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Abstract

Hydrothermal dolostone is one of the major producing hydrocarbon reservoirs in intracratonic basins in North America. The Hudson Platform is the largest intracratonic basin in North America but it is also the least explored. A first round of exploration took place from 1968-1985 period and resulted with the drilling of 5 dry wells in the central part of Hudson Bay and a few dry wells onshore Manitoba and Ontario. The first round of exploration occurred before the recognition of the economic significance of fault-controlled dolostone bodies.

Fault-controlled porous dolostone and dolostone breccia, interpreted to be hydrothermal have been identified at two localities along the northern shore of Southampton Island (northern Hudson Bay). The dolostone breccia is partly cemented by saddle dolomite cement with up to 25% open pore space. In a well drilled near the town of Churchill in NE Manitoba, a 14 m interval of brecciated dolostone with dissolution porosity and partial infill by saddle dolomite cement was identified. In one part of this interval, dolomitization and silicification are physically associated to a vertical fracture that has been crosscut by the core.

Oxygen and carbon stable isotope analyses of the dolomite cement yielded very negative $\delta^{18}O$ ratios similar to those of coeval hydrothermal dolomite in other intracratonic basins. In the absence of microthermometric fluid inclusion data, the interpretation as being the result of precipitation from a high temperature fluid is still a working hypothesis. The $\delta^{13}C$ ratios can be very negative, a situation commonly associated with the presence of biogenic-derived bicarbonate ions in the diagenetic fluid. The $\delta^{18}O$ ratios of groundmass fabric-retentive dolomite have been acquired to compare with those of the saddle dolomite; the former yielded slightly more negative values than those of Upper Ordovician seawater and suggest that groundmass dolomitization likely proceeded from near marine fluid at slightly elevated temperature.

Introduction

Fault-controlled dolostone bodies are significant conventional reservoirs for oil and gas in North America (Davies and Smith, 2006). The first technical description of this type of reservoir is found in Hurley and Budros (1990) from the Michigan basin in the USA. In those days, exploration drilling of structural highs was the norm although some holes drilled on seismic structural lows of the Michigan Basin (the “Albion-Scipio trend”) were producers of a significant volume of oil. It was demonstrated that extensional to transtensional faulting was responsible for brecciation of carbonate units resulting in local collapse of the affected areas and formation of U-shaped synform features visible on the seismic for which the term “sag” was introduced. Within these sags, highly porous dolostone zones were irregularly distributed in the limestone host. Detailed petrographic and geochemical studies resulted with the proposition that high-temperature brines were responsible for significant limestone dissolution and replacement by dolomite, with local massive cementation by saddle dolomite (Searl, 1989). The distribution of dolostone zones and intensity of cementation were linked to active upward circulation of hot brines along fault planes and lateral migration in porous limestone intervals leading to the development of porous dolostone reservoirs (Davies and Smith, 2006).

Following the recognition of fault-controlled dolostone bodies, significant controversy on multiple aspects of this type of play were discussed in the scientific literature (Machel and Lonnee, 2002) and it was difficult to convince exploration companies that in a specific tectonic setting, drilling structural lows in a carbonate platform might prove a wise economic decision. The formation of such reservoirs result from a complex process of early fluid circulation and contrary to common belief, is not limited to a specific geological period but to a specific tectonic environment.

Hydrothermal dolostone reservoirs are now producing large volumes of hydrocarbons in the Ordovician successions of intracratonic basins of the USA (Michigan, Illinois), in the Appalachian basin of eastern USA (New York), in the Jurassic carbonates at the Atlantic margin of Nova Scotia, in the Devonian of the Western Canada Sedimentary Basin and in the largest Jurassic fields of the Middle East (Davies and Smith, 2006).

The development of the hydrothermal dolostone reservoir model is fairly recent relative to the hydrocarbon history in North America and this type of play was overlooked in areas explored prior to the mid-1980s. The intracratonic Hudson Platform in northern Canada was actively explored from1968 to 1985 and five dry wells were drilled on a structural high in the central part of the basin (Hamblin, 2008).

Geological setting

The Hudson Platform (Fig. 1) is located in central Canada, and with a surface close to 600 000km^2 it represents the largest Paleozoic sedimentary basin of Canada (Hamblin, 2008). It is also the largest of the intracratonic basins of North America. The Hudson Platform is however, the least geologically understood of all Canadian sedimentary basins and is a truly frontier basin with respect to hydrocarbon exploration.

The Hudson Platform is limited by tectonic highs or “arches”. The Cape Henrietta Maria Arch separates the platform from the Moose River Basin to the south and the Boothia-Bell Arch marks the limit with the Foxe Basin to the north (Fig. 1).

