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2011

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doi:10.4095/288027

This publication is available from the Geological Survey of Canada Bookstore
(http://gsc.nrcan.gc.ca/bookstore_e.php).
It can also be downloaded free of charge from GeoPub (http://geopub.nrcan.gc.ca/).

Recommended citation
Lavoie, D., Obermajer, M. and Fowler, M.G., 2011. Rock-Eval/TOC Data from Cambrian-Ordovician of the Saint Lawrence Platform and Humber Zone, and Silurian-Devonian of the Gaspé Belt Successions, Quebec; Geological Survey of Canada, Open File 6050, 1 CD-Rom.

ABSTRACT

Results from over 3600 Rock-Eval/TOC analyses are provided for Paleozoic rock samples that originate from either 66 petroleum exploration wells or from outcrop locations in southern and eastern Quebec. Each sample is assigned to a stratigraphic unit.

EXPERIMENTAL

Rock-Eval/TOC analysis provides fast and reliable characterization of the quantity and quality of sedimentary organic matter, as well as its thermal maturity. Pyrolysis experiments were conducted using Delsi Rock-Eval II and Rock-Eval VI units equipped with a Total Organic Carbon analysis module.

A typical Rock-Eval II experiment was initiated with heating of a pulverized rock sample at 300ºC for 3 min in helium atmosphere, when naturally occurring hydrocarbons (free and adsorbed) are volatilized. During the next stage, the oven temperature is steadily increased to 600ºC at a rate of 25ºC/min and decomposition of kerogen occurs. The final stage involves oxidation and combustion of the residual organic matter at 600ºC. The amount of hydrocarbons volatilized at 300ºC and evolved from kerogen at 300ºC to 600ºC is quantitatively determined by a flame ionization detector, and recorded as the S1 and S2 peaks, respectively. The temperature measured at the maximum of the S2 peak is referred to as Tmax. The quantity of organic CO_2 generated from 300ºC to 390ºC, determined by a thermal conductivity detector, comprises the S3 peak. The percentage of carbon in CO_2 formed during oxidation at 600ºC and in the hydrocarbon peaks S1 and S2 is used to define the total organic carbon content (TOC), expressed as a weight percentage. The determination of the quality of organic matter is based upon the calculation of Hydrogen (HI) and Oxygen (OI) indices (HI=S2/TOCx100, OI=S3/TOCx100) which are related to the atomic H/C and O/C ratios (Espitalié et al., 1977).

The OI versus HI cross plots ("pseudo van Krevelen diagrams") can be used as an organic matter type indicator at low and moderate maturities. The Tmax is an indicator of relative thermal maturity. According to Espitalié et al. (1985) the oil window is defined by the following Tmax ranges:

440º-448ºC (Type I), 430º-455ºC (Type II) and 430º-470ºC (Type III). A cross plot of Tmax versus HI is used to constrain estimations of organic matter type and its thermal maturity, while the Production Index (PI=S1/[S1+S2]) is used to indicate staining of a sample or as an additional maturity parameter.

The tables also contain additional parameters specific to Rock-Eval 6 analysis that are not provided by the Rock-Eval II. These are % MINC which is the percent of carbon derived from inorganic sources and PC and RC which are the percent of pyrolyzable and residual (i.e. inert) carbon respectively, which together add up to % TOC. There are three OI values provided by the Rock-Eval 6 as this instrument is capable of distinguishing carbon monoxide (OICO) and carbon dioxide (not provided in tables) and these are combined to give the true Oxygen Index (OI). TPKS2 is the actual temperature in the oven at the top of the S2 peak. A correction is made to give a Tmax value equivalent to that provided by the Rock-Eval II instruments where the thermocouple was located further away from where the sample was pyrolized. For the majority of these samples, Tmax is about 39°C lower than the TPKS2 value.

GUIDELINES FOR INTERPRETATION

Various authors have discussed guidelines for the interpretation of Rock-Eval data (e.g. Espitalié et al., 1985; Peters, 1986 Lafargue et al., 1998). Rock-Eval/TOC parameters have significance only above threshold TOC, S1 and S2 values. If TOC is less than less than or equal to 0.3% then all parameters have questionable significance. Oxygen Index (OI = S3/TOC) has questionable significance if TOC is less than or equal to 0.5% and Tmax if S2 values are less than about 0.20 mg HC/g rock. Results can be affected by mineral matrix effects, especially in lower TOC content samples. These either retain generated compounds, generally lowering the S1 or S2 peaks, while increasing Tmax, or can also liberate inorganic CO_2 and thus increase S3 and OI. These effects are more significant if TOC, S1 and S2 are low. OI values greater than 150 mg/g TOC suggest either low TOC or a mineral matrix CO_2 contribution during pyrolysis. Note that TOC and Hydrogen Index decrease with increasing thermal maturity due to hydrocarbon generation. A threshold of 2% TOC is generally believed to be necessary for rock to source economic accumulations of liquid hydrocarbons although units with lower TOC contents can contribute to gas accumulations.

It should be emphasized strongly that the data presented here is from the analysis of all samples provided to the GSC laboratory over the years for Rock-Eval analysis. Thus samples represent a variety of facies and lithologies and not just those thought to be possible source rocks. This explains why many of the samples have very low TOC contents. Many of the samples from wells are cuttings and thus represent lithologies over a depth interval such as 10 m and hence will tend to have lower TOC contents than core samples or outcrop where one lithology was preferentially sampled. Formation names are those provided by the originator of the sample or the well operator and may not be correct or correspond to present day stratigraphy for the sample locality.

In the accompanying files, the data is split between field and well samples and between the geological domains. Note that for some wells in the St. Lawrence Platform section (A160, A163, A185, A187, A194), drilling was spudded in tectonic slivers of the Humber Zone to end-up in the underlying autochthonous platform succession. They were listed in with the remaining A wells for consistency. For each of these data sub-sets, histograms of all TOC values are presented as well as HI versus OI plots where only those values with S2 higher than 0.2 mg HC/g rock are used.

