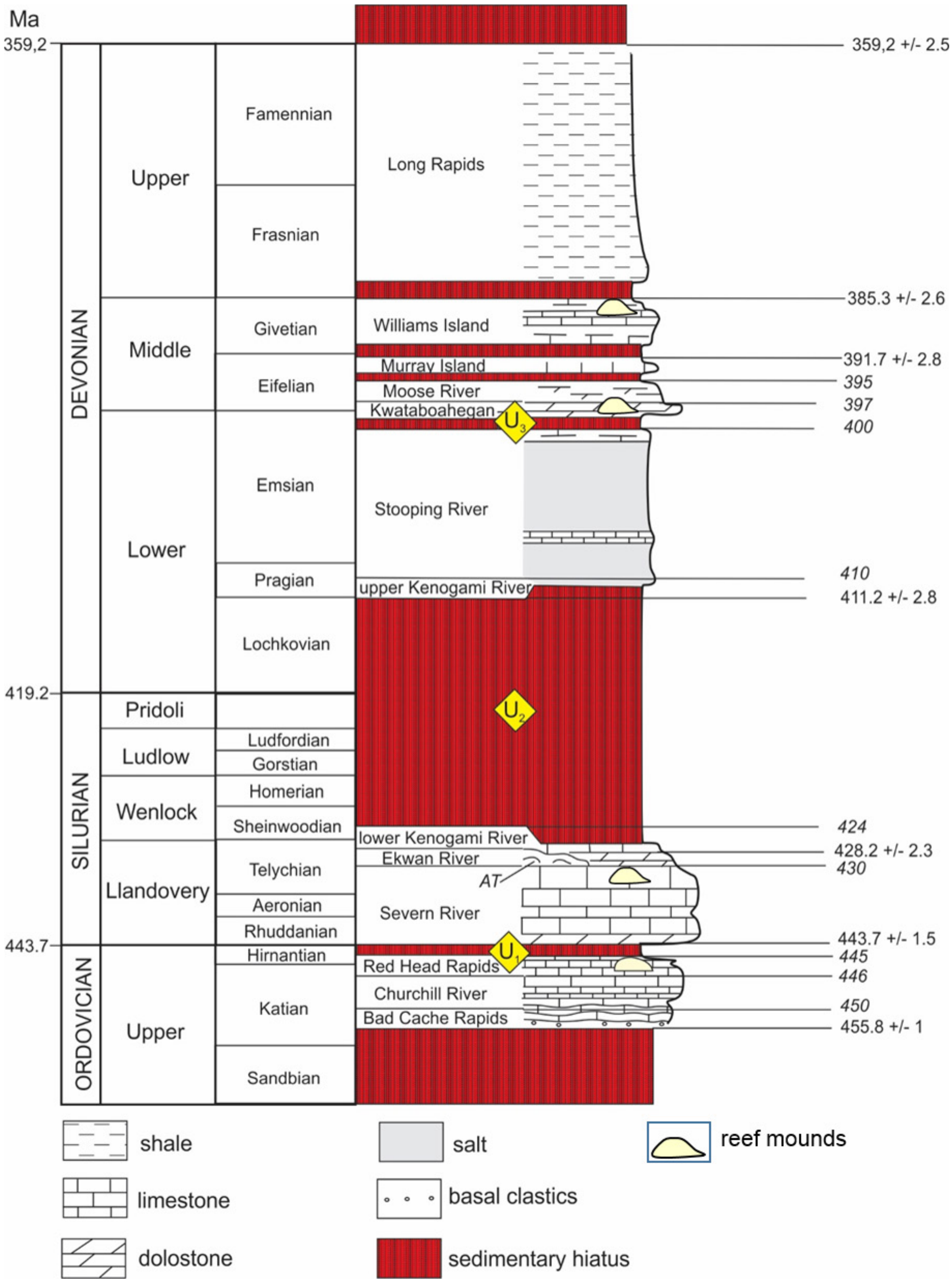

Figure A-1. Stratigraphic column of the Hudson Bay basin rock formations *(modified from* Lavoie et al., 2015).

