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ABSTRACT

The Hudson Bay Basin is the largest intracratonic basin in North America but also the least known from a geological point of view and the only one without hydrocarbon production and reserves.

The Hudson Bay Basin, in north-central Canada, is bounded by smaller satellite basins, Moose River Basin to the south and Foxe and Hudson Strait basins to the north. It was explored for hydrocarbons from the late 1960's to the mid 1980's. However, after the drilling of five offshore wells, the industry stopped exploration programs as the basin was considered to be thermally immature with a too thin succession and problematic source rock distribution. As part of its new Geomapping for Energy and Minerals program, the Geological Survey of Canada included the Hudson Bay Basin in its research portfolio with the goal to generate a modern understanding of the geological framework of the basin and a precise knowledge of its hydrocarbon systems.

The Hudson-Foxe basins GEM-1 project benefited from limited but significant research activities before its official launch in 2008. The evaluation of recent and vintage geoscientific data led to the definition of the most pertinent research activities and the development of collaborative networks with provincial, territorial and academia stakeholders. The first phase of the research led to the proposal of modern stratigraphic frameworks at the local (provincial, territorial) and regional (offshore) scales and extensive geochemistry works on hydrocarbon source rocks and their burial and thermal histories. Satellite data were acquired over the entire offshore domain of the Hudson Bay and Foxe basins in the search for evidence for active hydrocarbon systems.

After the completion of Phase 1 (2008-2013), a new round of research activities were defined as part of the GEM-2 program (2013-2020). For the new Hudson Bay – Ungava project, research activities were defined aiming to understand local and/or regional factors responsible for burial and exhumation histories as they pertain to regional or local hydrocarbon prospectivity. The research led to a basin-scale stratigraphic framework coupled with detailed analyses of hydrocarbon generation and appraisal of the best potential reservoir unit.

GEM supported research for the intracratonic Hudson Bay, Foxe and Moose River basins has resulted, in early 2019, in the publication of 14 peer-reviewed papers, 43 Open File reports (GSC, CNGO, GC, MGS and OGS), 13 GSC paleontological reports, 11 B.Sc. theses and 1 M.Sc. thesis. The main conclusion of the 11 years of research suggests that the Hudson Bay Basin has an oil potential likely significant compared to the belief at the start of the research and integration of the multiple data set allows to propose Paleozoic-Cenozoic filled half grabens as the potential most significant hydrocarbon play of the basin.

RÉSUMÉ

Le Bassin de la Baie d'Hudson est le plus grand bassin intracratonique en Amérique du Nord mais est également le moins connu géologiquement et le seul sans production d'hydrocarbures réserves connues.

Le Bassin de la Baie d'Hudson au centre-nord du Canada, est bordé par des bassins satellites plus petits, le Bassin de Moose River au sud et les bassins de Foxe et du Détroit d'Hudson au nord. Il a été exploré pour les hydrocarbures de la fin des années 60 jusqu'au milieu des années 80. Cependant après le forage de cinq puits d'exploration en milieu marin, l'industrie a arrêté ses travaux de recherche sur la prémisse que le bassin était immature thermiquement avec une succession trop mince et une distribution problématique des roches-mères. Dans le cadre de son programme de Géocartographie pour l'Énergie et les Minéraux (GEM), la Commission géologique du Canada a inclus le Bassin de la Baie d'Hudson dans son portfolio de recherche visant à générer une compréhension moderne de l'architecture géologique du bassin et une connaissance plus précise de ses systèmes à hydrocarbures.

Le projet Bassins Hudson-Foxe du programme GEM-1 a profité d'activités de recherches limitées mais importantes avant sa mise en place. L'évaluation de ces résultats et les anciennes données géoscientifiques ont mené à la définition d'activités de recherche pertinentes et le développement de réseaux collaboratifs de recherche avec les partenaires provinciaux, territoriaux et universitaires. La première phase de la recherche a conduit à l'élaboration de schémas stratigraphiques modernes aux échelles locales (provinces, territoires) et régionales (domaine marin) ainsi que des travaux importants sur la géochimie des roches mères à hydrocarbures traitant également leur enfouissement et évolution thermique. Des données satellitaires furent acquises pour l'ensemble du domaine marin des bassins de la Baie d'Hudson et de Foxe à la recherche d'indices de systèmes pétroliers actifs.

Après la fin de la Phase 1 (2008-2013), de nouvelles activités de recherche furent proposées dans le cadre du programme GEM-2 (2013-2020). Pour le nouveau projet Baie d'Hudson - Ungava, ces activités de recherche furent définies dans le but de comprendre les mécanismes locaux et/ou régionaux responsables pour l'histoire d'enfouissement et d'exhumation en tant qu'éléments critiques d'évaluation du potentiel local ou régional en hydrocarbures. Le recherche a mené à la définition à l'échelle du bassin, d'un schéma stratigraphique intégré sur lequel est greffé des analyses détaillées de génération d'hydrocarbures et l'évaluation de l'unité avec le plus grand potentiel réservoir.

La recherche supportée par GEM sur les bassins intracratoniques de la Baie d'Hudson, de Foxe et de Moose River a généré, au début de 2019, 14 publications dans des journaux scientifiques, 43 rapports et dossiers publics (CGC, CNGO, GC, MGS et OGS), 13 rapports de paléontologie de la CGC, 11 thèses de baccalauréat et une thèse de maîtrise. La conclusion principale de ces 11

années de recherche est que le Bassin de la Baie d'Hudson a un potentiel pétrolier (huile) probablement plus important que ce qui était considéré au début du projet et que l'intégration des données diverses et de multi-sources permettent de proposer les demi-grabens à remplissage Paléozoïque – Cénozoïque comme le « play » ayant éventuellement le potentiel en hydrocarbures le plus significatif du bassin.

INTRODUCTION

Hudson Bay Basin is the largest intracratonic basin in North America. It is connected to smaller satellite basins, Moose River Basin to the south and Foxe and Hudson Strait basins to the north. The geological study of this large, marine-dominated, area goes back to the 19th century when explorers started to describe sedimentary rock units along the shore of many Arctic islands. Modern geological descriptions, mostly stratigraphy and paleontology, started in the mid-20th century when earth scientists described the onshore and offshore rock successions, resulting in local stratigraphic nomenclatures that correlated poorly from one area to another.

At the start of the initial Hudson Bay-Foxe Basins project (GEM-1, 2008-2013) and subsequent Hudson Bay-Ungava project (GEM-2, 2013-2020) of the Geomapping for Energy and Minerals (GEM) program of the Geological Survey of Canada, the overall research goals were to propose a modern understanding of the geological framework of the basin and provide more precise knowledge of its hydrocarbon systems. The research plans for the 2 phases of the project were designed to address these major goals. In the following text, the term Hudson Bay project will be used for both phases of the GEM programs.

Phase 1 (2008-2013)

A significant number of diverse research activities were carried out before 2008, these activities were largely independent of each other and were based in provincial, territorial and federal geological surveys as well as in universities and oil and gas exploration companies (see historical context). At the start of Phase 1, significant efforts were made to find and assemble all pertinent historical information, in particular at the National Energy Board, curator of hydrocarbon exploration data from the area. The assessment of the vintage geological and hydrocarbon system data resulted in modern reevaluation of the most pertinent digital data which served as cornerstone for the development of research activities done in collaboration with provincial, territorial, and university stakeholders. The activities were defined to address the most critical issues for the holistic understanding of this large sedimentary basin.

The major recognized issues were: 1) the need for a modern stratigraphic framework at the local (provincial, territorial) and regional (offshore) scales as the available frameworks were outdated and did not correlate, 2) acquisition of modern subsurface information in the offshore domain as no digital seismic data were available, 3) a modern understanding of the hydrocarbon source rock units and the thermal / burial history of the basin, which were the most critical issues raised by industry scientists when they stopped exploration in the mid-1980s and 4) the need to use remote sensing (RADARSAT-2) for acquisition of data over the entire marine domain

To address issue #2, significant time and efforts were devoted in the definition of a 5000 km-linear acquisition seismic program with the development of a scientific partnership with a major international academic institution with offshore seismic capacity. In support for the survey, regional marine seismic noise modeling was done (Zykov and Chorney, 2013) as well as an environmental impact analysis (Hawkins, 2011). For various departmental and external reasons, the survey did not materialize. Therefore, our understanding of the subsurface geometry of the basin still has to rely on paper copies of poor- to fair-quality seismic lines. Nevertheless, a major re-evaluation of the sub-surface Hudson Bay and resulting new tectonic evolution model based on the best seismic data available was released (Pinet et al., 2013a). All the other activities for Phase 1 of the Hudson Bay project were synthesized in GSC Open File reports (Lavoie et al., 2013; Huot-Vézina et al., 2013) and in a peer-reviewed scientific paper on hydrocarbon systems (Lavoie et al., 2015). Before the start of Phase 2 of the program, a total of 3 external scientific papers were published together with 14 GSC and CNGO Open File reports, 2 GSC paleontological reports, 5 Manitoba Geological Survey (MGS) Reports of Activities, 5 Ontario Geological Survey (OGS) Open File Reports, 8 B.Sc. theses, and 10 formal oral and poster presentations.

Phase 2 (2013-2020)

Following the completion of Phase 1, a major GSC internal process of evaluating outstanding scientific issues led to the proposition of research activities in new areas or in areas covered but not completed during GEM-1. The Hudson Bay and adjacent areas were identified as needing key geoscientific knowledge for modern appraisal for both their hydrocarbon and mineral potential. In particular, for the sedimentary basin and hydrocarbon component, the following main scientific questions were still debated:

1. How have geodynamic factors recorded as faulting and/or variable burial and exhumation influenced the architecture and petroleum prospectivity of the Hudson Bay basin?
2. Can sub-basins with distinct hydrocarbon prospectivity be identified in the Hudson Bay basin?

Based on these scientific questions and results from Phase 1, a new geoscientific research program was set up with provincial and territorial partners and with other government research agencies. New research plans at various universities that could help address specific aspects of the two research questions were also defined and funded.

The planned research activities to address the remaining issues were focused on: 1) the definition of a regional, basin-scale, modern stratigraphic understanding, focusing amongst other things, on source rock distribution, 2) the evaluation of the most promising hydrocarbon reservoirs, 3) the precise evaluation of hydrocarbon generation potential of Upper Ordovician black limy shales, 4) the refinement of burial/exhumation scenarios in order to evaluate areas with greater potential for hydrocarbon generation, and 5) a marine high resolution hydrographic survey to map seafloor under areas where potential oil slicks at the water surface were identified from RADARSAT-2 image analyses during phases 1 and 2 .

Here again, significant time, efforts and consultations with local communities were devoted to the planning of marine surveys. Acquisitions were scheduled for falls 2016 and 2017; in both cases, issues with the assigned hydrographic ships resulted in the cancellation of the scientific cruises. In 2018, GSC management decided not to fund the Hudson Bay marine survey. This means that the geochemistry and geology underlying potential oil slicks identified by the Transport Canada maritime spill surveillance airborne program (see further in text) in the Arctic (in the immediate vicinity of seafloor pockmarks identified in an ArcticNet survey; Roger et al., 2011), and other potential oil slicks identified through RADARSAT-2 image analyses remain uncharacterized. At the time of writing this synthesis (early 2019), a total of 11 peer-reviewed scientific papers and book chapters, 8 GSC and CNGO Open File reports, 11 GSC paleontological reports, 1 GC Open File report, 6 MGS Reports of Activities, 7 OGS Open File Reports, 1 M.Sc. and 3 B.Sc. theses and 21 formal abstracts have been released or are currently in press as science products of the second phase of the GEM program.

The synthesis of Hudson Bay research between 2008 and 2018

This report summarizes the main advances in geoscience knowledge for the Hudson Bay and satellite basins made during the GEM programs. The report offers an overview of results for the major themes covered over 10 years of research. Themes discussed are: 1) tectonic framework, 2) stratigraphy, 3) sedimentology, 4) petroleum systems (source and reservoir rocks, thermal-burial history, and hydrocarbon generation) and 5) evidence for active petroleum systems. A section on our evaluation of the remaining geoscience questions pertinent to the Hudson Bay sedimentary basin concludes the report.

PREVIOUS GEOLOGICAL WORK

Hudson Bay was explored by English explorer and navigator Henry Hudson in 1610 and, given its relatively remote location and lack of identified resources, it remained poorly known geographically and geologically well into the 20th century. It remains one of the least studied sedimentary basin in Canada. The Phanerozoic succession of the Hudson Bay Basin is largely covered by marine waters. Its southern onshore extension forms the Hudson Bay Lowland and consists of relatively thin succession of nearly flat-lying sedimentary rocks exposed in northeastern Manitoba, northern Ontario and northward, on the southern part of Southampton Island as well as on Coats and Mansel islands in Nunavut. Similarly, the Foxe Basin is a sedimentary basin largely covered by marine water, with preserved onshore erosional margins expressed as nearly flat-lying strata on Melville Peninsula, in the northern part of Southampton Island, on southeast and south Baffin Island and on other smaller islands. The Hudson Strait basin is confined to marine areas except for Akpatok Island in Ungava Bay.

Early geologists exploring in the Hudson Bay area made episodic observations starting in the 1880s (Bell, 1884, 1885; Low, 1887; Dowling, 1901; Wilson, 1902; Parks, 1904). The first fairly comprehensive summary of the stratigraphy was by Savage and van Tuyl (1919). Little work was done on Paleozoic strata of the Hudson Platform during the 1920s-1940s. Studies of Paleozoic strata restarted in the 1950s (e.g., Nelson, 1952; Hogg et al., 1953; Fritz et al., 1957), but it was only in the mid to late 1960s up to the 1970s that regional-scale mapping was conducted by GSC officers along major rivers in Manitoba and Ontario and on Southampton, Coats and Mansel islands (Nelson, 1963, 1964; Nelson and Johnson, 1966; Sanford et al., 1968; Sanford and Norris, 1973; Cumming 1975; Heywood and Sanford, 1976). Rocks of Ordovician, Silurian, Devonian, Jurassic/Cretaceous and Cenozoic ages were mapped although the geology is obscured by the very low relief, swampy muskeg terrain that covers the Hudson Bay Lowland. A comprehensive bibliography of the geology of Hudson Bay was published by Verma (1978).

The early exploration history of the Moose River Basin has been summarized in papers by Bell (1904), Savage and Van Tuyl (1919) and Kindle (1923). The Geological Survey of Canada Operation Winisk in 1967 covered parts of the Moose River Basin and resulted in number of local and regional contributions (Norris and Sanford, 1968, 1969; Sanford et al., 1968; Sanford and Norris, 1975; Price, 1978; Verma, 1982). The mapping program led in the recognition of a carbonate-dominated stratigraphic succession that correlates relatively well with the Hudson Bay Basin for the Ordovician and Silurian and a Devonian succession largely not represented in the onshore Hudson Bay Basin in Ontario and Manitoba. Subsequent work by geologists in the Engineering and Terrain Geology Section of the OGS (Russell and Telford, 1984; Telford, 1988; Sanderson and Telford, 1985) led to refinement of the Devonian stratigraphy in the Moose River Basin.

The first geological observations for Foxe Basin are those of Parry (1824, 1825) who recognized carbonate strata and collected fossils. The first significant regional geological coverage of the onshore extension of the Foxe Basin was part of a major GSC mapping operation (Trettin, 1975) that used the Paleozoic stratigraphy defined at the northern end of Baffin Island by Lemon and Blackadar (1963) and Trettin (1969). A recent summary of the geology and paleontology of Foxe Basin was provided by McCracken and Bolton (2000).

Akpatok Island in the Hudson Strait was noted by Henry Hudson in 1610, but the first geological observations were those of Bell (1899) who described and collected rocks and fossils from the island, the latter were assigned a Middle Ordovician age by Whiteaves (1899). A five weeks geological expedition from Oxford University in 1931 led to the first measured stratigraphic section for the island (Cox, 1933). The abundant fossils collected at that time were described as covering the Middle to Late Ordovician. The first stratigraphic correlations with the succession on Southampton Island in the Hudson Bay are those of Workum et al. (1976) who studied in detail the lithostratigraphy and biostratigraphy of the core of the Premium Homestead Akpatok L-26 well drilled in 1969.

PREVIOUS HYDROCARBON EXPLORATION

Hydrocarbon exploration and production successes in intracratonic basins to the south (Michigan and Illinois basins) and southwest (Williston Basin) were the driving force behind the exploration activities that took place for both the onshore and offshore domains of the study area.

Oil and gas exploration in the Moose River Basin goes back to the early 1920s (Kindle, 1923; Dyer, 1928). The James Bay Basin Oil Company Ltd. drilled three wells along the Moose River in 1929 (Satterly, 1953). Stratigraphic drilling was undertaken by the Ontario government in 1930 with the Onakawana A hole (Martison, 1953), again in the late 1940s and early 1950s (Hogg et al., 1953) and the 1980s (Bezys, 1989; Russell et al., 1985). The Ontario Oil, Gas and Salt Resource (OGSR) Library database documents 32 oil and gas exploration shallow wells and 6 government stratigraphic tests (Fig. 1). In addition, there was drilling activity exploring for Cretaceous lignite resources in the Mattagami Formation (Telford et al., 1991). A summary of the hydrocarbon systems of the Moose River Basin (and Hudson Bay Basin) was proposed by Hamblin (2008).

For the Hudson Bay Basin, onshore drilling started in 1966 (Manitoba) and in 1970, a total of 5 hydrocarbon exploration wells (3 in Manitoba and 2 in Ontario; Fig. 1) were drilled; moreover, a significant number of base metal exploration and stratigraphic wells were also drilled. Given the nature of the terrain, no onshore seismic reflection data was acquired to help locate the hydrocarbon exploration wells.

