Hudson Bay, Hudson Strait, Moose River, and Foxe basins: synthesis of Geo-mapping for Energy and Minerals program activities from 2008 to 2018

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Lavoie, D., Pinet, N., Zhang, S., Reyes, J., Jiang, C., Ardakani, O.H., Savard, M.M., Dhillon, R.S., Chen, Z., Dietrich, J.R., Hu, K., Craven, J.A., Roberts, B., Duchesne, M.J., Brake, V.I., Huot-Vézina, G., Galloway, J.M., McCracken, A.D., Asselin, E., Decker, V., Beauchemin, M., Nicolas, M.P.B., Armstrong, D.K., and Hahn, K.E., 2022. Hudson Bay, Hudson Strait, Moose River, and Foxe basins: synthesis of Geo-mapping for Energy and Minerals program activities from 2008 to 2018; in *Sedimentary basins of northern Canada: contributions to a 1000 Ma geological journey and insight on resource potential, (ed.) D. Lavoie and K. Dewing; Geological Survey of Canada, Bulletin 609, p. 37–76. https://doi.org/10.4095/326090*

Abstract: As part of its Geo-mapping for Energy and Minerals program, the Geological Survey of Canada included the Hudson Bay Basin in its research portfolio with the goal of generating a modern understanding of its geological framework and a precise knowledge of its hydrocarbon systems.

The Hudson Bay–Foxe Basins GEM-1 project led to the proposal of modern stratigraphic frameworks and produced extensive geochemical data on hydrocarbon source rocks as well as data on diverse burial-thermal indicators. Satellite data were acquired over the entire offshore domain in the search for evidence for active hydrocarbon systems.

For the Hudson–Ungava GEM-2 project, the aim of the research activities was to better understand local and regional factors associated with the burial and exhumation histories as they pertain to regional or local hydrocarbon prospectivity. This research led to a basin-scale stratigraphic framework coupled with detailed analyses of hydrocarbon generation and the appraisal of the best potential reservoir units.

Résumé : Dans le cadre de son programme Géocartographie de l'énergie et des minéraux, la Commission géologique du Canada a inclus le bassin de la baie d'Hudson dans son portefeuille de recherche dans le but d'obtenir une compréhension moderne de son cadre géologique et une connaissance précise de ses systèmes pétroliers.

Le projet des bassins de la baie d'Hudson et de Foxe de GEM-1 a mené à la proposition de cadres stratigraphiques modernes et généré de nombreuses données géochimiques sur les roches mères d'hydrocarbures ainsi que des données sur divers indicateurs thermiques et d'enfouissement. Des données satellitaires ont été acquises sur l'ensemble du domaine extracôtier afin de trouver des preuves de l'existence de systèmes pétroliers actifs.

Dans le cadre du projet Hudson–Ungava de GEM-2, les activités de recherche visaient à mieux comprendre les facteurs locaux et régionaux associés aux histoires d'enfouissement et d'exhumation, en lien avec le potentiel pétrolier régional ou local. Cette recherche a mené à la proposition d'un cadre stratigraphique à l'échelle du bassin, associé à des analyses détaillées de la génération d'hydrocarbures et à une évaluation des unités ayant le meilleur potentiel réservoir.

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INTRODUCTION

The Hudson Bay Basin is the largest intracratonic basin in North America. It is connected to smaller satellite basins, including the Moose River Basin to the south and the Foxe and Hudson Strait basins to the north. The geological study of this large, marine-dominated area goes back to the nineteenth century, when explorers started to describe sedimentary rock units along the shore of many Arctic Islands. Modern geological descriptions, mostly stratigraphic and paleontological in nature, started in the mid-twentieth 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–Ungava project (GEM-2, 2013–2020) of the Geo-mapping for Energy and Minerals (GEM) program of the Geological Survey of Canada (GSC), the overall research goals were to propose a modern understanding of the geological framework of the basin and to provide more precise knowledge of its hydrocarbon systems and potential. Research initiatives for the two phases of the program were designed to address these major goals. In this paper, the term 'Hudson Bay project' will be used for both phases of the GEM program.

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* 'Previous geological work' and 'Previous hydrocarbon exploration' sections). 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 re-evaluation of the most pertinent data, which served as a 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) the 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 burial-thermal 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 the second issue, significant time and efforts were devoted to defining a 5000 km linear-acquisition seismic program through the development of a scientific partnership with a major international academic institution with marine-vessel capacity to acquire offshore seismic data. In support of the survey, regional marine seismic noise-modelling was done (M. Zykov and N.E. Chorney, unpub. rept., 2013) as well as an environmental-impact analysis (C.M. Hawkins, unpub. rept., 2011). For various departmental and external reasons, the survey did not materialize. Therefore, current understanding of the subsurface geometry of the basin is reliant on paper copies of poor- to fair-quality seismic lines. Nevertheless, a major re-evaluation of the subsurface of Hudson Bay and the resulting new tectonic-evolution model based on the best seismic data available was released (Pinet et al., 2013a). All the other activities completed under phase 1 of the Hudson Bay project were synthesized in GSC Open File reports (Huot-Vézina et al., 2013; Lavoie 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 project, a total of three external scientific papers were published together with fourteen GSC and Canada-Nunavut Geoscience Office (CNGO) Open File reports, two GSC paleontological reports, five papers in the Manitoba Geological Survey (MGS) Report of Activities series, five Ontario Geological Survey (OGS) Open File Reports, eight B.Sc. theses, and ten formal oral and poster presentations.

Phase 2 (2013–2020)

Following the completion of phase 1, a major GSC internal review process of evaluating outstanding scientific issues led to research activities being proposed in new areas or in areas covered, but not completed, during GEM-1. The need to acquire key geoscientific knowledge on Hudson Bay and adjacent areas to appraise both their hydrocarbon and mineral potential was identified. More specifically, where the sedimentary basin and the hydrocarbon component were concerned, the following main scientific questions were still the subject of debate:

- How have geodynamic factors, recorded as faulting and/or variable burial and exhumation, influenced the architecture and petroleum prospectivity of the Hudson Bay Basin?
- Can subbasins with distinct hydrocarbon prospectivity be identified in the Hudson Bay Basin?

Based on these scientific questions and the results from phase 1, a new geoscientific research project 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 for addressing the remaining issues were focused on: 1) the definition of a regional, basin-scale, modern stratigraphic understanding focused, 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 shale units, 4) the refinement of burial and/or exhumation scenarios to evaluate areas with greater potential for hydrocarbon generation, and 5) a marine high-resolution hydrographic survey to map the seafloor under areas where potential oil slicks at the water surface had been identified from RADARSAT-2 image analyses during phases 1 and 2.

Here again, significant time, effort, and consultation with local communities were devoted to the planning of marine surveys. Line acquisitions were scheduled for the fall of 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. The result of this combination of circumstances is that the geology of the underlying potential natural oil slicks identified through Transport Canada's National Aerial Surveillance Program (*see* 'Evidence for active hydrocarbon systems' section) 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 (summer 2019), a total of eleven peer-reviewed scientific papers and book chapters, eight GSC and CNGO Open File reports, eleven GSC paleontological reports, one Geomatics Canada Open File report, six papers in the MGS Report of Activities series, seven OGS Open File Reports, one M.Sc. and three B.Sc. theses, and twenty-one formal abstracts have been released or are currently in press as science products of the second phase of the GEM program.

The synthesis of research in the Hudson Bay area between 2008 and 2018

In this report, the main advances in geoscience knowledge for the Hudson Bay and satellite basins made during the GEM program are summarized. The report offers an overview of the results from the research carried out on the following major themes over a period of 10 years: 1) tectonic framework; 2) stratigraphy; 3) sedimentology; 4) petroleum systems (source and reservoir rocks, burial-thermal history, and hydrocarbon generation); and 5) evidence of active petroleum systems. An evaluation of the remaining geoscience questions pertinent to the Hudson Bay sedimentary basin concludes this paper.

An unedited version of this paper was previously released as Geological Survey of Canada Open File 8507.

PREVIOUS GEOLOGICAL WORK

Hudson Bay was explored by English 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 twentieth century. It remains one of the least studied sedimentary basins in Canada. The Phanerozoic succession of the Hudson Bay Basin is largely covered by marine waters (Fig. 1). Its southern onshore extension forms the Hudson Bay Lowland and consists of relatively thin successions of nearly flat-lying sedimentary rocks exposed in northeastern Manitoba, northern Ontario and, in its northern extension, 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, on the northern part of Southampton Island, on southeastern and southern 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 appeared in Savage and Van Tuyl (1919). Little work was done on Paleozoic strata of the Hudson Bay Basin during the 1920s to 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). Ordovician, Silurian, and Devonian carbonate-dominated rock units, and Jurassic and/or Cretaceous and Cenozoic clastic-dominated units were mapped, although efforts were hindered due to the geology being obscured by the very low relief, swampy muskeg terrain that covers the Hudson Bay Lowland. A comprehensive bibliography of the geology of the Hudson Bay Basin was published in 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 (1924). Operation Winisk carried out by the Geological Survey of Canada in 1967 covered parts of the Moose River Basin (Fig. 1) and resulted in a 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 to the recognition of a carbonate-dominated stratigraphic succession that correlates relatively well with Ordovician and Silurian strata of the Hudson Bay Basin as well as the identification of a Devonian succession largely not represented in the onshore Hudson Bay Basin in Ontario and Manitoba.

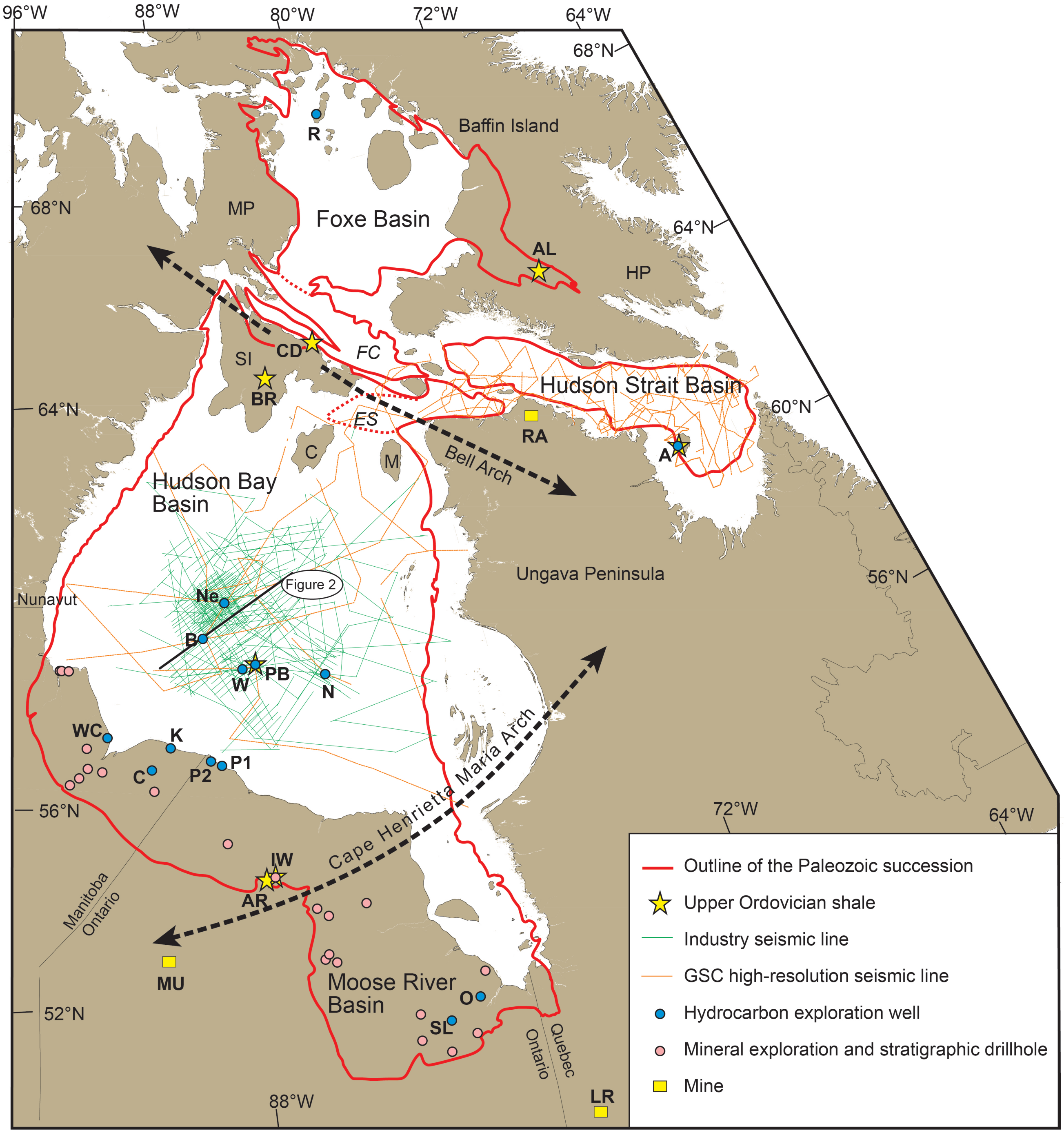

Figure 1. Map and extent of the Hudson Bay Basin and adjacent basins; thick line in Hudson Bay Basin is location of cross-section on Figure 2 (*modified from* Lavoie et al., 2015). Multichannel industry seismic lines and Geological Survey of Canada (GSC) high-resolution seismic lines are depicted. Hydrocarbon 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 Province 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 = Aquitaine et al. 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 #49212 and #49204. Tens of mineral exploration, stratigraphic, and geotechnical drillholes in Ontario and Manitoba are not shown. Mines: LR = La Ronde gold mine; MU = Musselwhite gold mine; RA = Raglan nickel mine. Place names: AL = Amadjuak Lake; AR = Asheweig River section; BR = Boas River section; CD = Cape Donovan section; C = Coats Island; ES = Evans Strait; FC = Foxe Channel; HP = Hall Peninsula; M = Mansel Island; MP = Melville Peninsula; SI = Southampton Island.