The onshore extension of the Hudson Platform in Manitoba, Ontario and Nunavut has been studied by means of conventional mapping and stratigraphic surveys (Nelson and Johnson, 1966; Sanford and Norris, 1973; Norris 1993) and a regional stratigraphic framework has been proposed (Sanford and Grant, 1990 and 1998). Local stratigraphic nomenclature however, can still be found on early geological maps and in old well descriptions.

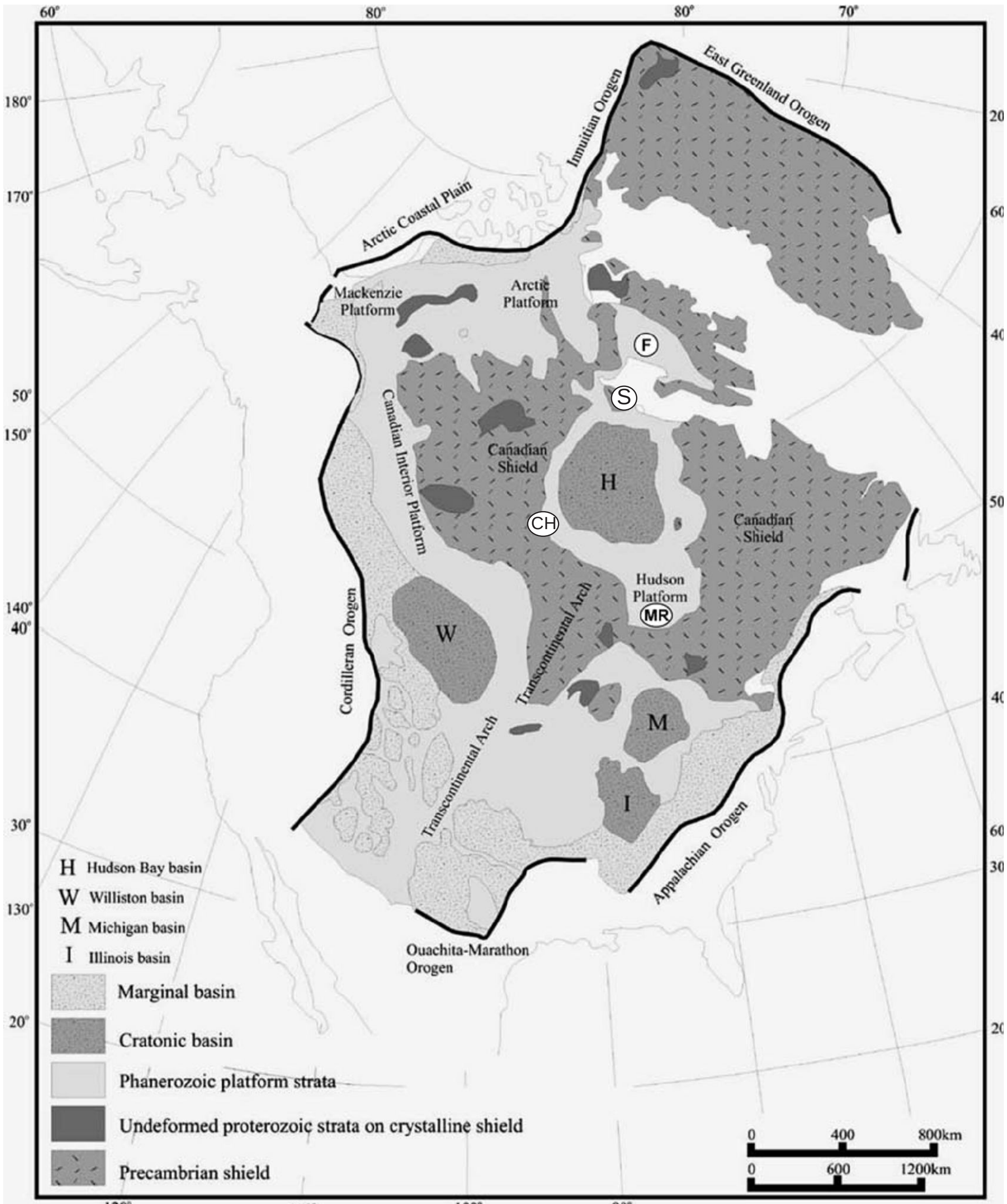

Figure 1: Location of the Hudson Platform and adjacent intracratonic basins in North America. MR is for Moose River basin, F is for Foxe basin and the location of the Rowley well. S is for Southampton Island and CH is for the town of Churchill. Modified from Burgess (2008).

Based on the interpretation of poor to fair quality marine seismic reflection data, a maximum thickness of 2.5km of preserved strata has been proposed (Sanford and Grant, 1998; Hamblin, 2008). The stratigraphy of the Hudson Platform (Fig. 2) can be summarized as being represented by an Upper Ordovician to Lower Silurian shallow marine carbonate platform with local reefs, overlain by Upper Silurian mixed clastic and evaporite.