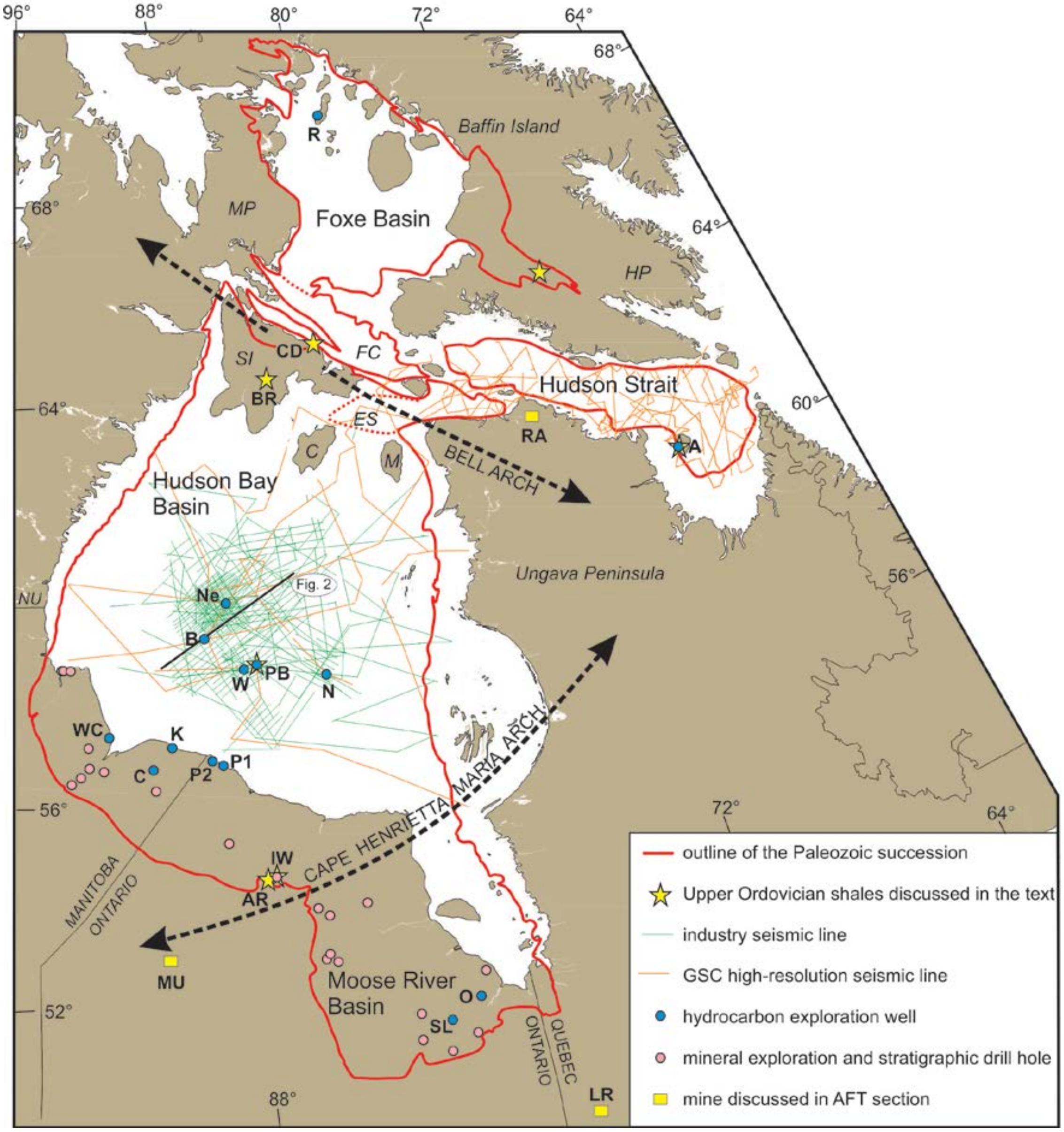

Figure 1. Map and extent of the Hudson Bay Basin and adjacent basins. Multichannel industry seismic lines and Geological Survey of Canada (GSC) high-resolution seismic lines are depicted. Hydrocarbon exploration wells: A = Premium Homestead Akpatok L-26; B = Trillium et al. Beluga O-23; C = Houston et al. Comeault No. 1; K = Sogepet Aquitaine Kaskattama No. 1; N = Aquitaine et al. Narwhal South O-58; Ne = ICG et al. Netsiq N-01; O = Consumer Oil and Gas Onakwahegan No. 2; P1 = Aquitaine Pen Island No. 1; P2 = Aquitaine Pen Island No. 2; PB = Aquitaine et al. Polar Bear C-11; R = Rowley M-04; SL = Aquitaine Sandbank Lake No. 1; W = Aquitaine et al. Walrus A-71; WC = Merland Exploration Whitebear Creek No. 1. Base metal exploration drillhole: IW = Inco-Winisk. LR = La Ronde gold mine; MU: Musselwhite gold Mine. AR = Asheweig River section; CD = Cape Donovan section; BR = Boas River section. NU = Nunavut; SI = Southampton Island; C = Coats Island; FC = Foxe Channel; M: Mansell Island; MP = Melville Peninsula, HP= Hall Peninsula, ES: Evans Strait. Tens of mineral exploration, stratigraphic and geotechnical drillholes in Ontario and Manitoba are not shown. Thick line is location of cross-section on Figure 2. Modified from Lavoie et al. (2015).

Industry offshore drilling started in 1969 shortly after a first marine seismic acquisition program showed that the sedimentary succession preserved in the central part of Hudson Bay is much thicker than its onshore counterpart. From late 1960s to 1990s, the industry and the Geological Survey of Canada acquired over 46,000 and 40,000 linear-km of deep and shallow seismic, respectively (Fig. 1). Industry seismic acquisition was largely concentrated in the central part of Hudson Bay and resulted in generally low quality seismic lines due to acquisition problems. Based on the seismic information, the industry drilled 5 offshore wells between 1969 and 1985 (Fig. 1), four of them targeting fault plays. For all these offshore wells, local stratigraphic nomenclatures were defined largely based on well cuttings. No commercial discoveries were recorded from the onshore and offshore wells, although traces of oil and gas and bitumen-impregnated rocks were reported from all offshore wells. The lack of significant success resulted in the abandonment of the basin by the industry and the pessimistic conclusions that the succession was largely devoid of potential source rocks and too thin to be thermally mature (Tillement, 1975). Industry data (paper copies of seismic lines, digital well logs, cuttings and few cores) were submitted to the National Energy Board for future use.

There has been no industry seismic reflection acquisition in the Foxe Basin. Nonetheless, one exploration well (Rowley M-04; 533 m) was drilled in 1971 on Rowley Island (Fig. 1) near the northern reach of the Foxe Basin (Trettin, 1975). No commercial accumulations were encountered although oil stains and bitumen were reported (Fustic et al., 2018).

As with the Foxe Basin, no industry seismic data was acquired in Hudson Strait, although 9000 linear-km of GSC high resolution seismic data (1985-1993) is available (MacLean et al., 1986; MacLean, 2001; Pinet et al., 2013b; Pinet et al., in press). One short, dry exploration well (Premium Homestead Akpatok L-26; 335 m) was drilled in 1969 on Akpatok Island (Workum et al., 1976) (Fig. 1).

In the late stage of the first phase of hydrocarbon exploration, a resource evaluation concluded that the Hudson Bay Basin has a limited resource potential of 818 MMbl (130 x 10^6 m^3) of recoverable oil and 3.2 Tcf (90 x 10^9 m^3) of recoverable gas (Procter et al., 1984). However, the geological data at that time was considered inadequate for a confident resource estimate. Two recent qualitative appraisals of the hydrocarbon potential of the Hudson Bay, Moose River and Foxe basins have been published (Hanna et al., 2018, 2019; Fustic et al., 2018) and conclude that the Paleozoic succession in the Hudson Bay Basin has locally experienced oil window conditions with generation and expulsion of hydrocarbons (Hanna et al., 2018) however, no hydrocarbon potential was suggested for the Moose River Basin (Hanna et al., 2019). The qualitative evaluation of the hydrocarbon potential for the Foxe Basin concluded on a very low potential (Fustic et al., 2018).

REGIONAL GEOLOGICAL CONTEXT

Hudson Bay Basin

The Hudson Bay Basin is a large Phanerozoic sedimentary basin in Canada, only second to the Western Canada Sedimentary Basin. It covers 970,000 km^2 (about 10% of the area of Canada), of which 2/3 is covered by water. The Hudson Bay Basin sedimentary succession also encompasses onshore parts of northeastern Manitoba and northern Ontario (the Hudson Lowland) and Nunavut (Figure 1). The Hudson Bay Basin is separated from the Moose River Basin by the Cape Henrietta-Maria Arch whereas the Bell Arch separates Hudson Bay Basin from Foxe Basin; the two arches are broad positive basement-involved structural elements for which the formation mechanism(s) is poorly understood. The Hudson Bay Basin, the Moose River Basin and the onshore areas (Hudson Lowland and onshore Nunavut) also known as the Hudson Platform (*sensu* Sanford and Norris, 1973) unconformably overlies and is encircled by Precambrian rocks. The basement includes metamorphic and igneous rocks of the Paleoproterozoic Trans-Hudson Orogen, a tectonic suture zone marking the contact between the Superior and Churchill cratons that underlie the southern and northern parts of the Hudson Bay Basin, respectively (Eaton and Darbyshire, 2010).

The Hudson Bay Basin surface area significantly exceeds that of other intracratonic basins (e.g., Michigan, Illinois, Williston basins), but the Hudson Bay basin is characterized by the thinnest and the shortest-time preserved sedimentary succession of the intracratonic basins of North America (Quinlan, 1987; Pinet et al., 2013a). This has been attributed to the stiff lithospheric root and high elastic thickness beneath the basin, which may have existed during its formation (Kaminski and Jaupart, 2000). Compared to other intracratonic basins of North America, Hudson Bay Basin also differs by its location farther from plate-boundaries at the time of basin initiation and by the presence of a fault system that attests of significant lithospheric stretching during basin formation.

Several recent geophysical studies focus on the deep lithospheric architecture of the region (see Bastow et al., 2014 for a review). Among the main results, Darbyshire et al. (2013) and Porritt et al. (2015) conclude that the lithosphere is the thickest (estimates between 240-280 km and ~350 km, respectively) beneath central Hudson Bay and the thinnest (~ 190 km) beneath the Hudson Strait. Moreover, ambient noise tomography (Pawlak and Eaton, 2010) reveals a low-velocity anomaly in the Hudson Bay, coincident with the zone of normal faulting imaged in seismic, reinforcing the idea that crustal stretching was the primary mechanism of basin formation.

The Hudson Bay Basin Paleozoic succession consists of Upper Ordovician to Upper Devonian rocks with a known maximum preserved thickness of about 2500 m in Hudson Bay (Pinet et al., 2013a). Thin upper Paleozoic (Bashkirian, Pennsylvanian) strata were reported from Nahrwal O-58 by Tillement et al. (1976), but upper Paleozoic strata have not been identified in any other studies and so their presence remains uncertain. Strata of Mesozoic to recently documented freshwater sediments of probably mid-Cenozoic (Miocene) age (Galloway et al., 2012) locally occur at the top of the succession.

Based on outcrop and offshore wells data, the sedimentary succession is strongly dominated by various shallow marine limestone and dolostone lithofacies, a thick succession of subtidal evaporites of Early Devonian age is locally present in the offshore domain whereas onshore, Upper Ordovician and Middle Devonian evaporites are interbedded with the carbonate lithofacies. Clastic strata are present as a thin veneer of sandstone at the base of the Paleozoic succession and as some organic-rich and lean calcareous shales of Late Ordovician and Late Devonian age. The new biostratigraphic data coupled with well logs and seismic date allows to identify 4 significant unconformities within the succession 1) Late Ordovician-early Silurian; 2) late early Silurian-late Early Devonian; 3) Middle-early Late Devonian; 4) Late Devonian-Mesozoic/Cenozoic) (Hu et al., 2011; Pinet et al., 2013a) (Fig. 2).

The Hudson Bay sedimentary succession is the erosional remnant of a more extensive cratonic cover that probably had episodic connection during the Paleozoic (Sanford, 1987) and possibly Mesozoic (White et al., 2000) with platformal areas to the north (Arctic Platform) and south (St. Lawrence Platform, Michigan and Williston basins).

Moose River Basin

The Moose River Basin is the southernmost tectono-stratigraphic element of the large intracratonic system centered on the Hudson Bay and about one third of it is under the waters of James Bay (Fig. 1). The Moose River Basin is separated from the Hudson Bay Basin by a tectonic high of the Precambrian basement, the Cape Henrietta-Maria Arch and, given the relative dissimilitude in the basal stratigraphic succession (Armstrong et al., 2018), the two basins were imperfectly to not connected at the onset of sedimentation. The map distribution of geological units in the Moose River Basin is characterized by a concentric pattern with units younging towards the erosional margin of the basin to the southeast (Nicolas and Armstrong, 2017).

The Moose River Basin Paleozoic succession, as for the Hudson Bay Basin, consists of Upper Ordovician to Upper Devonian rocks with a maximum preserved thickness of about 1000 m (Johnson et al., 1992). Thin veneer of Mesozoic clastics and lignite unconformably overlies the Paleozoic succession (Sanford and Grant, 1998).

The Upper Ordovician carbonate succession presents some stratigraphic differences with the adjacent succession of the Hudson Bay Basin as the Churchill River Group is seemingly absent in the Moose River Basin with the Red Head Rapids Formation overlying the Bad Cache Rapids Group (Hahn et al., 2016; Armstrong et al., 2018). Detailed facies analyses of the Ordovician succession suggest that some significant differences in lithologies exit and can be explained either by lateral facies zonation or different subsidence rates (Turner and Armstrong, 2015); conodont biostratigraphy and carbon isotope chemostratigraphy are critical tools to stratigraphically tie both areas (McCracken et al., 2013; Hahn et al., 2017).

The Devonian succession in the Moose River Basin has a composite thickness of about 600 m and consists of, in ascending order, the upper member of the Kenogami River Formation and the Sextant, Stooping River, Kwataboahegan, Moose River, Murray Island, Williams Island and Long Rapids formations (Sanford et al., 1968; Larmagnat and Lavoie, in prep.). The Sextant and Long Rapids formations are mainly siliciclastic rocks, whereas the other units are predominantly marine carbonate rocks with evaporites in the Moose River Formation and shale in the Williams Island Formation. Regional compilations and detailed investigations of Devonian stratigraphy in the Moose River Basin include Sanford et al. (1968), Sanford and Norris (1973), Norris (1986, 1993), Telford (1988) and Bezys and Risk (1990).

Foxe Basin

In the Foxe Basin, the sedimentary succession occurs in the Foxe-Baffin structural depression (Trettin, 1975). The Paleozoic succession is either in normal fault contact against Archean basement or unconformably overlies the latter. The succession is Middle-Upper (?) Cambrian to lower Silurian in age. Absolute sediment thickness is equivocal; in the northern part of Baffin Island, up to 350 m of interpreted Cambrian clastic sediments and dolostone have been mapped (Tretttin, 1975). The thickness of that Cambrian interval decreases towards the south to a 64 m succession in the Rowley M-04 well. Cambrian sediments are unknown on Melville Peninsula and south Baffin Island. On the other hand, the Lower to Upper Ordovician succession has a rather constant, but incomplete thickness of 150 m on Melville Peninsula and southern Baffin Island (Zhang and Lavoie, 2013; Zhang, 2013) to a maximum thickness of 310 m in the Rowley M-04 well where the contact with Silurian strata is identified (Trettin, 1975). Up to 140 m of Lower Silurian strata have been described in the Rowley well (Trettin, 1975). Based on high resolution seismic data in the adjacent Hudson and Evans straits (Fig. 1), a thicker succession (1.5 km; Pinet et al., 2013b; Lavoie et al., in press), including a poorly constrained post-Silurian age rock package, is assumed in the Foxe Channel, at the contact between the Hudson Bay Basin and Foxe Basin.

Two unconformities are either postulated on limited biostratigraphic control (Cambrian-Ordovician) or defined on decent fossil data (Middle Ordovician). The lower Paleozoic succession of the Foxe Basin is the erosional remnant of a more extensive cratonic cover that had connections with platformal areas to the north (Arctic Platform), south (Hudson Bay Basin and Strait) (Lavoie et al., in press) and to the east, the latter confirm by the identification of carbonate xenoliths with Ordovician conodonts in Mesozoic kimberlites on Hall Peninsula (Zhang and Pell, 2014; Fig. 1)

Hudson Strait Basin

The Hudson Strait Basin is located in an E-W elongated zone including from west to east, the Hudson Strait and Ungava Bay which form a major composite topographic feature connecting the Hudson Bay and Foxe basins with the Labrador Sea (Fig. 1). This zone corresponds to a ~700 km long body of water with maximal depths reaching 900 m in its eastern part. Fault-controlled basins are expressed in the free-air gravity field as several disconnected lows, up to ~80 mGal in amplitude (Pinet et al., 2013b).

Two distinct rock assemblages are recognized based on GSC high resolution seismic (Sanford and Grant, 1998; MacLean, 2001; Pinet et al., 2013b; in press). The lower assemblage corresponds to the Paleozoic units, which are the erosional remnants of a more extensive cratonic cover that had connections with platformal areas to the north (Foxe Basin) and south (Hudson Bay Basin). Onshore, this Paleozoic succession surrounding the Hudson Strait and forming Akpatok Island in Ungava Bay (Fig. 1) is nearly flat-lying, even if the contact between the Paleozoic succession and the basement is often marked by steeply-dipping faults with minor (< 10 m) offsets (Heywood and Sanford, 1976). The upper assemblage is restricted to fault-controlled offshore sub-basins having a half-graben geometry. These sub-basins record an extensional (or transtensional) tectonic event of poorly constrained age not documented to the south and possibly linked with the initial stages of extension in the future Labrador Sea (Pinet et al., 2013b). Deformed zones characterized by open folds attest of a subsequent episode of shortening (Pinet et al., in press). The fault array is presently the locus of moderate intraplate earthquakes with thrust focal mechanisms (Steffen et al., 2012).

The thickness of the sedimentary package is highly variable from less of 600 m on the immediately surrounding islands (Pinet et al., in press), to approximately 2.6 km in the offshore fault-controlled easternmost sub-basin (Pinet et al., 2013b). One short (335 m) well located on Aktapok Island was terminated in Precambrian basement and intercepted a Lower to Upper Ordovician succession (Workum et al., 1976).

NEW TECTONIC MODEL

As with most intracratonic basins, the mechanisms responsible for the formation of the Hudson Bay Basin are yet not fully understood. The mechanisms invoked to explain the formation of intracratonic basins include thermal relaxation following slow lithospheric stretching (Armitage and Allen, 2010), thermal relaxation related to magmatic upwelling (Klein and Hsui, 1987), lithospheric flexure due to tectonic loading (Quinlan and Beaumont, 1984) or folding (Cloetingh and Burov, 2010), subsidence due to negative dynamic topography (Burgess et al., 1997; Heine et al., 2008) and densification of the lithosphere due to phase changes (Fowler and Nisbet, 1985).