This report contains files (*.xls format) with Rock-Eval/TOC data archived at GSC-Calgary. These files include the following data fields:

Sample Data

1. SAMP_ID – a GSC-Calgary curation number
2. LOC_ID – Location ID/Unique Well Identifier
3. LOC_NAME – Section name/Well name
4. SAMP_LAT – Surface Latitude
5. SAMP_LONG – Surface Longitude (negative is west)
6. DEPTH_FROM – Depth of sample top from Kelly Bushing. May sometimes be sample midpoint.
7. DEPTH_TO – Depth of sample base
8. DEPTH_UNIT – Feet or Metres
9. EQUIP_TYPE – Rockeval II or Rockeval 6

Rockeval Parameters:

10. TOC - Total Organic Carbon (weight percent)
11. TMAX - maximum temperature at S2 peak (ºC)
12. S1 - hydrocarbons volatilized at 300ºC (mg HC/g rock)
13. S2 - hydrocarbons evolved from kerogen at 300ºC to 600ºC (mg HC/g rock)
14. S3 - organic CO_2 generated from 300ºC to 390ºC (mg/g rock)
15. RC – residual carbon
16. PC – pyrolysable carbon
17. MINC – mineral carbon
18. HI - Hydrogen Index (mg hydrocarbons/g organic carbon)
19. OICO - Oxygen Index CO (mg CO/g organic carbon)
20. OI - Oxygen Index CO_2 (mg CO_2/g organic carbon)
21. TPKS2 – maximum temperature of surface S2
22. S3CO – CO from organic and mineral sources
23. PI - Production Index (S1/[S1+S2])
24. UNIT – stratigraphic unit

REGIONAL GEOLOGICAL SETTING OF THE PALEOZOIC SUCCESSIONS IN QUEBEC

The Paleozoic basins of Quebec are hydrocarbon frontier basins that are immediately adjacent to some of the most densely populated areas in North America. The onshore segments of the primarily Lower Paleozoic basins of Quebec have been the subject of recent geological framework studies over the last decade (1 National Mapping and 1 Targeted Geoscience Initiative projects) that provided considerable information on the hydrocarbon potential in this area. The offshore extension of these basins has not been studied since the 1980s.

The Paleozoic successions can be assigned to distinct basins based on their age, tectonic history and hydrocarbon systems (Lavoie, 2008; Lavoie et al., 2009):

1- The Cambrian-Ordovician St. Lawrence autochthonous shallow marine platform of southern Quebec and Anticosti and its coeval allochthonous deep water facies (now preserved in the Taconian Humber and Dunnage zones of the Quebec Appalachians)(Figure 1);

2- The Silurian-Devonian shallow to deep marine Gaspé Belt in eastern Québec (Figure 2);

3- The Devonian-Permian mostly terrestrial Maritimes basin that only forms a thin veneer in southern Gaspé Peninsula, although rocks of this age occur throughout the Gulf of St. Lawrence and the Magdalen Islands.

Hydrocarbons producing fields or discoveries are known in the first two domains in Quebec whereas significant production occurs from the Maritimes basin in New Brunswick. As we only have one Rock-Eval analysis for the Maritimes basin, its geology is not discussed here. Interested readers are referred to the recent syntheses of Hu and Lavoie (2008), Hu and Dietrich (2010) and in the resource evaluation of Lavoie et al. (2009).

St. Lawrence Platform in southern Quebec

The Lower Paleozoic St. Lawrence Platform records the development of the Iapetan Cambrian-Lower Ordovician clastic to carbonate rift and passive margin (Potsdam and Beekmantown groups) followed by a Middle-Upper Ordovician Taconian foreland carbonate (Chazy, Black River and Trenton groups) and clastic (Utica Shale) shelves cap by Upper Ordovician deep marine Appalachian-derived clastics (Sainte-Rosalie, Lorraine and Queenston groups) (Lavoie, 2008; Lavoie et al., 2008). The top of the peritidal-dominated Beekmantown Group is cut by an unconformity correlated with the craton-wide Sauk-Tippecanoe sequence boundary (Lavoie et al., in press). A sandstone unit covered the unconformity that was followed by Middle to Upper Ordovician subtidal, foreland basin carbonates. Final collapse of the carbonate shelf occurred in early Late Ordovician with deposition of the deep marine Utica Shale source rock that was followed by Taconian flysch and molasses. The carbonate facies are gently southeast-dipping. Extensional faults were active during sedimentation of the Taconian foreland basin. The upper clastics are affected by a regional syncline (Chambly-Fortierville syncline) locally with a sub-vertical southeastern flank which, based on reprocessed seismic lines, appear to be locally marked by the development of a triangle zone (Castonguay et al., 2006, 2010). Neither the syncline nor the triangle zone seem to affect the underlying carbonates.

Exploration history. The Lower Paleozoic St. Lawrence carbonate platform was initially tested for hydrocarbons in the late 1950s-1970s. Gas shows were reported in most wells in both passive margin (Beekmantown Group) and foreland basin (Trenton Group) carbonates. However, these first exploration efforts failed to encounter economic accumulations. Several organic matter studies resulted in a detailed maturity map of the St. Lawrence Platform and the recognition of the source rock potential of the Utica Shale (Bertrand, 1991; Bertrand and Lavoie, 2006). In the 1990s, a new round of exploration targeted the deep autochthon below the Taconian Nappes, again without significant success. All these previous exploration campaigns tested faulted structural highs and unconformity-bounded Lower Ordovician units. More recent exploration activities have focused on hydrothermal dolostones (Lower and Middle Ordovician) (Lavoie et al., 2005; Thériault 2007; Lavoie et al., 2008; Lavoie et al., 2009; Lavoie and Chi, 2010). The first significant exploration success occurred in early 2007, when Talisman Energy reported from their second exploration well, significant natural gas flows up to 9 MMcf/d from hydrothermally-dolomitized intervals of the Trenton-Black River.

Source Rocks. Very little oil has been recovered from wells drilled in the St. Lawrence Plaform, just a 46.9ºAPI oil reported from a well north of Montréal. Previous work has demonstrated that the Upper Ordovician Utica Shales have potential for gas (Bertrand, 1991). This older data showed the Utica Shales to have TOC contents of up to 2.6% and Hydrogen Index (HI) values up to 294 mg HC/g TOC which taking maturity into account, as well as organic petrographic observations, suggested this interval originally contained Type II kerogen. The Utica Shale is a similar facies and is grossly time equivalent with the Upper Ordovician Macasty Formation on Anticosti Island (see below) and the Upper Ordovician Pointe Bleue Formation (TOC contents up to 15.5% and HI up to 633 mg HC/ g TOC) in the Lac Saint-Jean outlier.