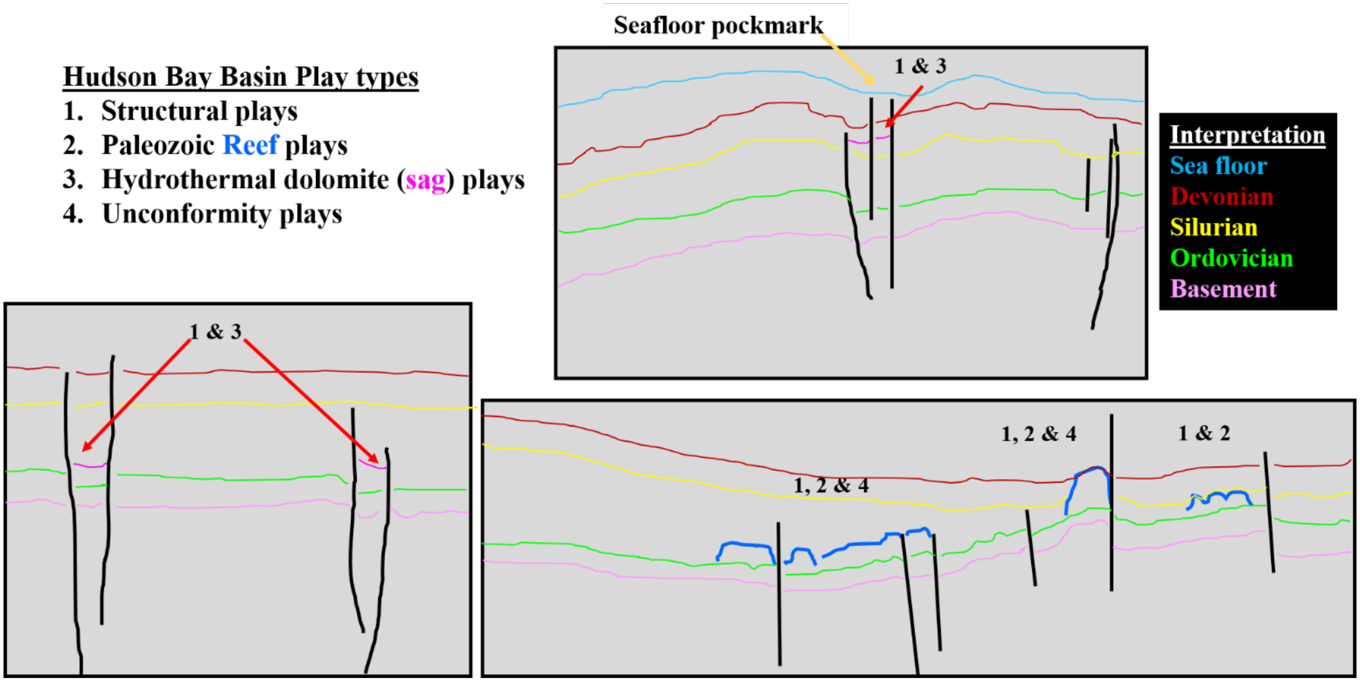

Figure A-2. Hudson Bay play types.

Mega-Sequence 3 – Mesozoic – Cenozoic Eras

Poorly consolidated Mesozoic to Cenozoic sediments seen in the Netsiq N-01 (Hu and Dietrich, 2012) have been seismically mapped in the center of Hudson Bay and in isolated grabens near Southampton Island. The recovered section in the Netsiq well was approximately 100 m, but thicker packages may exist in the grabens to the north. This mega-sequence is not considered to be very prospective. No plays were considered for this mega-sequence. The significance of this sequence is indirect as its presence might imply deeper burial (and maturity) for Upper Ordovician source rocks. Interestingly, these interpreted post-Paleozoic aged grabens are commonly, but not invariably, underlying potential oil slicks observed through RADARSAT image analyses on seawater surface (Pinet et al., 2013b; Decker et al., 2013).

Source Rocks

No conventional source rock intervals in this mega-sequence have been identified.

Reservoir

There is limited potential in the Mesozoic to Cenozoic. The formations are poorly consolidated with mixed lithologies.

Trap

Some unconformity and structural traps are identified.

Seal

The unconsolidated units of this mega-sequence make poor seals.

APPENDIX B. MINING ACTIVITY AND MINERAL POTENTIAL SUMMARY

The provinces and territories encompassed in the study area are rich in a variety of economic minerals. Figure 3 attempts to capture zones with potential economic mineral occurrences. However, due to the complex geology and the size of the region evaluated, these zones are broad and smaller occurrences may not be represented. There is also potential for undocumented mineral occurrences due to the remote nature of many parts of the study area.

Exploration in northeastern Manitoba is primarily focused on nickel (Ni), gold (Au), and diamonds (Figure 3). Nickel exploration and development is concentrated around contact zones between the Archean Superior province and surrounding Proterozoic geology. Over 150 Mt of nickel has been produced from the Thompson nickel belt. Nearer to the study area, the Fox River belt has been explored for its nickel potential (manitoba.ca/minerals). In the Kivalliq region of Nunavut, nickel exploration has focused around Ferguson Lake, starting in the 1950s and recently explored by Canadian North Resources (Gov. Nunavut, 2017).

In 2016, microdiamonds were discovered by the Manitoba Geological Survey, and the presence of kimberlite indicator minerals, carbonatites, and lamprophyre suggests that deep mantle magmas (potentially diamond-bearing) are present throughout Manitoba (manitoba.ca/minerals). The majority of diamond exploration is in Archean and Proterozoic rocks. In Nunavut, Dunnedin Ventures Inc. is expanding exploration at the Kahuna kimberlite site (Gov. Nunavut, 2017).

Gold was first discovered in Manitoba in 1890 and is still currently being explored for and produced. Eastern Manitoba (within the Superior province) contains both past gold mines and current active projects within the Oxford-Stull domain and the Rice Lake belt (manitoba.ca/minerals). As of 2017, there were 18 active gold projects in Kivalliq as well as the Meadowbank gold mine (operated by Agnico Eagle Mines Ltd.). The Meadowbank mine began operation in 2010 and is projected to remain open until 2018. In 2019, the Amaruq and Meliadine projects are scheduled to begin production (Gov. Nunavut, 2017).

Paleoplacer Uranium was discovered ~100 km west of Churchill, MB, in the Great Island Basin (manitoba.ca/minerals). In Kivalliq, the Angilak project contains 2.83 Mt of U_3O_8 ore at a grade cutoff of 0.2%. This project also contains copper, molybdenum, and silver (Gov. Nunavut, 2017).

Mineral potential in the proximity of the Moose River and Belcher basins is discussed by Hanna et al. (2018). A brief summary of the mineral resources identified onshore in Hanna et al. (2018), that may extend offshore include: limestone, lead, zinc, nickel, copper, iron, fluorite, barite, silver, gold, coal, chromite, lithium, gypsum, peat, granite carving stone, and micro-diamonds. Viability of offshore mineral resources requires that a regulatory framework is established allowing offshore mineral mining in Canada.