Based on vintage industry seismic data, the Hudson Bay Basin appears to have a relatively simple geometry, characterized by a lower sedimentary package cut by high-angle faults, overlain by a saucer-shape, essentially underformed upper sedimentary package (Pinet et al,, 2013a). This geometry contrasts with the ones documented in other intracratonic basins of North America where no major structure has been documented.

In the Hudson Bay Basin, normal (or transtensional) faults imaged on seismic reflection profiles provide clear evidence that lithospheric stretching from very minor horizontal extension on normal (or transtensional) faults is the primary mechanism controlling the long-term accommodation of the basin (Pinet et al., 2013a). However, backstripping, based on paleontological data and well correlations, reveals an irregular subsidence history marked by several periods of non deposition and/or erosion (Pinet et al., 2013a). Moreover, significant changes in the depocenter location during the Paleozoic and variable exhumation values required by maturation and apatite fission-track data indicate that other mechanisms influenced the subsidence/exhumation history of the basin. In particular, the influence of far-field events and dynamic topography transmitted in the continental interior (creating long-wavelength tilting and unconformities) is a potential scenario (Pinet et al., 2013a; Pinet, 2016).

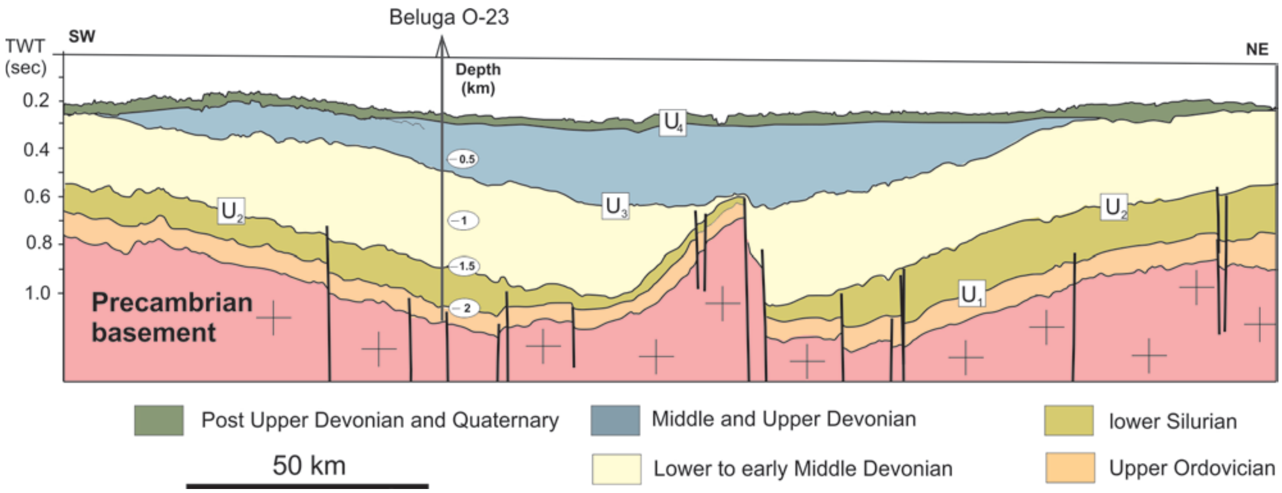

Figure 2: Interpretation of seismic reflection profile S6348. The profile is in central Hudson Bay, across the Beluga O-23 well location (Figure 1) and depicts major lithostratigraphic intervals and unconformities (U1 to U4). Vertical axis on the left is two-way travel time and a depth scale is shown adjacent to the Beluga O-23 well line. Modified from Pinet et al. (2013a).

It has been proposed that at the North American craton scale, some evidence of the Paleozoic tectonic events that shaped the Appalachian orogen on its eastern side might be recorded by the NNW-trending central high in Hudson Bay, a normal-fault array extending for a minimum length of 500 km (Pinet et al., 2013a, Pinet, 2016). It is suggested that tectonic stresses applied to the continental margin during the Silurian–earliest Devonian Salinian orogeny (Tremblay and Pinet, 2016) were transmitted over a distance of over 1400 km in the continental interior, where they induced the normal-fault reactivation of older structural discontinuities. The shutdown of tectonic activity along the Hudson Bay central high during the latest Early Devonian to earliest Middle

Devonian is interpreted as resulting from a change in the direction of plate convergence during the Acadian orogeny (Pinet, 2016).

NEW STRATIGRAPHIC FRAMEWORK

At the start of the GEM program, the Hudson Bay, Foxe and Hudson Strait basins were characterized by a plethora of local onshore (Manitoba, Ontario, Nunavut) stratigraphic nomenclatures with the offshore domain having a well to well-based specific stratigraphic framework. Prior to the GEM-1 program, there has been some efforts at various scales, to uniformize all these frameworks but nonetheless these served as cornerstones for our work (Sanford and Grant, 1998; Zhang and Barnes, 2007; Hamblin, 2008).

New data

Onshore hydrocarbon exploration wells (1 in Ontario, 3 in Manitoba and 2 in Nunavut) were relogged and sampled. Close to 100 stratigraphic, mineral and geotechnical wells (some of them are shown on Fig. 1) were also studied and sampled at various scales. The stratigraphic succession recorded by logs of the 5 offshore wells was also re-evaluated (Hu et al., 2011).

From these and extensive field and laboratory stratigraphic surveys and research from 2008 to 2017 in **Ontario** (Armstrong and Lavoie, 2010; Armstrong, 2011, 2012, 2014, 2015; Galloway et al., 2012; Armstrong et al, 2013; Ratcliffe and Armstrong, 2013; McCracken et al., 2013; Hahn and Armstrong, 2013; Chow and Armstrong, 2015; Turner and Armstrong, 2015; Galloway, 2015, 2016; Gouwy, 2016; Braun et al., 2016; Hahn et al., 2016, 2017; McCracken, 2016, 2017a, b, c, d, e), **Manitoba** (Nicolas and Lavoie, 2009, 2010, 2012; Nicolas, 2011, 2016; Ramdoyal et al., 2012, Nicolas et al., 2014; Nicolas and Young, 2014; McCracken, 2015; Nicolas and Clayton, 2015; Eggie et al., 2015; Nicolas and Armstrong, 2017) and **Nunavut** (Zhang, 2008; 2011a, b, 2012, 2013a, b, 2014, 2018; Zhang and Lavoie, 2013; Zhang and Mate, 2014; McCracken, 2017f), a total of 3800 samples for stable isotopes chemostratigraphy ($\delta^{13}C_{VPDB}$ and $\delta^{18}O_{VPDB}$) in carbonates, 480 samples for conodonts, 330 samples for chitinozoans were analyzed and used, with detailed lithostratigraphic observations, to propose a new stratigraphic framework for the Ordovician – Silurian (Fig. 3; Armstrong et al., 2018). The stratigraphic synthesis of the Devonian rock package is currently in progress and will be released in 2020 (Lavoie and Larmagnat, in prep.) A significant number of B.Sc. (11) and M.Sc. (1) theses were also produced and listed under the sedimentology section.

In order to complement the stratigraphic work, a magnetotelluric survey was completed over the Kaskattama Highland in 2017, at the junction between Ontario and Manitoba (Craven et al., 2017). The detailed sub-surface information is pending, but it will eventually helps to better constrain the lateral extension of stratigraphic units, in particular, the Upper Ordovician shaly lime mudstone succession that seems to disappear to the west near the border with Manitoba.

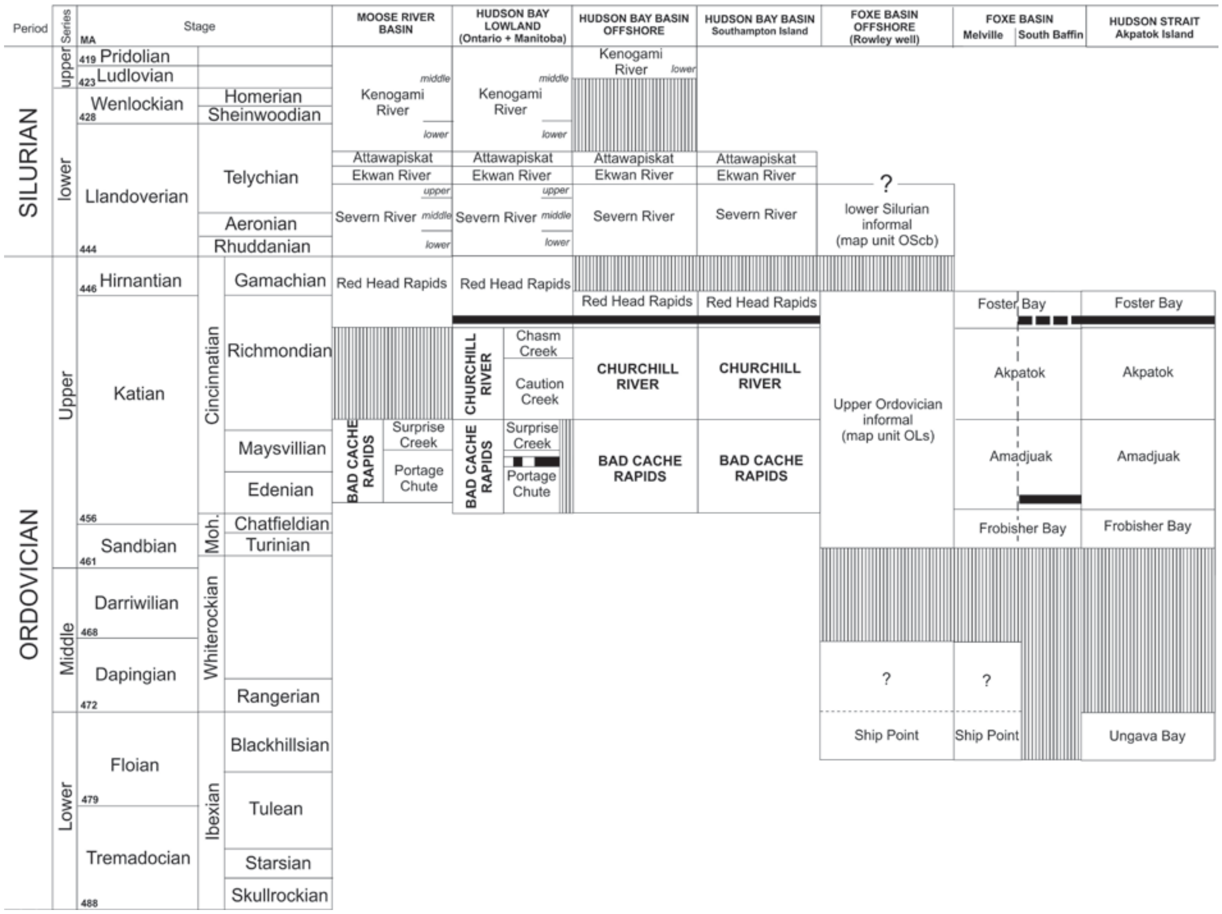

Figure 3: Correlation of the Ordovician – Silurian stratigraphy for main studied areas. Vertical hatched patterns is for non-deposition or erosion. Solid black boxes indicate stratigraphic position of organic black limy mudstone previously all assigned to the Boas River Formation. Horizontal dotted black line indicate stratigraphic position of some Upper Ordovician organic-rich units for which the presence or extension is equivocal. Foxe Basin offshore is from Trettin (1975). Stratigraphic assignment: **GROUP**, Formation, *member.* Moh. = Mohawkian. Modified from Armstrong et al. (2018). Time scale from Gradstein (2004).

The details of these correlations are in Armstrong et al (2018), which contains details on local to regional redefinition of the stratigraphy. The report also offers an extensive presentation of all provincial, territorial and federal stratigraphic interim reports as well as university undergraduate theses that contributed to various aspects of this specific research. Recent re-evaluation of the chitinozoan fauna in the Ship Point Formation suggests that the unit could equivocally extends into the Middle Ordovician (Fig. 3). Of all the stratigraphic refinements reached through the GEM program, the most important is our new understanding of the Upper Ordovician black limy shales.

The Ordovician black limy shales – the problem with the original Boas River Formation

The term “Boas River” was introduced by Heywood and Sanford (1976) for an Upper Ordovician organic matter rich, carbonate mudstone unit on Southampton Island. A 2–2.5 m thick succession is found along the Boas River and the unit was assumed to be present between the Bad Cache

Rapids and Churchill River groups. This informal unit was later given formation status and its presence reported on Baffin Island, Akpatok Island and in northern Ontario (Sanford and Grant, 1990, 1998, 2000). Nelson and Johnson (1966) reported the presence of thin and platy petroliferous interbeds within the lower carbonate beds of the Red Head Rapids Formation along Sixteen Mile Brook on Southampton Island.

Based on extensive field observations and conodont determinations, Zhang (2008) reassigned all organic rich intervals on Southampton Island to the Richmondian Red Head Rapids Formation (Fig. 3). The Richmondian organic-rich beds are proposed to be present on Akpatok Island in the Foster Bay Formation (Zhang, 2018; Zhang and Riva, 2018). However, organic rich limy mudstones on southern Baffin Island assigned to the Boas River Formation by Sanford and Grant (2000) are characterized by Edenian conodonts (McCracken 2000) and included in the lower part of the Amadjuak Formation by Zhang (2012) (Fig. 3). The presence of two black organic-rich limy mudstone intervals (a lower Edenian and an upper Richmondian) in the Foxe Basin and Hudson Bay and Strait areas has recently been confirmed by new graptolite data (Zhang and Riva, 2018).

In northern Ontario, a 10 m interval of shaly lime mudstone assigned to the Boas River Formation (Sanford and Grant, 1990) was described in 2 mineral exploration cores (Inco-Winisk wells) with conodont fauna suggestive of a dominant middle Maysvillian age (McCracken, 1990). The Boas River Formation was assumed to be, like on Southampton Island (Heywood and Sanford 1976), present between the Bad Cache Rapids and the Churchill River groups. A recent re-examination of the encasing lithologies suggests that the black lime mudstone interval is instead near the stratigraphic top of the Portage Chute Formation (Fig. 3; Hahn et al. 2016). A 4 m outcrop section of fissile organic-rich lime mudstone was described on the Asheweig River (Armstrong, 2011). The outcrop appears lithologically similar to the upper few metres of the Boas River Formation in the core intervals. However, conodonts reported from the Asheweig River exposure suggest that it is Richmondian and should be assigned to the Red Head Rapids Formation (Zhang 2011). Thus there appear to be two organic-rich shaly lime mudstones in northern Ontario, one of mid-Maysvillian age and another of late Richmondian in age (Fig. 3).

Zhang and Riva (2018) proposed to designate all the Upper Ordovician organic-rich carbonate mudstones in the sedimentary succession within and around the Hudson Bay Basin as specific informal facies, either within the Richmondian interval (Red Head Rapids and Foster Bay formations) or within the Edenian (Amadjuak Formation) or in middle Maysvillian (Portage Chute Formation) (Fig. 3).

SEDIMENTOLOGY

Most of our activities on the nature of the sedimentary succession focussed on the establishment of a regional coherent stratigraphic framework. Nonetheless, some specific undergraduate and graduate projects targeted the sedimentological and paleoenvironmental interpretations of some specific units.

Upper Ordovician reefs on Southampton Island

Small and large carbonate buildups of Late Ordovician (Katian or Richmondian) age are found on Southampton Island at the northern edge of the Hudson Bay Basin (Heywood and Sanford 1976; Zhang 2008, 2010). Similar mounds were mapped on Melville Peninsula in the onshore outcrop belt of the Foxe Basin (Trettin, 1975; Zhang, 2013). On Southampton Island, these mounds belong to the Red Head Rapids Formation; they are partly dolomitized and are up to 400 m in length, 250 m in width with minimum exposed vertical relief of 15 m (Fig. 4). In outcrops they consist of a massive core with thinner stratiform counterparts that show no significant compositional variation. The massive cores were loosely described in the past as micritic, algal, or microbial limestones with calcareous metazoans of subsidiary importance (Heywood and Sanford, 1976). The reefs contain large voids and vugs that are locally partly filled with dead oil (Heywood and Sanford, 1976) and bitumen (Lavoie et al., 2018a).

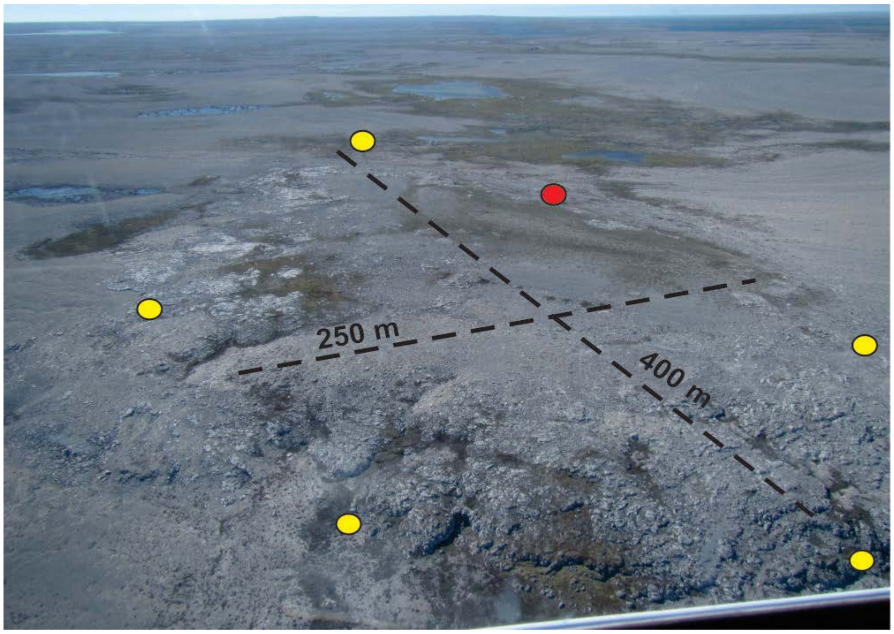

Figure 4: Helicopter view of the studied mound on Southampton Island. The dots represent the base of sections that were measured perpendicularly to the mound axis and reported in Castagner (2016). The red dot locates the section from which a diagenetic study was focused (see further).

Castagner (2016) and Castagner et al. (2016) have presented a detailed description of internal facies architecture of the mound at its best exposed locality on Southampton Island. The Red Head Rapids Formation massive mound is primarily composed of boundstone and cementstone, including various proportions of early calcified sponge tissues, microbial encrusters, synsedimentary cement and small colonial metazoans. The accretionary mechanisms of the Red Head Rapids Formation were mainly the result of frame building by early calcified sponges and small colonial corals and binding by calcimicrobes for the boundstone facies, and of marine cement precipitation for the cementstone facies. The Red Head Rapids Formation mounds have a biotic composition more in common with the sponge-microbial reefs which dominated worldwide in the Early Ordovician compared to metazoan (corals, stromatoporoids, bryozoans) framestone reefs that characterized the Middle and Late Ordovician carbonate ramp settings at the margin of Laurentia (Webby, 2002).