The data present in this report divides samples from the St. Lawrence Platform into those collected from outcrop and those sampled from wells (mostly cuttings). Most outcrop samples have low TOC contents with only two out of fifty-four having greater than 2% TOC. Of these, one is identified as Macasty Formation and comes from an outcrop on the north coast of Anticosti Island and will be discussed later. The other sample is identified as from the Les Fonds Formation, south of Quebec City. It has a TOC content of 2.59%, a HI of 214 mg HC/g TOC and a Tmax of 452°. This suggests a late mature potential source rock that could have had significant initial hydrocarbon potential. Most of the remaining samples that have TOC contents greater than 1% are from the Utica Shale in the area south of Quebec City. Their maturity based on this Rock-Eval data suggests that they are in the later part of the oil window but there is still potential to generate hydrocarbons as indicated by their HI values in the 200-300 mg HC/g TOC range. Some mature samples of the Neuville Formation (Upper Trenton Group) also have TOC contents greater than 1% and HI values in the 160-260 mg HC g/TOC range. Samples from other units are organic-lean.

As evident from the histogram of TOC values for the St. Lawrence Platform well samples, most intervals penetrated are organic-lean with little or no hydrocarbon potential. This is not unexpected as cuttings were taken at regular intervals down a well (e.f. every 50 ft for the Soquip et al.

Saint Hugues well or 20 ft for the Soquip Pintendre Levis No. 1 well) rather than sampling preferentially zones containing potential source rocks. Only 24 of the 1184 samples have TOC contents greater than 2% and all but three of these are from the Utica Shale. The best hydrocarbon potential is apparently shown by two Lorraine Formation samples from the Notre-Dame-du-Bon Conseil well at 13,500 and 13,700 ft which have TOC contents of 5.1% and 2.99% and HI values of 807 and 818 mg HC/g TOC respectively. However, all samples from this well have very high S1 values and very low Tmax values (395 and 396°C for the two high TOC samples). This suggests that rather than representing source rocks, this Rock-Eval data is reflecting contamination by drilling additives in these samples. The other non Utica Shale sample with greater than 2% TOC (2.02%) is also a Lorraine Formation sample from the Bald Mountain Cap Sainte #1 well. This mature sample has a Tmax value of 441° and a HI of 268 mg HC/g TOC and appears to represent a potential source rock interval.

Data for two samples from the Chambord #1 well drilled in the Lac St Jean area are provided here. These samples are from Late Ordovician units, Pointe Bleue and Chute aux Galets, and are both immature organic-rich samples with excellent hydrocarbon source potential.

Maturation and generation. Maturation increases southwards in the St. Lawrence Platform and three maturation domains have been proposed. The Quebec City area is the least mature sector (Bertrand, 1991; Bertrand and Lavoie, 2006; Lavoie et al., 2009). A significant maturation jump is noted at the Appalachian structural front. Studies of wells show that maturation positively correlates with depth. The Utica Shale is in the upper part of the condensate zone in the northernmost sector of the St. Lawrence Platform. Elsewhere, the Utica Shale is within the condensate to dry gas zones. Maturation of the source rock was the result of depth of burial and preceded the formation of the Chambly-Fortierville syncline (Bertrand and Lavoie, 2006; Lavoie et al., 2009). Hydrocarbon generation occurred before the emplacement of the Taconian allochthons over the platform. The Utica Shale has generated its entire hydrocarbon potential in this area.

Migration and accumulation. Based on geochemical and maturation data, generation of hydrocarbons from the Utica Shale commenced at the onset of the Late Ordovician Taconian Orogeny (Bertrand et al., 2003). The presence of thermogenic and biogenic gas in the Pointe-du-Lac Quaternary reservoir indicates that the Utica Shale still has locally some potential to generate biogenic (Antrim-type) gas (Saint-Antoine and Héroux, 1993). Recent gas shows in the St. Lawrence Platform (Dundee, Bécancour, Batiscan, Gentilly) imply an up-dip (southeast to northwest) and vertical (along some of the extensional faults) migration of hydrocarbons generated from the Upper Ordovician Utica Shale towards Lower and Middle Ordovician hydrothermally-altered carbonate reservoirs. A detailed petrographic study of the Beekmantown dolostones indicates a liquid hydrocarbon migration event after chemical compaction and a later phase of gas migration (Chi et al., 2000a). There is no absolute age data on hydrocarbon migration.

Reservoir facies. The reservoirs that have been of most interest are within intertidal to shallow subtidal facies of the Lower Ordovician (upper Tremadocian-Arenigian) Beekmantown Group (Chi et al., 2000a; Bertrand et al., 2003; Salad Hersi et al., 2003; Lavoie et al., 2008; 2009). Depositional facies include peritidal dolostones and marine limestones. Facies are arranged in meter-thick shallowing-upward cycles (Salad Hersi et al., 2003). The upper beds are locally karsted as a result of sub-aerial exposure at the Sauk-Tippecanoe sequence boundary. Porous potential reservoir units only formed where dissolution and secondary dolomitization / brecciation occurred. The late secondary dolomitization is of hydrothermal origin (Lavoie et al., 2009). Pore-coating bitumen and methane inclusions in late quartz cement indicate two pulses of hydrocarbon migration (Chi et al., 2000a).

The other major targets are within the Upper Ordovician (lower Caradocian) Trenton and Black River groups (Thériault, 2007; Lavoie et al., 2008, 2009). The favourable facies are shallow subtidal, bioclastic and oolitic limestones (e.g., Deschambault Formation of the Trenton Group and Leray, Lowville and Pamelia formations of the Black River Group). Potential reservoir development is associated with hydrothermal dissolution and dolomitization. Proximity to extensional faults is a prerequisite for development of secondary porosity. Two gas discoveries in the Trenton-Black River groups have recently been publicized by Questerre Energy / Talisman.

Secondary targets consist of the Cambrian and Middle Ordovician basal sandstone units that overly the Precambrian and Sauk-Tippecanoe unconformities, respectively (Salad Hersi et al, 2002; Lavoie et al., 2009). These nearshore sands are locally porous and gas shows have been reported. Finally, most of the wells that intercepted the Upper Ordovician flysch sandstones on the southern flank of the Chambly-Fortierville syncline have produced various amounts of gas (Lavoie et al, 2008, 2009).

Porosity and Permeability. Dolostones of the Beekmantown Group contain vuggy, moldic, intercrystalline and fracture porosities. Multiple events of dolomitization are known (early, late burial and hydrothermal; Chi et al., 2000a). Measured porosities in the Beekmantown Group is highly variable (Lavoie, 2009) and can even reach 17% in the deep, allochthon- buried successions. The limestones of the Trenton Group are locally fractured, although current interest lies in the potential presence of hydrothermal dolostones in that unit (Lavoie, 2009). Recent tests report gas flows up to 9 MMcf/d.