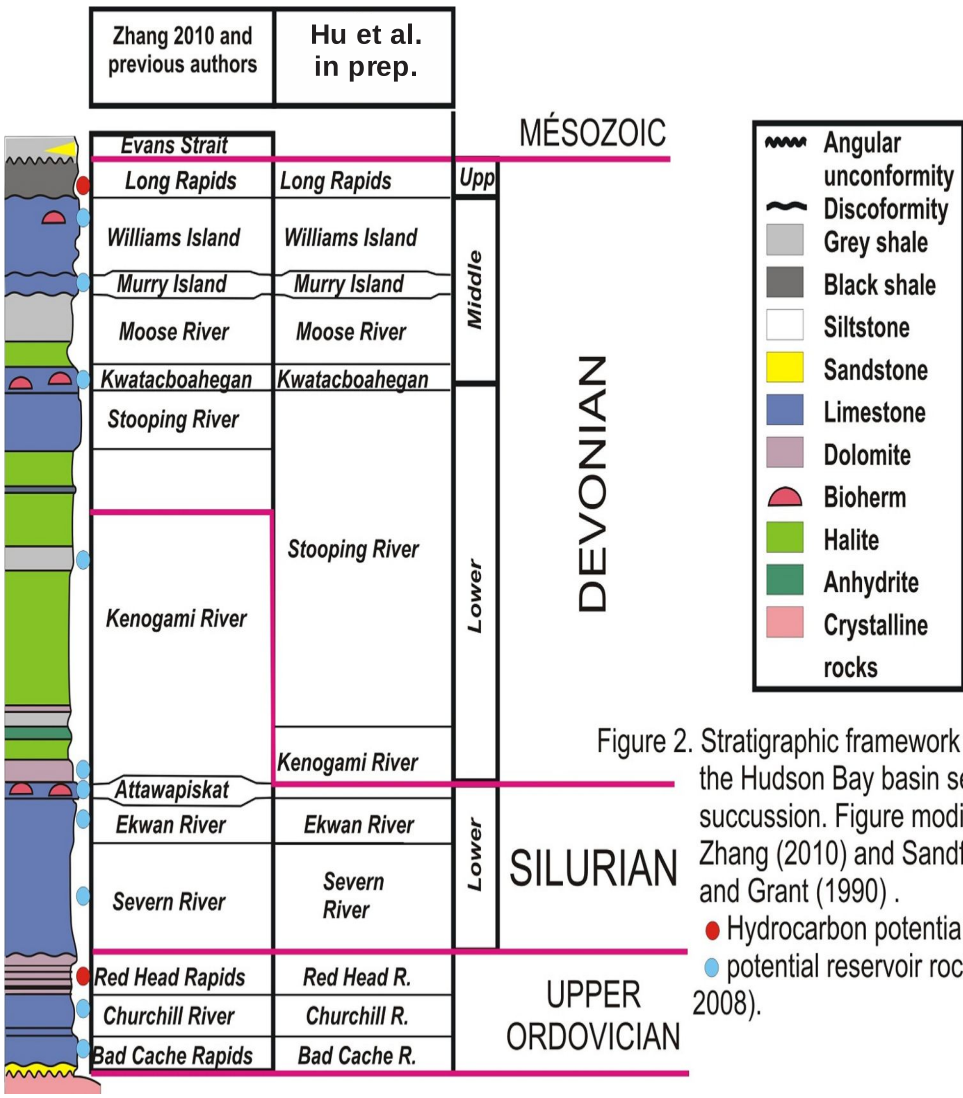

Figure 2. Stratigraphic framework of the Hudson Bay basin sedimentary succession. Figure modified from Zhang (2010) and Sandford and Grant (1990) . ● Hydrocarbon potential source rocks ● potential reservoir rocks (Hamblin, 2008).

A significant hiatus occurred from the late Silurian (Pridolian) to Early Devonian (Lavoie et al., 2011). A thick Lower Devonian evaporite succession is overlain by a Middle to Upper Devonian carbonate platform with local reefs and minor clastics. Finally, uppermost Devonian fine grained clastics are found at the top of the preserved Paleozoic sedimentary accumulation.

The Paleozoic succession is unconformably overlain locally by a Jurassic (?) - Cretaceous diversified assemblage of lacustrine, fluvial and marine clastic facies (Hamblin, 2008). A recent detailed palynological study of interpreted Mesozoic-aged clastics in northern Ontario has led to the identification of abundant and diversified Mid-Tertiary to Pliocene pollen and spores mixed with likely reworked Late Cretaceous palynomorphs (Galloway, 2011). Similar mixed Mesozoic-Cenozoic assemblages are reported in Manitoba (Galloway, 2011) and in the Narwhal well in Hudson Bay (Williams and Barss, 1976). The map distribution of post-Paleozoic sediments beneath the waters of Hudson Bay relies on the interpretation of high-resolution seismic data and remains largely hypothetic.