The studied Red Head Rapids Formation mound developed in a restricted, hypersaline shallow water environment that formed during the Late Ordovician glacio-eustatic sea-level fall that ended in the development of the Ordovician-Silurian unconformity within the Hudson Bay Basin (Lavoie et al., 2013). This regression resulted in conditions of restricted basin circulation with the formation of a saline stratified ocean water column, as evidenced by the presence of coeval precipitation in Late Ordovician time of a locally thick succession of subtidal evaporites in the subsurface of the central Hudson Bay Basin (Hu et al. 2011). On Southampton Island, anoxic and hypersaline conditions are recorded in the presence of supratidal evaporites (possibly glauberite; Heywood and Sanford, 1976), the nature of conodont biofacies (Zhang and Hefter, 2009) as well as in the source rock organic geochemistry and biomarkers (Macauley et al., 1990; Zhang, 2011b). The hypersaline environment was unfavorable for open marine stenohaline taxa (James and Jones 2015), thus explaining the low diversity present in the Red Head Rapids Formation reef. On the other hand, sponges and microbes were ideally adapted to survive under such extreme environmental conditions (Scholle and Ulmer-Scholle, 2003).

Upper Ordovician black shaly lime mudstone

Upper Ordovician shaly lime mudstone was encountered as a circa 10 m-thick interval in the INCO–Winisk drill holes and as a 4 m outcrop exposure along the Asheweig River (Armstrong, 2011). This interval is commonly described as an organic-rich black lime mudstone (Armstrong, 2011; St. Jean, 2012), although the organic content varies through the formation and occurs in enriched horizons that contain over 50% dark brown, discontinuous, wispy laminations (Hahn and Armstrong, 2013). These horizons are generally several millimetres to a centimetre thick and are interstratified with laminae that contain between 5 and 30% of dark brown, discontinuous, wispy laminations. Ostracod shells are present in all microfacies of the interval, but are more abundant in the laminae with a slightly lower organic content. Ostracods commonly occur as disarticulated fragments that lie parallel to bedding. Laminae that contain dominantly articulated ostracods are present sporadically. Graded beds have been described locally (St. Jean, 2012). This interval was interpreted to record deep-water deposition as distal tempestites in an outer shelf or ramp setting with restricted anoxic to dysoxic waters (St. Jean, 2012).

Ordovician-Silurian carbonates in Manitoba

As part of the Phases 1 and 2 of the Hudson Bay project, a significant number of B.Sc. theses on facies analyses of selected units in the succession were carried out at the Department of Geological Sciences at the University of Manitoba (Wheadon, 2011; Wong, 2011; Duncan, 2012; Lapenskie, 2012; Ramdoyal, 2012; Pietrus, 2013; Eggie et al., 2014; Demski et al., 2015). These studies were initially focused on the paleoenvironmental setting at or near the Ordovician-Silurian boundary and were combined with carbon isotope chemostratigraphy to help locating the Ordovician-Silurian boundary. These studies were later extended to the Lower Silurian carbonates with a research diagenetic component (porosity evolution in carbonates, oil inclusions in cements).

Ordovician-Devonian carbonates in Ontario

In the second phase of the GEM-Hudson Bay project, grants to the Laurentian University led to important joint research between the university and the Ontario Geological Survey. Significant research results on Upper Ordovician litho- and chemostratigraphy (Turner and Armstrong, 2015) and on the establishment of a sequence stratigraphic framework for the Ordovician (Hahn et al., 2016) were instrumental for the regional stratigraphic synthesis (Armstrong et al., 2018). Moreover, B.Sc. theses at the University of Ottawa (St. Jean, 2012; Bibby 2013) and University of Manitoba (Braun, 2016) provided facies analyses on both carbonate and shale units.

PETROLEUM SYSTEMS

The two phases of the GEM program were designed to result in increased resource exploration activities and successes through diverse geoscientific research and models made available to the resource industry. In the case of the Hudson Bay projects on the Phanerozoic succession, a better understanding of the hydrocarbon potential and potential hydrocarbon systems of this large sedimentary basin was the ultimate goal. The previous and only exploration phase (1969-1985) ended up with pessimistic conclusions about regional extent / limited thickness of hydrocarbon source rocks and the burial / thermal history of the succession. Little to no work and analyses on potential reservoir units were carried out before the GEM program.

The dissemination of new petroleum systems data and models generated significant industry interest for the Hudson Bay Basin with Canadian and International oil and gas exploration companies inquiring about acquiring exploration licenses in the Hudson Bay. However, the offshore domain is currently under a federal exploration moratorium so no exploration licenses have been issued.

Source rocks

Three distinct Upper Ordovician limy shale intervals with source rock potential are identified in the Hudson Bay Basin and surrounding areas (Fig. 3). These source rocks vary slightly in age; the youngest interval (Richmondian) occur within cyclic peritidal carbonate-evaporite succession whereas the older ones (Edenian and Maysvillian) are associated with subtidal marine carbonates. The Edenian (lower Upper Ordovician) source rock occurs in the Amadjuak Formation in southern Baffin Island, the Maysvillian (middle Upper Ordovician) source rock is found in the Portage Chute Formation in northern Ontario (Fig. 3). Late Richmondian (upper Upper Ordovician) limy shales are found in the Red Head Rapids Formation in Southampton Island and in northern Ontario as well as in the Foster Bay Formation on Akpatok Island (Macauley, 1986, 1987; Macauley et al, 1990; Zhang, 2008, 2012, 2018; Zhang and Riva, 2018; Armstrong et al., 2018). Interestingly, Upper Ordovician black shale xenoliths in Mesozoic-aged kimberlite on Hall Peninsula allow to extend the source rock (Amadjuak Formation?) to the east in Paleozoic times. The revision of the stratigraphic nomenclature of the limy shales is discussed in Zhang and Riva (2018) and in Armstrong et al. (2018) and is summarized above. Some thin organic-rich shales intervals in the lower Silurian Severn River Formation in Manitoba and in the offshore Middle Devonian Stooping Island and Williams Island formations have been documented through the course of this research project (Lavoie et al., 2013; Zhang and Hu, 2013). Finally, hypothetical presence of Carboniferous source rocks will be briefly discussed.

The presence of Upper Ordovician potential hydrocarbon source rocks in the northern part of the Hudson Bay basin was known for decades (Macauley, 1981, 1984, 1986, 1987; Macauley et al, 1990). These shales are outcropping on Southampton, Baffin and Akpatok islands and were characterized by Rock-Eval 2 analyses over these years; the results indicated that shales in particular on Southampton Island have very high hydrocarbon yields and given their immature thermal rank, were designated as oil shales (Macauley, 1984). An Upper Ordovician (Maysvillian) organic matter rich unit was found in mineral exploration cores in northern Ontario (INCO-Winisk; McCracken, 1990); an outcrop of younger (Richmondian) limy shale unit was also mapped out along the Asheweig River (Armstrong, 2011; St-Jean, 2012).

All the above Ordovician occurrences were intensively studied for their organic geochemistry through Rock-Eval 6 and organic petrography and in the phase 2 of the Hudson Bay GEM project, the immature shales were subjected to programmed closed hydrous pyrolysis.

Ordovician source rocks – Rock-Eval

Onshore occurrence - These source rocks have been described from the Ordovician succession on southern Baffin Island (Amadjuak Formation) with divergent thickness estimates of 2 m (Zhang, 2012) and 12 to 14 m (Macauley, 1987), on Southampton Island (Red Head Rapids Formation) with a combined thickness of 2 to 3 m over a 20 m interval and on Akpatok Island (Foster Bay Formation) with a thickness estimated to be around 10 to 12 m (Macauley, 1987) (Figs. 1 and 3). Zhang (2008, 2012) revisited the localities of Macauley (1986, 1987) and a newly identified section (Cape Donovan, Southampton Island, Fig. 1), and collected new samples for Rock- Eval 6 analyses. All the Rock-Eval analyses of samples from Southampton Island were made before the start of GEM-1 and are presented here for comparison purposes. Measured total organic content (TOC) values range from 0.31 to 34.1% (average 10.1%), Hydrogen Index (HI) values from 97 to 795 mg HC/g TOC (average 557) and Oxygen Index (OI) values from 8 to 106 mg CO_2/g TOC (average 37). Hydrocarbon yields range from 0.32 to 230.80 kg HC/t. The detailed results are presented in Lavoie et al. (2013). The new Rock- Eval 6 analyses indicate the Upper Ordovician shales in the northern area of the Hudson Bay Basin have high total organic carbon (TOC) and hydrocarbon yields potential. The shales on Akpatok Island (Foster Bay Formation) have slightly lower TOC values compared to the two other intervals which have comparable TOC and HI values even if they are of different ages.

Upper Ordovician source rock has been identified through the re-logging of two mineral exploration wells drilled in Northern Ontario (Fig. 1; INCO-Winisk #49212 and #49204; Armstrong and Lavoie, 2010) as well as in a newly discovered outcrop (Asheweig River, Fig. 1; Armstrong, 2011; St-Jean, 2012). In the two INCO-Winisk wells, the thickness of bituminous lime mudstone is 6 and 9.5 m, whereas an incomplete (base missing) stratigraphic section of 4 m of lime mudstone has been measured along Asheweig River. Samples from the INCO-Winisk wells and Asheweig River yield TOC values from 0.41% to 12.84% (average 7%), hydrogen index (HI) values from 180 to 634 mg HC/g TOC (average 549) and oxygen index (OI) values from 12 to 120 mg CO_2/g TOC (average 30). Hydrocarbon yields range from 0.75 to 74.8 kg HC/t

(Lavoie et al., 2013). Even if the INCO-Winisk wells and Asheweig River shales have different ages, they exhibit comparable Rock-Eval values.

Offshore wells – To re-evaluate the source potential in offshore Hudson Bay Basin, an extensive sampling of well cuttings of Ordovician-Silurian intervals was carried out in the Narwhal South O-58, Polar Bear C-11 and Beluga O-23 wells (Zhang and Dewing, 2008), this and subsequent resampling of hand-picked black cuttings (see below) were before the start of the Hudson Bay GEM project. Rock-Eval 6 results of these samples failed to identify any intervals with significant source rock potential in the Upper Ordovician succession. Following these initial results, Zhang (2008) re-examined the cuttings for an interval in the Polar Bear C-11 well that contains three zones of anomalously high radioactivity, as indicated by well gamma ray logs (Hu et al., 2011). Analyses of handpicked dark-coloured sample fragments from these zones indicated good hydrocarbon source rock potential (measured TOC values of 0.29 to 5.73%, HI values of 109 to 538 mg HC/g TOC, and hydrocarbon yields of 26.98 to 38.40 kg HC/t). The dark-coloured samples had significantly higher TOC (2 to 4 fold increase) than unsorted cutting samples; Zhang (2008) correlated three zones in the Narwhal South O-58, Polar Bear C-11 and Beluga O-23 wells to three oil shale intervals in the Red Head Rapids Formation on Southampton. Subsequent to these interpretations, a detailed petrophysical analysis of well log data indicated thin, organic-rich shale beds are present in the Upper Ordovician strata in all offshore wells, with the thickest cumulative section of 14 m in the Beluga O-23 well (Hu and Dietrich, 2012).

Ordovician source rocks – Type of organic matter and organic geochemistry

Petrographic observations for Baffin and Southampton islands oil shales are reported in Macauley et al. (1990), whereas the new petrographic observations for occurrences in northern Ontario are reported in Lavoie et al. (2013). For the source rock intervals, the organic matter consists of marine flora and fauna (acritarchs, algae, chitinozoans, conodonts and graptolites) and a dominant component of matrix bituminite with minor liptinite. The petrographic observations indicate a dominant marine Type II organic matter. Small amount of Type I *Gloeocapsomorpha prisca* have been identified for all localities (Reyes et al., 2016a, 2018).

Limited gas chromatography (GC) data indicate that organic matter types in the Ordovician Red Head Rapids and Amadjuak formations in the northern Hudson Bay Basin (Macauley et al., 1990; Zhang, 2011b) are unlike the well-documented Ordovician source rocks in southern Ontario (Collingwood Formation) and Saskatchewan (kukersites of the Yeoman Formation), but more similar to Silurian source rocks in the Michigan Basin. Compared to the Ordovician source rocks in southern Canada, the Hudson Bay Basin source rocks have higher abundances of C_{19} + *n*-alkanes and acyclic isoprenoids, and lower pristane/phytane ratios. These geochemical signatures indicate that Hudson Bay Basin source rocks were deposited in photic zone of hypersaline and highly reducing environments in which anaerobic bacteria reworked the organic matter. Hypersaline-reducing environments are also indicated by the presence of 1-alkyl-2, 3, 6-

trimethylbenzenes (which form in the presence of sulphur bacteria) in the aromatic fractions of source rocks in the Red Head Rapids Formation. The Ordovician source rocks in Hudson Bay Basin also have low C32/C34 ratios and distributions of 17α(H) - 21β(H)-hopanes that are very similar to the Silurian hypersaline source rocks in the Michigan Basin (Summons and Powell, 1987).

GC extracts from Edenian limy shales in the Inco-Winisk cores in northern Ontario indicate that the Upper Ordovician source rock has higher pristane to phytane (Pr/Ph) ratios than those of the Ordovician source rocks in the northern part of the Hudson Bay (average ratios of 1.1 and 0.62, respectively; Zhang, 2011b; Lavoie et al., 2013), but still lower than those of Upper Ordovician source rocks in southern Ontario (0.97 to 1.72; Obermajer et al., 1999). These Pr/Ph values suggest reducing conditions, but not as severe as those indicated for the Red Head Rapids shales.

The geochemical results indicate that Richmondian-aged shale (Red Head Rapids Formation) in northern Hudson Bay Basin were deposited in reducing and hypersaline settings; the cyclic carbonate-evaporite lithologic succession is consistent with the organic geochemistry information. The geochemical analyses of the Edenian-aged shale (Portage Chute Formation) in the INCO-Winisk cores of northern Ontario suggest less reducing and no hypersaline conditions, in agreement with the normal subtidal environment of the encasing sediments.

The organic-rich limy shale within the succession in northern Hudson Bay (Red Head Rapids Formation) is interpreted to be dominated by Type II-S (sulphur-rich) kerogen. The presence of Type II-S organic matter (OM) is significant because this type of OM will generate oil at lower maturation temperature compared to Type II or Type I OM (Hunt and Hennet, 1992), an assertion confirmed by the hydrous pyrolysis of these rocks (see below and Reyes et al., 2016). Even if the geochemical indicators from the Edenian-aged shales do not point unequivocally to Type II-S, the pyrolysis experiment on shales of the Amadjuak Formation also resulted in the rapid (low temperature) generation of hydrocarbons (see below and Reyes et al., 2016).

Ordovician source rocks – closed hydrous pyrolysis

To fully understand the hydrocarbon potential, generation scenario and geochemical properties of the Upper Ordovician source rocks, an artificial maturation study was carried out using closed system pyrolysis. Four immature organic-rich Upper Ordovician shale samples (Red Head Rapids from Northern Ontario and Southampton Island, Amadjuak, and Foster Bay formations from Hudson Bay Basin / Strait and adjacent Foxe Basin) were artificially matured using modified hydrous pyrolysis at temperatures between 310 and 350^{o}C for 72 hours (Reyes et al., 2016a). Conventional hydrous pyrolysis was also used using the Parr reactor at 310^{o}C, 330^{o}C and 350^{o}C for 3 days. Additionally, immature Devonian shale sample from the Western Canada Sedimentary Basin (WCSB) was also subjected to closed system anhydrous pyrolysis (no water added) using the Parr reactor at 330^{o}C for 3 days. This was done to evaluate the influence of water during thermal maturation and hydrocarbon generation (Jiang et al., 2018).

Organic petrography and geochemical analysis (Rock-Eval analysis, biomarker, whole oil analysis) of solvent extracts were performed on the samples before and after the completion of each stage of hydrous pyrolysis. The data and information collected from the experiments were analyzed and applied to our current understanding of the burial history and hydrocarbon generation potential of these formations and the Hudson Bay and Foxe basins as a whole. The complete methodology, results and data interpretations were presented in open file report (Reyes et al., 2016a), conference abstracts (Reyes et al., 2016b, c; 2017a, b) and peer reviewed publications (Jiang et al., 2018, Reyes et al., 2018).

Key Findings

- All organic geochemical parametres (HI, OI, S1, S2, S2:S3, TOC, PI, PC and T_{max}) and the amount of expelled hydrocarbons indicate that these organic-rich rocks generate significant amounts of oil with increasing thermal maturation. The increased S1 and PI, partnered with decreased in S2 and TOC, indicates hydrocarbon generation through thermal degradation and transformation of organic matter (kerogen) into petroleum product (oil and gas) with increasing pyrolysis temperature.
- The samples reached hydrocarbon generation window after 310^{o}C pyrolysis temperature (first step) with corresponding average vitrinite-like particles reflectance ($R_{o\text{-vit-like}}$) of 0.70% and Rock-Eval T_{max} of 433-436^{o}C. As the pyrolysis temperature increases, the measured T_{max} also increases reaching as high as 455^{o}C after 350^{o}C pyrolysis (last step), which is at the threshold between oil and gas windows. The results also indicate that the high amount of extractable organic matter (EOM) sorbed and retained in the rock matrix may cause possible T_{max} suppression (Fig. 5). Additional studies are currently underway to pursue on this finding (Reyes et al., 2019).
- The reflectance of graptolite, chitinozoan, bitumen and vitrinite-like macerals increase with increasing pyrolysis temperature. The conversion equations ($R_{o\text{-vit-like}} = 0.77R_{chi}$ and $R_{o\text{-vit-like}} = 0.79R_{grap}$) derived from the artificially matured Ordovician samples for converting zooclast R_o to vitrinite-like maceral R_o are fairly comparable to the equations derived from geologically matured Paleozoic rocks (Bertrand, 1990; Petersen et al., 2013). The lack of thermal decomposition of zooclast macerals suggested that they have little contribution to hydrocarbon generation (Reyes et al., 2018).
- Qualitative petrographic analysis shows that bright fluorescing oil and reddish orange fluorescing solid bitumen were generated after 310^{o}C pyrolysis. Peak bitumen and oil generation and expulsion were reached at pyrolysis temperatures between 310-330^{o}C (T_{max} = 435-441^{o}C) and 340-350^{o}C (T_{max} = 440-455^{o}C), respectively. The quantity of the oil expelled during the experiment varies between samples depending on the pyrolysis temperature, quality and quantity of TOC and the initial thermal maturity of the samples (Reyes et al., 2016a). It is important to note that isotropic solid bitumen can still be observed in-situ and in newly created pore spaces even after most of the generated oil has been expelled. The newly created pore spaces are the results of the dissolution and recrystallization of carbonate minerals and thermal decomposition of organic matter (Reyes et al., 2018).