Traps and seals. The St. Lawrence Platform strata form a broad monocline with no fold closure. In the target zone (Lower to Middle Ordovician succession), extensional faults are the most likely traps for reservoirs (Lavoie et al., 2008, 2009). The top of the Beekmantown Group is marked by the Sauk-Tippecanoe sequences boundary that, if not breached by faults, could have acted as a seal. The Utica Shale could not only have been a source of hydrocarbons but also likely sealed off the underlying Trenton Group. Diagenetic seals produced by lateral transition from porous hydrothermal dolostones to tight carbonates are expected in the Beekmantown and Trenton groups (Lavoie et al., 2009). Finally, compressional structural elements such as a triangle zone and duplexes are locally documented along the south-east limb of the Chambly-Fortierville syncline (Castonguay et al., 2006; Lavoie et al., 2008). Considerable evidence for breaching of gas-filled hydrocarbon reservoirs in the form of venting pockmarks on the St. Lawrence seafloor have been reported (Pinet et al., 2008a; Lavoie et al., 2008, 2009, 2010a)

Exploration plays. The actual play concept for exploration in the St. Lawrence platform is derived from the model of fault-controlled hydrothermal dolomitization that has proven highly successful in coeval rocks in eastern USA (e.g., Albion-Scipio in Michigan Basin; Fingers Lake area in Appalachian Basin of New York; Hurley and Budros, 1990; Smith 2006, respectively). Detailed petrographic and geochemical studies in the Beekmantown Group have revealed the presence of late saddle dolomite in both field and well samples (Chi et al., 2000a). Reprocessed seismic profiles have documented the presence of still untested fault-bounded platform sags (Castonguay et al., 2010). Movement along these faults is assumed to have taken place during the early Taconian foreland basin development (e.g., Chazy to Trenton) as suggested by thickness increases on the downthrown block. There has been a significant hydrocarbon discovery that indicates the Upper Ordovician hydrothermal dolomite play extends from New York and Ontario into southern Quebec (Lavoie et al., 2008, 2009).

Secondary types of conventional play consist of the Cambrian to Middle Ordovician porous sandstone units that are structurally in favourable contact with the Upper Ordovician Utica Shale (Lavoie et al., 2009). Finally, compressive structural plays involving deep marine impure Upper Ordovician flysch sands at the Appalachian structural front are also possible.

St. Lawrence Platform on Anticosti Island

Anticosti Island is part of the St. Lawrence Platform. Strata consist, in ascending order, of the Romaine, Mingan, Macasty, Vauréal, Ellis Bay formations, and the Anticosti Group (Lavoie et al., 2008, 2009). The Lower Ordovician Romaine Formation consists of passive margin peritidal limestone and dolostone (Lavoie et al, in press; Desrochers et al., in press). The top of the unit is cut by an unconformity correlated with the craton-wide Sauk-Tippecanoe sequence boundary. A thin sandstone unit covers the unconformity. This was followed by the Middle Ordovician Mingan

Formation subtidal, foreland basin carbonates. The Mingan Formation corresponds to the Chazy and Black River groups in the St. Lawrence Lowland, although its uppermost section may be Trentonian in age. The Upper Ordovician Macasty Formation is a good hydrocarbon potential source rock (Bertrand, 1987). The Upper Ordovician Vauréal Formation consists of clastic Taconian flysch in the lower part and foreland carbonates in the upper part. It is followed by carbonates of the Late Ordovician Ellis Bay Formation and the Early Silurian Anticosti Group. The strata beneath Anticosti Island are not strongly folded, and dip slightly SSW. A number of synsedimentary normal faults, striking ENE-WNW, are indicated by seismic data (Bordet et al., 2010).

Exploration history. Exploration on Anticosti Island started in the late 60s. Initial drilling failed to identify economic accumulation of hydrocarbons. However, the recovered cores / cuttings enabled a detailed stratigraphic framework to be developed including the identification of a good source potential rock and potential reservoirs (Bertrand, 1987). Between 1997 – 2006 there was a second period of exploration that included over 600 kms of new seismic data and the drilling of eight new wells. No commercial discoveries were made. The presence of locally thick intervals of porous hydrothermal dolostones in the Romaine and Mingan formations was noted as possible reservoirs (Lavoie et al., 2005; Lavoie et al., 2008, 2009; Lavoie and Chi, 2010; Desrochers et al., in press).

Source Rocks. No oil has been recovered from wells drilled on Anticosti Island. Earlier studies using organic matter petrography and Rock-Eval analysis showed that the Upper Ordovician Macasty Formation has significant source rock potential with TOC values range up to 7.1wt% and HI values up to 485mg HC/g TOC indicating Type II organic matter (Bertrand, 1987).

The table of St. Lawrence Cambro-Ordovician outcrop data includes the results from one Macasty sample collected from the north coast of Anticosti Island. It is similar marginally mature, excellent potential source rocks with an average TOC content of 7.07% and HI value of 476 mg HC/g TOC. The data presented in the table derived from the analysis of samples from wells drilled on Anticosti Island also shows the Macasty Formation to have excellent hydrocarbon potential. The majority of samples have TOC contents greater than 2.5% with values up to 5.7%, and HI values ranging up to 485 mg HC/g TOC. The results also show that samples identified as from English Head or Trenton strata have similar hydrocarbon potential; these may actually be Macasty samples. The results from the Saumon and Dauphine wells indicate extensive potential source rock intervals, with samples from 835 to 970m in the Saumon well and 875 to 920 m in the Dauphin well all showing significant hydrocarbon potential. Maturity is generally immature to marginally mature for the cutting samples. As suggested by lower HI values and higher Tmax and PI values, the Macasty Formation in the Jupiter and Rollif wells appears to have generated some hydrocarbons but still has significant portion of its generative potential remaining. The data suggests that a major risk for finding economic accumulations of hydrocarbons on Anticosti Island is finding a mature source rock interval.

Maturation and generation. Maturation increases southwesterly on Anticosti Island and also positively correlates with depth (Bertrand, 1987). The Macasty source rock is within the oil window in the northeastern half of the island and in the condensate zone for the southwestern segment of the island. Potential reservoir units immediately underlie the Macasty. Modelling suggests that the Macasty Formation in southern Anticosti Island (ARCO well) entered the oil window in Early Silurian time and moved into the gas zone in Lochkovian (Bertrand, 1987; Lavoie et al., 2005; Chi et al., 2010). No data is available for the sections on the northern side of the island.