Hydrothermal dolostone in Hudson Platform and Arctic Platform

Two field sections on Southampton Island at Cape Donovan (Zhang, 2008, 2010 and Fig. 1) and one core drilled near Churchill in Manitoba (Fig. 1) have yielded megascopic, microscopic and geochemical evidence of hydrothermal dolomite.

Southampton Island – Field occurrence

The first and best section that hosts the interpreted hydrothermal dolostone is located at 64°45'39.8"N, 82°22'30.1"W on the northern coast of Southampton Island (Zhang, 2008, 2010). The dolostone occurs in the Upper Ordovician Red Head Rapids Formation and consists of a 10 – 15 m thick massive dolostone breccia (Fig. 3a) with dolostone and limestone clasts cemented by coarse-grained dolomite cement (Fig. 3b). The highly brecciated zones irregularly alternate with metric areas where the well-bedded facies is preserved. The 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 (Fig. 3c) suggesting little displacement and hydraulic fracturing. The breccia is associated with fractures and faults with a general orientation of N187/70. The highly fractured zone is 15 meters wide.

The dolomite cement imperfectly fills the pore space between carbonate clasts resulting in a highly irregular distribution of pore space in the outcrop with values visually estimated to vary between 5 to 25% (Fig. 3b and 4a). Open pore space can be fairly large, up to a few centimetres in diameter; although the effective connectivity between the pores is currently unknown. The abundance of cement is seemingly controlled by its location within the fracture zone with decreasing cement abundance moving away from the main fault; eventually, the breccia is essentially clast-supported with no visible cement (Fig. 4b).