Subsequent work by geologists from the Engineering and Terrain Geology Section of the Ontario Geological Survey (Russell and Telford, 1984; Sanderson and Telford, 1985; Telford, 1988) led to refinement of the Devonian stratigraphy in the Moose River Basin.

The first geological observations recorded on the Foxe Basin are those of Parry (1824, 1825), who recognized carbonate strata and collected fossils on various shores. 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 imported the Paleozoic stratigraphy defined at the northern end of Baffin Island in Blackadar and Lemon (1963) and Trettin (1969). Prior to the GEM program, the most recent summary of the geology and paleontology of Foxe Basin was provided in McCracken and Bolton (2000).

Akpatok Island in the Hudson Strait was noted by Henry Hudson in 1610, but the first geological observations about it were those made by Bell (1899), who described and collected rocks and fossils from the island, the latter of which were assigned a Middle Ordovician age by Whiteaves (1899). A five-week geological expedition from Oxford University in 1931 led to the first measured stratigraphic section for the island (Cox, 1933a, b). 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 Hudson Bay are those found in Workum et al. (1976), in which the lithostratigraphy and biostratigraphy of the core from the Premium Homestead Akpatok L-26 well drilled in 1969 are studied in detail.

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 go back to the early 1920s (Kindle, 1924; 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 in the 1980s (Russell et al., 1985; Bezys, 1989). The Ontario Oil, Gas and Salt Resources Library database documents 32 oil and gas shallow exploration wells and 6 government stratigraphic tests holes (Fig. 1). Additionally, drilling activity (over 125 wells) for lignite resources in the Cretaceous Mattagami Formation occurred between 1926 and 1986 (Telford et al., 1991). A summary of the hydrocarbon systems of the Moose River Basin (and Hudson Bay Basin) was presented in Hamblin (2008).

In the Hudson Bay Basin, onshore drilling started in 1966 (Manitoba) and in 1970, a total of five hydrocarbon exploration wells (three in Manitoba and two 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 have been acquired to help locate the hydrocarbon exploration wells.

Industry offshore drilling in Hudson Bay started in 1969, shortly after the first marine seismic-data acquisition program showed that the sedimentary succession preserved in the central part of the bay is much thicker than its onshore counterpart. From the late 1960s to 1990s, industry and the GSC acquired over 46 000 and 40 000 line-kilometres of deep and shallow seismic data, respectively (Fig. 1). Seismic-data acquisition by industry 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 five offshore wells between 1969 and 1985 (Fig. 1), four of them targeting fault plays. Local stratigraphic nomenclatures were defined largely based on well cuttings for these offshore wells. 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 a few cores) was submitted to the National Energy Board for future use.

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

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

In the late stages of the first phase of hydrocarbon exploration, a resource evaluation concluded that the Hudson Bay Basin has a limited resource potential of 130×10^6 m^3 (818 MMBl) of recoverable oil and 90×10^9 m^3 (3.2 TCF) of recoverable gas (Procter et al., 1984); however, the geological data at that time was considered inadequate to provide a reliable resource estimate. Three recent qualitative appraisals of the hydrocarbon potential of the Hudson Bay, Moose River, and Foxe basins have been published (Fustic et al., 2018; Hanna et al., 2018, 2019) and their authors concluded 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, second only to the Western Canada Sedimentary Basin. It covers 970 000 km^2 (about 10% of the area of Canada), of which two thirds is covered by water. The Hudson Bay Basin sedimentary succession also encompasses onshore parts of northeastern Manitoba and northern Ontario (the Hudson Bay Lowland), and Nunavut (Fig. 1). The Hudson Bay Basin is separated from the Moose River Basin by the Cape Henrietta Maria Arch, whereas the Bell Arch separates the Hudson Bay Basin from the Foxe Basin; the two arches are broad, positive-relief, basement-involved structural elements with a poorly understood formation mechanism(s). The Hudson Bay Basin, Moose River Basin, and onshore areas (Hudson Bay Lowland and onshore Nunavut), also known as the Hudson Platform (*sensu* Sanford and Norris, 1973), unconformably overlie, and are 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 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; Burgess, 2019). 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 North American intracratonic basins, the Hudson Bay Basin also differs by its location far from plate boundaries at the time of basin initiation and by the presence of a fault system that attests to significant lithospheric stretching during basin formation.

Several recent geophysical studies have focused on the deep lithospheric architecture of the region (*see* Bastow et al., 2015). Among the main results, Darbyshire et al. (2013) and Porritt et al. (2015) concluded that the lithosphere is at its thickest (estimates between 240–280 km and ~350 km, respectively) beneath central Hudson Bay and at its thinnest (~190 km) beneath the Hudson Strait. Moreover, ambient-noise tomography (Pawlak and Eaton, 2010) revealed a low-velocity anomaly in Hudson Bay, coincident with the zone of normal faulting imaged in seismic data, which corroborated the hypothesis identifying crustal stretching as 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). Upper Paleozoic (Lower Pennsylvanian [Bashkirian]) strata were reported from the Narwhal South O-58 well in Tillement et al. (1976), but as they have not been identified in any other studies, their presence remains uncertain. Strata of Mesozoic to recently documented freshwater sediments of probably mid-Cenozoic (Miocene) age (Galloway et al., 2012) occur locally at the top of the succession.

Based on outcrop and offshore well 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 present locally in the offshore domain, whereas onshore, Upper Ordovician and Middle Devonian evaporites are interbedded with 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 shale units of Late Ordovician and Late Devonian age. New biostratigraphic data, coupled with offshore well logs and seismic data, allow for the identification of four 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 and/or Cenozoic (Fig. 2; Hu et al., 2011; Pinet et al., 2013a).

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 (Fig. 1) is the southernmost tectonostratigraphic element of the large intracratonic system centred on Hudson Bay and about one third of it is submerged beneath the waters of James Bay. The Moose River Basin is separated from the Hudson Bay Basin by the Cape Henrietta Maria Arch, a tectonic high of Precambrian basement and, given the relative dissimilitude in the basal

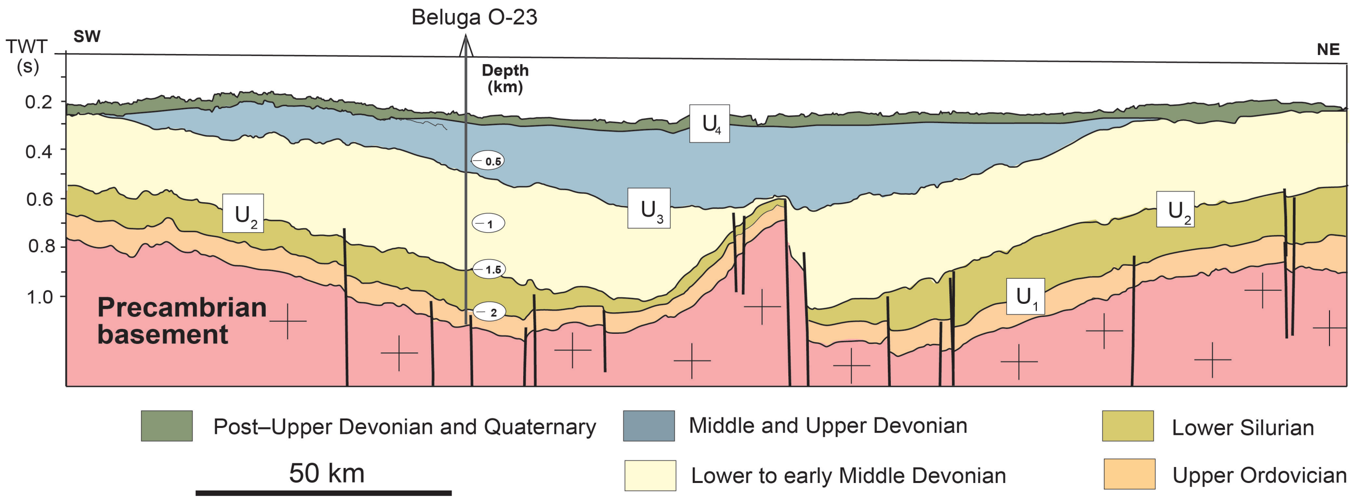

Figure 2. Interpretation of a seismic-reflection profile in central Hudson Bay, across the Beluga O-23 well (Fig. 1), depicting major lithostratigraphic intervals and unconformities (U_1 to U_4). Vertical axis on the left is two-way traveltime (TWT) and a depth scale is shown adjacent to the Beluga O-23 well line. *Modified from* Pinet et al. (2013a).

stratigraphic succession (Armstrong et al., 2018), the two basins were possibly 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 toward the erosional margin of the basin to the southeast (Nicolas and Armstrong, 2017).

The Moose River Basin Paleozoic succession, as with 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 veneers of Mesozoic clastic rocks and lignite unconformably overlie 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 exist 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; Larmagnat and Lavoie, this volume).

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, this volume). 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) part of the Arctic Platform (Norris, 1993). 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. 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 (Trettin, 1975). The thickness of that Cambrian interval decreases toward the south to a 64 m thick succession in the Rowley M-04 well. Cambrian sediments are unknown on Melville Peninsula and southern 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, 2012, 2013a; Zhang and Lavoie, 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 M-04 well (Trettin, 1975). Based on high-resolution seismic data in the adjacent Hudson and Evans straits (Fig. 1), the presence of a thicker succession (1.5 km; Pinet et al., 2013b; Lavoie et al., in press), including a poorly constrained post-Silurian rock package, is assumed in the Foxe Channel, at the contact between the Hudson Bay and Foxe basins.

Two unconformities are either postulated on limited biostratigraphic control (Cambrian–Ordovician boundary) or defined on sufficient fossil data (Middle Ordovician). The lower Paleozoic succession of the Foxe Basin represents 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 east; the last confirmed by the identification of carbonate xenoliths with Ordovician conodonts in Mesozoic kimberlites on Hall Peninsula (Fig. 1; Zhang and Pell, 2014).

Hudson Strait Basin

The Hudson Strait Basin is located in an east–west elongated zone including 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 body of water approximately 700 km long, 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 approximately 80 mGal in amplitude (Pinet et al., 2013b).

Two distinct rock assemblages are recognized based on GSC high-resolution seismic data (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 the 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 subbasins having a half-graben geometry. These subbasins record an extensional (or transtensional) tectonic event of poorly constrained age that is not documented to the south and is possibly linked with the initial stages of extension in the future Labrador Sea (Pinet et al., 2013b). Deformed zones characterized by open folds attest to 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 than 600 m on the immediately surrounding islands (Pinet et al., in press) to approximately 2.6 km in the offshore fault-controlled easternmost subbasin (Pinet et al., 2013b). One well (Premium Homestead Akpatok L-26), located on Aktapok Island and reaching only 335 m in depth, 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 not yet 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, 2011), 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-shaped, essentially undeformed upper sedimentary package (Pinet et al., 2013a). This geometry contrasts with that observed 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 nondeposition and/or erosion (Pinet et al., 2013a). Moreover, significant changes in the depocentre location during the Paleozoic and variable exhumation values required by maturation and apatite fission-track data indicate that other mechanisms influenced the subsidence and/or exhumation history of the basin. In particular, the influence of far-field events and dynamic topography transmitted within the continental interior (creating long-wavelength tilting and unconformities) is a potential scenario (Pinet et al., 2013a; Pinet, 2016).

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 north-northwest-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 was further suggested that tectonic stresses applied to the continental margin during the Silurian–earliest Devonian Salinian Orogeny (Tremblay and Pinet, 2016) were transmitted across a distance of over 1400 km within the continental interior, where they induced 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, Moose River, 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 these frameworks but nonetheless these served as cornerstones for this study (Sanford and Grant, 1998; Zhang and Barnes, 2007; Hamblin, 2008).