- One of the major findings of this study is the high concentration of low molecular weight (MW) cyclopentanones, 2-cyclopenten-1-ones and phenols in hydrous pyrolysates of the Ordovician shale core samples after hydrous pyrolysis at 310 °C for 3 days. This is an important findings because there have been no other previous reports on the occurrence of cyclopentanones and 2-cyclopenten-1-ones in geological samples or related pyrolysates, especially at high relative concentrations. The results indicate that water has played a key role in the formation of these low MW oxygen-containing compounds.

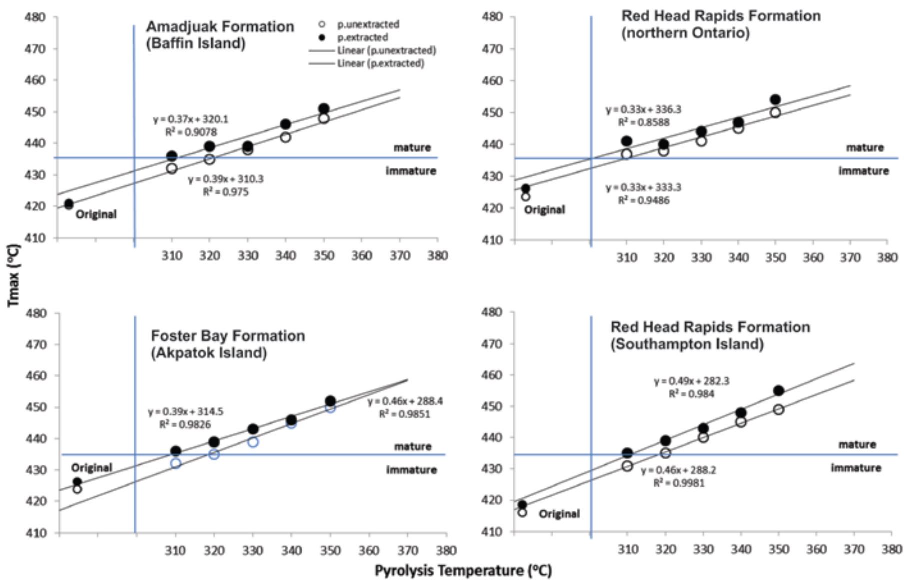

Figure 5. Rock-Eval measured T_{max} after hydrous pyrolysis, before (white circles) and after (black circles) solvent extraction as a function of pyrolysis temperature. These graphs show increase in the thermal maturity after each stage of hydrous pyrolysis. The post extraction T_{max} data clearly show possible but variable T_{max} suppression due to high volume of free hydrocarbon and soluble organic (solid bitumen-asphaltenes). Modified from Reyes et al. (2016a).

Silurian source rocks – Rock-Eval

Systematic sampling (80 samples) for Rock-Eval analyses was done in 8 Manitoba mineral and hydrocarbon exploration cores. 11 samples of the Severn River Formation in three wells have fair to good hydrocarbon potential with TOC over 1% and hydrocarbon yields ranging between 3.98 kg HC/t to 29.33 kg HC/t. On the basis of Rock-Eval indices on these samples, a dominant Type II organic matter is suggested, no other geochemical analyses are available. The presence of potential Type II source rock in the Lower Silurian Severn River Formation had not been reported before (Lavoie et al., 2013).

Devonian source rocks – Rock-Eval

Based on pronounced gamma ray kicks in the Middle Devonian section of the Beluga O-23 well, 28 samples of handpicked cuttings of black mudstone fragments were collected for Rock-Eval analyses. Detailed evaluation of the data is presented in Zhang and Hu (2013) who identified, based on petrophysical analyses, 5 narrow distinct zones of higher organic content. Stratigraphically, this interval covers from the lower part of the Givetian Williams Island Formation to the upper part of the Emsian Stooping River Formation. This interval consists of interbedded shales (black and grey) with significant zones of evaporites and limestones.

For the selected samples from this interval, TOC values range between 1.6 and 17.64% (average of 9.07%), with HI values between 142 and 495 (average of 390) and OI values from 26 to 135 (average of 46). The Moose River Formation has the highest average TOC (average 9.17%). All the samples have high to very high yields (S1 + S2) that range from 5.52 to 86.67 kg HC/t and all samples would qualify as good to excellent hydrocarbon source rocks. From HI, OI, T_{max} and PI values, the samples are Type II organic matter and are immature (T_{max} < 420°C; PI < 0.1).

Upper Devonian hydrocarbon source rocks in the onshore Moose River Basin have been known for a long time. In this area, the Long Rapids Formation (85 m thick) includes beds of marine, organic-rich black mudstone, which alternate with grey-green mudstones (Bezys and Risk, 1990; Hamblin, 2008). The formation straddles the Frasnian-Famennian boundary (Bezys and Risk, 1990). The Long Rapids Formation has TOC values ranging between 2.42 and 11.21% with HI values between 175 and 519. These samples are excellent potential source rocks with hydrocarbon yields from 5.47 kg HC/t to 59.53 kg HC/t of rock. These mudstones are immature (T_{max}< 424°C).

Carboniferous source rocks (?)

The presence of Carboniferous sediments at the top of the Narwhal South O-58 has been reported by Tillement et al. (1976), however, a re-evaluation of the cutting samples from 344 to 384 m (now assigned to the Upper Devonian Long Rapids Formation; Hu et al., 2011) has led to the identification of mixed Bashkirian (Early Pennsylvanian), Early Cretaceous and Cenozoic (Paleogene) assemblages (Williams and Barss, 1976). The mixing of these elements has been hypothesized to result from caving of Cretaceous and Cenozoic sediments or from contamination of the drilling mud from improperly cleaned mud tank from previous drilling.

Nonetheless, the presence of Carboniferous sediments elsewhere in the Hudson Bay Basin cannot be entirely discarded given the young age (latest Devonian; Famennian) of the uppermost preserved strata and the limited number of data (five wells), especially in areas with a thick sedimentary package present in fault bounded half-graben (see map of Sanford and Grant, 1998). Even more equivocal is the presence of potential hydrocarbon source rock. The Lower Mississippian (Tournaisian) rocks in eastern Canada are hosts to lacustrine oil shale deposits which are source for oil and natural gas sandstone reservoirs (Dietrich et al., 2011). Further to the north, in the Sverdrup Basin, slightly younger Middle to Upper Mississippian (Visean to Serpukhovian) lacustrine to marginal marine black shales of the Emma Fiord Formation are a major potential source rock (Galloway et al., 2018).

Burial history and maturation

One of the primary goal of the GEM Hudson Bay project consisted in a modern evaluation of the maturation and thermal history of Paleozoic strata in the Hudson Bay Basin and their regional variation. This was done through the integration of multiple organic-matter based conventional tools and approaches, including a review of existing information as well as strategic acquisition of new data together with the evaluation of new mineral-based approaches that were not tested before this project.

Organic matter methods – Rock-Eval data

Previous comparisons of Rock-Eval results with other thermal indicators in the global literature have raised the possibility of inaccuracies in some T_{max}-based maturation interpretations, including incorrect evaluation of thermal rank in the case of hydrogen-rich organic matter (T_{max} suppression; Snowdon, 1995; Dewing and Sanei, 2009); inaccurate T_{max} where early generated hydrocarbons are present (Synnott et al., 2018) and erratic S2 and T_{max} values in strata of low organic matter content (Dewing and Sanei, 2009). Samples with S2 > 0.35 mg HC/g rock provide the most reliable T_{max} values (Dewing and Sanei, 2009) and that value was used as threshold for our interpretation of T_{max} data (Lavoie et al., 2013); as such any samples with S2 value lower than 0.35 mg HC/g rock was not included in our thermal evaluation.

Onshore source rocks T_{max} values - T_{max} values of outcrop samples surrounding the Hudson Bay Basin and Strait indicate that they are all immature (T_{max} values lower than 435°C; Lavoie et al., 2013). However, the T_{max} values of samples from the base of onshore exploration well Comault #1 (Manitoba) (Figure 1) indicate that the threshold of oil generation (>435°C) is locally reached for Ordovician strata (Lavoie et al., 2013).

Offshore wells T_{max}-depth trends - Three offshore wells (Beluga O-23, Narwhal South O-58 and Polar Bear C-11; Figure 1) have sufficient T_{max} data for evaluation of maturation-depth trends and interpretation of thermal rank (Lavoie et al., 2013, 2015). The Beluga O-23 well best-fit correlation line for the T_{max} data intersects the 430°C (Type II-S OM) and 435°C (Type II OM) oil window threshold at 1500 m in the lower part of the Devonian Stooping River Formation, and at 2000 m in the Upper Ordovician Red Head Rapids Formation, respectively. For the Narwhal South O-58 well, T_{max} data indicate the top of the oil window occurs at 830 m in the lower Silurian Severn River Formation (for Type II-S OM), and 1220 m in the Upper Ordovician Churchill River Group (for Type II OM; Lavoie et al., 2013, 2015). In the Polar Bear C-11 well, the top of the oil window occurs at 740 m in the lower Silurian Severn River Formation and 1400 m in the Upper Ordovician Churchill River Group for Type II-S and Type II OM, respectively.

The Rock-Eval data suggests that the Upper Ordovician source rocks can locally reach oil window conditions in the deeper geological section of the offshore domain (Lavoie et al., 2015), an interpretation supported by a recent basin modelling project (Hanna et al., 2018).

Organic matter methods – petrography

Onshore source rocks organic matter reflectance - Organic matter $Ro_{vit\text{-}equiv}$ values for Upper Ordovician chitinozoans and graptolites from the onshore INCO-Winisk wells vary from 0.48 to 0.54% (Reyes et al., 2016a, 2018), indicating the strata are immature for Type II-S source rocks. It is important to note that the reflectance values of 0.55 to 0.69% reported in Armstrong and Lavoie (2010), Reyes et al. (2011) and Lavoie et al. (2013) were chitinozoan reflectances (Ro_{chit}) and not converted to vitrinite equivalent. Organic matter $Ro_{vit\text{-}equiv.}$ values from Ordovician oil shale outcrop samples on Southampton Island (Red Head Rapids Formation) vary from 0.48 to 0.55% (Zhang, 2011b; Lavoie et al., 2013), indicating that these source rocks are also immature.

Offshore organic matter reflectance - Petrographic determination of organic matter reflectance has been completed for three wells in the Hudson Bay Basin (Beluga O-23, Polar Bear C-11 and Narwhal South O-58; Figure 1, Bertrand and Malo, 2012). Data originate from various carbonate facies with organic matter (OM) particle and was not restricted to OM-rich shales.

In the Beluga O-23 well, the $Ro_{vit\text{-}equiv.}$ values vary from 0.45 to 0.67% in Devonian samples, 0.65 to 0.69% in Silurian samples and 0.61 to 0.73% in Ordovician samples (Bertrand and Malo, 2012; Lavoie et al., 2015). A best fit regression line indicates the top of the oil window occurs at 1000 m in Devonian strata for Type II-S OM or 2200 m in Ordovician strata for Type II OM. Using the method of Dow (1978) and a surface Ro value of 0.25%, the estimated amount of eroded strata is 2400 m. The Narwhal South O-58 and Polar Bear C-11 have poor $Ro_{vit\text{-}equiv.}$-depth correlation due to either anomalously high Devonian and/or low Ordovician values (Bertrand and Malo, 2012).

The organic matter reflectance values for the Beluga O-23 well support the overall conclusion from Rock-Eval T_{max} data as both data set indicates that the Upper Ordovician source rock entered the oil window.

Mineral-based methods – Apatite Fission Tracks (AFT)

Thermochronology using apatite grains is a tool that provides time / temperature estimates based on a reasonable understanding of the geological history of a sedimentary basin (stratigraphy, unconformities and tectonic scenario). Apatite Fission Tracks analysis (AFT) provides detailed information in the 60 to 120°C thermal range, which is correlative to the upper part of the oil window. The evaluation of the U-Th/He ratios in apatite generates time / temperature constraints in the 50 to 80°C range, and thus provide important information on the cooling history (exhumation) of a sedimentary basin.

During Phase 1 of the project, 7 samples (3 from metamorphic units intercepted at the immediate bottom of exploration holes, 3 from Precambrian outcrops and one from an outcrop of Ordovician basal sandstone on Southampton Island) were analyzed for AFT (Lavoie et al., 2013). Initial AFT ages were reported in Lavoie et al. (2013), with new analyses and interpretations on the same samples later (Pinet et al., 2016). The attempt to use U-Th/He in apatite for higher resolution of the late exhumation history did not yield realistic results (Lavoie et al., 2013) and will not be discussed any further. Seventeen additional samples from open pit and underground mines were analyzed during Phase II of the project to better constrain the burial/exhumation scenarios (Pinet, 2018 and in press). For all these studies, chemical composition of the apatites has been evaluated.

Inverse modeling of AFT data provides an estimate of the maximum temperature experienced during the Paleozoic burial episode and, with much less accuracy, the timing of maximum heating. For the two wells that have both organic matter maturation and AFT data, the measured vitrinite equivalent (Bertrand and Malo, 2012) values are higher than the calculated reflectance using AFT inverse modeling results.

AFT data indicate geographic variations in the timing and degree of Phanerozoic heating episodes suggesting that the Hudson Bay Basin and surrounding Canadian Shield did not react as a single entity during the last 500 Ma. The key findings of the AFT study are as follow:

- Apatite fission-track (AFT) ages for the Precambrian rocks located immediately below the Paleozoic cover (Beluga, Narwhal and Akpatok wells) and for the Ordovician sandstone are younger than the age of the base of the sedimentary cover indicating that fission tracks experienced significant partial annealing and samples were subjected to temperatures higher than 60°C but lower than 120°C during the Phanerozoic, therefore all of them have reached oil window conditions. The track length distributions suggest slow cooling.
- Inverse modelling of the Beluga and Narwhal well samples indicates that the base of the sedimentary succession reached temperature of 62 to 77˚C and 62 to 80˚C, respectively.
- Among all samples, the Akpatok Island sample yields the youngest AFT age (215.1 ± 15.0 Ma) and recorded the highest best fit maximal temperatures (85°C for the base geological model; Pinet et al., 2016). The specificity of the Hudson Strait area thermal history is confirmed by a relatively young age (280.8 ± 37.7) for a Precambrian sample from the Raglan mine in northernmost Quebec, adjacent to the Hudson Strait (Pinet, in press).
- Preliminary interpretation of the sample at the base of the Paleozoic on Southampton Island (Pinet et al., 2016) suggests a maximal burial temperature between 65 and 85˚C with a best fit of 72 ˚C (*see* Fig. 7). Other material from the same island are presently being investigated (McDanell, in progress).
- Archean greywacke samples from a 3.6 km vertical section in the La Ronde Mine, 240 km to the south of the preserved Paleozoic succession in Quebec yield AFT ages ranging from 413 ± 51 Ma near the surface to 148.5 ± 6.3 for the deepest sample. Inverse modeling of the results supports the presence of a Paleozoic cover on top of the Archean units at La Ronde Mine (Fig. 1). The post-maximum burial cooling rate history shows a deceleration at around 260 Ma, this possibly but equivocally suggests the end of erosion of more friable carbonates and the return to the very resistant basement greywackes at the surface (Pinet, 2018).

- AFT analyses from the Canadian Shield surrounding the Hudson Bay show highly variable results suggesting that eastern Manitoba experienced significant Phanerozoic burial whereas no record of a Paleozoic cover is found from samples coming from the Musselwhite Mine, one hundred kilometres south of the actual erosional southern limit of the Hudson Bay Lowland in northern Ontario (Pinet, in press). The Musselwhite Mine is roughly located over the Cape Henrietta – Maria Arch (Fig. 1).

AFT results collected during the GEM projects complement those reported for the southern Canadian Shield (Pinet and Brake, 2018) and will be integrated in an on-going GEM project aiming to collect new low-temperature geochronology data in order to provide new insights in the four dimensions exhumation pattern of the Hudson Bay area and adjacent areas. Preliminary interpretation at the scale of Canada suggests that the increase in temperature due to burial was maximal in east-central Hudson Bay, an area that experienced only limited subsequent exhumation compared to other parts of Canada landmass.

Mineral-based methods – Fluid inclusions

Fluid inclusions (flinc) entrapped in a mineral phase, when pristine, record the temperature, pressure and chemistry of the ambient fluid at the time of precipitation of that mineral phase. Late fractures cutting through depositional facies and / or late cement phases in pore space, are best suited to evaluate some of the late conditions (fluid temperature and chemistry) during the burial or post-burial history of a succession. Our work on Upper Ordovician microbial and cement reefs on Southampton Island (see above) has led to the recognition of early marine aragonite (now calcite) cement and late calcite cement filling secondary (dissolution) pore space (Castagner, 2016: Castagner et al., 2016). The analysis of microthermometric data on fluid inclusions in these cement phases was done to better constraint the diagenetic evolution of this potential hydrocarbon reservoir (see “reservoir section” for details), but also to provide some information about early and late fluid chemistries and temperatures of precipitation, hence providing some information about estimates of minimal burial depths when using the late cements (Lavoie et al., 2018a).

Microthermometry of abundant tiny fluid inclusions in the recrystallized synsedimentary cements are characterized by high homogenization temperatures (T_h between 72.1 and 177.4°C; average of 117.9 ±25°C) (*see* Fig. 7). These high temperature estimates clearly indicate a non-primary marine origin of these assemblages and in combination with the $\delta^{18}O_{VPDB}$ signature of these cements, suggest the presence of high temperature brines ($\delta^{18}O_{VSMOW}$ of +3 to +12‰; *see* Fig. 7) at the time of a recrystallization event when the flinc were possibly entrapped or reset (Lavoie et al., 2018a). The late calcite cement contains fluid inclusions indicative of lower entrapment temperature (T_h between 74.3 and 134.7°C; average of 92.6 ±9.7°C) (*see* Fig. 7) from a cooler fluid having a $\delta^{18}O_{VSMOW}$ signature ranging between +1 and -2‰ (*see* Fig. 7).