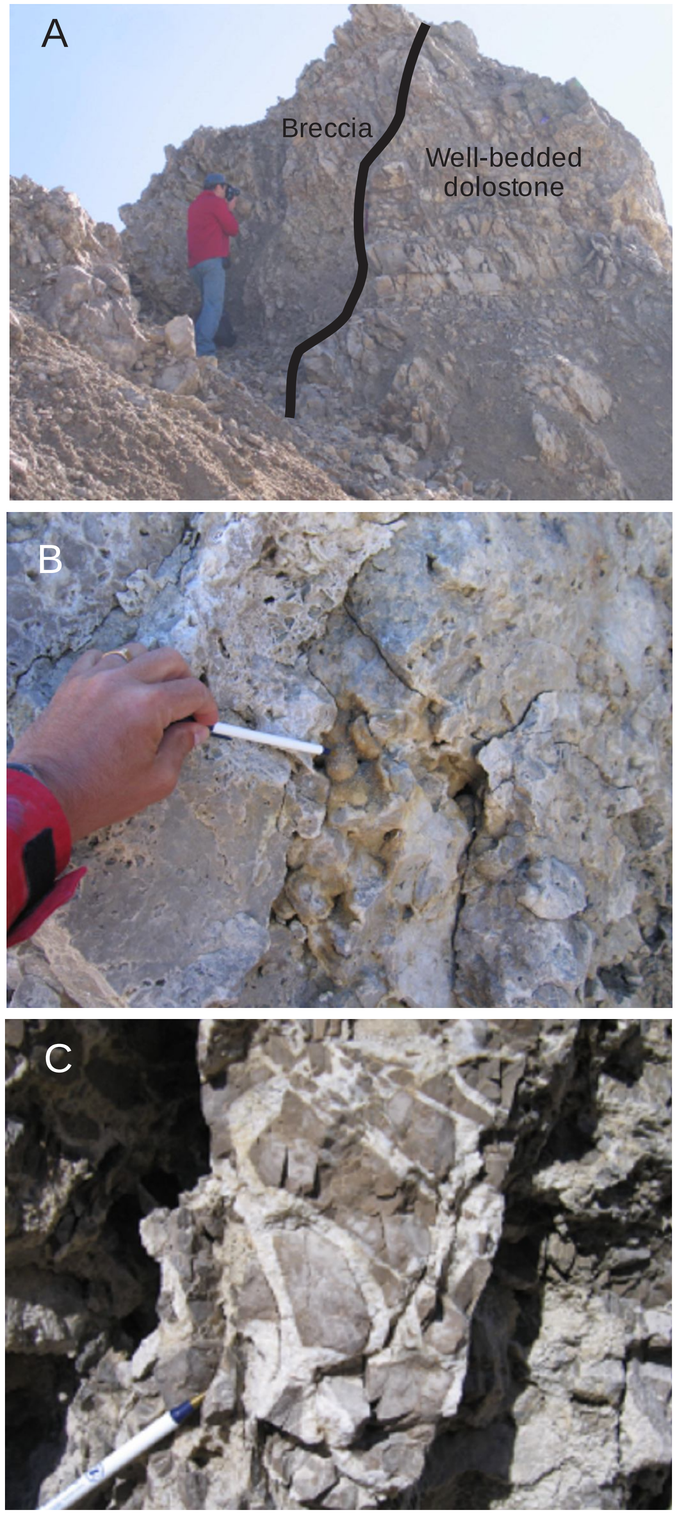

Figure 3: A) Faulted-contact between massive dolostone breccia to the left and well-bedded dolostone to the right. B) Massive dolostone breccia with saddle dolomite cement and 20% open pore space with pen pointing to a large pore. C) Dolostone breccia with jigsaw-puzzle texture healed by isopachous layers of saddle dolomite.

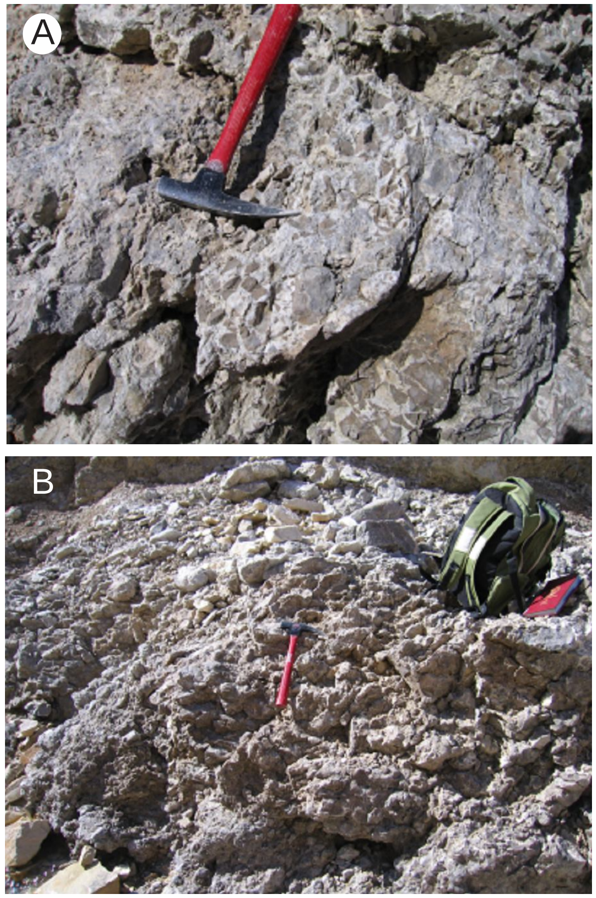

Figure 4: A) Dolostone fragments cemented by isopachous rinds of saddle dolomite cement. B) clast-supported (cement-free) dolostone breccia away from the fluid-feeding fracture.

A second section, adjacent to the first, (64°45'30.1"N, 82°22'03.6"W) presents fault-controlled dolomitized intervals. The dolomitized bodies are more massive with less open pore-space and cement. The dolomitized zone is approximately 12 meters wide and is limited by extensional fractures.

Core M-04-03 – Churchill Manitoba

The well M-04-03 was a stratigraphic well drilled in 2003 by the Manitoba Geological Survey near the town of Churchill in northeastern Manitoba (58,73° N - 93,82°W). This well was part of a 5 well drilling program aimed at understanding the subsurface geology near Churchill. The well was drilled to a total depth of 102.8 m with the contact between the Precambrian metamorphic basement and the overlying Paleozoic succession measured at 99.6 m. The Paleozoic succession is dominated by various dolomitic facies. Dolomicrite strongly dominates the sedimentary section. Locally, dolomicrite is associated with thin (cm) zones of ‘crinkly-laminated’ dolomudstone, possible cryptomicrobial mats and at places, sulphate nodules (up to 5 %) that range from a few mm to the core diameter (5 cm) encased in the dolostone. Interspersed in the dominant dolomicrite are cm-thick layers of intraclastic and bioclastic (gastropods) dolowackestone and dolopackstone that compose up to 10 % of the core(?).

From 53 m to 67 m, brecciated and porous dolomitic facies form up to 30 % of the core. Decimetric porous and locally brecciated intervals are irregularly found in the dolomicrite facies. (Fig. 5a). Dissolution porosity is present at some intervals and open pore space can be significant. In addition to up to 20 % open pore space the pore throat can measure as much as 4 cm. Dolomite cement was insufficient to entirely fill pore space (Fig. 5b). Millimetre-sized isopachous layers of coarse-grained dolomite cement locally rim pore walls (Fig. 5a). At 66.2 m, a vertical fracture cut through the carbonates and was the conduit for fluid migration as silicification and dolomitization are spatially controlled by this fracture (Fig. 5c).