New data

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

From these wells, as well as extensive field and laboratory stratigraphic surveys, and research undertaken from 2008 to 2017 in Ontario (Armstrong and Lavoie, 2010; Armstrong, 2011, 2012, 2014, 2015; Galloway et al., 2012; Armstrong et al., 2013; Hahn and Armstrong, 2013; McCracken et al., 2013; Ratcliffe and Armstrong, 2013; Chow and Armstrong, 2015; Turner and Armstrong, 2015; Braun et al., 2016; Hahn et al., 2016, 2017); Manitoba (Nicolas and Lavoie, 2009, 2010, 2012; Nicolas, 2011, 2016; Ramdoyal et al., 2013; Nicolas et al., 2014; Nicolas and Young, 2014; Eggie et al., 2014; Nicolas and Clayton, 2015; Nicolas and Armstrong, 2017; A.D. McCracken, unpub. GSC Paleontological Report 1-ADM-2015, 2015), and Nunavut (Zhang, 2008, 2011a, b, 2012, 2013a, b, 2014, 2018; Zhang and Lavoie, 2013; Zhang and Mate, 2014), a total of 3800 samples for stable isotopes chemostratigraphy ($\delta^{13}C_{VPDB}$ and $\delta^{18}O_{VPDB}$) of carbonates, 480 samples for conodont and 330 samples for chitinozoan analyses were studied, along 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 included in the volume (Larmagnat and Lavoie, this volume). Additionally, eleven B.Sc. and one M.Sc. theses were produced and are listed below in the 'Sedimentology' section.

As a complement to 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 subsurface information is pending, but it will eventually help to better constrain the lateral extension of stratigraphic units, in particular, the Upper Ordovician black limy shale succession in Ontario that seems to pinch out to the west near the border with Manitoba.

The details of these correlations are in Armstrong et al. (2018), which contains details on local to regional stratigraphic redefinition. 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 extend into the Middle Ordovician (Fig. 3). Of all the stratigraphic refinements reached through the GEM program, the most important is the new understanding of the Upper Ordovician black limy shales.

Ordovician black limy shales: problem with the original Boas River Formation

The term 'Boas River' was introduced by Heywood and Sanford (1976) for an Upper Ordovician, organic-rich, carbonate-rich shale unit on Southampton Island. A succession of the unit 2 to 2.5 m thick is found along the Boas River and 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 black limy shale on southern Baffin Island, assigned to the Boas River Formation by Sanford and Grant (2000), was characterized by Edenian conodonts (McCracken, 2000) and included in the lower part of the Amadjuak Formation (Zhang, 2012; Fig. 3). The presence of two organic-rich black, limy shale intervals (a lower Edenian and an upper Richmondian) in the Foxe Basin as well as the Hudson Bay and Hudson Strait areas has recently been confirmed by new graptolite data (Zhang and Riva, 2018).

In northern Ontario, a 10 m interval of black limy shale assigned to the Boas River Formation (Sanford and Grant, 1990) was described in two mineral exploration cores (INCO-Winisk wells), with conodont fauna suggestive of a

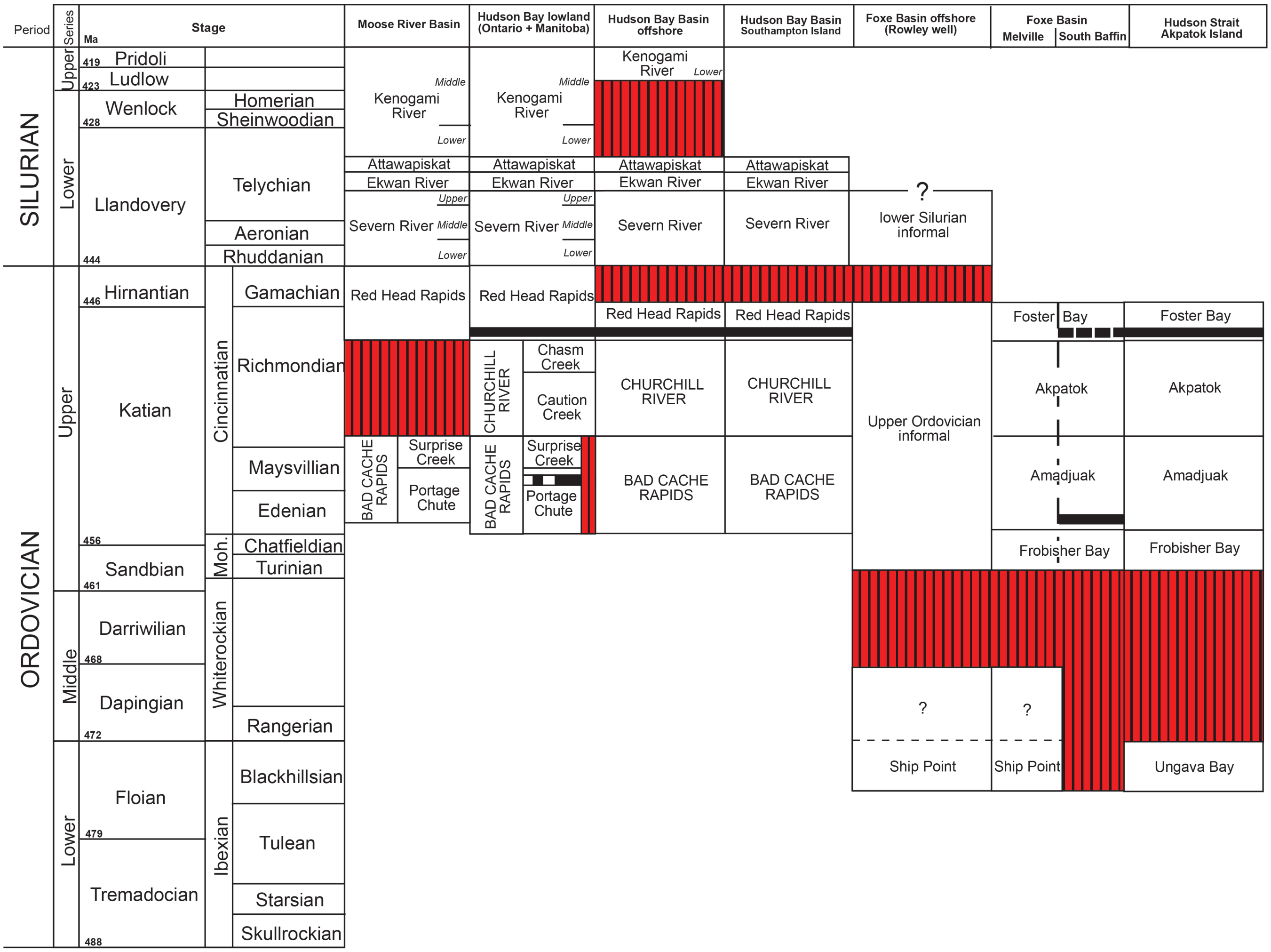

Figure 3. Correlation of the Ordovician–Silurian stratigraphy for the study areas (*modified from* Armstrong et al., 2018; time scale from Gradstein et al., 2004). The vertical red hatched pattern represents nondeposition or erosion. Solid black boxes indicate stratigraphic position of organic-rich black limy shale previously all assigned to the Boas River Formation. The horizontal black dotted line indicates the 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.

dominant middle Maysvillian age (A.D. McCracken, unpub. GSC Paleontological Report 03-ADM-1990, 1990). The presence of the Boas River Formation between the Bad Cache Rapids and the Churchill River groups was assumed, just as it has been on Southampton Island (Heywood and Sanford, 1976). A recent re-examination of the encasing rock units suggested that the black limy shale interval lies 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 black limy shale was described on the banks of 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, 2011a). Thus, there appears to be two organic-rich black limy shales in northern Ontario, one of mid-Maysvillian age and another of late Richmondian age (Fig. 3).

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

SEDIMENTOLOGY

Most of the work dealing with the nature of the sedimentary succession focused 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 Foxe Basin (Trettin, 1975; Zhang, 2013a). On Southampton Island, these mounds belong to the Red Head Rapids Formation; they are partly dolomitized and reach up to 400 m in length and 250 m in width, with a minimum exposed vertical relief of 15 m (Fig. 4). In outcrop, 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 partly filled locally with dead oil (Heywood and Sanford, 1976) and bitumen (Lavoie et al., 2018a).

Castagner (2016) and Castagner et al. (2016) presented a detailed description of the architecture of the internal facies of such a 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 rare, 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, of binding by calcimicrobes in the case of the boundstone facies, and of marine cement precipitation in that of the cementstone facies. The mounds of the Red Head Rapids Formation have a biotic composition more in common with the sponge-microbial reefs, which dominated worldwide in the Early Ordovician, compared to the 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 with 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 leading to ocean-water–column salinity stratification, as evidenced by the presence of coeval precipitation in Late Ordovician time of a locally thick succession of subtidal evaporites in the upper part of the Red Head Rapids Formation in the subsurface of the central Hudson Bay Basin (Hu et al., 2011). On Southampton Island, anoxic and hypersaline conditions are recorded by 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 unfavourable to open-marine stenohaline taxa (James and Jones, 2015), thus explaining the lack of diversity in the Red Head Rapids Formation reef. Sponges and microbes, on the other hand, were ideally adapted to survive under such extreme environmental conditions (Scholle and Ulmer-Scholle, 2003).

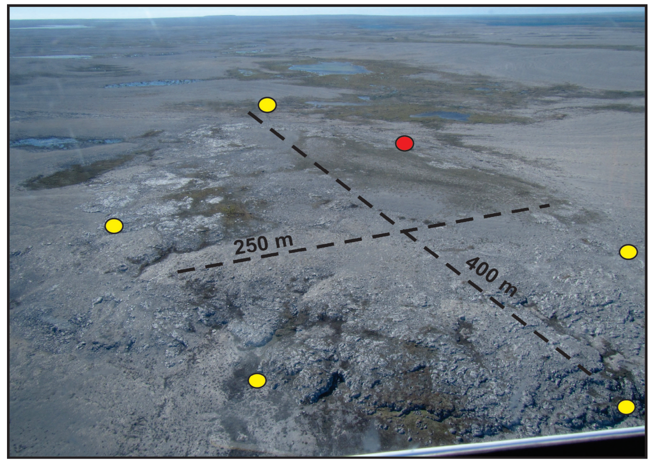

Figure 4. Helicopter view of the studied carbonate mound on Southampton Island. The dots represent the base of sections that were measured perpendicularly to the mound axis and reported in Castagner (2016). The red dot locates the section on which a diagenetic study was focused. Photography courtesy of A. Desrochers, University of Ottawa.

Upper Ordovician black limy shale

Upper Ordovician black limy shale was encountered as an interval approximately 10 m thick in the INCO–Winisk drillholes and as a 4 m outcrop exposure along the Asheweig River (Armstrong, 2011). This interval is commonly described as an organic-rich black limy shale (Armstrong, 2011; St. Jean, 2012), although the organic content varies throughout 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 containing 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 carbonate units in Manitoba

As part of 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 of 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 in locating the Ordovician–Silurian boundary. These studies were later extended to the lower Silurian carbonate units, with a focus on diagenetic components (porosity evolution in carbonate, oil inclusions in cements).

Ordovician–Devonian carbonate units in Ontario

In the second phase of the GEM program, grants to Laurentian University led to important collaborative research between the university and the Ontario Geological Survey on the Hudson Bay project. 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) contributed greatly to the development of the regional stratigraphic synthesis (Armstrong et al., 2018). Moreover, B.Sc. theses at the University of Ottawa (St. Jean, 2012; Bibby 2013) and the 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 projects and models made available to the resource industry. In the case of the Hudson Bay project on the Phanerozoic succession, a better understanding of the hydrocarbon systems and potential of this large sedimentary basin was the ultimate goal. The previous, and only, exploration phase (1969–1985) ended with pessimistic conclusions on the regional extent and/or limited thickness of hydrocarbon source rocks and the burial-thermal history of the succession. Little to no work and analyses on potential reservoir units was carried out before the GEM program.

The dissemination of new petroleum-system data and models generated significant industry interest for the Hudson Bay Basin, with both Canadian and international oil- and gas-exploration companies inquiring about acquiring exploration licences in Hudson Bay; however, the offshore domain being currently under a federal exploration moratorium, no exploration licences have been issued.

Source rocks

Three distinct Upper Ordovician black 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) occurs within a cyclic peritidal carbonate-evaporite succession, whereas the older intervals (Edenian and Maysvillian) are associated with subtidal marine carbonate units. 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) black 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; Armstrong et al., 2018; Zhang and Riva, 2018). Interestingly, Upper Ordovician to lower Silurian carbonate and black shale xenoliths found in kimberlite of Mesozoic age on Hall Peninsula allow for the extension of the source rock (Amadjuak or Severn River formations) to the east (Zhang and Pell, 2014; Zhang et al., 2014). The revision of the stratigraphic nomenclature of the black limy shales is discussed in Zhang and Riva (2018), and in Armstrong et al. (2018), as well as summarized above. Some thin organic-rich black shale 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, the hypothetical presence of Carboniferous source rocks will be briefly discussed.