Migration and accumulation. Modelling suggests that over 75% of generated hydrocarbons have migrated out of the Macasty Formation (Bertrand, 1987; Chi et al., 2010). The Macasty is overlain by shales and flysch sediments of the Vauréal Formation. Fluid flow simulation indicates overpressure in the Macasty by Early Silurian time (Chi et al., 2010). Up-dip (south to north) migration was proposed with vertical migration along some of the major fault planes is assumed. Migration is documented in the in the Romaine Formation by the presence of pore-coating bitumen and abundant hydrocarbon fluid inclusions in a post-secondary dissolution, late pore-filling calcite cement.

Reservoir facies. The primary drilling target on Anticosti was shallow water, intertidal to shallow subtidal facies of the Lower Ordovician (Arenigian) Romaine Formation (Lavoie et al., 2005, 2008, 2009: Lavoie and Chi, 2010). Depositional facies include peritidal dolostones and shallow open marine peloidal / bioclastic / intraclastic limestones (Desrochers et al., in press). Facies are arranged in metre-thick shallowing-upward cycles. The upper beds are locally karsted as result of sub-aerial exposure at the Sauk-Tippecanoe sequence boundary (equivalent to the St. George Unconformity in Western Newfoundland; Lavoie et al., in press). Porous potential reservoir units formed where dissolution and secondary dolomitization / brecciation occurred. The secondary dolomitization is of hydrothermal origin (Lavoie et al., 2005, 2009; Lavoie and Chi, 2010). The lateral and vertical distribution of the reservoir is highly variable and relates to the proximity of the hydrothermal fairway and thus the HTD model is applicable (Lavoie et al., 2005, 2009; Lavoie and Chi, 2010).

A secondary target is the Middle Ordovician Mingan Formation (equivalent to Table Head Group in Newfoundland and Chazy – Black River groups in southern Quebec) (Lavoie et al., 2008, 2009; Lavoie and Chi, 2010). The facies is shallow subtidal bioclastic limestones. Potential reservoir development is associated with hydrothermal dissolution and dolomitization.

Porosity and Permeability. Measured porosities and permeabilities from selected samples of Romaine Formation dolostones from the LGCP well, range from 1.6 to 9% (average of 6%) and from 0.01 to 96 md (average of 10 md). However, locally intensely dolomitized and brecciated meter-thick intervals visually show up to 30% of open pore space. Pores are irregular in size (from 1 mm to 1 cm) and shapes (usually parallel to bedding). In most porous intervals, significant late (syn-secondary porosity development) mm- to cm-sized open fractures are present and likely enhance the overall permeability of the unit. Petrophysical analyses of Anticosti wells confirm the high porosity / permeability of both the Romaine and Mingan formations (Hu and Lavoie, 2008).

Traps and seals. The Anticosti strata form a broad monocline with no fold closure. In the target zone (Lower to Middle Ordovician succession), extensional faults are the most likely traps for reservoirs (Lavoie et al., 2005, 2008, 2009). The top of the Romaine Formation is marked by the Sauk-Tippecanoe sequences boundary that, if not breached by faults, could have acted as a seal. The shales of the Macasty Formation could not only have been a source of hydrocarbons but also likely a seal for the underlying Mingan Formation (Lavoie et al, 2009). Diagenetic seals produced by lateral transition from porous hydrothermal dolostones to tight limestones are expected to be present in the Mingan Formation. Such diagenetic seals are also potentially present in the Romaine Formation although because of initial high porosity (early dolomitization), they might not be as well developed.

Exploration plays. The play concept for exploration in Anticosti Island is derived from the model of fault-controlled hydrothermal dolomitization that has proven highly successful in coeval rocks in eastern USA (e.g., Albion-Scipio; Fingers Lake; Hurley and Budros, 1990; Smith 2006). Detailed petrographic and geochemical studies in both the Romaine and Mingan formations have documented the presence of hydrothermal dolostones in both units (Lavoie et al., 2005, 2008, 2009; Lavoie and Chi, 2010). Recent seismic profiles on Anticosti Island have indicated the presence of significant pre-Macasty platform sags limited by extensional faults (Lavoie et al., 2005, 2008, 2009; Bordet et al. 2010). Movement along these faults is assumed to have taken place during the early Taconian foreland basin development (e.g., Mingan) as suggested by thickness increases on the downthrown block. Previous exploration efforts were based on the premise that the Upper Ordovician Macasty Formation was the most likely hydrocarbon source rock on Anticosti. Hence an extensional context was sought in order to have the Upper Ordovician source and Lower-Middle Ordovician reservoir rocks in favourable position. Recent documentation of Lower Ordovician source rocks in adjacent western Newfoundland (Green Point Formation) and Quebec Appalachians (Rivière Ouelle Formation) opens new untested perspectives for the island. Pre to syn-Taconian up-dip migration from the platform-adjacent basin is a viable scenario given the syn-taconian porosity generation event from fault-focused hydrothermal fluid migration (Lavoie et al., 2009; Lavoie and Chi, 2010)

Appalachian Humber Zone

The Foreland Fold and Thrust Belt of eastern Quebec occupies the outer domain of the Taconian Humber Zone in the Quebec Reentrant (Lavoie et al., 2003; Lavoie, 2008; Lavoie et al., 2008, 2009; Allen et al., 2009, 2010). The zone encompasses a Cambrian-Ordovician rift and passive, margin shallow (Potsdam, Beekmantown, Chazy, Black River, Trenton, Utica and Lorraine groups and equivalent units) and deep (Saint-Roch, Trois Pistoles groups and Rivière Ouelle, Tourelle, Deslandes and Cloridorme formations and equivalent units) marine sediments. The shallow marine units form tectonic slices transported over unknown distances (Bertrand et al., 2003). Locally, the thrust slices are still rooted in the autochthonous platform and form the parautochthonous domain to some authors (Castonguay et al., 2010). Coeval slope facies and overlying flysch were transported into the basin from late Middle Ordovician (southern Quebec) to early Late Ordovician (in Gaspé) as thin-skin slices above the Lower Paleozoic shelf (Castonguay et al., 2010). This was accompanied by ophiolite obduction (Thetford Mines, Mont Albert and others) and represents the classic Taconian Orogeny event. In the Humber Zone of Quebec, 12 distinct tectonostratigraphic nappes are correlated (Lavoie et al., 2003, Lavoie, 2008, Castonguay et al., 2010). Post Late Ordovician sedimentation in the onshore domain of the Humber Zone of Quebec is unknown with an unconformity separating the succession from the Acadian Gaspé Belt. However, post Late Ordovician sediments are recognized over the marine extension of the St. Lawrence Platform and Humber Zone in the St. Lawrence estuary / gulf (Pinet et al., 2008a). Acadian (Early to Middle Devonian) deformation of the Humber Zone is locally well expressed in folds and faults although the magnitude of that Acadian orogenic phase is considered to be small compared to the Taconian orogenesis (Pinet et al., 2008b, 2010; Castonguay et al., 2010).