Petrography of pore-filling dolomite in Core M-04-03

Saddle dolomite cement is present as a pore-filling phase or as a rim on partially open pore space. The saddle dolomite is euhedral, coarse-grained (up to 2 mm in size) and displays the typical sweeping extinction. The saddle dolomite is loaded with abundant dark inclusions that define the growth zone. Associated with the pore space, sulphate laths and quartz cements sometimes post-date the earlier dolomite cement.

Away from pore space, small interlocking planar (non-saddle) dolomite crystals form

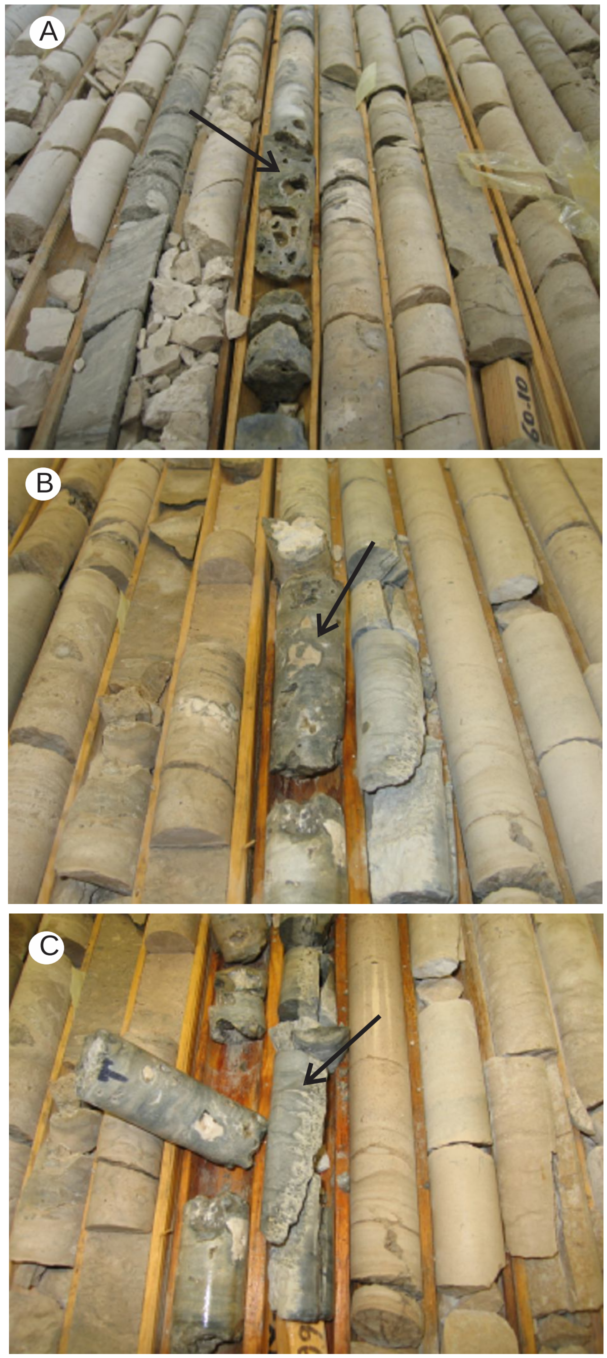

Figure 5: A) Highly porous dolomitic breccia interval with saddle dolomite rind (arrow) on pore wall. B) Dissolution porosity (arrow) filled with saddle dolomite cement. C) Vertical fracture (arrow) separating a silicified and dolomitized zone to the right and largely unaltered carbonates to the left. All core diameters are 5 cm.

the groundmass of the dolomitic facies. This groundmass is facies-retentive as depositional laminations are still visible and testifies to an early to shallow burial origin.

Stable isotope signature of dolomites in the Ordovician section of the Hudson Platform and Arctic Platform

$\delta^{18}O$ and $\delta^{13}C$ ratios are routinely acquired to provide preliminary ideas on the origin of the dolomite phases. 20 dolomite samples from Southampton Island, M-04-03 and M-05-03 wells in Manitoba and Rowley well in the Foxe Basin (Fig. 1) have been analyzed for their $\delta^{18}O$ and $\delta^{13}C$ ratios (Table 1 and Fig. 6). The analyses were done at the GSC Delta Lab and all data is reported relative to the VPDB standard; precision on both isotopes is better than 0.1 ‰.