The presence of Upper Ordovician hydrocarbon source rocks in the northern part of the Hudson Bay Basin has been known for decades (Macauley, 1981, 1984, 1986, 1987; Macauley et al., 1990). These shales outcrop on Southampton, Baffin, and Akpatok islands, and were characterized by Rock-Eval 2 analyses over the years; the results indicated that the shales (particularly those on Southampton Island) have very high hydrocarbon yields and, given their immature thermal rank, they were designated as oil shales (Macauley, 1984). An Upper Ordovician (Maysvillian) organic-rich unit was found in northern Ontario mineral-exploration cores (from INCO-Winisk wells; A.D. McCracken, unpub. GSC Paleontological Report 03-ADM-1990, 1990) and an outcrop of a younger (Richmondian) black limy shale unit was also mapped along the Asheweig River (Armstrong, 2011; St-Jean, 2012).

The organic geochemistry of all the above Ordovician occurrences was intensively studied using Rock-Eval 6 analysis and organic petrography. In phase 2 of the GEM program, the immature shales were subjected to programmed closed-system hydrous pyrolysis.

Rock-Eval results from Ordovician source rocks

Onshore occurrence

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 m to 14 m (Macauley, 1987); on Southampton Island (Red Head Rapids Formation) with a combined thickness of 2 m to 3 m over a 20 m interval; and on Akpatok Island (Foster Bay Formation) with a thickness estimated to be around 10 m to 12 m (Fig. 1, 3; Macauley, 1987). Zhang (2008, 2012) revisited the localities of Macauley (1986, 1987) and a newly identified section (Cape Donovan on Southampton Island; Fig. 1), as well as collected new samples for Rock-Eval 6 analyses. All 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 carbon (TOC) values range from 0.31 weight per cent to 34.1 weight per cent (average of 10.1 wt %), hydrogen index (HI) values from 97 mg to 795 mg HC/g TOC (average of 557), and oxygen index (OI) values from 8 mg to 106 mg CO_2/g TOC (average of 37 mg). Hydrocarbon yields range from 0.32 kg to 230.80 kg HC/t (detailed results are presented in Lavoie et al., 2013). The new Rock-Eval 6 analyses indicate that the Upper Ordovician black limy shales in the northern area of the Hudson Bay Basin have high TOC and hydrocarbon- yield potential. The black limy 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 relogging of two mineral exploration wells drilled in northern Ontario (INCO-Winisk #49212 and #49204; Fig. 1; 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 black limy shale is 6 m and 9.5 m, whereas an incomplete (base missing) stratigraphic section of 4 m of black limy shale has been measured along the Asheweig River. Samples from the INCO-Winisk wells and Asheweig River yield TOC values from 0.41 weight per cent to 12.84 weight per cent (average of 7 wt %), HI values from 180 mg to 634 mg HC/g TOC (average of 549), and OI values from 12 mg to 120 mg CO_2/g TOC (average of 30). Hydrocarbon yields range from 0.75 kg 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 offshore in the Hudson Bay Basin, an extensive sampling of well cuttings of Ordovician–Silurian intervals was carried out in the Aquitaine et al. Narwhal South O-58 and Polar Bear C-11, and Trillium et al. Beluga O-23 wells (Zhang and Dewing, 2008); this, along with subsequent resampling of handpicked black cuttings (*see* below), was completed before the start of the Hudson Bay 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 from 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 cuttings from these zones indicated good hydrocarbon source-rock potential (measured TOC values of 0.29–5.73 weight per cent, HI values of 109–538 mg HC/g TOC, and hydrocarbon yields of 26.98–38.40 kg HC/t). The dark-coloured cutting samples had significantly higher TOC (double to fourfold 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 Island. Subsequent to these interpretations, a detailed petrophysical analysis of well-log data indicated that thin, organic-rich shale beds are present in the Upper Ordovician strata in all offshore wells, with the thickest cumulative section of 14 m noted in the Beluga O-23 well (Hu and Dietrich, 2012).

Type of organic matter and organic geochemistry of Ordovician source rocks

Petrographic observations for the Baffin and Southampton islands oil shales are reported in Macauley et al. (1990), whereas new petrographic observations for occurrences in northern Ontario and northern Southampton Island (Cape Donovan) are reported in Lavoie et al. (2013) and Zhang (2011b), respectively. 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 preponderance of marine Type II organic matter. Small amounts of Type I *Gloeocapsomorpha prisca* have been identified for all localities (Reyes et al., 2016a, 2018).

Limited gas-chromatography data indicate that organic matter types in the Ordovician Red Head Rapids and Amadjuak formations in the northern Hudson Bay and Foxe basins (Macauley et al., 1990; Zhang, 2011b), respectively, are unlike the well documented, more or less coeval Ordovician source rocks in southern Ontario (Collingwood Formation) and Saskatchewan (kukersites of the Yeoman Formation), but bear a greater similarity to Silurian source rocks of the Michigan Basin. Compared to 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 ratios of pristane to phytane. These geochemical signatures indicate that the Hudson Platform source rocks were deposited in hypersaline and highly reducing photic-zone 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 of the Red Head Rapids Formation. The Ordovician source rocks in the Hudson Platform also have low C32/C34 ratios and distributions of 17α(H)–21β(H)-hopanes that are very similar to the Silurian hypersaline source rocks of the Michigan Basin (Summons and Powell, 1987).

Gas-chromatography extracts from Edenian black limy shales in the INCO-Winisk cores of 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 Hudson Bay (average ratio of 1.1:0.62, respectively; Zhang, 2011b; Lavoie et al., 2013), but still lower than those of Upper Ordovician source rocks of southern Ontario (0.97:1.72; Obermajer et al., 1996). 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 shale of Richmondian age (Red Head Rapids Formation) in the northern Hudson Bay Basin was deposited in reducing and hypersaline settings; the cyclic carbonate–evaporite lithological succession is consistent with the organic geochemistry information. The results of the geochemical analyses of the shale of Edenian age (Portage Chute Formation) in the INCO-Winisk cores of northern Ontario suggest a less reducing setting and average marine salinity, which corresponds 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 is significant because this type of organic matter will generate oil at lower maturation temperatures compared to Type II or Type I organic matter (Hunt and Hennet, 1992), an assertion confirmed by the hydrous pyrolysis of these rocks (*see* below and Reyes et al., 2016a, b, c). Even if the geochemical indicators from the shales of Edenian age do not point unequivocally to Type II-S organic matter, 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., 2016a).

Closed-system hydrous pyrolysis of the Ordovician source rocks

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 Formation from northern Ontario and Southampton Island of the Hudson Bay Basin, and Amadjuak and Foster Bay formations from the Foxe Basin and Hudson Strait, respectively) were artificially matured using modified hydrous pyrolysis at temperatures between 310°C and 350°C for 72 hours (Reyes et al., 2016a). Conventional hydrous pyrolysis was also used using a reactor system, manufactured by the Parr Instrument Company, at 310°C, 330°C, and 350°C for 3 days. Additionally, an immature Devonian shale sample from the Western Canada Sedimentary Basin was also subjected to closed-system anhydrous pyrolysis (no water added) using the Parr reactor at 330 °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, biomarker, and 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 combined with the current understanding of the burial history and hydrocarbon-generation potential of these formations, and the Hudson Bay, Hudson Strait, and Foxe basins as a whole. The complete methodology, results, and data interpretations were presented in an 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 parameters (HI, OI, PI, PC, S1, S2, S2:S3, TOC, 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 values, combined with decreased S2 and TOC values, indicate hydrocarbon generation through thermal degradation and transformation of organic matter (kerogen) into petroleum product (oil and gas) with increasing pyrolysis temperature.
- The samples reached the hydrocarbon-generation window after pyrolysis at 310°C (first step), with corresponding average reflectance of vitrinite-like particles

($R_{o\text{-vit-like}}$) of 0.70% and Rock-Eval T_{max} values of 433°C to 436°C. As the pyrolysis temperature increases, the measured T_{max} also increases, reaching as high as 455°C after pyrolysis at 350°C (last step), which is at the threshold between the oil and gas windows. The results also indicate that the high amount of extractable organic matter sorbed and retained in the rock matrix may cause possible T_{max} suppression (Fig. 5). Additional studies are currently underway to corroborate this finding (Reyes et al., 2019).

- The reflectance of chitinozoan, graptolite, bitumen, and vitrinite-like macerals increases 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 suggests that they contribute little to hydrocarbon generation (Reyes et al., 2018).
- Qualitative petrographic analysis shows that bright fluorescing oil and reddish-orange–fluorescing solid bitumen were generated after pyrolysis at 310°C. Peak bitumen and oil generation and expulsion rates were reached at pyrolysis temperatures ranging from 310°C to 330°C (T_{max} = 435–441°C) and 340°C to 350°C (T_{max} = 440–455°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 result 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 cyclopentanones, 2-cyclopenten-1-ones and phenols in hydrous pyrolysates of the Ordovician shale core samples after hydrous pyrolysis at 310°C for three days. This is an important finding because there have been no other previous reports

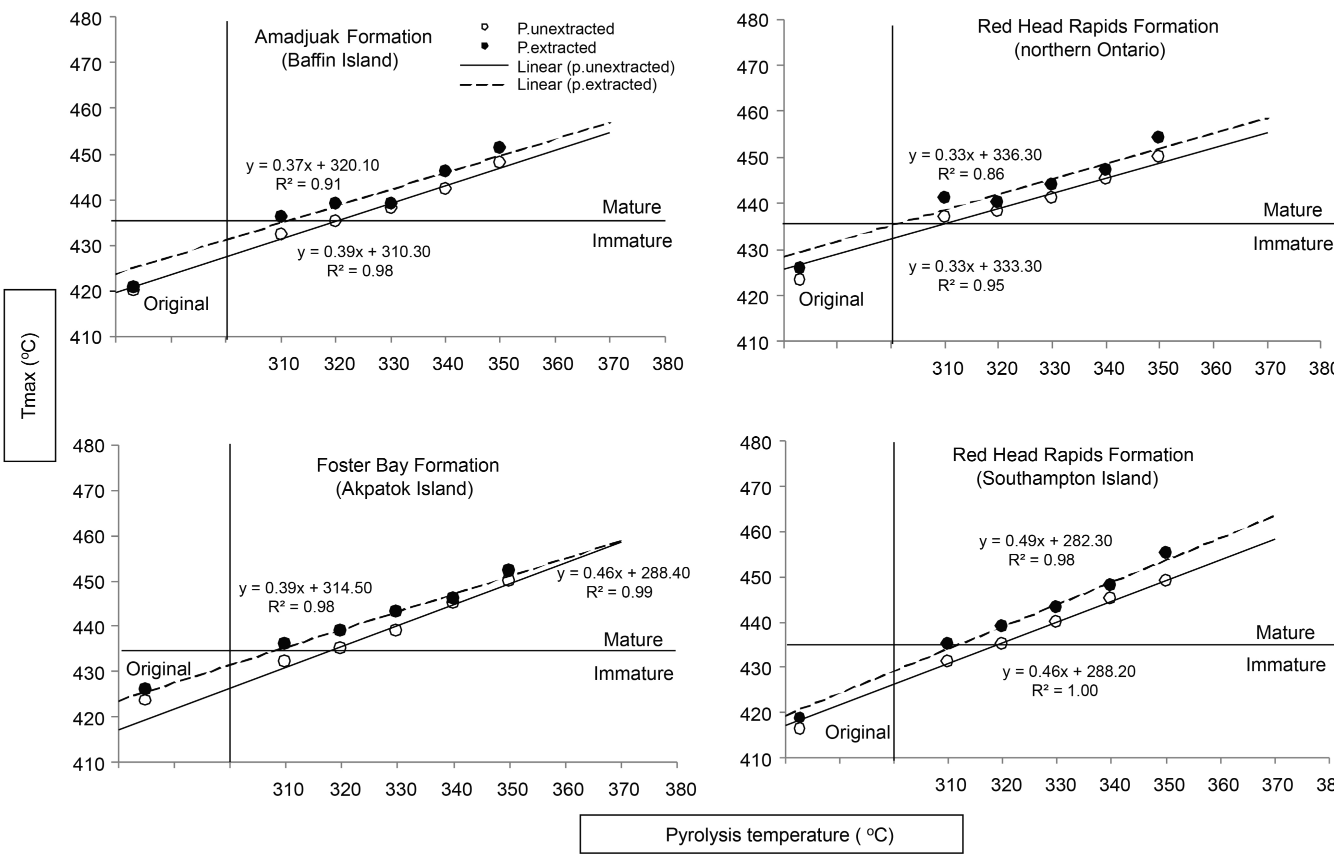

Figure 5. Rock-Eval measured T_{max} after hydrous pyrolysis, before (white circles) and after (black circles) solvent extraction (p., or pyrolysate) as a function of pyrolysis temperature. These graphs show an increase in the thermal maturity after each stage of hydrous pyrolysis. The postextraction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

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 molecular weight, oxygen-containing compounds.