Exploration history. The oldest report of surface seeping oil in the Humber Zone of Quebec goes back to 1958 with soaking oil noted in a gravel pit in the Montmagny area. Most of the early hydrocarbon exploration in Quebec focussed on the St. Lawrence Platform and on the Gaspé Belt. The Lower Paleozoic Appalachians did not receive significant attention until a late 1960s exploration seismic survey by Shell Canada on a foothill-style concept. This led to the successful drilling of the Saint-Flavien gas field (Bertrand et al., 2003a). A few other exploration wells have been drilled subsequently in the Humber Zone of Quebec, most of which encountered gas shows. Three wells drilled in the Rivière du Loup area (Parke wells) documented a significant porous reservoir unit (Hu and Lavoie, 2008). Finally, natural gas was observed in some shallow water wells in the eastern Quebec drilled in a fractured deep marine clastic unit (Lavoie et al., 2008; Lavoie et al., 2009).

Source Rocks. Liquid hydrocarbon fluid inclusions and, more commonly, methane inclusions have been reported in fracture-filling quartz cements in Cambrian - Lower Ordovician coarse-grained submarine fan deposits (Chi et al., 2000b). The source rock for these hydrocarbons has yet to be determined. Isotopic analysis of the gas in the Saint-Flavien gas field suggests a thermogenic origin (Saint-Antoine and Héroux, 1993). At the Appalachian structural front, the best-known source rock is the Upper Ordovician Utica Shale with TOC values reaching 2.6% and HI up to 154. The organic matter is of Type I/II algal origin. The more or less coeval black shales in tectonic mélanges (the Ruisseau Isabelle and Cap Chat mélanges in Gaspé and the Pointe-Aubin and Rivière Etchemin mélanges in southern Quebec) have TOC values up to 5.5% and HI up to 306 mg/g HC (Lavoie et al., 2009). The Lower Ordovician Rivière Ouelle Formation (and correlatives) has relatively thick shale intervals with some source rock potential (TOC up to 3.7%) (Bertrand et al., 2003b).

As evident from the histogram of TOC values for Cambro-Ordovician samples from the Humber Zone, most were very organic-lean; 80% have a TOC content less than 0.5%. Twelve samples have TOC contents greater than 2%. These are from the following units; Saint Roch (1), Sainte Damaste (1), Rivière Ouelle - Anse-du-Crapaud (1), Pointe de la Martinère (2), Mélange de Pointe Aubin (3), Rivière Ouelle (3) and Cloridorme (1). These high TOC samples tend to be the exception to the mostly organic-lean samples from the same units and most are highly mature with no remaining hydrocarbon generative potential. The exception are the Mélange de Pointe Aubin samples with TOC contents in the 3.19 to 5.49% range and HI values between 201 and 306 mg HC/g TOC. Based on this

Rock-Eval data and organic petrography, Comeau et al. (2004) suggested that these samples most likely come from blocks of Utica Shale from the underlying autochthous platform. The highest TOC sample (7.25%) is from the Lower Ordovician Rivière Ouelle Formation on the northern part of the Gaspé Peninsula. Many other units show samples that have TOC content greater than 1%, including several from the Kamouraska Formation from the Kamouraska area and the Anse-du-Crapaud Member of the Rivière Ouelle Formation, north of Matane.

Maturation and generation. Surface maturity data indicate a northeasterly decrease in thermal maturity of sediments from the US border (overmature; Ro > 3%) towards Quebec City (oil window – condensate; Ro ~ 1.3%) (Bertrand and Lavoie, 2006). In eastern Quebec, condensate to dry gas zones are noted in the Cambrian-lower Ordovician rock units of the external domain of the Humber Zone between Quebec City to the Montmagny area (Bertrand and Malo, 2010). From Montmagny towards the Gaspé Peninsula, surface maturation data for the coeval succession is higher with dry gas to overmature domains (Bertrand, 1987; Bertrand and Malo, 2010; Lavoie et al., 2009). In the few wells that have been studied, a depth related maturation increase is observed (Bertrand and Lavoie, 2006; Lavoie et al., 2009). Evidence for transported burial maturation is indicated by significant maturity jumps from one tectonic slice to the other and at the transition between the St. Lawrence Platform and the Appalachian basin (Bertrand et al., 2003; Bertrand and Malo, 2010). The presence of units with lower maturity values in the lower nappes of the structural stack is probable. Burial history modelling suggests that the Utica Shale entered the oil window during Late Ordovician and that these source rocks were significantly buried beneath syn-orogenic Taconian flysch. It is only in the Quebec City to Montmagny area that the shales have any remaining hydrocarbon potential and these are in the condensate to dry gas zone (Lavoie et al., 2008; Bertrand and Malo, 2010).

Migration and accumulation. In the Saint-Flavien gas field, the gas accumulation formed after maximum burial and is assumed to be late Taconian in age (Bertrand et al., 2003a). Combined fluid inclusions and organic matter maturation studies show a strong correlation between type of hydrocarbon inclusions (oil, methane), homogenization temperature of aqueous inclusions and Ro of autochthonous organic matter (Chi et al., 2000b). This suggests that in most cases, some migration occurred during or near maximum burial. Late fractures commonly host hydrocarbon fluid inclusions in diagenetic phases (silica, calcite), solid petroleum residue (impsonite) and gas shows. This supports a late tectonic scenario of migration through fractures (Levine et al., 1991).

Reservoir facies. The main reservoir targets are fractured intervals in thrust slices of intertidal to shallow subtidal facies of the Beauharnois Formation (Beekmantown Group) (Bertrand et al., 2003a; Lavoie et al., 2008, 2009). Depositional facies include peritidal dolostones and various open-marine limestones. Evidence for local episodic subaerial exposure and carbonate dissolution is minor. Reservoirs occur where burial and hydrothermal dolomitization formed thick intervals that were preferentially fractured during tectonic emplacement. The calcite-cemented fractures were later (post or during late emplacement) dissolved creating the porosity. The lateral and vertical distribution of the reservoir is highly variable, and compartmentalization occurs through faulting (Bertrand et al., 2003a; Lavoie et al., 2009).