Mineral-based methods – Clumped isotopes

Context - The ambiguity concerning the thermal evolution of the Upper Ordovician succession in the Hudson Bay Basin enticed the development of yet another paleothermometric approach, the carbonate clumped isotope systematics, to attempt tackling a part of that evolution. Carbonate clumped isotopes represents a new and growing field of isotopic research with good potential for contributing to basin analysis. Importantly, thermometry using carbonate-clumped isotopes does not require knowing the isotopic signal of parent water to estimate the precipitation temperature. Hence, the approach offers the potential of providing both, the temperature of precipitation and $\delta^{18}O$ signal of parent water. At the start of the GEM-2 program, no Canadian laboratory had the capacity of producing clumped isotope results. For these reasons, through its GEM program and using its Delta-Lab facility for stable isotope geochemistry, the GSC opted for the development of an ultra-purification CO_2 extraction line and the acquisition of an isotope ratio mass spectrometre (IRMS) dedicated to the analysis of carbonate clumped isotopes.

Background - There are several naturally occurring CO_2 molecules differing only by their isotopic composition (isotopologues), between masses 44 and 51 (or 60 and 67 for CO_3 in carbonates) with mass 44 representing, and by far, the most abundant isotopologue ($^{12}C^{16}O^{16}O$) in nature (98.4%). In the rarer molecules containing more than one heavy isotopes (excluding mass 46 with ^{17}O), the isotopologues of mass 47 are the most abundant (0.0046% or 45 ppm), with $^{13}C^{18}O^{16}O$ forming 97% of this mass. Hence, the systematics for carbonate-clumped isotopes rely on measuring the deviation in abundances of the doubly-substituted $^{13}C^{18}O^{16}O$ isotopologue from those expected if the heavy isotopes were randomly distributed. This deviation, Δ_{47} value, is defined as:

$$\Delta_{47} = \left[\frac{R^{47}\text{measured}}{{}^{*}2\text{x}R^{13}\text{x}R^{18}+2\text{x}R^{17}\text{x}R^{18}+R^{13}\text{x}\,(R^{17})^2} - \frac{R^{46}\text{measured}}{{}^{*}2\text{x}R^{18}+2\text{x}R^{13}\text{x}R^{17}+(R^{17})^2} - \frac{R^{45}\text{measured}}{{}^{*}R^{13}+2\text{x}R^{17}} \right] + 1 \quad \text{eq (1)},$$

where $R^{47}_{measured}$ equals the number of mass 47 clumped molecules to the number of mass 44 molecules obtained during an IRMS analysis of a given sample. Based on thermodynamic principles, values of the random ratios as expressed by the dividers in eq. 1 (*) are calculated using bulk stable isotope composition ($\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$) obtained during the same analysis, and expressed in eq. 1 as R^i. The R^i used here represents the ratio of the rare (18, 17 and 13) to the abundant regular stable isotopes (16 and 12, for O and C isotopes respectively) in the pool of all O and C atoms contributing to this given CO_2 sample. In carbonates precipitated at thermodynamic equilibrium, the doubly-substituted isotopologues are predicted to be enriched relative to the random distribution by up to nearly 2‰ at earth-surface temperatures (Wang et al., 2004), with Δ_{47} decreasing with rising temperature (Eiler, 2007).

Temperature and Δ_{47} relation - The preliminary relation between temperature and Δ_{47} values of carbonates precipitated at controlled low temperatures is determined for the Delta-Lab

(Fig. 6). The resulting relationship compares well with the most recent temperature frames corrected for digestion of carbonates at 90°C (Bernasconi et al., 2018; Bonifacie et al., 2017; Kelson et al., 2017). The preliminary framework of the GSC can therefore serve to estimate the apparent precipitation temperature of natural carbonates precipitated at low temperature.

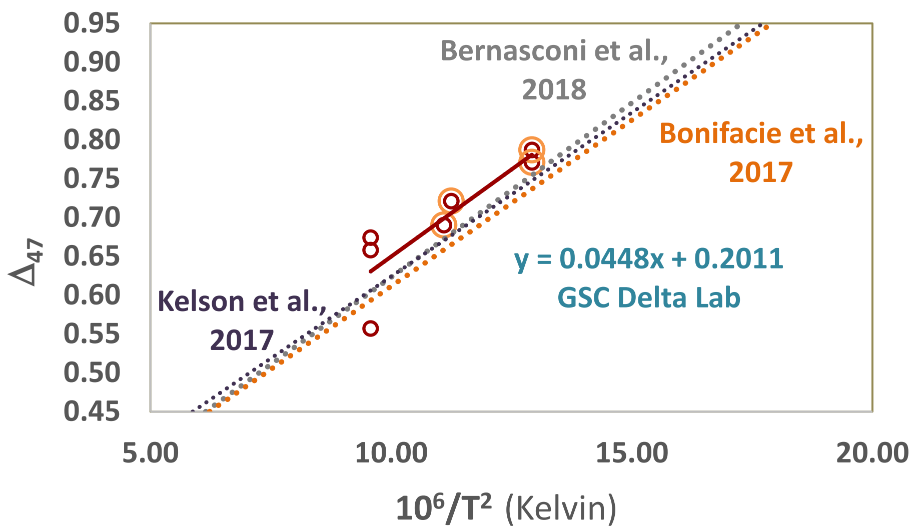

Figure 6. Preliminary temperature frame (June 2018) developed at the GSC Delta-Lab linking temperature to the clumped isotopic results (Δ_{47} in ‰) obtained for carbonates precipitated in the laboratory (solid red line). Green circles show results for carbonates precipitated at 5, 25 and 27°C converted in Kelvin (+273.15); red circles include also the results for 50°C. The slope of the line is the same when including or not the 50°C results. Dotted lines illustrate the most recent temperature frameworks documented in the literature as indicated.

Application to Upper Ordovician carbonates of the Red Head Rapids Formation - This first application of the clumped isotope systematics investigates Upper Ordovician reef carbonates from the Red Head Rapids Formation on Southampton Island discussed in previous sections. The subsampling for this specific isotopic characterization targeted late calcite cement filling pore space, as well as recrystallized carbonate material from the original reef framework dominantly comprised of sponges, calcified cryptomicrobial features, and syn-sedimentary cement (Castagner, 2016). All Δ_{47} results shown here were produced during periods of analytical stability as monitored by using the international ETH carbonates with known Δ_{47} values.

The temperatures derived from the Δ_{47} results range between 26 and 66°C, without marked differences between late cement and replacement phases (Table 1). When combining these temperatures with the calcite $\delta^{18}O_{VPDB}$ results, the calculated parent-water $\delta^{18}O_{VSMOW}$ values range between -5.7 and 4.3‰. Replacements of marine components with the highest apparent temperature (41 to 66°C) show the most elevated water values (up to 3.4‰). Late cements yield the lowest temperature range (26 to 46°C) and the lowest water values (down to -5.7‰; Table 1).

Table 1. Isotopic results for late cements and diagenetic phases replacing the marine components of the reef carbonates. The clumped isotopic results combined with the preliminary temperature frame (equation on Fig. 6) produce the listed apparent temperatures (T).

Phase	**Sample***	**δ^{13}C/‰** VPDB	**δ^{18}O/‰** VPDB	**Δ_{47}/‰** CDES+	**T** °C	**$\delta^{18}O_{H2O}$/‰** VSMOW
Late cement	11-1	2.3	-8.5	0.701	26	-5.7
	37-6	1.4	-8.1	0.676	34	-3.8
	58#	-1.0	-11.4	0.641	46	-5.3
	65A-1	2.4	-7.5	0.701	26	-4.6
Replacement	15-81	2.9	-6.6	0.588	66	3.4
	37-5	2.8	-4.9	0.642	46	1.3
	38-5	2.8	-7.1	0.611	57	1.6
	58A-1	1.6	-7.7	0.654	41	-2.0

* Most samples treated and analyzed in triplicates, # sample replicated 6 times.

+ Carbon dioxide equilibrated scale.

The preliminary data set obtained for the selected samples suggest two possible interpretations: (1) the replacement of original reef material and late pore-filling cements precipitated different thermal conditions from distinct parent waters; or (2) reordering or microscale recrystallization affected the integrity of the initial Δ_{47} values, and generated apparent temperatures departing from the real thermic range swaying during the replacement and cementation periods.

(1) The apparent temperatures based on the Δ_{47} results range between 26 and 46°C, and 41 and 66°C, for late cements and replacements, respectively (Table 1). For comparison, the marine carbonate $\delta^{18}O_{VPDB}$ arrays for Late Ordovician (Katian and Hirnantian) reported in the literature (Shields et al., 2003) help estimate the most probable marine water $\delta^{18}O_{VSMOW}$ values at -3.5 to -0.2‰, and -1.4 to +1.8‰, respectively. If the Δ_{47}-derived temperatures are valid, they suggest parent-water $\delta^{18}O_{VSMOW}$ values for replacements of the early reef components to range between -2.0 to +3.4‰ and show affinities with a marine water origin. The parent-water $\delta^{18}O_{VSMOW}$ values for late cements would be between -5.7 and -3.8‰, suggesting an influence from lighter parent water. In other words, the rough estimates presented here suggest that replacement of early marine phases

took place from warm waters of marine affinities, whereas different proportions of light- and marine-like waters generated the late cements of the Red Head Rapids Formation.

However, the clumped- and Flinc-derived temperature and parent water composition greatly differ. The Δ_{47}-derived $\delta^{18}O_{VSMOW}$ of parent waters for late cements are lower than those obtained using Flinc results (Fig. 7), but partly overlap with the Flinc-derived $\delta^{18}O_{VSMOW}$ for marine replacement phases (Fig. 7). The Δ_{47}-derived temperature ranges (26-46°C, 41-66°C) also strikingly differ from the ones obtained through the Flinc study (Fig. 7) of the late cement (74-134°C; average 93 ±10°C, n=26) and replacement phases (72 to 177°C; average 118 ±25°C, n=66), respectively. One replacement sample analyzed for both clumped and Flinc techniques yields a Δ_{47}-derived T of 66°C, on the low end of the homogenization T (T_h) range (Fig. 7). The discrepancy between the clumped isotopes and Flinc studies may partly derive from the sampling scope of the two techniques; sub-sampling for clumped isotopes determination with the preparation from off-line system used here require relatively large amount of carbonate (30 mg, i.e., 10 mg for each of the triplicates), whereas T_h measurements operate at microscale. The Flinc measurements at fine scale may record discrete expressions of high temperature events that the bulk sampling for clumped isotopes may blur. Another possibility is that the clumped-derived temperature ranges arise from altered Δ_{47} values (see option 2 below).

(2) There are limitations to the applications of clumped isotopes for the sheer purpose of determining precipitation temperatures. Early studies of carbonatites indicated that closed-system (solid-state) re-equilibration of clumped isotopes may occur without alteration of regular stable isotope ratios ($\delta^{13}C_{VPDB}$ and $\delta^{18}O_{VPDB}$) at temperatures above 250°C, if exposure at such temperature persists over long periods (10^8 years; Dennis and Schrag, 2010). For early phases undergoing burial diagenesis, it has been suggested that clumped-isotopes reordering or fine recrystallization of carbonates may operate without textural disruption, at temperatures above 100°C, and that material produced during burial may undergo reordering to lower temperature-Δ_{47} values during retrograde cooling, down to a ‘closing temperature’ (e.g., Henkes et al., 2014). Moreover, a recent case study reports alteration under shallow burial conditions (maximum temperature of 45°C) of the Δ_{47} values in marine carbonates with preserved textures (Winkelstern and Lohmann, 2016). Given the proposed complex thermal history based on the various paleothermometric results for the Red Head Rapids Formation, from marine to progressive burial diagenesis (maximum burial temperature estimated at ~72°C (Pinet et al., 2016), possibly with superimposed hydrothermalism (up to 174°C; Lavoie et al, 2018a), then, cooling down, Δ_{47} alteration may have occurred in the studied diagenetic phases. The replacement phases of early marine reef components and the pore-filling cements may have partly recrystallized at various stages of the thermal evolution, or contain Δ_{47} values locked at closing temperatures during cooling-down.

In closing, further research is required for finalizing the temperature frame for the interpretation of clumped isotopes and for validating this preliminary set of data. Importantly, sub-sampling of carbonates destined to analysis of clumped isotopes must systematically proceed on the exact counterparts of thin sections used for Flinc determination to allow for direct comparison of temperature derived from the two techniques. In addition, the planned research dealing with finer scale analysis of clumped isotopes using an online-automated sample-treatment system requiring less than 2 mg per carbonate digestion will help make a final decision relative to interpretation in terms of options 1 and 2.

Comparison of thermal scenarios between organic matter and mineral-based methods

The uncertainty concerning the thermal maturity and history of offshore Upper Ordovician succession in the Hudson Bay basin was raised after the completion of Hudson Bay GEM-1 project. The uncertainty was based on the varying results from several organic petrographic and geochemical analyses (Lavoie et al., 2013, 2015).

In the offshore domain, the reflectance (R_o) analysis of various organic macerals (Bertrand and Malo, 2012) and apatite fission tract (AFT; Lavoie et al., 2013; Pinet et al., 2016) analysis suggested that the Upper Ordovician source rocks have entered the oil window, even if the two data set differs in the interpreted magnitude of that event. Detailed re-examination of the Rock-Eval T_{max} data for the Upper Ordovician offshore source rocks succession suggested that they are immature with T_{max} values invariably 3 to 5°C lower than the values of the adjacent non-source rock interval, but still with acceptable S2 values over 0.35 mg HC/g rock (Lavoie et al., 2013). Lavoie et al. (2013) attributed the low T_{max} (< 435 °C) values to possible T_{max} suppression because of high total organic carbon (TOC) and hydrogen index (HI) in the source rocks, and thus the latter have reached oil window conditions (Lavoie et al., 2013, 2015). Nonetheless, subsequent analytical results of the oil extracted from the immature onshore shale intervals suggested that the T_{max} suppression has limited effects and that the onshore organic matter rich intervals are immature (Reyes et al., 2016a, 2018). Detailed study of potential T_{max} suppression is ongoing (Reyes et al., 2019 and in progress).

The uncertainty concerning the rank of thermal maturity is well illustrated on Southampton Island where different methods have been used on Upper Ordovician samples (basal sandstone, limy shale and carbonate reef). OM-based data (T_{max}, organic matter reflectance and to some extent hydrous pyrolysis) suggest immature conditions recorded by the shales (<60°C). This conclusion is valid for the extensively studied section at Cape Donovan on the northern coast of Southampton Island (Fig. 1) but also for the organic matter rich interval in the central part of the island (type section of the formerly named ‘Boas River Shale”; Zhang, 2008).

Mineral-based data suggest early oil window conditions (AFT, Fig. 7) and potential early hydrothermal conditions and oil window conditions for late cements (FI, Fig. 7). Apatite Fission tracks results (range 65 to 85°C, best fit 72°C; Pinet et al., 2016) are intermediate between the OM- and Mineral (FI)-based results (Fig. 7). Clumped isotopes results from reef carbonate material (recrystallized components and late cements) do not suggest high temperatures for both type of carbonates (Table 1 and Fig. 7), this either related to a spatially restricted local hydrothermal event or analysis of samples with Δ_{47}-altered values (see above and Lavoie et al., 2018b). Nevertheless the temperature vs $\delta^{18}O_{VSMOW-FLUID}$ plots for marine replacements and late cements do not show significant overlap for both fluid inclusions and clumped isotope data (Fig. 7). For both, the higher temperature is associated with more positive $\delta^{18}O_{VSMOW-FLUID}$ (Fig. 7).

This limited comparison of diverse organic and mineral-based thermal indicators suggests that some methods might be more sensitive to specific events and it is highly desirable to generate data from more than one approach to evaluate the burial / thermal history of a succession.

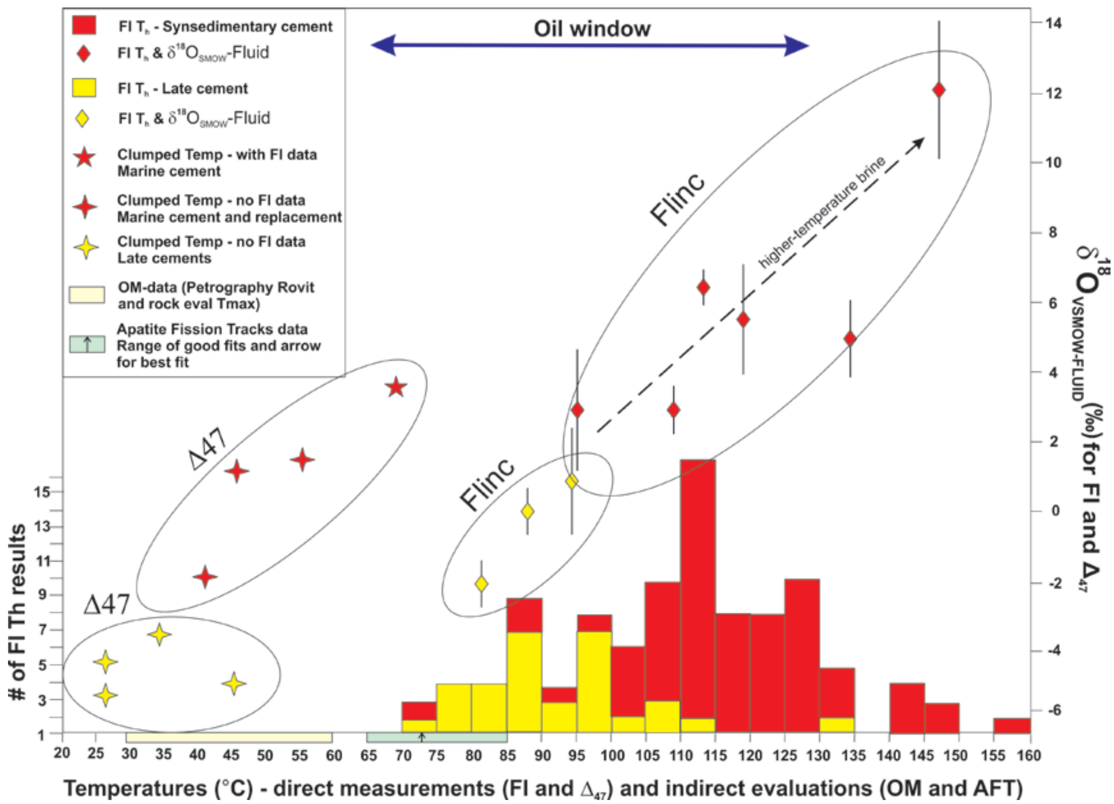

Figure 7. Summary of organic-based and mineral-based thermal indicators from the Ordovician succession on Southampton Island. The lozenges are calcite samples with both FI and $\delta^{18}O_{VPDB}$ data allowing to evaluate the average $\delta^{18}O_{VSMOW}$ of parent fluid, the associated vertical bar is for the range of FI data for a specific sample. The stars are calcite samples with temperature estimates from clumped isotope analyses together with the conventional $\delta^{18}O_{VPDB}$ data form the same calcite allowing to calculate $\delta^{18}O_{VSMOW}$ of parent fluid. Some clumped isotope data, lower than 20°C are outside the range of the plot. Modified from Lavoie et al. (2018b).