Rock-Eval analyses of Silurian source rocks

Systematic sampling (80 samples) for Rock-Eval analyses was done in eight Manitoba mineral and hydrocarbon exploration cores. Eleven samples of the Severn River Formation in three wells have fair to good hydrocarbon potential with TOC over 1 weight per cent and hydrocarbon yields ranging between 3.98 kg HC/t to 29.33 kg HC/t. Based on Rock-Eval indices, a dominant Type II organic-matter content is suggested for these samples; 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) and its potential presence as clasts in kimberlites on Hall Peninsula has been hypothesized (Zhang et al., 2014).

Rock-Eval analyses of Devonian source rocks

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, five 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 shale units (black and grey) with significant zones of evaporite and limestone units (Larmagnat and Lavoie, this volume).

For the selected samples from this interval, TOC values range between 1.6 weight per cent and 17.64 weight per cent (average of 9.07 wt %), with HI values varying between 142 mg and 495 mg HC/g TOC (average of 390 mg) and OI values, between 26 mg and 135 mg CO_2/g TOC (average of 46 mg);the Moose River Formation has the highest average TOC (average of 9.17 wt %). All the samples have high to very high yields (S1 + S2) that range from 5.52 kg to 86.67 kg HC/t and all samples would qualify as good to excellent hydrocarbon source rocks. Based on the 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 since Kindle (1924), who compared them with the better known organic-rich Kettle Point Formation in southern Ontario. The Long Rapids Formation (85 m thick) straddles the Frasnian–Famennian boundary and includes beds of marine, organic-rich black mudstone that alternate with grey-green mudstone (Bezys and Risk, 1990; Hamblin, 2008; Larmagnat and Lavoie, this volume). The Long Rapids Formation mudstone is immature (T_{max} <424°C) and has TOC values ranging between 2.42 weight per cent and 11.21 weight per cent with HI values ranging between 175 mg and 519 mg HC/g TOC. These samples are excellent potential source rocks with hydrocarbon yields from 5.47 kg to 59.53 kg HC/t of rock.

(?)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 m 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) palynomorph assemblages (G.L. Williams and M.S. Barss, unpub. GSC Paleontological Report 11-77GLW, 1976). The mixing of these elements has been interpreted as the result of caving of Cretaceous, and Cenozoic sediments or of drilling-mud contamination from improperly cleaned mud tanks 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 well data (five wells), especially in areas with a thick sedimentary package present in fault-bounded half-grabens (*see* map in Sanford and Grant, 1998). Even more equivocal is the presence of potential hydrocarbon source rocks. The Lower Mississippian (Tournaisian) rocks in eastern Canada are host to lacustrine oil-shale deposits, which are source rocks for oil and natural gas sandstone reservoirs (Dietrich et al., 2011). In the nearby Williston Basin, the Famennian–Tournaisian Bakken Formation is one of the major unconventional oil-shale plays in North America (Gaswirth et al. 2013) and, although less known, the organic-rich black shale of the coeval Sunbury Formation occurs in the Michigan Basin (Swezey et al., 2015). 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 goals of the GEM Hudson Bay project was to provide 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 untested before this project.

Rock-Eval data from organic-matter pyrolysis methods

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 evaluations 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 greater than 0.35 mg HC/g rock provide the most reliable T_{max} values (Dewing and Sanei, 2009) and, as such, that value was used as a threshold for interpretation of T_{max} data (Lavoie et al., 2013). Any samples with S2 values lower than 0.35 mg HC/g rock were not included in the thermal evaluation.

Onshore outcrops T_{max} values

The 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 the onshore exploration well Houston et al. Comeault No. 1 (Manitoba; Fig. 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; Fig. 1) have sufficient T_{max} data for the evaluation of maturation-depth trends and interpretation of thermal rank (Lavoie et al., 2013, 2015). The best-fit correlation line for the T_{max} data of the Beluga O-23 well intersects the 430°C (Type II-S organic matter) and 435°C (Type II organic matter) 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 that the top of the oil window occurs at 830 m in the lower Silurian Severn River Formation (for Type II-S organic matter), and at 1220 m in the Upper Ordovician Churchill River Group (for Type II organic matter; 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 organic matter, respectively.

Interpretation of the Rock-Eval data suggests that 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 qualitative petroleum-resource assessment project for Hudson Bay (Hanna et al., 2018).

Petrography results from organic matter

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 equivalents. 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 (Bertrand and Malo, 2012). Data originated from various carbonate facies with organic matter particles and were not restricted to organic-rich shale units.

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 organic matter or 2200 m in Ordovician strata for Type II organic matter. Using the method of Dow (1978) and a surface Ro value of 0.25%, the estimated thickness of eroded strata is 2400 m. The Narwhal South O-58 and Polar Bear C-11 wells 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, with both data sets indicating that the Upper Ordovician source rock entered the oil window.

Apatite fission-track results from mineral-based methods

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-track (AFT) analysis provides detailed information in the 60°C 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°C to 80°C range and thus provides important information on the cooling history (exhumation) of a sedimentary basin.

During phase 1 of the GEM program, seven samples (three from metamorphic units intercepted at the immediate bottom of exploration holes, three from Precambrian outcrops, and one from an outcrop of Ordovician basal sandstone on Southampton Island) were subjected to AFT analysis (Lavoie et al., 2013). Initial AFT ages were reported in Lavoie et al. (2013), with new analyses and interpretations on the same samples updated by 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. Additional samples from open-pit and underground mines were analyzed during phase 2 of the GEM program to better constrain the burial and/or exhumation scenarios (Pinet, 2018; N. Pinet and K.T. McDannell, work in progress, 2019; McDannell et al., this volume). For all these studies, chemical composition of the apatites has been evaluated.

Inverse modelling 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 values using AFT inverse-modelling results (Pinet et al., 2016).

Data from AFT analysis indicate geographic variations in the timing and degree of Phanerozoic heating episodes, which suggests that the Hudson Bay Basin and surrounding Canadian Shield did not react as a single entity during the last 500 Ma.

Key findings

- Apatite fission-track 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 that samples were subjected to temperatures higher than 60°C, but lower than 120°C during the Phanerozoic; therefore, all samples have reached oil-window conditions. Also, 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 temperatures of 62°C to 77°C and 62°C 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 Ma) for a Precambrian sample from the Raglan mine in northernmost Quebec, adjacent to the Hudson Strait (N. Pinet and K.T. McDannell, work in progress, 2019).
- 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°C and 85°C, with a best fit of 72°C; other material from the same island is presented elsewhere in this volume (McDannell et al., this volume).
- Archean greywacke samples from a 3.6 m 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 Ma for the sample recovered at the greatest depth. Inverse modelling 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 carbonate units and the return at the surface of very resistant basement greywacke (Pinet, 2018).
- Interpretation of AFT analyses from the Canadian Shield surrounding Hudson Bay reveals highly variable results, which suggests that eastern Manitoba experienced significant Phanerozoic burial, whereas no record of a Paleozoic cover is found from the Musselwhite mine samples, 100 km south of the actual erosional southern limit of the Hudson Bay Lowland in northern Ontario (N. Pinet and K.T. McDannell, work in progress, 2019). The Musselwhite mine is roughly located over the Cape Henrietta Maria Arch (Fig. 1).

The AFT results collected during phases 1 and 2 of the Hudson Bay project of the GEM program complement those reported for the southern Canadian Shield (Pinet and Brake, 2018) and are integrated in a GEM transarctic project undertaken to collect new low-temperature geochronology data to provide new insights on the four-dimensional exhumation pattern of the Hudson Bay region and adjacent areas. Preliminary interpretation at the country scale 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 the Canadian landmass.

Fluid-inclusion data from mineral-based methods

Fluid inclusions 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 postburial history of a succession. The work done on Upper Ordovician microbial and cement reefs on Southampton Island (*see* above) has led to the recognition of early marine aragonite or high-magnesium calcite (now low-magnesium 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 not only to better constrain the diagenetic evolution of this potential hydrocarbon reservoir (*see* 'Reservoir quality' section), but also to provide some information about early and late fluid chemistries, and temperatures of precipitation, thereby 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 is characterized by high homogenization temperatures (T_h between 72.1°C and 177.4°C; average of 117.9 ± 25°C). These high-temperature estimates clearly point to a nonprimary marine origin for these inclusions and, in combination with the $\delta^{18}O_{VPDB}$ signature of these cements, are suggestive of the presence of high-temperature brines ($\delta^{18}O_{VSMOW}$ of +3‰ to +12‰) at the time of a recrystallization event, when the fluid inclusions were possibly entrapped or reset (Lavoie et al., 2018a). The late calcite cement contains fluid inclusions indicative of lower entrapment temperatures (T_h between 74.3°C and 134.7°C; average of 92.6 ± 9.7°C) from a cooler fluid having a $\delta^{18}O_{VSMOW}$ signature ranging between +1‰ and −2‰.

Clumped-isotope data from mineral-based methods

Context

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

Background

Several naturally occurring CO_2 molecules differ only by their isotopic composition (isotopologues), with masses ranging between 44 and 51 (or 60 and 67 for CO_3 in carbonate), with mass 44 representing by far the most abundant isotopologue ($^{12}C^{16}O^{16}O$) in nature (98.4%). In rarer molecules, containing more than one heavy isotope (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:

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

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 equation 1 (*), are calculated using bulk stable-isotope compositions ($\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$) obtained during the same analysis and expressed in equation 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 as temperature rises (Eiler, 2007).

Relationship between temperature and Δ_{47}

The preliminary relationship between temperature and Δ_{47} values of calcite precipitated at controlled low temperatures is determined for the data collected in the GSC's laboratory (Fig. 6). The resulting relationship compares well with the most recent temperature frames corrected for digestion of carbonate at 90°C (Bonifacie et al., 2017; Kelson et al., 2017; Bernasconi et al., 2018). The preliminary framework of the GSC can therefore be used to estimate the apparent precipitation temperature of natural calcite precipitated at low temperature.

Application to Upper Ordovician carbonate units of the Red Head Rapids Formation

The first application of clumped-isotope systematics was used to investigate 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 synsedimentary cement (Castagner, 2016). All Δ_{47} results shown here were produced during periods of analytical stability as monitored by using the international ETH carbonate, a high-temperature carbonate standard developed at the Geological Institute ETH Zürich, 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 3.4‰. Replacements of marine components with the highest apparent temperature (41°C to 66°C) show the most elevated water values (up to 3.4‰). Late cements yield the lowest temperature range (26°C to 46°C) and the lowest water values (down to −5.7‰; Table 1).

The preliminary data set obtained for the selected samples suggests two possible interpretations: 1) the replacement of original reef material and late pore-filling cements precipitated under 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 that departed 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°C and 46°C, and 41°C and 66°C for late cements and replacements, respectively (Table 1).

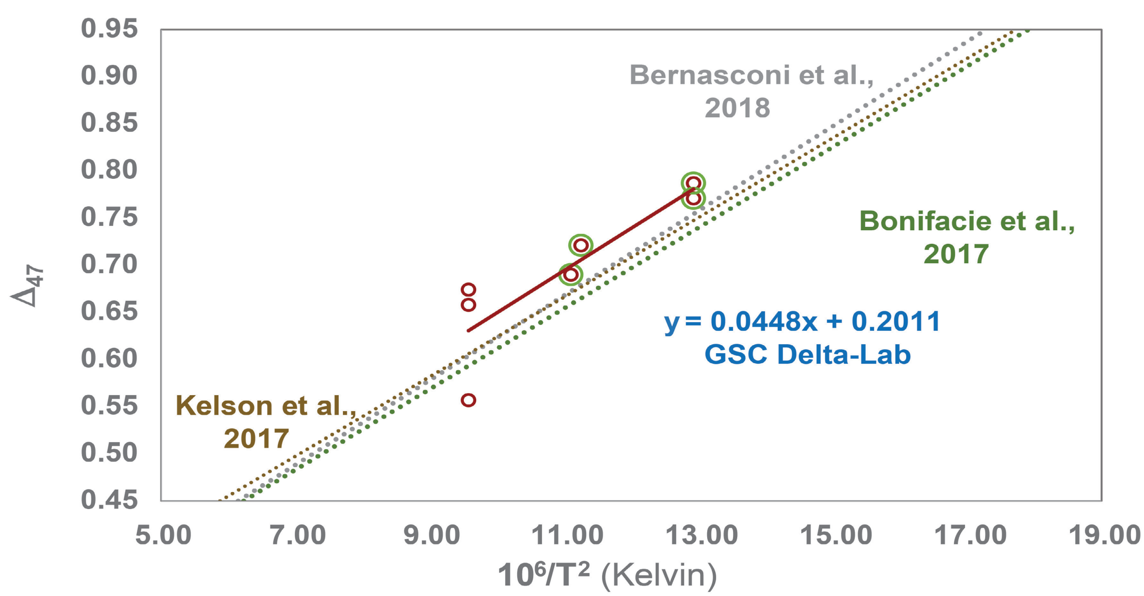

Figure 6. Preliminary temperature frame (June 2018) developed at the Geological Survey of Canada (GSC) Delta-Lab linking temperature to the clumped-isotope analysis results (Δ_{47} in ‰) obtained for carbonates precipitated in the laboratory (solid red line). Green circles show results for carbonates precipitated at 5°C, 25°C, 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 whether the 50°C results are included or not. Dotted lines illustrate the most recent temperature frameworks documented in the literature as indicated.