Saddle dolomite cement – Six dolomite samples from the Cape Donovan section on Southampton Island and 7 samples from the Core M-04-03 in Manitoba have been analyzed (Table 1 and Fig. 6). The Southampton saddle dolomites have yielded $\delta^{18}O$ ratios ranging between –14.2 and –12.4 ‰ and $\delta^{13}C$ ratios comprised between –4.6 and –3.1 ‰. The saddle dolomite cement in Core M-04-03 has yielded $\delta^{18}O$ ratios ranging between –17.4 and –10.3 ‰ and $\delta^{13}C$ ratios comprised between –8.3 and –1.4 ‰.

Locality	Sample ID	Nature	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
Southampton	DL-1	Saddle dolomite	-13,3	-3,8
Southampton	DL-1	Saddle dolomite	-12,4	-3,4
Southampton	DL-2	Saddle dolomite	-13,9	-3,1
Southampton	DL-2	Saddle dolomite	-14,2	-3,4
Southampton	DL-15	Saddle dolomite	-13,7	-4,3
Southampton	DL-15	Saddle dolomite	-13,3	-4,6
M-04-03 core	DL-7	Saddle dolomite	-15	-2,6
M-04-03 core	DL-7	Saddle dolomite	-16,2	-4,1
M-04-03 core	DL-8	Saddle dolomite	-15,4	-1,6
M-04-03 core	DL-8	Saddle dolomite	-10,3	-1,4
M-04-03 core	DL-9	Saddle dolomite	-16	-5,4

M-04-03 core	DL-10	Saddle dolomite	-14,1	-4,6
M-04-03 core	DL-12	Saddle dolomite	-17,4	-8,3
M-04-03 core	DL-3	Groundmass dolomite	-7	1,4
M-04-03 core	DL-4	Groundmass dolomite	-6,3	-0,4
M-04-03 core	DL-5	Groundmass dolomite	-6,1	0
M-04-03 core	DL-6	Groundmass dolomite	-6	0,2
M-05-03 core	DL-11	Groundmass dolomite	-7,8	-1
Rowley core	DL-13	Groundmass dolomite	-4,7	-5,1
Rowley core	DL-14	Groundmass dolomite	-4,5	-2,9

Table 1: δ18O and δ13C ratios of dolomites in the Hudson Platform and Foxe basin.

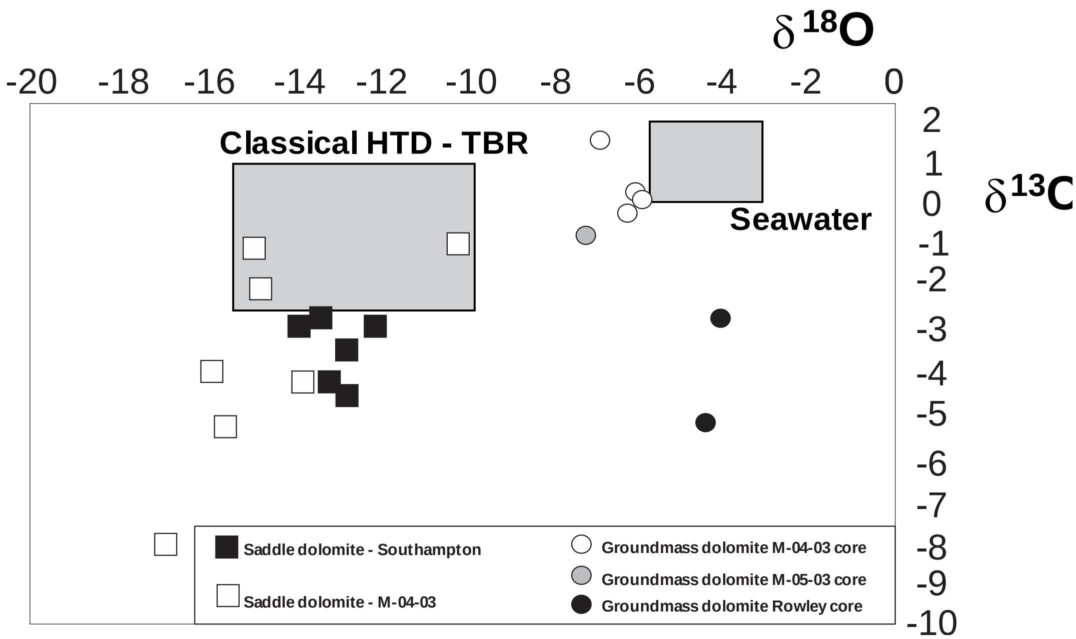

Figure . 6: $\delta^{18}O$ vs $\delta^{13}C$ plot for saddle dolomite and groundmass dolomite from various localities in the Hudson platform and Foxe Basin. Classical HTD-TBR refers to hydrothermal dolomite found in the Trenton and Black River Groups.