APPENDIX C. HYDROCARBON GENERATION MODEL

This study has generated three-dimensional thermal history models using depth converted surface grids interpreted from seismic and one-dimensional models at each of the offshore well locations. The one-dimensional models study the effects of rifting, deposition/erosion, and radiogenic heat production in the crust on organic thermal maturity and build from the one-dimensional models of Lavoie et al. (2013). The purpose of geologic modeling is to evaluate the (possible) maturation and timing of oil generation in the Hudson Bay Basin.

Input parameters

Source Rock

Within the Hudson Bay Basin, organic rich facies are most prevalent in the Upper Ordovician succession. Rock-Eval data from onshore samples (Southampton Island, South Baffin Island, Ontario, INCO wells; Lavoie et al., 2013) identify zones of high TOC within immature shales. In the offshore wells, systematic Rock-Eval analyses did not identify any organic rich zones in the Ordovician (Lavoie et al., 2013), but petrophysical logs and Rock-Eval on hand-picked black shale cuttings indicate several thin, organic rich beds (Zhang, 2008, Hu and Dietrich, 2012, Lavoie et al., 2013). Geochemical data (hydrogen-oxygen indices) and gas chromatography data (Macauley et al., 1990; Zhang 2011b) indicate the predominance of Type II organic matter with the potential for some Type II-S organic matter (sulfur rich organic matter will generate oil more readily). The studies of Reyes et al. (2016) and Jiang et al. (2018) document the rapid generation of oil at low burial temperatures from artificial maturation through hydrous pyrolysis.

In the one-dimensional models, two end-member scenarios are tested using a Type II-S and Type II (equivalent to Type A and Type B respectively; Pepper and Corvit, 1995) kerogen within the Upper Ordovician Bad Cache Rapids and Red Head Rapids Formations (assumed initial potential values for use in Genesis: initial HI=600 mg/g/TOC, initial TOC=10%).

A regional hypothetical source rock was placed in the three-dimensional model as a 25 m thick organic rich layer within the Ordovician succession, 100 m above the basement (Figure C-1). This is an optimistic estimate for both the thickness and spatial extent of the organic rich facies, but was necessary to model the potential for oil generation throughout the basin.