Table 1. Isotopic results for late cements and diagenetic phases replacing the marine components of the reef carbonate. The clumped-isotope analysis results combined with the preliminary temperature frame (expressed by the equation y = 0.0448x + 0.2011) produce the listed apparent temperatures (T).

Phase	Sample*	δ^{13}C VPDB (‰)	δ^{18}O VPDB (‰)	Δ_{47}CDES+ (‰)	T (°C)	δ^{18}O 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 were treated and analyzed in triplicate
[#] Sample was replicated six times
CDES: carbon dioxide equilibrated scale
VPDB: Vienna Pee Dee Belemnite
VSMOW: Vienna Standard Mean Ocean Water

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 indicate parent-water $\delta^{18}O_{VSMOW}$ values for replacement of the early reef components to range between −2.0‰ to +3.4‰ and show affinities with a marine-water origin (Table 1). The parent-water $\delta^{18}O_{VSMOW}$ values for late cements would be between −5.7‰ and −3.8‰, which result would suggest an influence from lighter parent water. In other words, interpretation of the rough estimates presented here suggests that replacement of early marine phases occurred in warm waters of marine affinities, whereas different proportions of light- and marine-like waters generated the late cements of the Red Head Rapids Formation.

The clumped-isotope– and fluid-inclusion–derived temperatures and parent-water compositions greatly differ. The Δ_{47}-derived $\delta^{18}O_{VSMOW}$ of parent waters for late cements are lower than those obtained using fluid-inclusion results (Fig. 7), but partly overlap with the fluid-inclusion–derived $\delta^{18}O_{VSMOW}$ values for marine replacement phases (Fig. 7). The Δ_{47}-derived temperature ranges (26–46°C, 41–66°C) also significantly differ from the ones obtained through the fluid-inclusion study (Fig. 7) of the late cement (74–134°C; average 93 ± 10°C, n = 26) and replacement phases (72–177°C; average 118 ± 25°C, n = 66), respectively. One replacement sample analyzed using both the clumped-isotope and fluid-inclusion techniques, yielded a Δ_{47}-derived temperature of 66°C, on the low end of the homogenization T (T_h) range (Fig. 7). The discrepancy between the clumped-isotope and fluid-inclusions studies may partly derive from the sampling scope of the two techniques; subsampling for clumped-isotope determination, with preparation from the offline system used here, requires relatively large amounts of carbonate (30 mg, i.e. 10 mg for each of the triplicate samples), whereas T_h measurements operate at the microscale. The fluid-inclusion 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-isotope–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 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-isotope 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 reported alteration under shallow-burial conditions (maximum temperature of 45°C) of the Δ_{47} values in marine limestone 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

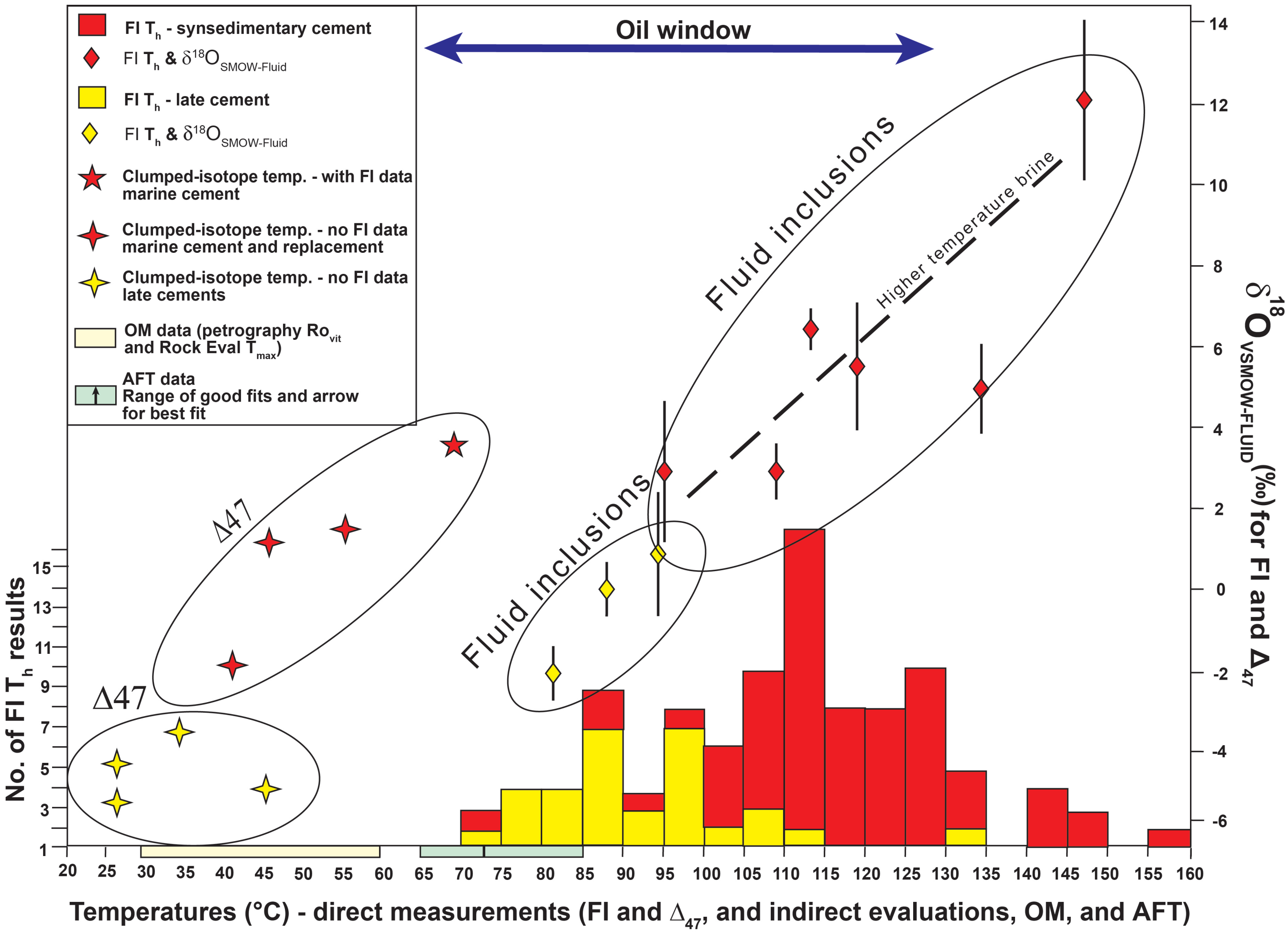

Figure 7. Summary of organic-matter (OM) and mineral-based (fluid inclusion (FI), apatite fission-track (AFT), and Δ_{47}) thermal indicators from the Ordovician succession on Southampton Island. The lozenges represent calcite samples with both fluid-inclusion and $\delta^{18}O_{VPDB}$ data, allowing for the evaluation of the average $\delta^{18}O_{VSMOW}$ of the parent fluid and the associated vertical bar is for the range of fluid-inclusion data for a specific sample. The stars represent calcite samples with temperature (temp.) estimates from clumped-isotope analyses, together with the conventional $\delta^{18}O_{VPDB}$ data from the same calcite allowing to calculate $\delta^{18}O_{VSMOW}$ of the parent fluid. Some clumped-isotope data lower than 20°C are outside the range of the plot. *Modified from* Lavoie et al. (2018b).

~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 thermal evolution or contain Δ_{47} values locked at closing temperatures during cooling.

In closing, further research is required to finalize the temperature frame for the interpretation of clumped isotopes and to validate this preliminary set of data. More importantly, subsampling of carbonates for the purpose of clumped-isotope analysis must be systematically undertaken on the exact counterparts of thin sections used for fluid-inclusion determinations to allow for direct comparison of temperatures derived from the two techniques. In addition, planned research relying on the finer scale analysis of clumped isotopes using an online, automated sample-treatment system, which requires less than 2 mg per carbonate digestion, will help in reaching a final decision relative to the choice of interpretation between options 1 and 2.

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

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

In the offshore domain, the interpretation of the results from the reflectance (R_o) analysis of various organic macerals (Bertrand and Malo, 2012) and AFT (Lavoie et al., 2013; Pinet et al., 2016) analysis suggested that the Upper Ordovician source rocks entered the oil window, even if the two data sets differ in the interpreted magnitude of that event. Detailed re-examination of the Rock-Eval T_{max} data for offshore source rocks from the Upper Ordovician succession suggested that the rocks are immature, with T_{max} values invariably 3°C to 5°C lower than the values of the adjacent nonsource rock interval, but still with acceptable S2 values of 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 TOC and HI in the source rocks, indicating the latter have reached oil-window conditions (Lavoie et al., 2013, 2015); however, interpretation of subsequent analytical results from the analysis of the oil extracted from the immature onshore shale intervals suggested that the T_{max} suppression has limited effects and that the onshore organic-rich intervals are immature (Reyes et al., 2016a, 2018). A detailed study of potential T_{max} suppression is ongoing (Reyes et al., 2019; J. Reyes, C. Jiang, D. Lavoie, S. Zhang, and D.K. Armstrong, work in progress, 2019).

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). Interpretation of organic-matter–based data (T_{max}, organic-matter reflectance and, to some extent, hydrous pyrolysis) suggests 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-rich interval in the central part of the island (type section of the formerly named 'Boas River Shale'; Zhang, 2008).

Interpretation of mineral-based data suggests early oil-window conditions (AFT; Fig. 7), and potential early hydrothermal conditions and oil-window conditions for late cements (fluid inclusions, Fig. 7). Apatite fission-track results (range 65°C to 85°C, best fit 72°C; Pinet et al., 2016) are intermediate, falling between the organic-matter– and mineral (fluid inclusion)–based results (Fig. 7). Analysis of the clumped-isotope results from reef-carbonate material (recrystallized components and late cements) does not suggest high temperatures for both types of carbonates (Table 1 and Fig. 7). This is 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 versus $\delta^{18}O_{VSMOW\text{-}FLUID}$ diagrams for marine replacements and late cements do not show significant overlap for both fluid-inclusion and clumped-isotope data (Fig. 7); for both, the higher temperature is associated with more positive $\delta^{18}O_{VSMOW\text{-}FLUID}$ values (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 that generating data from more than one approach to evaluate the burial-thermal history of a succession is highly desirable.

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 an eroded succession 1500 m thick, 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 (TOC 10 wt %), distributed over a 65 m thick stratigraphic interval (Hu and Dietrich, 2012). 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 significant Type II-S kerogen is seen as a favourable 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 temperatures 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 three-dimensional modelling exercise has been carried out using a similar data set, 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 parameters, whereas 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). The kerogen-transformation ratio within the Red Head Rapids Formation varies between the wells from 6% to 33% for Type II-S and from 2% to 16% for Type II. A favourable 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 limestone, reefs, hydrothermal carbonate breccia, and siliciclastic units. The sedimentary strata within the basin have many similarities to the successions in the Michigan and Williston basins, where Paleozoic carbonate units are significant reservoirs (Anna, 2013; Swezey et al., 2015). 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 the Hudson Bay Basin. Porous sandstone within this interval may form thin, but widespread reservoirs.

Hydrothermal breccia

Carbonate-hosted discordant breccia interbedded with stratiform units is interpreted to be of fault-controlled hydrothermal origin. The breccia zones occur within the Upper Ordovician succession and are known from outcrop on Southampton and Akpatok islands, and core from 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 carbonate units as its formation mechanism is not restricted to a precise time interval (Davies and Smith, 2006).

On Southampton Island, the porous carbonate-hosted breccia occurs in the Upper Ordovician Red Head Rapids Formation and consist of a 10 m to 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 diameter. Fragments are highly angular, unsorted, and have a jigsaw-puzzle fabric suggestive of minor 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% and 25%. Open pore space can be fairly large, up to a few centimetres in diameter, although the effective connectivity between the pores is currently unknown.

Hydrothermal alteration, dissolution, and brecciation have also been observed in cores from some shallow stratigraphic holes drilled near the town of Churchill, Manitoba (Lavoie et al., 2011). The carbonate cements associated with those events share a similar isotopic composition with those on Southampton Island. Because of the limited exposure in the Hudson Bay Lowland, a magnetotelluric survey was carried out to evaluate if this geophysical tool could help with mapping, in the subsurface, the presence and extension of porous carbonate units encased in tight muddy limestone (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 summer 2018 to map out, in the subsurface, the potential hydrothermal carbonate 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 subsurface geological interpretation is ongoing.