Hydrocarbon generation models

GEM models

Lavoie et al. (2015) evaluated the possible magnitude and timing of oil generation in the Hudson Bay Basin; one-dimensional subsidence - thermal maturation models were derived from known or estimated basin stratigraphy, lithology, source rock thickness, organic matter type and burial depths.

Subsidence models were derived from the Beluga O-23 well, the deepest well in the basin and the one with the best biostratigraphic control. Two burial scenarios were modelled, based on differing interpretations of the magnitude of post-Devonian erosion. Model 1 includes a 1500 m thick eroded succession, using initial estimates from Rock-Eval data (Dietrich et al., 2009). The age of the eroded section is interpreted to be Late Devonian. Minor post-Devonian sedimentation in the Hudson Bay Basin is not considered significant for the burial/thermal history. In Model 2 the thickness of the eroded succession is increased to 2400 m, in agreement with organic matter reflectance data (Lavoie et al., 2013). The two models approximate the minimum and maximum amounts of eroded (missing) sections, based on available maturation data.

The model stratigraphy includes an Upper Ordovician hydrocarbon source rock section, consisting of 14 m of organic-rich shale beds (10% TOC), distributed over a 65 m thick stratigraphic interval. Hydrocarbon-generation models were based on Type II-S organic matter, as interpreted for Ordovician source rocks in the Hudson Bay Basin and regular Type II organic matter. As noted above, the presence of a significant Type II-S kerogen is seen as a favorable element for hydrocarbon prospectivity in the deeper part of the basin as this type of organic material is prone to generate oil at lower burial temperature compared to normal marine Type II and lacustrine Type I kerogens.

The maturation history models indicate Ordovician source rocks entered the oil window in the Late Devonian (Lavoie et al., 2015). The hydrocarbon generation models indicate fair oil expulsion from Type II-S source rocks for the Model 1 depth scenario (130-142 mg/g-TOC, 38-40 % transformation) and good oil expulsion for the Model 2 depth scenario (180-190 mg/g-TOC, 48-50 % transformation). In contrast, the models indicate only minimal oil expulsion for Type II source rocks, for both depth scenarios. Most of the oil expulsion occurred during the Late Devonian, providing a favourable timing relationship for potential charging of Upper Ordovician to Middle Devonian reservoirs in the basin.

Recent non-GEM hydrocarbon generation model

As part of a qualitative hydrocarbon resource evaluation of the Hudson Bay Basin, a 3D modeling exercise has been carried out with the similar dataset, with the exception of a slightly thicker source rock interval (25 m) (Hanna et al., 2018). The model evaluated both Type II and Type II-S source rocks under low and high heat flow conditions (42 mW/m^2 and 58 mW/m^2, respectively).

The high heat model is the best-case scenario, testing the combined influences of the most optimistic parametres, where the low heat model represents the minimum requirements to reach the initial stages of generation. For each model, generation occurs in the Late Devonian and only the high heat flow model led to any significant hydrocarbon generation.

In the deepest part of the basin (Beluga O-23 well) the Ordovician and lowest Silurian strata are within the oil window (Ro=0.51-0.69). Kerogen transformation ratio within the Red Head Rapids Formation varies between the wells from 6-33% for Type II-S and from 2-16% for Type II. Favorable oil window maturation domain is limited to the central part of the basin where the eroded Paleozoic sediment package is assumed to be the thickest (Hanna et al., 2018).

Potential reservoirs

The Hudson Bay Basin contains a variety of potential hydrocarbon reservoirs, including platform limestones, reefs, hydrothermal carbonate breccias, and siliciclastics. The sedimentary strata within the basin have many similarities to the successions in the Michigan and Williston basins, where Paleozoic carbonates are significant reservoirs. Reservoir potential is documented from detailed outcrop, core and well log studies, and complemented with interpreted seismic data.

Upper Ordovician reservoirs

Basal sandstone - A thin (3-6 m) basal clastic section was encountered in all wells drilled to basement in Hudson Bay Basin. Porous sandstones within this interval may form thin but widespread reservoirs.

Hydrothermal breccia - Carbonate bedding-discordant breccia interbedded with stratiform units are interpreted to be fault-controlled hydrothermal in origin. These occur within the Upper Ordovician succession; these are known from outcrops (Southampton and Akpatok islands) and core material (Manitoba) (Lavoie et al., 2011). It is important to note that this type of reservoir even if only currently known in the Upper Ordovician succession, could also be present in the Silurian to Devonian carbonates as its formation mechanism is not restricted to a precise time interval.

On Southampton Island, the porous carbonate breccia occurs in the Upper Ordovician Red Head Rapids Formation and consists of a 10 – 15 m thick massive breccia with dolostone and limestone clasts. The highly brecciated zones irregularly alternate with metre-scale areas where the well-bedded facies is preserved. Carbonate fragments can make up to 90% of the breccia and the clasts range from 1 cm to 20 cm in diametre. Fragments are highly angular, unsorted and have a jigsaw-puzzle fabric that suggest little displacement and hydraulic fracturing. The breccia is associated with fractures and faults.

Calcite (+ minor dolomite) cement imperfectly fills the pore space between carbonate clasts resulting in a highly irregular distribution of pore space in the outcrop with values visually estimated to vary between 5 to 25%. Open pore space can be fairly large, up to a few centimetres in diametre; although the effective connectivity between the pores is currently unknown.

Hydrothermal alteration, dissolution and brecciation has also been observed in cores from some shallow stratigraphic holes drilled near the town of Churchill in Manitoba (Lavoie et al., 2011). The carbonate cements associated with that event have similar isotopic composition as those on Southampton Island. Because of the limited exposure in the Hudson Lowlands, a magnetotelluric survey was carried out to evaluate if this geophysical tool could help in mapping out in the subsurface, the presence and extension of porous carbonates encased in tight muddy limestones (Roberts and Craven, 2012; Bancroft et al., 2014); the results were positive and the survey even located a potential structural discontinuity (fault?) present within the domain with the highest calculated porosity (Roberts and Craven, 2012).

A magnetotelluric survey was also carried out in the summer 2018 in order to map out in the sub-surface, the size of the potential hydrothermal dolomite body identified at Cape Donovan (Lavoie et al., 2011). The survey identified a large range of high to low conductivity values defining multiple zones (Craven et al., 2018). The sub-surface geological interpretation is in progress.

Microbial cement reef - The Red Head Rapids Formation contains large reefal structures of microbial-algal origin. In outcrop, these locally occur immediately above the Upper Ordovician source rocks (Zhang, 2010). The reefs contain large vugs that are locally filled with bitumen (Heywood and Sanford, 1976) and have been mapped on Southampton Island and Melville Peninsula. In a recent re-analysis of marine seismic profiles in Hudson Bay, these seismic-scale structures have been interpreted on many profiles (Hanna et al., 2018).

The reef facies on Southampton Island have been studied by Castagner (2016) and Castagner et al. (2016) and consist of microbial and sponge boundstone and cementstone (see above). The reefs are very porous and a diagenetic study has been done in order to constrain the history and timing of porosity evolution with respect to eventual hydrocarbon charge (Lavoie et al., 2018a).

The cementstone is made up of isopachous layers and botryoids of former aragonite, now calcite cement. Secondary dissolution porosity and small fractures are cutting through the bioherm. Secondary pore-fillings consist of drusy calcite cement and subsequent bitumen. The $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values of late cements are invariably more negative than those of the marine cements. The combined $\delta^{18}O_{VPDB}$ and fluid inclusion (see above) data suggest that burial cements precipitated from a fluid having $\delta^{18}O_{VSMOW}$ values between +1 and -2‰, whereas the marine cements data indicate resetting of the fluid inclusions in the presence of a high temperature, $\delta^{18}O_{VSMOW}$ heavy brine (+3 to +12‰). The higher T_h values recorded in the marine cement represent resetting of initial or entrapment of new fluid inclusions from fracture-controlled circulation of basement-derived fluids (Lavoie et al., 2018a). The petrographic and geochemical data suggest that fracture-controlled high temperature brine circulation occurred after the inception of burial and recrystallization of original marine aragonite to calcite, which resulted in the generation of significant secondary porosity that was later filled by lower temperature burial cements and hydrocarbons (Lavoie et al., 2018a).

Lower Silurian reservoirs

The lower Silurian succession contains porous metazoan reefs in the Attawapiskat Formation, which are correlative to the hydrocarbon productive reefs of the Guelph Formation in southern Ontario (Lavoie et al., 2015). The Attawapiskat Formation contains atoll-like metazoan buildups, up to 200 m in diametre, with vertical relief up to 10 m (Suchy and Stearn, 1993). These lower Silurian reefs are found in outcrops on Southampton Island, Manitoba and northern Ontario. They are locally very porous.

The study of porosity in the Attawapiskat Formation of Manitoba allowed the recognition of a complex history represented in a succession of marine, burial and late-stage meteoric events expressed in multi-stage calcite, dolomite, sulphate cements affected by at least 2 episodes of dissolution and alteration of previous cements (Ramdoyal, 2012; Ramdoyal et al., 2013; Eggie et al., 2014). The multiple dissolution, dolomitization and dedolomitization events generated a high amount of secondary porosity that is still open.

Oil shows in the Attawapiskat Formation have been reported from some wells drilled in Manitoba and Ontario (Johnson, 1971). Seismic data indicate that the reefs are common above structural highs in the central part of the Hudson Bay Basin.

Middle Devonian reservoirs

Carbonates of the Middle Devonian Kwataboahegan and Williams Island formations form potential reservoirs. The Kwataboahegan Formation in the Moose River Basin is a bituminous limestone forming massive and thick metazoan buildups (Telford, 1988; Chow and Armstrong, 2015). The Kwataboahegan Formation has been encountered in most of the onshore and offshore wells. The carbonate facies can be very vuggy with locally coarse crystal fills of calcite, celestite and fluorite that might indicate hydrothermal alteration of the carbonates. The formation is rich in bitumen, either as pore/vug filling or as mm- to cm-thick stringers impregnating the dolomitic facies (Chow and Armstrong, 2015). On seismic data, Kwataboahegan reefs are abundant in central Hudson Bay Basin.

The Williams Island Formation is the youngest known carbonate formation in the Paleozoic succession of Hudson Bay Basin. The formation contains porous and brecciated platform limestones, reefs and dolostones (Telford, 1988; Hu et al., 2011). Seismic data indicate that pinnacle and barrier reefs occur in the formation (Lavoie et al., 2013), similar to the reservoirs found in the Middle Devonian Winnipegosis Formation in the Williston Basin (Dietrich and Magnusson, 1988) and Traverse Formation in the Michigan Basin (Swezy et al., 2015).

Reservoir quality

Petrophysical analyses of well log data indicate that many limestone, dolomite, sandstone, and conglomerate intervals in the Hudson Bay Basin have sufficient porosity and permeability to form good quality hydrocarbon reservoirs (Hu and Dietrich, 2012). Since Lavoie et al. (2013, 2015), no new work has been done on that theme.

Porosity-depth profiles for the five Hudson Bay offshore wells provide information on reservoir characteristics and trends between different wells and stratigraphic units (Hu and Dietrich, 2012). An overall trend of decreasing porosity with depth occurs in all wells. Log-derived porosity values are predominantly between 5 to 17% in Devonian carbonates, including the Williams Island, Murray Island, Kwataboahegan and Stooping River formations. Core and log analyses indicate that porosity values vary from 5 to 20% in Devonian carbonate intervals in the Beluga O-23 and Walrus A-71 wells. A wide porosity range (5 to 15%) also occurs in carbonates in the Silurian Severn River Formation in the Netsiq N-01, Polar Bear C-11 and Narwhal South O-58 wells. Ordovician carbonates are characterized by porosity values from 5 to 10% in the Polar Bear C-11, Narwhal South O-58 and Walrus A-71 wells. Sandstones in the basal Ordovician section have highest porosity values (10 to 15%) in the Narwhal South O-58, Beluga O-23 and Netsiq N-01 wells.

Traps and seals

The last evaluation of traps and seals is found in Lavoie et al. (2013, 2015). Well drilling records (mud weights, repeat formation tests, and well kick occurrences) indicate that reservoir strata penetrated in deeper parts of the Hudson Bay Basin are overpressured (Hu and Dietrich, 2012). The highest reservoir pressures occur in the Walrus A-71 and Netsiq N-01 wells (pore pressures up to 70% above hydrostatic pressure). These pressures indicate that effective seals are present. Impermeable strata (potential seals) identified from log data include evaporites, shales and tight limestones. Traps would be largely dominated by stratigraphic-diagenetic types (unconformity, lateral facies transition). Structural traps in the fault hangingwall are also expected.

Hydrocarbon plays

At the conclusion of Phase 1 of the Hudson Bay GEM project, Lavoie et al. (2013, 2015) proposed 5 conceptual conventional hydrocarbon plays in Lower Paleozoic strata in the Hudson Bay Basin. The conventional play types include structural fault blocks, reefs, fault-bounded sags (with associated hydrothermal dolomites), unconformity traps, and salt dissolution structures (Fig. 8). Of these, only the fault block and Devonian-Silurian reefs have been tested by some of the drill holes in the central part of Hudson Bay.

No other plays have been proposed as part of the second phase of the Hudson Bay project although the conceptual reef play has been better defined through the detailed study of the Upper Ordovician reef on Southampton Island.

As part of their independent qualitative evaluation of hydrocarbon potential of the Hudson Bay Basin, Hanna et al. (2018) recognized and defined on reprocessed seismic data, 4 of these plays (the salt dissolution play was not recognized). Moreover, they split some of the plays on the basis of their age, resulting in 3 structural (Ordovician, Silurian and Devonian) and 2 reefs (Ordovician, Silurian/Devonian lumped together) plays.

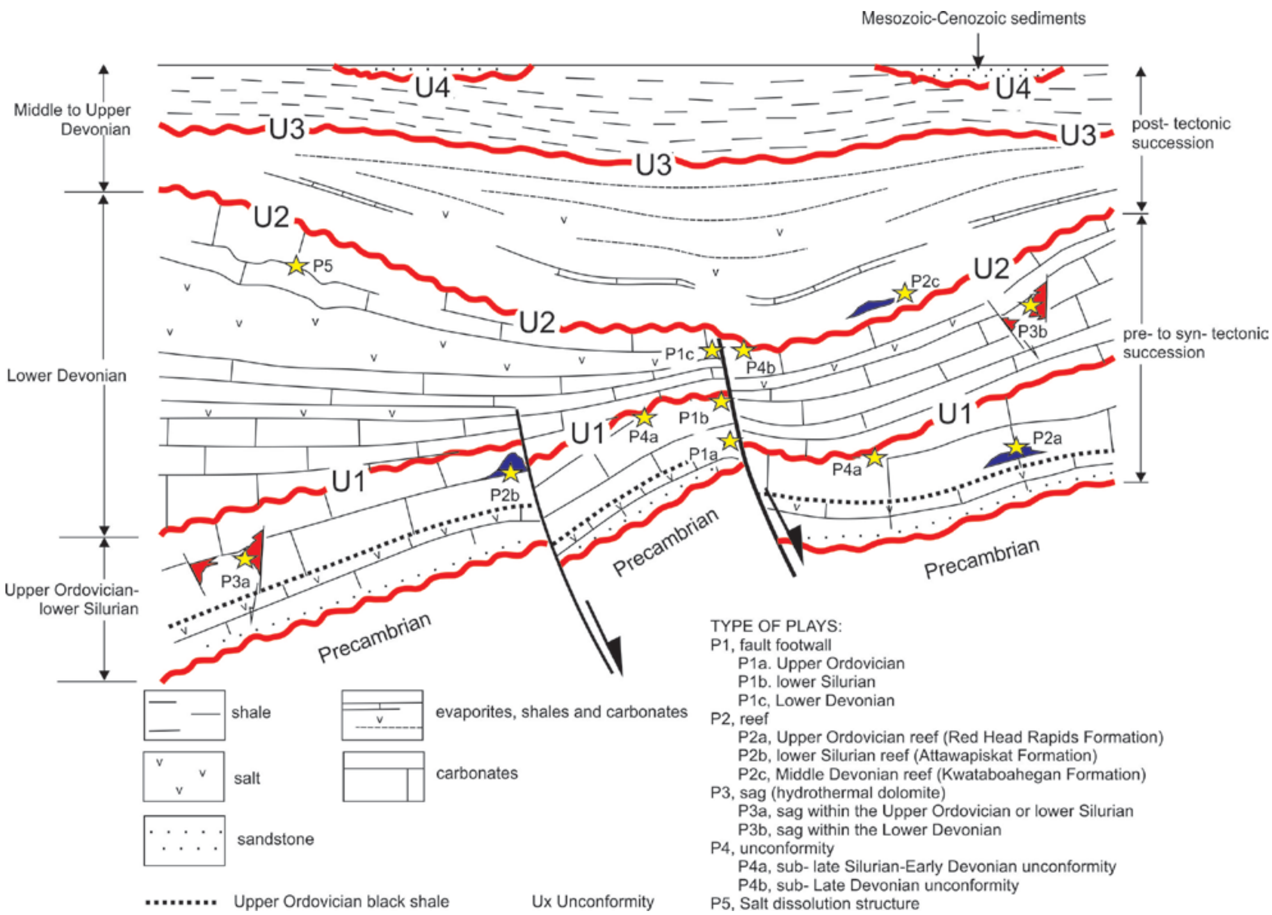

Figure 8. Schematic illustration of conceptual plays in the sedimentary successions of the Hudson Bay Basin. Not to scale. Modified from Lavoie et al. (2015).