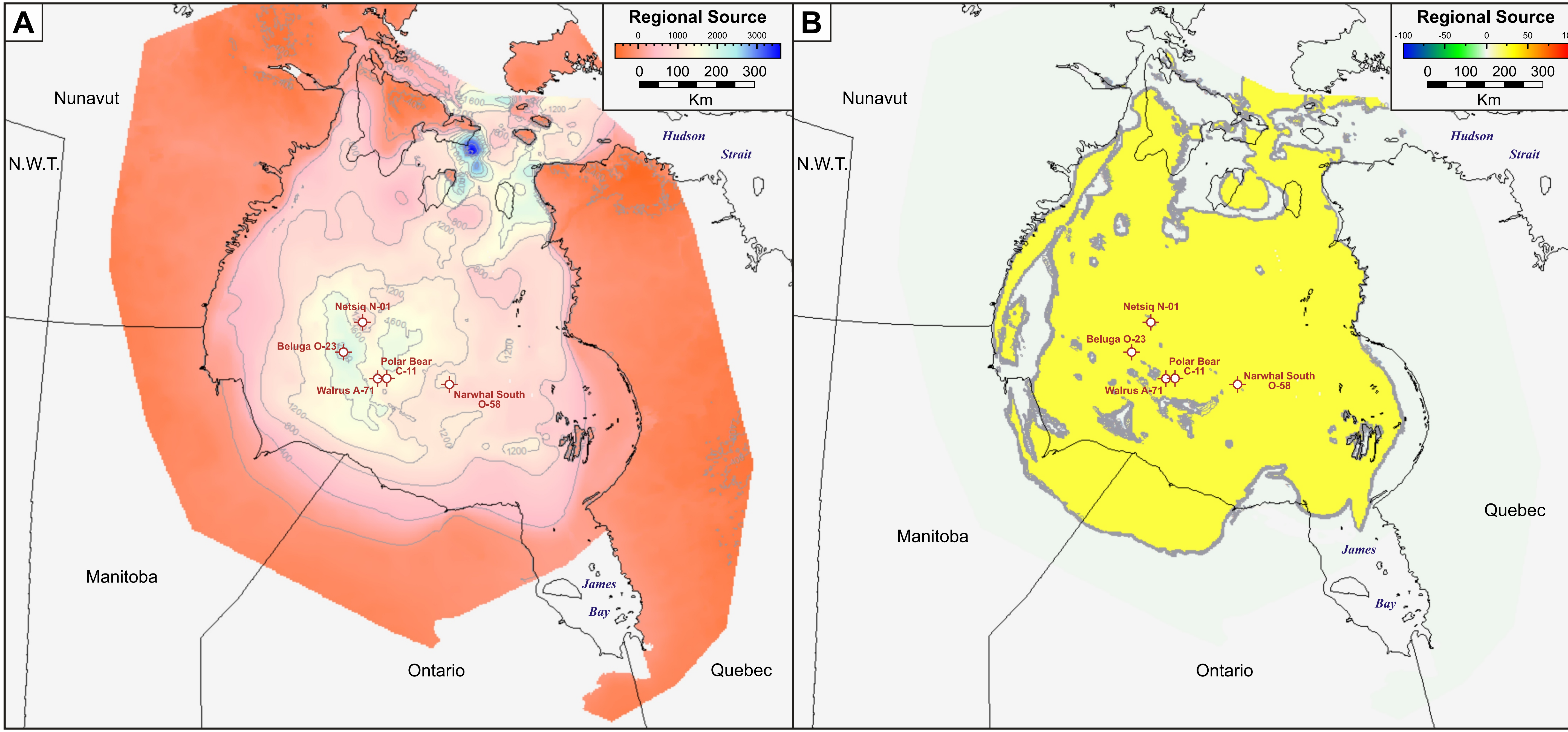

Figure C-1. Hudson Bay source rock. Hypothetical distribution of regional Ordovician source rock in the 3D model. A) This structure map of source rock layer is a duplicate of the seismically mapped basement surface which is then shifted 100 m stratigraphically upwards. B) Source rock isopach is 25 m thick throughout the basin. Holes in the isopach are those regions where the Ordovician succession is less than 100 m thick.

Subsidence and Basin History

Lithology, stratigraphy, and ages for each one-dimensional model are derived from petrophysical logs, new biostratigraphic data and previous regional studies (Lavoie et al., 2015, Hu and Dietrich, 2012, Hu et al., 2011, Lavoie et al., 2013). Numerous unconformities in the stratigraphy constrain the age for missing sections that may improve the chances of maturation (Lavoie et al., 2015). There is potential for deposition and erosion at three main unconformities:

A. U2: unconformity separating the Upper Silurian to Lower Devonian strata (424-411.2 Ma) – coeval to the Boothia uplift and the Caledonian orogeny (Pinet et al., 2013), and may reflect eustatic variations. There is little to no effect on maturation history.

B. Post Devonian (358-250 Ma) – onset of sag phase of basin subsidence (Pinet et al., 2013) and aligns with predicted cooling age of apatite fission tracks (Lavoie et al., 2013; Pinet et al., 2016). Based on thermal maturation data with a constant low geothermal gradient, from 1.5 to 2.5 km of post-Devonian strata might have been eroded (Lavoie et al., 2015).

C. Cretaceous and younger (93-2 Ma) – The total preserved sediment thickness in nearby Hudson Strait is ~2500 m, of which ~600 m is Ordovician (Pinet et al., 2013b), while isolated Cretaceous sediments overlie the Hudson Bay and offshore Paleozoic succession. Recent apatite fission-track analysis on southern Baffin Island suggests regional burial in the Cretaceous of ~1.8 to 3.8 km by Albian-Cenomanian time (assumed surface temp. of 20°C and geothermal gradient of 25°C/km) that was later removed via erosion beginning ca. 90-80 Ma (McDannell et al., 2018). In addition, Cretaceous burial of ~1.4 km is inferred from thermochronology (fully eroded by ca. 45 Ma) for the western Canadian Shield (Ault et al., 2015).

The spatial extent of the missing section for each unconformity was estimated using paleogeography maps of Ron Blakey (©2013 Colorado Plateau Geosystems Inc.) and the associated isopachs illustrate how the basin center migrates as the basin tilts from east to west between the Silurian and Devonian (Figure C-2; Pinet et al., 2013). Burial at the end-Ordovician unconformity (associated with a global glacio-eustatic sea level fall) is not modelled because it would take significant deposition and erosion between 445-443 Ma to have an impact on organic matter maturation. The organic-rich facies is too close to the surface at this point in geological time for maturation to be possible.