Hydrothermal dolomite plays are seismically characterized by the development of seismic fault sags (Davies and Smith, 2006). Even with the low-quality seismic profiles, a significant number of these seismic fault sags are visible on seismic profiles (Lavoie et al., 2013, 2015).

Microbial cement reef

The Red Head Rapids Formation contains large reefal structures of microbial-algal origin. In outcrop, these mounds 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 the evaluation of marine seismic profiles in Hudson Bay, these seismic-scale structures have been interpreted on several seismic profiles (Lavoie et al., 2013, 2015; 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 as well as cementstone (*see* above). The reefs are very porous, and a diagenetic study has been done to constrain the history and timing of porosity evolution with respect to eventual hydrocarbon charging (Lavoie et al., 2018a).

The cementstone is composed of isopachous layers and botryoids of former aragonite or high-magnesium, now low-magnesium calcite cement. Secondary dissolution porosity and small fractures cut 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 with $\delta^{18}O_{VSMOW}$ values ranging 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 the initial, or entrapment of new, fluid inclusions from fracture-controlled circulation of basement-derived fluids (Lavoie et al., 2018a). Interpretation of the petrographic and geochemical data suggests that fracture-controlled high-temperature brine circulation occurred after the inception of burial and recrystallization of original marine cement to low-magnesium 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 diameter, with vertical relief up to 10 m (Suchy and Stearn, 1993). Porous Silurian reef outcrops are found on Southampton Island, as well as in Manitoba and northern Ontario. Seismic data indicate that the reefs are common above structural highs in the central part of the Hudson Bay Basin (Lavoie et al., 2013, 2015).

The study of porosity in the Attawapiskat Formation of Manitoba revealed a complex history represented by a succession of marine, burial, and late-stage meteoric events expressed in multistage calcite, dolomite, and sulphate cements affected by at least two 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 Silurian units have been reported from the Sogepet Aquitaine Kaskattama Province No. 1 well drilled in Manitoba (Johnson, 1971); moreover, oil inclusion, bitumen, and staining are locally present in the Silurian carbonate units of Manitoba (Eggie et al., 2014). Petrophysical studies of wells suggest that bypassed hydrocarbon zones are abundant in the Attawapiskat and Severn River formations (Hu and Dietrich, 2012).

Middle Devonian reservoirs

Carbonate units 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 carbonate. The formation is rich in bitumen, either as pore and/or vug filling or as millimetre- to centimetre-thick stringers impregnating the dolomitic facies (Chow and Armstrong, 2015). On seismic data, interpreted Kwataboahegan reefs are abundant in central Hudson Bay Basin (Lavoie et al., 2013, 2015). Bitumen and gas were encountered in the formation in the Aquitaine et al. Walrus A-71 well (Hu and Dietrich, 2012; Lavoie et al., 2013, 2015).

The Williams Island Formation is the youngest known carbonate formation in the Paleozoic succession of the Hudson Bay Basin. The formation contains porous and brecciated platform limestone, dolostone, and reefs (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 (Swezey et al., 2015).

Reservoir quality

Petrophysical analyses of well-log data indicate that many limestone, dolostone, 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 the release of two recent publications (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 carbonate units, 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%–15%) also occurs in carbonate units in the Silurian Severn River Formation in the Netsiq N-01, Polar Bear C-11, and Narwhal South O-58 wells. Ordovician carbonate units 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 the highest porosity values (10–15%) in the Narwhal South O-58, Beluga O-23, and Netsiq N-01 wells.

Traps and seals

The latest 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 evaporite units, shale, and tight limestone. 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, five conceptual conventional hydrocarbon plays in lower Paleozoic strata in the Hudson Bay Basin were proposed in Lavoie et al. (2013, 2015). 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 drillholes 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 the hydrocarbon potential of the Hudson Bay Basin, Hanna et al. (2018) recognized and defined, on reprocessed seismic data, four of these plays (the salt-dissolution play was not recognized). Moreover, they split some of the plays based on their age, resulting in three structural (Ordovician, Silurian, and Devonian) and two reef (Ordovician, Silurian–Devonian combined) plays.

Risk considerations

Organic-rich limy shale has 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 are still ambiguous. Limited geochemical data indicate that 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 modelling suggests generation, the efficiency of expulsion has not been proven. More information on source-rock geochemistry and kinetic parameters is 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 along riverbanks are anecdotal (Cowell, 1982). 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 No. 1 well, and dead oil in the same formations occurs in the Comeault No. 1 well, both wells onshore Manitoba (Nicolas and Lavoie, 2012; Eggie et al., 2014). Even if no reservoir drill-stem tests were done in any of the offshore wells drilled in the Hudson Bay Basin, gas shows, and bitumen and oil staining were reported in all wells (Lavoie et al., 2013).

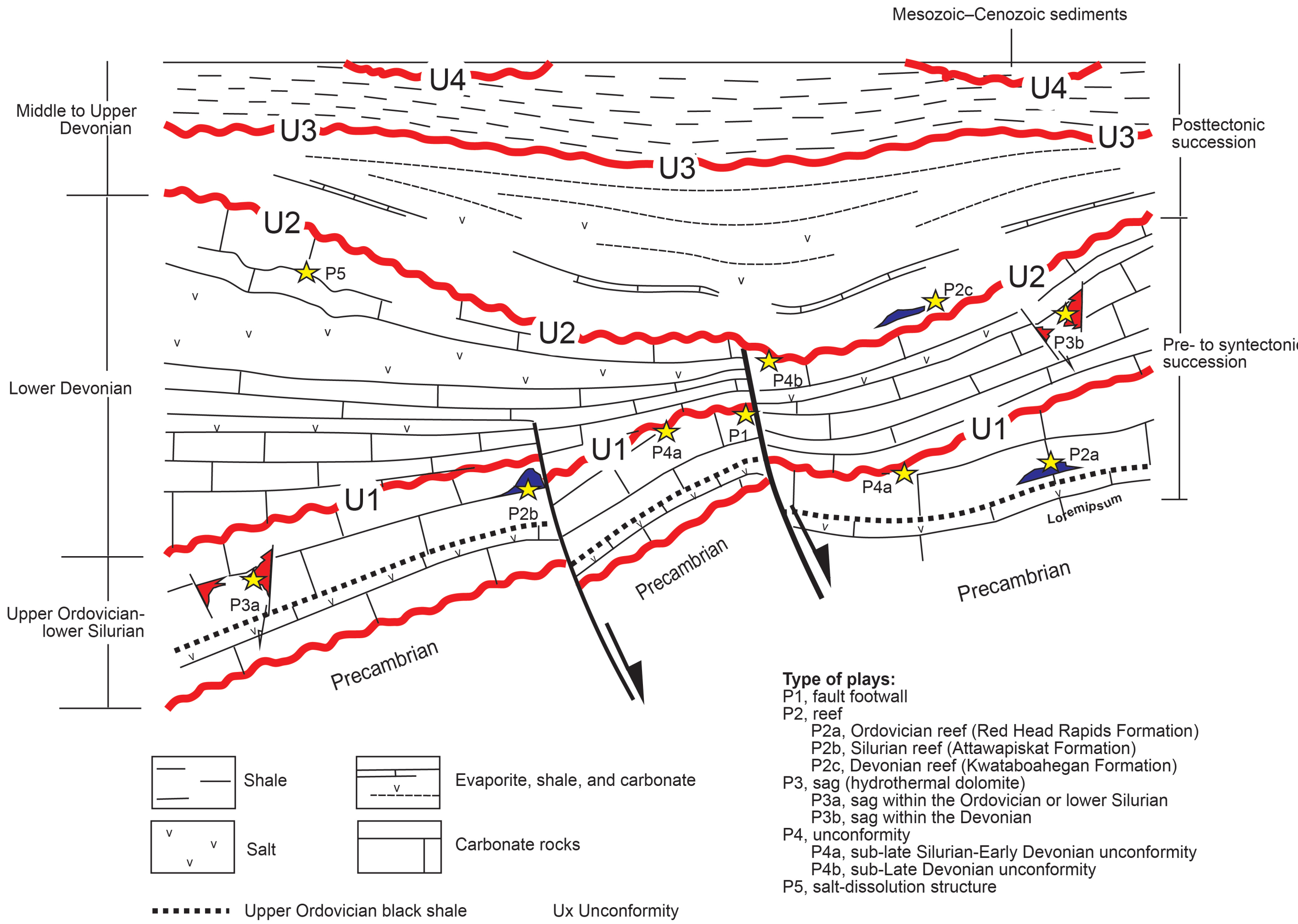

Figure 8. Schematic illustration (not to scale) of conceptual conventional hydrocarbon plays in the sedimentary successions of the Hudson Bay Basin (*modified from* Lavoie et al., 2015).

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

Petrophysical study of well data

Examination of petrophysical data (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 carbonate units in the Kwataboahegan, Attawapiskat, and Severn River formations as well as in Ordovician basal clastic units. The most prospective log-interpreted hydrocarbon zone is a 15 m interval in limestone of the 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 of centres of excellence, while their ship was transiting in the study area. Most of these random linear transects are located in the Hudson Strait, Foxe Channel, and Evans Strait. A few circular depressions (average diameter of 100 m and depth of 10 m; Roger et al., 2011) on the seafloor (pockmarks) have been mapped, but their origin still needs 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 southwestern peninsula of Baffin Island, a mound-shaped feature rises from the seafloor under about 200 m water (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 wide by 70 m high) shares similarities with seep-associated,

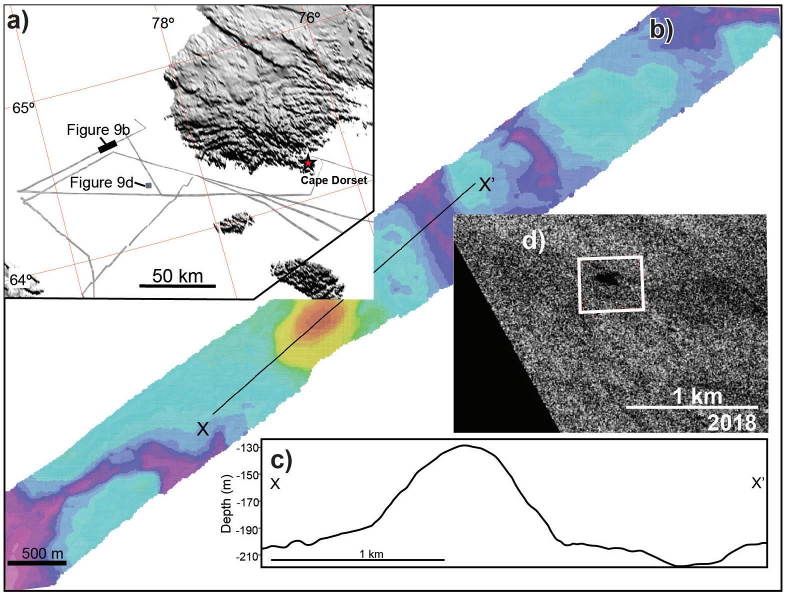

Figure 9. Deep-water mound southwest of Baffin Island: **a)** ArcticNet base map of high-resolution seafloor bathymetry; **b)** close-up of part of a seafloor-bathymetry line (9b on a) showing a map view of the mound feature and colour ranges corresponding to absolute water depths shown on c; **c)** cross-section (X–X' on b) of the mound-shaped feature; **d)** RADARSAT-2 slick anomaly 45 km east of mound show in b (*from* Beauchemin et al., 2018).

deep-water coral mounds described and seismically imaged by Jauer and Budkewitsch (2010) on the eastern side of Baffin Island and the Labrador coast. The development of deep-water mounds with corals (dominated by the scleractinian *Lophelia pertusa*) or without corals has been related to either hydrodynamic sediment accumulations (e.g. mud mounds) from fluid escape and current remobilization (Masson et al., 2003), an initial hydrocarbon seep-related chemosynthetic colonization stage followed by growth fueled by oceanic circulation and nutrient supply mechanisms (De Mol et al., 2002; Sumida et al., 2004), or cold-water chemosynthetic processes associated with hydrocarbon seepage (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 existence west of Baffin Island is unknown. The volume of the cone-shaped mound is about 32 km^3, putting it at the lower end of the size distribution of isolated, hydrocarbon-vent–associated mounds of Cenozoic age described from the Browse Basin, offshore Australia (Van Tuyl et al., 2018). It is noteworthy that this seafloor feature lies 45 km to the west of a multiyear RADARSAT-2 persistent anomaly identified in the image analyses during phase 1 (Decker et al., 2013) and phase 2 (Beauchemin et al., 2018) of the GEM program (Fig. 9). The exact nature of the mound-shaped structure will remain unknown until additional data are acquired.