Secondary target reservoirs are found in the thick Cambrian-Lower Ordovician coarse-grained submarine fan deposits. The “Green Sandstone’ unit” of the Saint-Roch Group (Lower Cambrian) is typified by open secondary porosity (water-filled in the Parke wells; Hu and Lavoie, 2008; Lavoie et al., 2009) related to significant dissolution of feldspars. The Kamouraska Formation quartzarenite (Lower Ordovician) is characterized by bitumen that coats both primary pore space as well as open late fractures (gas shows in shallow water wells in eastern Québec and hydrocarbon inclusions in late silica cement) (Chi and Lavoie, 2000a; Lavoie et al., 2008, 2009).

Other potential targets are hydrothermal dolostones in tectonic slices of the Middle Ordovician carbonate platform facies (Black River and Trenton groups equivalents), thick sand sheets in passive margin (Upper Cambrian Saint-Damase Formation) and flysch (Middle Ordovician Tourelle Formation) submarine fans (Lavoie et al., 2009).

Porosity and Permeability. In the Saint-Flavien gas field, the Beauharnois reservoir has porosity (fracture and minor intercrystalline) ranging between 2.8% and 15% (average of 6%) (Béland and Morin, 2000; Lavoie et al., 2009). Permeability ranges from 0.1 mD to 70 mD (average of 4 mD) in a 3.5 m average pay zone at 1500m. Drill Stem Tests in Parke wells suggest locally high permeability in the Cambrian sandstone (Hu and Lavoie, 2008).

Traps and seals. The Saint-Flavien gas field is hosted in a roll-over anticline cut by secondary extensional and reverse faults that provide excellent closures (Bertrand et al., 2003a; Lavoie et al., 2008, 2009; Castonguay et al., 2010). The presence of hydrothermal dolomites suggests that diagenetic seals are also likely to be present in tectonic slices of platform facies. Late Middle to Upper Ordovician shales of the flysch succession could likely form good stratigraphic seals above various carbonate reservoirs. Deep coarse-grained submarine fans are also involved in fold and thrust structural traps with deep marine shales (locally potential source rocks) possibly providing impermeable caps.

Exploration plays. At the Appalachian structural front, the current exploration play is focussed on the Saint-Flavien model of fault-imbricated tectonic slices of shallow marine Ordovician dolomitized (hydrothermal?) platform (Beekmantown / Black River-Trenton groups; Lavoie et al., 2009; Castonguay et al., 2010). Recent seismic acquisition program by the MRNQ in Gaspé indicates the presence of such imbricated platform units with roll-over anticlines and duplexes at relatively shallow depth (1 sec). Either Lower (Rivière Ouelle Formation) or Upper Ordovician (Utica and Ruisseau Isabelle shales) source rocks are the hydrocarbon source rocks. In Gaspé, surface maturation of the deep marine allochthons in the Humber Zone is high with no information on the maturity rank of the intercalated platform slices available (Bertrand, 1987; Bertrand and Malo, 2010). Using a hypothesis of transported maturation, this type of play would still be viable.

A secondary exploration play resides in the passive margin submarine fans. Thick successions of very coarse-grained facies are known in the Lower St. Lawrence Valley (Lavoie et al., 2003;

Lavoie, 2008: Lavoie et al., 2009). Significant secondary porosity has been documented through either dissolution of metastable aluminosilicates or in fractures (Hu and Lavoie, 2008). The succession is stratigraphically and structurally interstratified within potential source rocks that could also provide excellent seals. The fold and thrust belt tectonic scenario provides multiple tectonic traps that are imaged in recent and ancient seismic surveys (Castonguay et al., 2010).

The Gaspé Belt

The Gaspé Belt stretches from Gaspé Peninsula to southern Quebec. The stratigraphy consists of upper Middle Ordovician to Middle Devonian rocks (Bourque et al, 2000; Lavoie, 2008; Lavoie et al., 2009). Palinspastic reconstruction indicates that the clastic and carbonate shelves followed the Quebec Reentrant – St. Lawrence Promontory with a deeper basin to the southwest. The Gaspé Belt overlies either unconformably or paraconformably, or is in faulted contact with the Taconian zones. Fine-grained clastics dominate the stratigraphy with coarser grained units occurring at the end of the shallowing phases. Shallow marine reefal platform and carbonate complexes are restricted to the Wenlockian and Pridolian - Lochkovian. Surface structural elements consist of wide synclines and tight anticlines with late dextral transpressive Acadian faults in eastern Gaspé and reverse and thrust faults in western Gaspé – Témiscouata (Pinet et al., 2008b). The Silurian-Devonian successions are part of a major compressive domain that formed during the Salinic-Acadian orogenic pulse; the sequence is characterized by abundant compressional and extensional faults with highly variable local – regional cinematic related to the recently proposed deformation model (Pinet et al., 2008b). Extension in northern Gaspé started in late Early Silurian and occurred in response to building of the orogenic wedge to the south. This event is assumed to be responsible for providing an efficient plumbing system for fluid circulation in the basin (Lavoie and Chi, 2010). A significant number of seismic anomalies and bright spots are observed in untested Silurian potential reservoirs (Kirkwood et al., 2005; Lavoie et al., 2008, 2009).

Exploration history. Exploration in Gaspé Peninsula started in the mid-19th century because of the presence of seeping oils near major faults in eastern Gaspé. Initial drilling targeted Lower Devonian sandstones and limestones with minimal success (few barrels recovered). Extensive seismic coverage in early 1980s led to the first geophysical-based drilling. A small gas reservoir was discovered and put into production (Galt field; Kirkwood et al, 2005; Lavoie et al., 2008) and recently an oil discovery in Devonian sandstones was announced (Lavoie et al., 2008, 2009). Publication of detailed hydrocarbon-oriented (maturation/source rocks, reservoirs, traps and seals) research, Quebec Government seismic surveys in 2000-2002 and high resolution potential field data (Pinet et al., 2005; Brouillette et al., 2006) led to significant renewed interest in the area.