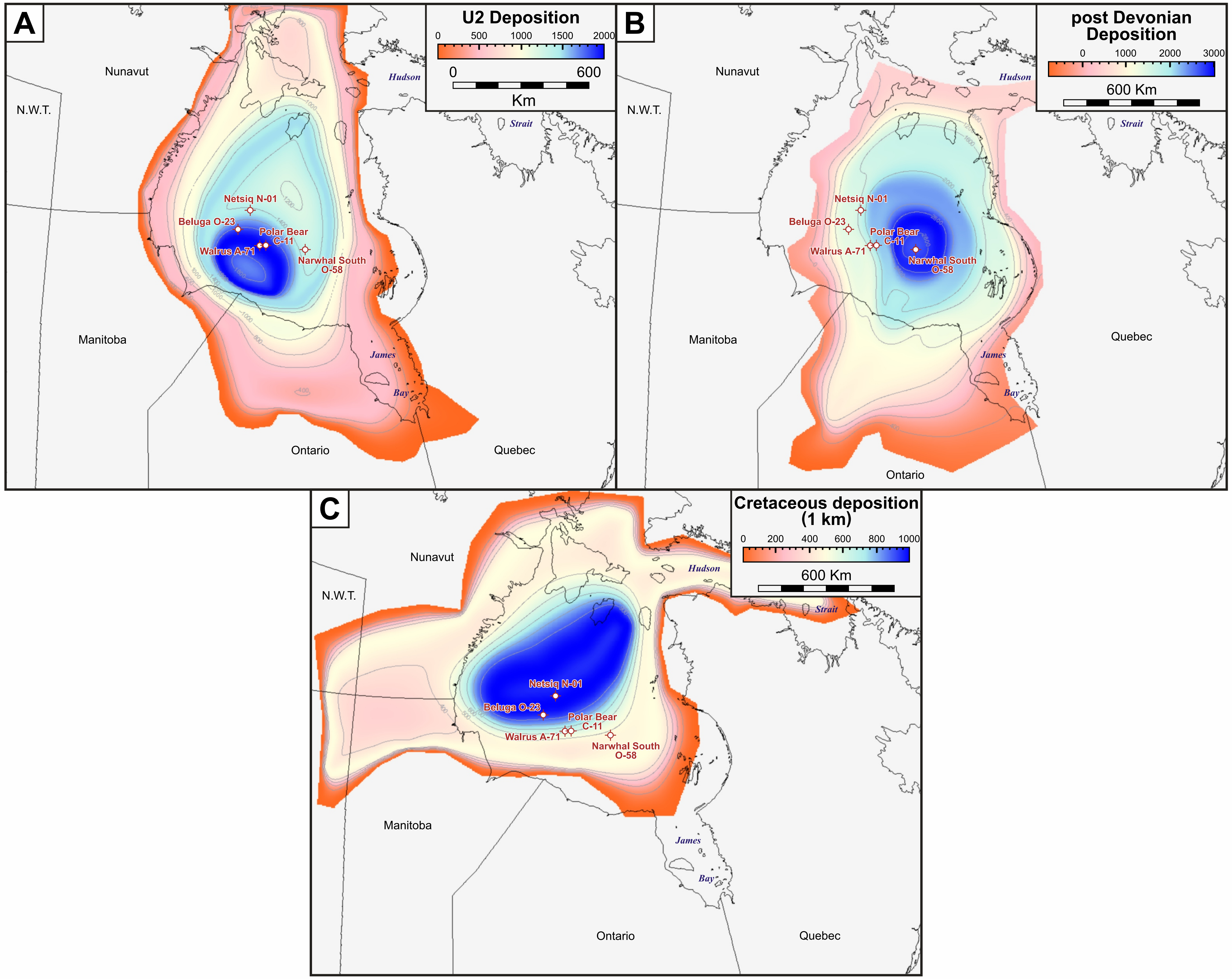

Figure C-2. Hudson Bay isopachs. Isopachs for sediment packages at each unconformity. Dark blue represents deepest part of sediment package. Contour shapes are based on Silurian (A: U2 unconformity), late Devonian (B: post Devonian unconformity), and Cretaceous (C: Cretaceous and younger) paleogeography maps (Ron Blakey, ©2013 Colorado Plateau Geosystems Inc.).

Thermal Parameters / Basin Evolution

Heat flow / temperature data

The thermal maturity model tests the effects of variable heat flow over time. Assuming a constant temperature of 1330°C at the base of the lithosphere (Jarvis and McKenzie, 1980), heat flow and surface temperature are influenced by crustal thinning events, lithology (specifically radiogenic heat production and thermal conductivity), and deposition/erosion. In 2013, Lavoie et al. estimated heat flows of 52-63 mW/m^2 in their one-dimensional models. Mareschal and Jaupart (2004) estimate heat flow in the Hudson Bay Basin between 27-32 mW/m^2. There are few control points in this area and heat flow through the basin is a source of uncertainty in the model. The two models created in this study estimate a present day heat flow of 58 mW/m^2 and 42 mW/m^2. Lower present day heat flow (35 mW/m^2) was briefly considered during the modelling process, but hydrocarbon generation did not occur. The value of 42 mW/m^2 was selected because this is where modelled generation was first observed. The high heat flow model (58 mW/m^2) correlates with unpublished data and is within the range of Lavoie et al. (2013).

Apatite fission track (AFT) analysis shows that basement rocks were exhumed to the near surface by the Late Devonian (approximately 452-230 Ma; Pinet et al., 2016), and estimated temperatures in the model do not exceed ~60°C since the Late Devonian. Vitrinite reflectance equivalent data in the offshore wells indicate that the Ordovician formations have nominally entered the oil window (Lavoie et al., 2013). However, there is controversy regarding the validity of the technique used to generate the maturation data (D. Lavoie, pers. comm.). The vitrinite reflectance equivalent data will be considered as the maximum extent of maturity for the more optimistic (high heat flow) model.

Rifts and hotspots

Rifts during the Ordovician and Devonian (stretch factor $\beta = 1.2$, Pinet et al., 2013a) increased heat flow in the Hudson Bay Basin during the Paleozoic. The Great Meteor Hotspot migrated through the basin between 214-175 Ma (Heaman and Kjarsgaard, 2000). The Ordovician stretching may have forced maturation on a localized scale, as evidenced by Ordovician hydrothermal dolomite on Southampton Island recording temperatures up to 165°C (Lavoie et al., 2018). An early high temperature fluid migration is needed for efficient hydrothermal alteration of carbonate (Davies and Smith, 2006). This localized heat flow was not modeled because the purpose of the three-dimensional basin model was to assess variations over a regional scale.

Radiogenic Heat production

Paleozoic sediments of the Hudson Bay Basin rest upon Archean Basement. Ashwal et al. (1987) estimated radiogenic heat production of five large geological provinces in North America (0.5 - 3.0 μW/m^3), including the Trans-Hudson Orogen (THO) (0.7 μW/m^3). The models use two end-members of radiogenic heat production approximating the stratigraphic and tectonic parameters described above:

A. High heat model - heat production 2.8 μW/m^3, upper bound of present day heat flow (58 mW/m^2; Figure C-3A)
B. Low heat model - heat production 1.5 μW/m^3, mid-range of present day heat flow (42 mW/m^2; Figure C-3B)

Note: The low heat production calculated for the THO was not used in the model because the mid-range heat production value of 1.5 μW/m^3 resulted in minimal oil generation. The purpose of the models are to show the most optimistic scenario (High Heat model) and the conditions necessary to allow for initial onset of maturation (Low heat model).