RADARSAT-2 images of potential oil slicks

During the first phase of the GEM Hudson Bay project, 41 dark targets were identified on RADARSAT-2 images acquired between 2010 and 2012 (Decker et al., 2013). The area covered consisted of the Hudson Bay Basin and Foxe Basin and Channel. Some of the dark targets have semiquatitative characteristics known to be associated with natural oil seeps, including a sharp boundary defining a small enclosed region (<1000 ha), sufficient backscatter contrast (i.e. –10 dB) between the background sea state and the dark region, as well as the 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 GEM Hudson Bay project, 1278 RADARSAT-2 marine images of Hudson Bay and Foxe Channel acquired in fall 2015, 2016, and 2017 were examined, and Hudson Strait was also included in this phase (Beauchemin et al., 2018). 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-slick candidates are reported (*see* Beauchemin et al., 2018 for location and corresponding images). The goal of the multiyear project was to look for persistence over time of sea surface expressions of seep candidates to assist in finding regions where oil seeps have a greater likelihood of originating. As a result, seven 'groups' of repetitive anomalies within a radius of 20 km to 38 km were identified (Beauchemin et al., 2018).

Side-looking airborne radar images of potential oil slicks

During the preparation of the high-resolution seafloor bathymetry for the second phase of the GEM Hudson Bay 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. During their routine surveillance flights, the plane was flown over areas where potential oil slicks were identified on RADARSAT-2 images. In the summer of 2017, the crew reported the presence of a major natural oil slick of 0.33 km^2 at latitude 62°50′20″N, longitude 80°53′58″W (Fig. 10). Two smaller natural oil slicks were also reported (lat. 62°50′07″N, long. 80°53′77″W and lat. 62°50′13″N, long. 80°53′84″W).

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

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 (and (?)Cenozoic) sediments that, at least in the northern part of Hudson Bay, have accumulated in half grabens (Pinet et al., 2013b); however, this observation could be coincidental and more data from the seafloor are critically needed to evaluate this potential relationship. The thickness (and exact age) of this younger than (?)Devonian succession is currently unknown, but it could have been instrumental in increasing the depth of burial of the Upper Ordovician source rocks, at least locally, thus allowing them to reach full maturity conditions and generate significant hydrocarbons. The thicker sedimentary succession deposited in a faulted half-graben could be an important element in defining eventual prospective areas in the Hudson Strait, Foxe Channel, and Evans Strait areas (Fig. 1).

CONCLUSIONS

Phases 1 and 2 of the GEM Hudson Bay project have led to significant improvements in the level of 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 four 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 the 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 press). 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 of critical importance, among other petroleum-system elements, for the distribution and accumulation 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 Baffin Bay, and sediment deposition occurred in disconnected half-grabens. The cumulative effect of the second and fourth phases has resulted in a variable burial history, explaining why some parts of the basin are still immature, whereas other parts may have reached oil-window conditions.

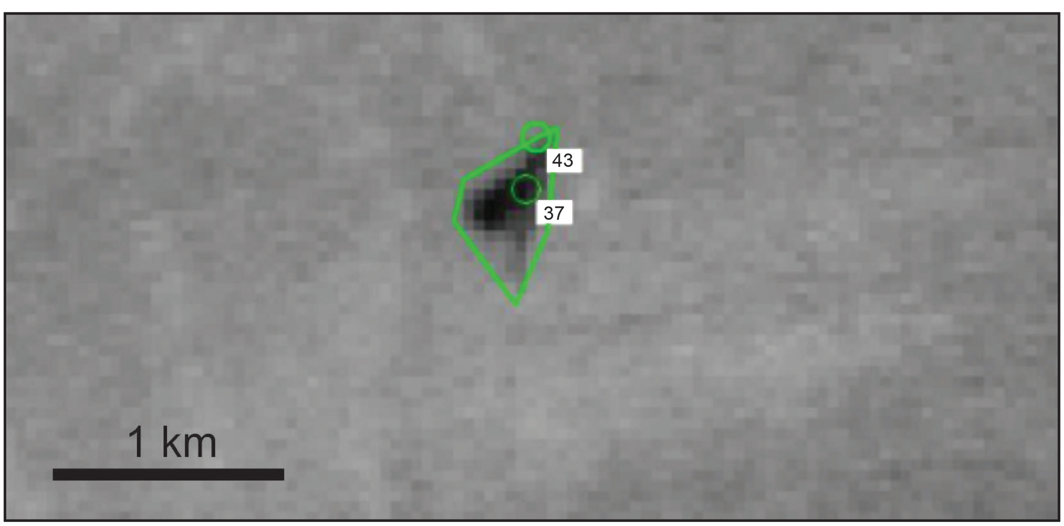

Figure 10. Side-lateral airborne radar image of natural oil slicks northwest of Mansel Island (location shown on Figure 11). The counts of 37 and 43 refer to the automatic detection of oil slicks from radar and include data on surface coverage of the slick and its interpreted thickness. Radar image courtesy of A. Skopalik, Transport Canada.

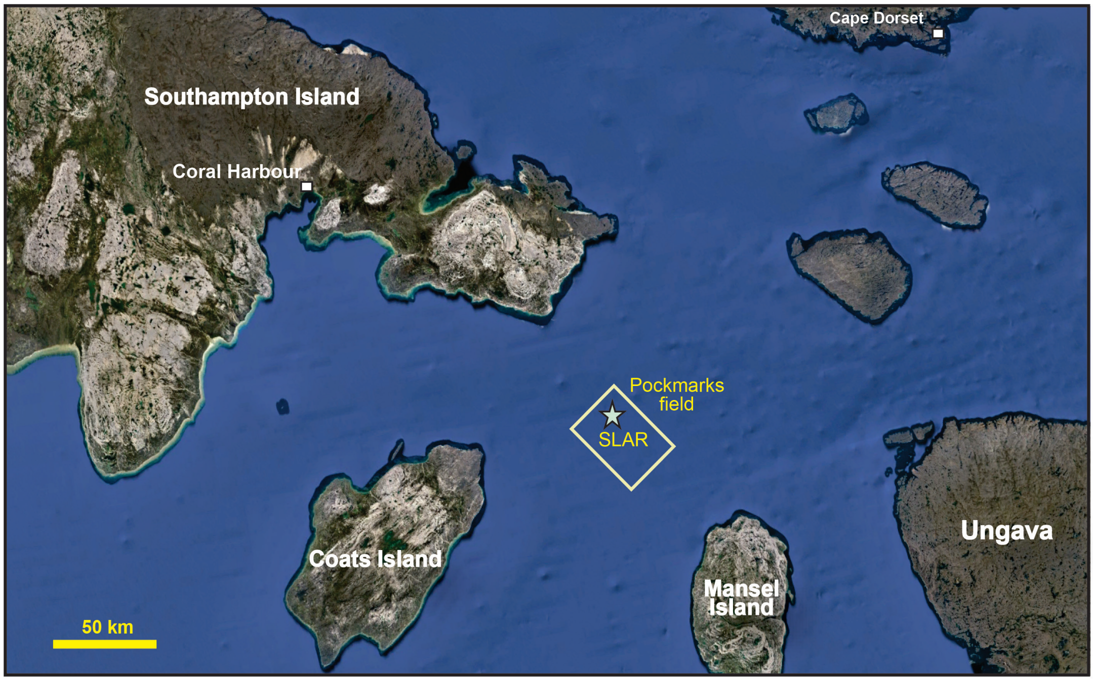

Figure 11. Location of the side-lateral airborne radar image of slicks (star) shown in Figure 10 and pockmark field (box) between Mansel and Coats islands. Map from Google Earth™ (©2019 Google LLC, used with permission; Google, 2019).

- Ordovician to Silurian rocks are widespread over this vast area from Nunavut to Manitoba, and Ontario, for which local stratigraphic nomenclatures were used. A major achievement of the project is the production of a unified stratigraphic framework based on the re-evaluation of type sections and the study of new field sections, coupled with extensive biostratigraphic and chemostratigraphic data. Devonian rock units are absent from Nunavut. A unified stratigraphic framework is presented in this volume and 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). Analysis of the geochemistry of some immature outcrops along the basin's actual margins suggests that the source rocks are very rich in Type II-S organic matter and a significant volume of oil can be generated at a low burial temperature based on artificial thermal-maturation experiments. The source-rock intervals are variable in thickness, a characteristic that probably relates to subtle, and still poorly documented, variations in the synsedimentary morphology of the basin.
- Re-evaluation of vintage and new thermal-maturation data indicates that, in the central part of Hudson Bay, the Upper Ordovician source rocks have reached 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 North American basins.
- Indirect indicators of active petroleum systems have been discovered and preliminarily interpreted. Radar imaging (satellite and airborne) indicates the presence of potential natural oil slicks (still to be confirmed) at the sea surface. High-resolution seafloor bathymetry data are

available for about 1% of the total seafloor. Nonetheless, this limited information led to the recognition of potential venting structures (pockmarks) on the seafloor at two specific localities.

- The co-occurrence of a pockmark field with a potential sea-surface (slick) airborne radar anomaly over an area where a thicker Paleozoic to Mesozoic (+(?)Cenozoic) succession was deposited in a half-graben might provide evidence for a leaking reservoir and support exploration interest for the thicker succession in these half-grabens.

FUTURE WORK

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 intracratonic Michigan 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, is dependent on marine research.

Significant time and effort were invested by project scientists in defining multitools and multipartner marine research projects (seismic reflection, high-resolution seafloor bathymetry, oil-slick and seafloor sampling). Unfortunately, due to a variety of reasons, these projects never materialized. Diverse marine surveys designed to address the four-dimensional evolution and evaluation of the hydrocarbon potential of the largest intracratonic basin in North America would be the obvious next step.

ACKNOWLEDGMENTS

First and foremost, many thanks to K. Dewing and N. Bingham-Koslowski, who took time off from their busy schedule and own syntheses to review this report. Their comments and suggestions are warmly appreciated.

From 2008 to 2018, the significant scientific advances on the Hudson Bay Basin and adjacent areas resulted from the scientific excellence and curiosity of all colleagues involved in the project. These dedicated geoscientists from diverse domains, and from multiple governmental and academic institutions, collaborated on many research themes. All participants were able to rely on many student field and lab assistants, who contributed to the success of the project. The list of authors of this synthesis is limited to government geoscientists and, as such, the authors would like to deeply acknowledge the contributions of many academic colleagues: R. Bertrand, M. Malo, and J. Riva (Institut national de la recherche scientifique – Eau Terre Environnement); J. Roger and P. Lajeunesse (Laval University); A. Castagner and A. Desrochers (University of Ottawa); D. Rudkin (Royal Ontario Museum); J. Jin (University of Western Ontario); E. Turner (Laurentian University); N. Chow and B. Elias (University of Manitoba); G. Young (Manitoba Museum); M. Haghnazar-Liseroudi (University of Calgary); and B. Kohn (University of Melbourne).

The presentation and interpretation of new geoscientific information usually comes after some important preparation and analyses of samples and data collected over the area of interest. The authors express their deepest gratitude to all laboratory personnel in various GSC and other federal, provincial, and university facilities who were instrumental in diligently providing the information and samples to the contributing geoscientists, thus allowing them to proceed. The authors acknowledge the support of M. Luzincourt, A. Smirnoff, and J. Bergeron (Stable Isotope Geochemistry Laboratory (Delta-Lab), Geological Survey of Canada, Québec); K. Lauzière and M. Boutin (Digital Cartography and Photogrammetry Laboratory (LCNP), Québec); P. Girard and A. de Coninck (INRS laboratory, Québec); R. Robinson, P. Webster, M. Obermajer, R. Vandenberg, M. Milovic, and K. Boyce (organic geochemistry and petrology laboratory, Calgary); K. Paull, K. Boyce, D. Then, S. deFreitas, and L. Tingley (conodont preparation laboratory, Calgary); L. Dancey and L. Tingley (palynology laboratory, Calgary); R. Fontaine and W. Dwyer (collections and curations, Calgary); H. Taylor (conodont preparation laboratory, Vancouver); K. Yeung, S. Evers, and J. Bonin (Ontario Geological Survey GIS and drafting); G. Benger, V. Varga, and C. Epp (Manitoba Geological Survey core laboratory). They also thank all administrative support personnel who took care of the heavy burden that comes with such large-scale projects; special thanks to M. Francis (Geological Survey of Canada, Calgary) and L. Chebab (Geological Survey of Canada, Ottawa) for their invaluable help, support, and patience over phases 1 and 2 of the Hudson Bay project, respectively.

Finally, over these years, the first author had the privilege to collaborate with excellent managers for which science was more than just an element in a project, but was rather the element around which everything else should revolve. Of these individuals associated with the Hudson Bay project, M. Fowler and K. Dewing, who were program managers of the hydrocarbon component of phase 1 of the GEM program, and R. Couture and D. Wright, both project managers of the Hudson–Ungava project during phase 2 of the GEM program, deserve special thanks. Their support and,

sometimes valid, criticisms certainly helped to better focus scientific activities, resulting in a more comprehensive and, hopefully, more significant project.

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