Risk considerations

Organic-rich shales have been identified in Upper Ordovician strata in several parts of the Hudson Platform, but the regional extent of these source beds is uncertain moreover, in outcrops these intervals are generally thin. Even if significant research efforts have been devoted to the understanding of thermal maturation, the current data is still ambiguous. Limited geochemistry data indicate the dominant organic matter type in Ordovician source rocks is Type II-S. As shown in the hydrocarbon generation models, this is a critical element for hydrocarbon generation in a basin that was not deeply buried, and even if modeling suggest generation, the efficiency of expulsion has not been proven. More information on source rock geochemistry and kinetic parametres are needed to fully constrain the type of organic matter and hydrocarbon generation potential. The hydrocarbon modelling indicates a favourable timing relationship for oil migration into basin reservoirs and traps. However, the long term preservation of early formed (Early - Late Devonian?) hydrocarbon traps may be problematic, given the interpreted magnitude of post-Devonian uplift and erosion.

Evidence for active hydrocarbon systems

The onshore Hudson Bay Basin has very few outcrops and hydrocarbon seeps are unknown. Bitumen has been described in vugs in Upper Ordovician reefs (Procter et al., 1984; Lavoie et al., 2018a). Live oil was reported in Upper Ordovician reefs (Heywood and Sanford, 1976) and observed in core samples from the Ekwan River and Severn River formations in the Kaskattama #1 well and dead oil in the same formations occurs in the Comeault #1 well, onshore Manitoba (Nicolas and Lavoie, 2012; Eggie et al., 2014). Even if no reservoir drill stem tests were done in any of the wells drilled in Hudson Bay Basin, gas shows, bitumen and oil staining were reported in all wells (Lavoie et al., 2013).

Historical onshore and offshore data document the local presence of hydrocarbons in the Hudson Bay Basin sedimentary succession. Moreover, re-analyses of vintage data and new observations make a stronger case for such presence.

Petrophysical study of well data

The petrophysical study (Hu and Dietrich, 2012; Lavoie et al., 2013) suggests that untested hydrocarbon zones may be present in all offshore wells. Most of the interpreted hydrocarbon zones are thin intervals (< 5 m). These zones are common in Silurian-Devonian carbonates in the Kwataboahegan, Attawapiskat and Severn River formations and in Ordovician basal clastics. The most prospective log-interpreted hydrocarbon zone is a 15 m interval in limestones of Kwataboahegan Formation in the Walrus A-71 well (Lavoie et al., 2015).

Pockmarks and deep-water mound from high resolution seafloor bathymetry

High resolution bathymetric data was acquired by the ArcticNet network while their ship was transiting in our areas of interest. Most of these random linear transects are located in the Hudson Strait, Foxe Channel and Evans Strait. A few circular depressions (average diametre of 100 m and depth of 10 m; Roger et al., 2011) on the seafloor (pockmarks) have been recognized but their origin still need to be confirmed by detailed seafloor mapping. Pockmarks are usually formed by the release of fluids from the subsurface (Judd and Hovland, 2007; Pinet et al., 2008) and may indicate gas, oil or other fluid leakage from subsurface reservoirs.

Adjacent to the southwest peninsula of Baffin Island, a mound-shaped feature rises from the seafloor under about 200 m water depth (Fig. 9). This feature is near the mapped contact between the Paleozoic succession and the Precambrian basement. The elongated mound (1000 m long by 550 m large by 70 m high) shares similarities with the seep-associated, deep-water coral mounds described and seismically-imaged by Jauer and Budkewitsch (2010) on the eastern side of Baffin Island and Labrador coast. The development of deep water mounds without or with corals (dominated by the scleractinian *Lophelia* sp.) has been related to either 1) hydrodynamic sediment accumulations (e.g. mud mounds) from fluid escape and current remobilisation (Masson et al., 2003), 2) initial hydrocarbon seep related chemosynthetic colonisation stage followed by growth fueled by oceanic circulation and nutrient supply mechanisms (De Mol et al., 2002; Sumida et al., 2004) or, 3) cold chemosynthetic processes associated with hydrocarbon seepages (Hovland and Risk, 2003). Deep-water scleractinian corals abound offshore Labrador and east of Baffin Island (Wareham, 2009), and their presence has been recognized in the eastern Hudson Strait (Wareham, 2009), although their presence west of Baffin Island is unknown. The volume of the cone-shaped mound is about 32 km^3, this would put it at the lower end of the size distribution of hydrocarbon vent associated isolated mounds of Cenozoic age in the Browse Basin, offshore Australia (Van Tuyl et al., 2018). It is noteworthy that this seafloor feature is 45 km to the west of a multiyear RADARSAT-2 persistent anomaly identified in the image analyses during the GEM-1 (Decker et al., 2013) and GEM-2 (Beauchemin et al., 2018) programs (Fig. 9). The exact nature of the mound-shaped structure will remain unknown until the acquisition of additional data.

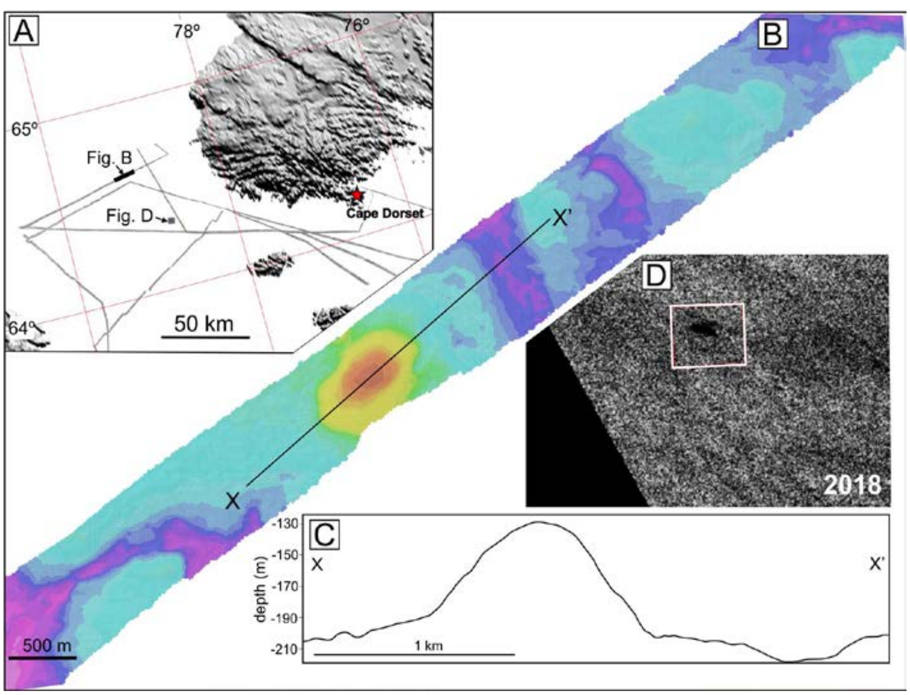

Figure 9. A) High resolution seafloor bathymetry ArcticNet coverage SW of Baffin Island. B) Close-up of part of a

line showing a map view of a mound feature. C) Cross-section (X-X' on B) of the mound shaped feature west of Baffin Island. The feature is 45 km west of multi-years RADARSAT sea surface (slick?) anomaly (D) located on inset A. Inset is modified from Beauchemin et al. (2018).

RADARSAT-2 images of potential oil slicks

During the first phase of the Hudson Bay GEM project, 41 dark targets were identified on RADARSAT-2 images acquired between 2010 and 2012 (Decker et al., 2013). The area covered consisted of Hudson Bay Basin and Foxe Basin and Channel. Some of the dark targets have semi-quantitative characteristics known to be associated with natural oil seeps, including a sharp boundary defining a small-enclosed region (< 1,000 ha), sufficient backscatter contrast (i.e. - 10 dB) between the background sea state and the dark region, and absence of oceanographic phenomena that may result in dark features. Dark targets identified in the same location over multiple years (as expected for natural oil seeps) occur in several areas in Hudson Bay (Decker et al., 2013). However, until sampling of the surface water in these specific areas is done, the true nature of these satellite image anomalies remains equivocal.

As part of the second phase of the Hudson Bay GEM project, new RADARSAT-2 images analyses in the marine environment of Hudson Bay and Foxe Channel were examined and for this phase, Hudson Strait was also covered (Beauchemin et al., 2018). 1278 images were acquired during the falls of 2015, 2016 and 2017. The potential slick candidates were identified using two methods: visual interpretation and semi-automated interpretation. Both methods make use of wind speed and chlorophyll-a data. A total number of 33 oil slicks candidates are reported (see Beauchemin et al., 2018 for location and corresponding images). The ultimate goal of the multi-years project was to look for persistence over time of sea surface expression of seep candidates in order to assist in finding regions with a greater likelihood of oil seep origin. As a result, 7 "groups" of repetitive anomalies within a radius of 20 to 38 km were identified (Beauchemin et al., 2018).

Airborne Side Radar images of potential oil slicks

During the preparation of the high resolution seafloor bathymetry for the second phase of the Hudson Bay GEM project, an informal collaboration agreement with Transport Canada operating the National Aerial Surveillance Program (NASP) was made. The NASP is designed to detect any oil spills from ships in Canadian waters. For the Arctic, the program has one airplane based in Iqaluit (Nunavut) equipped with side-looking airborne radar (SLAR). During their routine surveillance flights, the plane flown over areas where potential oil slicks were identified on RADARSAT-2 images. In summer of 2017, the crew reported the presence of a major natural oil slick of 0.33 km^2 at N62°50.20' and W80°53.58' (Figure 10). Two smaller natural oil slicks were also reported (N62°50.07' and W80°53.77'; N62°50.13' and W80°53.84').

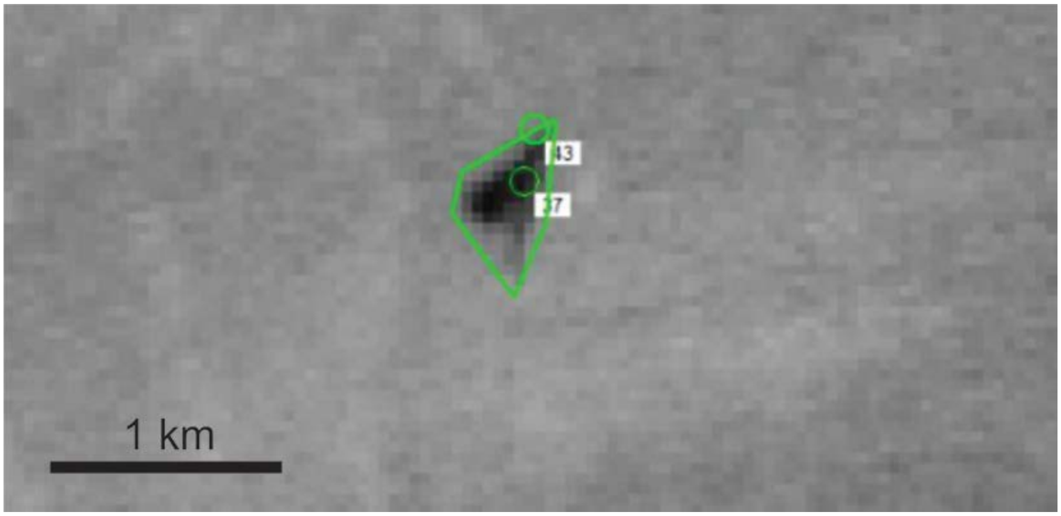

Figure 10. Side Lateral Airborne Radar (SLAR) image of natural oil slicks NW of Mansell Island.

It might be very significant that the natural oil slicks are found very close to one of the pockmark fields identified in Roger et al. (2011) (Figure 11).

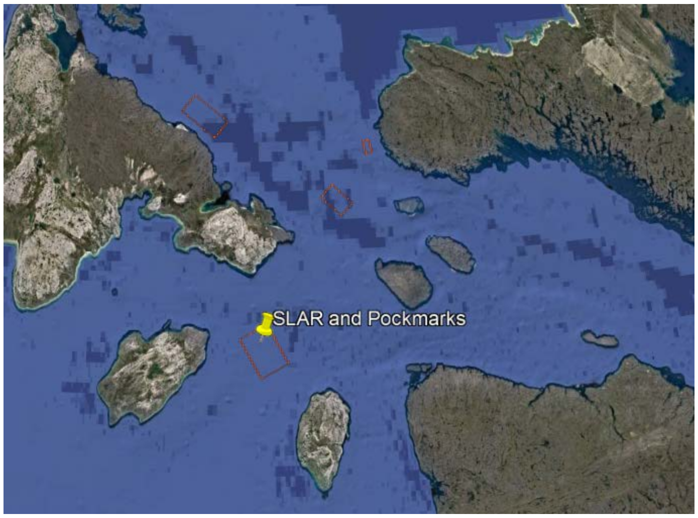

Figure 11. Location of the SLAR slicks (pin) and pockmark field (red box) between Mansell and Coats Island. Map from Google Earth (2019).

On the geological map of the Hudson Bay area (Sanford and Grant, 1998), the two known pockmarks fields are located in areas underlain by Mesozoic (+Cenozoic?) sediments that, at least in the northern part of the Hudson Bay, have accumulated in half-grabens (Pinet et al., 2013b). However, this observation could be co-incidental and more seafloor data are critically needed to evaluate this potential relationship. We currently do not know the thickness (and exact age) of this younger than Devonian (?) succession, but it could have been instrumental for, locally, increasing burial of the Upper Ordovician source rock to reach full mature conditions and generate significantly more hydrocarbons. The thicker sedimentary succession deposited in faulted half-graben could be seen as in important element in defining eventual prospective areas in the Hudson Strait, Foxe Channel and Evans Strait areas (Fig. 1).

CONCLUSIONS

The phases 1 and 2 of the Hudson Bay GEM project have led to significant improvements in our understanding of the geological framework and hydrocarbon potential of the largest intracratonic sedimentary basin in North America.

- A new tectonic evolution scenario is proposed and includes 4 main phases, each of them having potential impact on the hydrocarbon prospectivity of the basin. The first phase is marked by more or less continuous tectonism from the initiation of the Hudson Bay Basin in Late Ordovician to the end of Early Devonian, the initiation of the Foxe Basin to the north is seemingly older (Middle to Late Cambrian; Lavoie et al., in pess). The faulting has been interpreted to result from far field responses to various orogenic phases that took place at great distances (>1000 km) along the various margins of Laurentia. This first phase is critical, among other petroleum system elements, for the distribution (including thickness) of Upper Ordovician source rocks. During the second phase, from the Middle Devonian to at least the Late Devonian, the marine basin evolved as a relatively tectonically quiescent sag. A poorly known third phase may correspond to the deposition of mainly clastic rocks derived from the orogens to the east (Appalachians) and to the north (Franklinian mobile belt). Locally, at least in the north, old and new faults became active during a fourth phase of basin evolution possibly linked with the opening of the Baffin Bay and sediment deposition occurred in disconnected half grabens. The cumulative effect of phases 2 to 4 has resulted in variable burial history, explaining why some parts of the basin are still immature whereas other parts may have reached the oil window.
- Ordovician to Silurian rocks are widespread over this vast area from Nunavut to Manitoba and Ontario for which local stratigraphic nomenclatures were in used. A major achievement of the project is the unified stratigraphic framework based on the re-evaluation of type sections and the study of new field sections coupled with extensive biostratigraphy and chemostratigraphy. A new uniformized geological map is now available for the entire Manitoba – Ontario Hudson Bay Lowland.
- Detailed sedimentological studies are now available for important units: Ordovician reefs and source rocks, lower Silurian reefs and various Ordovician-Silurian carbonate units. The first sequence stratigraphic models are currently being developed integrating the new bio- and chemostratigraphic data with recent depositional facies interpretations.
- New research on the hydrocarbon systems has shed new light on the potential of this intracratonic basin from which no hydrocarbons have ever been produced. The overall conclusion being that the Hudson Bay Basin has, at least locally, a hypothetically higher

oil potential than previously assumed.

- Based on conodont and graptolite data, there are up to three intervals of Upper Ordovician source rocks (Armstrong et al., 2018). The geochemistry of some immature outcrops along the basin actual margins suggests that they are very rich in Type II-S organic matter and artificial thermal maturation generates significant volume of oil at low burial temperature. The source rock intervals are variable in thickness, a characteristic that probably relates to subtle, and still poorly documented variations in the syn-sedimentary morphology of the basin.
- Re-evaluation of vintage thermal data and new acquisition indicates that in the central part of the Hudson Bay, the Upper Ordovician source rocks have reach the oil window. Given the absence of data over most of the basin, the situation elsewhere is unknown.
- The comparison of various organic-based and mineral-based thermal indicators over a small area on Southampton Island suggests, based on discordant values, that great care should be taken in evaluating the thermal history of the basin on a single indicator.
- Conceptual exploration plays have been defined, some of which have been later identified on reprocessed seismic profiles (Hanna et al., 2018). Many of these plays (hydrothermal dolomites, reefs) are major oil reservoirs in the other intracratonic basins in North America.
- Indirect indicators of active petroleum systems have been discovered and preliminary interpreted. Radar imaging (satellite and airborne) suggests the presence of potential natural oil slicks (still to be confirmed) at the sea surface. High resolution seafloor bathymetry data is available for around 1% of the total seafloor. Nonetheless, this limited information lead to the recognition of potential venting structures (pockmarks) on the seafloor at two specific localities.
- The co-occurrence of a pockmark field with an airborne radar potential slick anomaly over an area where a thicker Paleozoic to Mesozoic (+Cenozoic?) succession deposited in a half-graben might provide evidence for a leaking reservoir and support the exploration interest for the thicker succession in these half-grabens.

WHAT'S NEXT

When considering the geological history and petroleum potential of the Hudson Bay and satellite basins, their size should always be kept in mind. The offshore Hudson Bay Basin alone represents around 570,000 km^2 and only five wells have been drilled. In comparison more than 20,000 wells have been finalized in the 300,000 km^2 Michigan intracratonic basin. The low level of past exploration and the generally poor quality of seismic data hamper a quantitative evaluation of the geological variability (including thickness of source rock intervals and organic maturation levels) suggested by new basin evolution models.

The Hudson Bay Basin is largely marine and given the relative paucity of outcrops on its onshore component, it is obvious that any new progress, especially with respect to the definition of its hydrocarbon potential, has to go through marine research.

Significant efforts and time were invested by scientists involved in the project in defining multi-tools and multi-partners marine research projects (seismic reflection, high resolution seafloor bathymetry, oil slick and seafloor sampling), unfortunately for multiple reasons, these projects never materialized. Diverse marine surveys designed to address the 4D evolution and evaluation of the hydrocarbon potential of the largest intracratonic basin in North America would be the obvious “what’s next”.

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