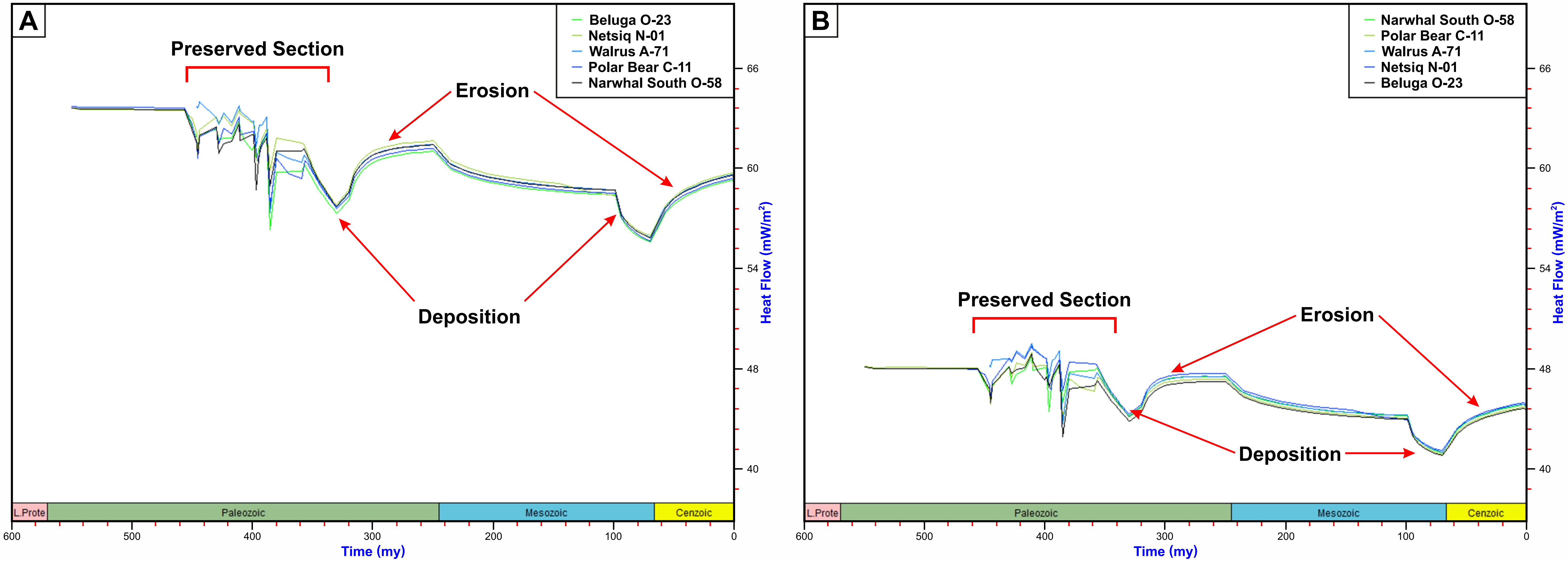

Figure C-3. Heat flow diagrams. Estimated heat flow at each well location over time for the A) high heat model and B) low heat model. Sedimentation, erosion, and lithosphere thinning cause the modelled variations in heat flow throughout time.

Results

The three-dimensional models outline zones of oil generation potential. The high heat model is the best-case scenario, testing the combined influences of the most optimistic parameters, where the low heat model represents the minimum requirements to reach the initial stages of generation. For each model, peak generation occurs in the Late Devonian due to the deposition (and subsequent erosion) of a proposed thick sedimentary package during the late sag phase of basin subsidence.

The one-dimensional model tested up to 4 km of sediment deposition and erosion at the U2 unconformity. Even with this unrealistic overestimate of burial at this time, the Ordovician source rock did not reach maturity. For this reason, an eroded sediment package at this unconformity was not modelled in the three-dimensional model.

High Heat Model Results

In the deepest part of the basin (Beluga O-23 well) the Ordovician and deepest Silurian strata are within the oil window (R_0=0.51-0.69; Figure C-4A). Kerogen transformation ratio within the Red Head Rapids varies between the wells from 6-33% for Type II-S and from 2-16% for Type II. Maturation potential is limited to the central part of the Basin where the eroded Late Devonian package sediment package is thickest (Figure C-5A). Silurian reservoir units are cooler than 80°C by ~300 Ma, greatly increasing the chance of biogenic degradation of any generated hydrocarbons. Similarly, Ordovician reservoir units are cooler than 80°C by ~280 Ma.

Low Heat Model Results

In the deepest part of the basin (Beluga O-23 well) the Ordovician strata are outside the oil window (R_0=0.43-0.54; Figure C-4B). Kerogen transformation ratio within the Red Head Rapids varies between the wells from 1 to 5% for Type II-S and less than 2% for Type II. Maturation potential is minimal for this thermal model and is limited to a small area in the central part of the basin where the eroded Late Devonian package sediment package is thickest (Figure C-5B). The Silurian reservoir units never reach temperatures of 80°C or higher (Beluga O-23, the deepest well, reaches a maximum temperature of 75°C approximately 320 Ma), greatly increasing the chance of biogenic degradation of what little hydrocarbons may have generated.