Fabric-retentive dolomite – Seven fabric-retentive groundmass dolomite from the Upper Ordovician sections in cores M-04-03 (n = 4) and M-05-03 (n = 1) in Manitoba and Rowley core (n = 2) in the Foxe Basin have been analyzed (Table 1 and Fig. 6). The samples from Manitoba have yielded $\delta^{18}O$ ratios ranging between –7.8 and –6.0 ‰ and $\delta^{13}C$ ratios comprised between –1.0 and +1.4 ‰ . The two samples from the Rowley well have yielded $\delta^{18}O$ ratios of –4.7 and

−4.5 ‰ and $\delta^{13}C$ ratios of −5.1 and −2.9 ‰.

Preliminary interpretation of stable isotope ratios – The stable isotope ratios of the saddle dolomite cements and the fabric-retentive groundmass dolomites define two very distinct $\delta^{18}O$ fields (Fig. 6). The saddle dolomites are characterized by very negative ratios whereas the groundmass dolomite is significantly less negative. However, both types of dolomites have $\delta^{13}C$ ratios that largely overlap and are characterized by a significant scatter of values.

It is hazardous to interpret dolomite origin only based on $\delta^{18}O$ and $\delta^{13}C$ ratios as in order to compare values, an understanding of the temperature of precipitation and / or the isotopic composition of the diagenetic fluid has to be acquired. This is commonly done through microthermometric analyses of fluid inclusions, a type of study which is not yet available for the Hudson Platform dolostone.

The $\delta^{18}O$ ratios of the groundmass dolomite are slightly more negative (Fig. 6) than the accepted values for Upper Ordovician seawater values (Shields et al., 2003); this is preliminarily interpreted as precipitation / replacement in the presence of a near-seawater fluid at slightly elevated temperature. The $\delta^{18}O$ ratios of the saddle dolomites are more widespread than those of the groundmass dolomite, however, they are significantly more negative than the latter and are in the general range of $\delta^{18}O$ ratios for saddle dolomite cements in the Upper Ordovician successions ("Trenton-Black River") in southern Quebec (Lavoie and Chi, 2010) and New York (Smith, 2006). The scatter of the data, and especially those from the M04-03 well, preliminarily suggests that precipitation could have occurred at very different (but elevated) temperatures and from fluids that might have variable $\delta^{18}O$ compositions.

The $\delta^{13}C$ ratios for both type of dolomites are very scattered and range from near normal marine bicarbonate source to very negative, the latter values are commonly found associated with the presence of biogenic-derived HCO_3^- in the diagenetic fluid. Interestingly, the most negative $\delta^{13}C$ ratios are found in dolomites (saddle and groundmass) that originate from the northern domain of the basin (Southampton Island and Rowley well). Further work is needed to determine if this is related to a geological cause or simply relates to the small size of our dataset.

Conclusions

Hydrothermal dolostones form major producing hydrocarbon reservoirs in intracratonic basins in the central part of North America. The identification and characterization of this specific type of hydrocarbon play was unknown during the first round of exploration of the Hudson Platform.

Fault-controlled dolostone bodies were identified at two sections at Cape Donovan on the northern shore of Southampton Island. The occurrences consist of thick dolostone breccia imperfectly cemented by coarse saddle dolomite cement. The cement abundance is higher close to a major feeding-fracture and away from that structural element, the breccia is cement-free and clast supported. Up to 25 % of pore space is visible in hand specimens. Brecciated dolomitic zones with dissolution porosity filled by saddle dolomite cement were logged in Core M-04-03 drilled near the town of Churchill in northeastern Manitoba. The saddle dolomite cement is associated with some sulphate and quartz cements. This altered zone has only be seen in one of the 5 wells drilled in that area by the Manitoba Geological Survey, but has been recently reported in the Silurian section of the Comeault well in eastern Manitoba (M. Nicolas, 2011 pers. comm. to D.L). Moreover, 2 dolostone breccias (10 m and 1 m) in the Upper Ordovician carbonates were cut by industry wells recently drilled in south Baffin Island.

Very negative $\delta^{18}O$ ratios and a wide scatter of $\delta^{13}C$ ratios characterize the stable isotope composition of saddle dolomite cements from the Upper Ordovician section on Southampton Island and in Manitoba. The $\delta^{18}O$ ratios are in the general field of values for hydrothermal dolomites in Upper Ordovician successions elsewhere. The very negative $\delta^{13}C$ values could be the result of incorporation of biogenic-derived bicarbonate ions in the diagenetic fluid.

The recognition of hydrothermal dolomites in the Hudson Platform generates new ideas on hydrocarbon plays in the Hudson Bay Platform, a hypothesis initially put forward by Sanford and Grant (1990). Re-examination of vintage seismic data allows to identifying possible "sag-like" structures similar to those of the intracratonic basin in North America.

Acknowledgments

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