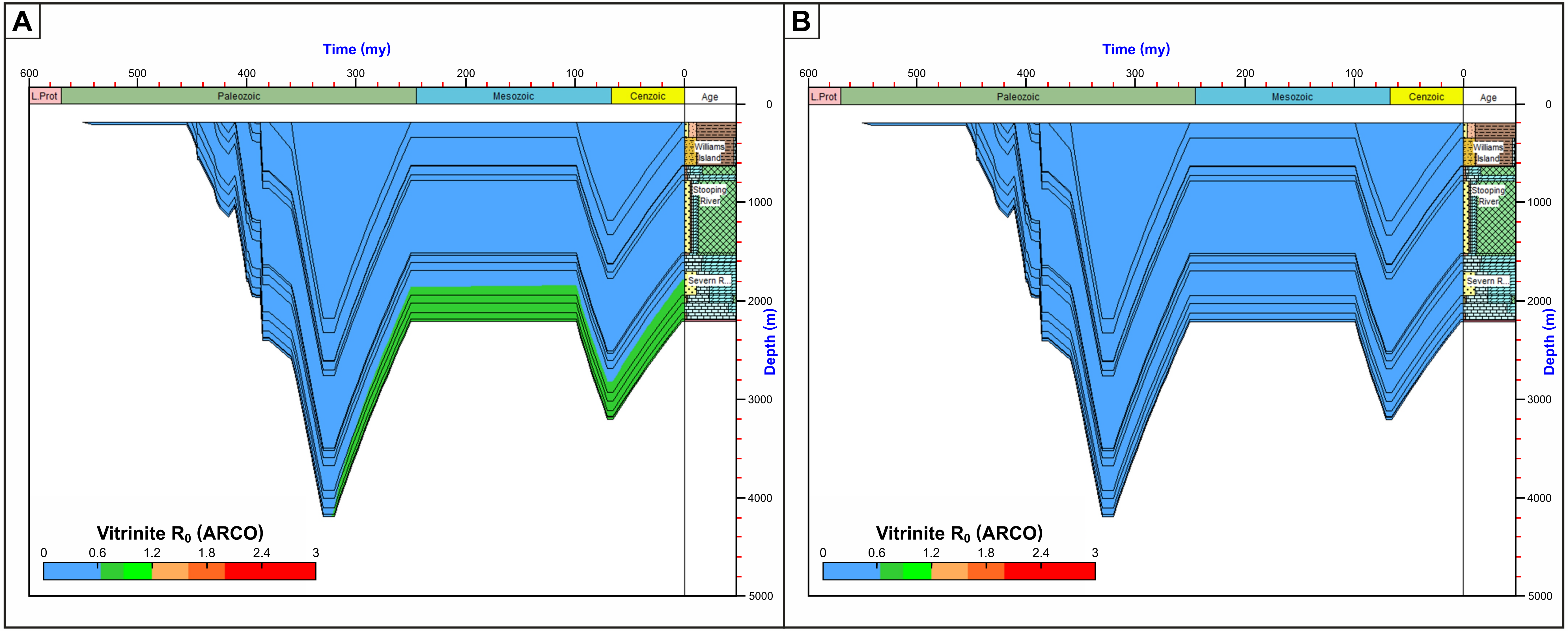

Figure C-4. Burial History. Burial history plot of Beluga O-23 displaying difference in maturity between the A) high heat model and B) low heat model. Based on modelled vitrinite reflectance, the Ordovician shales are expected to reach the oil window in the high heat model. Note: A Devonian shale is included in the model but remains immature as shown by the low vitrinite reflectance in these units.

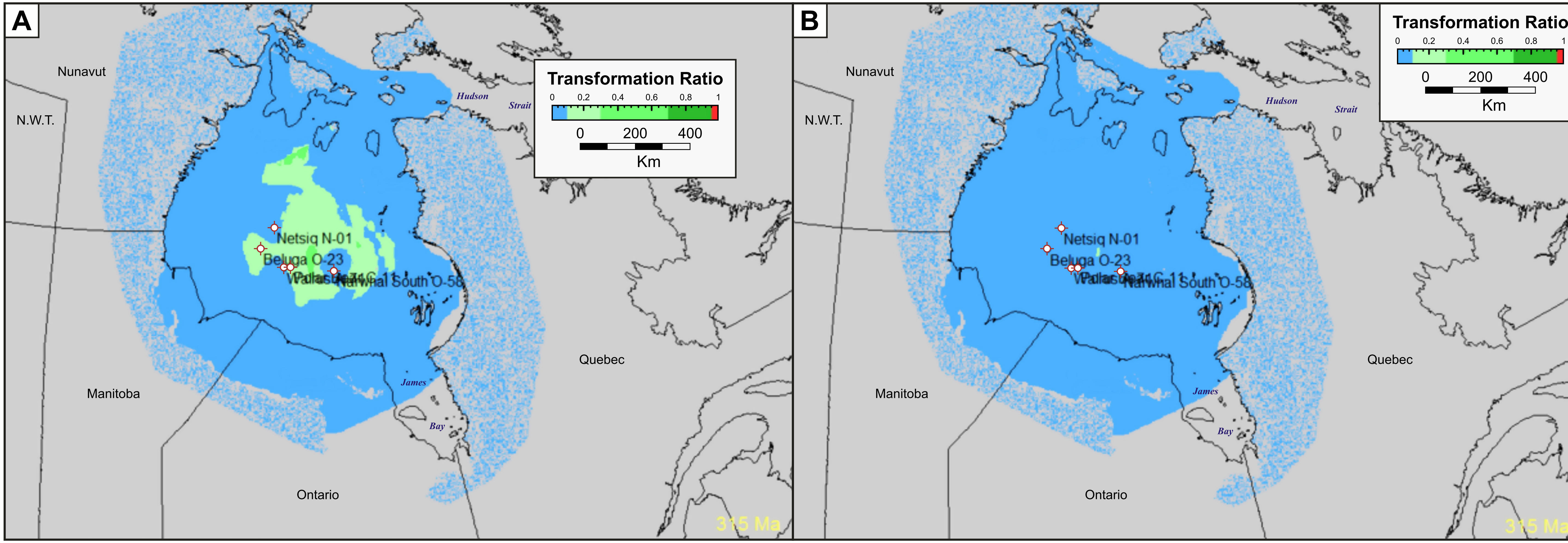

Figure C-5. Paleo-maturation maps (315 Ma) showing the spatial extent of oil generation for the high-heat model (A) and the low-heat model (B). The oil window is represented by a transformation ratio of 0.1 (green) for Type II-S organic matter.

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APPENDIX E. GLOSSARY OF TERMS

(* from or modified from Schlumberger Limited's The Oilfield Glossary, http://www.glossary.oilfield.slb.com)

***Carbonate**: A class of sedimentary rock whose chief mineral constituents (95% or more) are calcite and aragonite (both $CaCo_3$) and dolomite [$CaMg(CO_3)_2$]. Limestone and chalk are carbonate rocks.

Cenozoic: Geological Era approximately 66 million years ago to present.

***Clastic:** Sediment consisting of broken fragments derived from pre-existing rocks and transported elsewhere and redeposited before forming another rock. Examples of common clastic sedimentary rocks include siliciclastic rocks such as conglomerate, sandstone, siltstone and shale. Carbonate rocks can also be broken and reworked to form clastic sedimentary rocks.

***Formation**: A body of rock that is sufficiently distinctive and continuous, and can be mapped.

***Hydrate:** An unusual occurrence of hydrocarbon in which molecules of natural gas, typically methane, are trapped in ice molecules. More generally, hydrates are compounds in which gas molecules are trapped within a crystal structure. Hydrates form in cold climates, such as permafrost zones and in deep water. To date, economic liberation of hydrocarbon gases from hydrates has not occurred, but hydrates contain quantities of hydrocarbons that could be of great economic significance. Hydrates can affect seismic data by creating a reflection or multiple.

***Maturation**: The process of a source rock becoming capable of generating oil or gas when exposed to appropriate pressures and temperatures.

***Mega-sequence:** A large group of relatively conformable strata, normally from the same era, that represents cycles of deposition and is bounded by unconformities or correlative conformities.

Mesozoic: Geological Era approximately 145 to 252 million years ago.

***Migration:** The movement of hydrocarbons from their source into reservoir rocks.

***Mineral:** A crystalline substance that is naturally occurring, inorganic, and has a unique or limited range of chemical compositions. Minerals are homogeneous, having a definite atomic structure. Rocks are composed of minerals, except for rare exceptions like coal, which is a rock but not a mineral because of its organic origin. Minerals are distinguished from one another by careful observation or measurement of physical properties such as density, crystal form, cleavage (tendency to break along specific surfaces because of atomic structure), fracture (appearance of broken surfaces), hardness, lustre and colour. Magnetism, taste and smell are useful ways to identify only a few minerals.

Paleozoic: Geological Era approximately 252 to 541 million years ago.

***Petroleum System:** Geologic components and processes necessary to generate and store hydrocarbons, including a mature source rock, migration pathway, reservoir rock, trap and seal. Appropriate relative timing of formation of these elements and the processes of generation, migration and accumulation are necessary for hydrocarbons to accumulate and be preserved.

***Play:** A family of prospects and/or discovered pools that share a common history of hydrocarbon generation, migration, reservoir development, and trap configuration; forms a natural geological population limited to a specific area.

***Pool:** A subsurface oil accumulation. An oil field can consist of one or more oil pools or distinct reservoirs within a single large trap. The term "*pool*" can create the erroneous impression that oil fields are immense caverns filled with oil, instead of rock filled with small oil-filled pores.

Proterozoic: Geologic eon encompassing ages of 2500 – 541 million years ago. This eon represents the youngest portion of the Precambrian and is sub-divided into three geologic eras: Paleoproterozoic (oldest), Mesoproterozoic and Neoproterozoic (youngest).

***Reservoir:** A subsurface body of rock having sufficient porosity and permeability to store and transmit fluids. Sedimentary rocks are the most common reservoir rocks as they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

***Seal:** A relatively impermeable rock, commonly shale, anhydrite or salt that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

***Sequence:** A group of relatively conformable strata that represents a cycle of deposition and is bounded by unconformities or correlative conformities.

***Source rock:** A rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter.

***Trap:** A configuration of rocks suitable for containing hydrocarbons and sealed by a relatively impermeable formation through which hydrocarbons will not migrate. Traps are described as structural traps (in deformed strata such as folds and faults) or stratigraphic traps (in areas where rock types change, such as unconformities, pinch-outs and reefs). A trap is an essential component of a petroleum system.

***Unconventional resource**: An umbrella term for oil and natural gas that is produced by means that do not meet the criteria for conventional production. What has qualified as unconventional at any particular time is a complex function of resource characteristics, the available exploration and production technologies, the economic environment, and the scale, frequency and duration of production from the resource. Perceptions of these factors inevitably change over time and often differ among users of the term. At present, the term is used in reference to oil and gas resources whose porosity, permeability, fluid trapping mechanism, or other characteristics differ from conventional sandstone and carbonate reservoirs. Coalbed methane, gas hydrates, shale gas, fractured reservoirs, and tight gas sands are considered unconventional resources.