Source Rocks. Oil from exploration wells and seeps on the Gaspé Peninsula show a range in characteristics and quality, from 19.6º API (seeping oil) to 46.9º API (well). This reflects the level of thermal maturation of the oils and their degree of biodegradation (Fowler et al., 2008). Biomarker data suggests that most of the oils have a probable Lower Paleozoic (Ordovician?) source with some showing a contribution from Devonian age intervals (Fowler et al., 2008; Roy, 2008). Potential Ordovician hydrocarbon source rocks are known from within the Humber Zone (see above).
Almost all the Ordovician-Devonian outcrop samples for which data is presented here are organic-lean (over 90% of samples have TOC contents of less than 0.5%). Of the seven samples with TOC contents greater than 2%, two are from the Lower Devonian York River Formation with one being coal and the other being bitumen saturated sandstone. The coal sample has TOC values in the 60-67% range and HI values in the 417-466 mg HC/g TOC range; these values are high for coal. The other York River sample has TOC values in the 29.4-36.5% range and HI values in the 634-805 mg HC/g TOC range (based on multiple analyses with varying sample weight). These data indicate that the York River coal has significant hydrocarbon potential. None of the other units sampled in outcrop show more than one high TOC value and none of these show good hydrocarbon potential. The most organic-rich of these is a sample from the Gascons Formation from southern Gaspé that has a TOC content of 8.2% but a HI

of only 107 mg HC/g TOC. However, as it has a Tmax of 466°C, it is mature and thus could have had significant hydrocarbon potential in the past. Some Ordovician samples collected from outcrops in the Dunnage Zone in the southern Gaspé area have high TOC contents (Lavoie et al., 2008, 2009). Two samples of the Dubuc Formation have TOC contents of 4.74 and 5.75%. These mature samples still have some residual hydrocarbon potential as indicated by their HI values which range from 156 to 257 mg HC/g TOC. Thus this unit is a potential source rock. A highly mature sample of Mélange du Ruisseau Isabelle has a TOC content of 2.73%.

Almost all the Ordovician-Devonian samples obtain from wells drilled on the Gaspé Peninsula are also organic-lean. Only three samples have TOC contents greater than 2% and six more greater than 1%. Two marginally mature Battery Point Formation samples from the SOQUIP Douglas #1 well ((1200 and 1300m depth) drilled in northern Gaspé have TOC contents of 2.09 and 2.16% and HI values of 304 and 311 mg HC/g TOC suggesting some hydrocarbon source potential in this section. This appears to be confirmed by a Battery Point sample from the Petrolia Haldimand #1 well (735 m) which has a TOC content of 2.75% and a HI of 444 mg HC/g TOC. However, the very high PI value (0.53) and low Tmax (410°C) of this latter sample suggests drilling additive contamination or staining by in this section by biodegraded hydrocarbons. Some Forillon Formation samples from the Gulf Sunny Bank #1 well have elevated TOC values greater than 1% but low HI values. Samples from this section of the Sunny Bank well have extremely low PI values with almost all the organic carbon being in the S1 peak. As this zone is not oil stained, this again is most likely due to drilling contamination.

Maturation and generation. Maturation is highly variable and complex (Roy, 2008; Lavoie et al., 2008. 2009). Maturation increases southwesterly in eastern Gaspé and ranges from locally immature (Devonian Gaspé Sandstones) to dry gas zone (Upper Ordovician Matapédia Group) and to near metamorphism (Lower Devonian Fortin Group); it also positively correlates with depth. A southerly to southwesterly increase is observed in the Matapédia valley. Maturation is primarily related to burial with maximum burial predating late Acadian strike-slip faulting. Limited recent maturation data indicates that strata within the extension of the Gaspé Belt into southern Quebec are significantly overmature (Ro>5%). The lower Devonian source rocks generated hydrocarbons in late Early to Middle Devonian in response to tectonic fast subsidence and major burial of the succession under km-thick pile of orogen-derived clastics. Potential Ordovician source rocks would have generated hydrocarbons earlier in the tectono-sedimentary history of the Gaspé Belt, before and during the initial development of the Salinic compressive envelope (Early Silurian to earliest Late Silurian; Roy, 2008; Lavoie et al., 2009).

Migration and accumulation. Migration of hydrocarbons into porous potential reservoirs is supported by the presence of small-sized reservoirs, locally abundant hydrocarbon fluid inclusions and pore-filling bitumen (Lavoie et al., 2008; 2009). Data suggests that both early and late migration occurred (Lavoie et al., 2008; Lavoie and Chi, 2002, 2010). Early migration from pre-Lower Silurian source rocks that occurred before the development of a regional Upper Silurian unconformity is recognized in Upper Ordovician to Lower Silurian units (Matapédia Group, Val Brillant and Sayabec formations ; Lavoie and Morin, 2004 ; Lavoie et al., 2008, 2009: Lavoie and Chi, 2002, 2010). Later migration from potential Devonian source rocks or dismigration from older reservoirs is recorded in post-Late Silurian units (West Point Formation, Upper Gaspé Limestones and Gaspé Sandstones; Bourque et al., 2001; Lavoie et al., 2009). Gas is hosted by a fractured carbonate reservoir (Lower Devonian Upper Gaspé Limestones) and economic oil accumulations have been documented in the Lower Devonian Gaspé Sandstones. A number of "flat spots" and seismic anomalies in seismic data in western Gaspé – Témiscouata suggest the presence of other hydrocarbon accumulations.

Reservoir facies. The fractured outer shelf limestones of the Lower Devonian Upper Gaspé Limestones are proven gas reservoirs (Kirkwood et al., 2005) while the Lower Devonian Gaspé Sandstones are proven oil reservoirs (Lavoie et al., 2008, 2009). Potential reservoirs have been proposed based on the presence of either open pore space, bitumen or hydrocarbon fluid inclusions in the pore-filling paragenetic successions (Lavoie et al., 2008, 2009). Open pore space occurs in hydrothermal dolomites of the Lower Silurian peritidal Sayabec and La Vieille formations (with bitumen; Lavoie and Morin, 2004; Lavoie et al., 2009; Lavoie and Chi, 2010). Other potential reservoir units consist of (1) the Lower Silurian nearshore sandstones of the Val Brillant Formation (bitumen in secondary pores from dissolution of aluminosilicates; oil in Matapédia valley; Lavoie and Chi, 2002; Lavoie et al., 2009) and (2) the Upper Silurian – lowermost Devonian hydrothermally-altered platform reefs and pinnacles of the West Point Formation (abundant hydrocarbon inclusions in pore and fracture-filling calcites; Bourque et al., 2001; Lavoie et al., 2010).

Porosity and Permeability. Modern petrophysical measurements are available for the Galt gas field. A sample of the Lower Devonian gas-host Forillon Formation has 2.33% fracture porosity with a permeability of 0.59 md. Gaspé Sandstones (12 analyses) in central Gaspé have 0.2 to 9.6% Po and permeability ranging from 0.4 to 14.5 md (Hu and Lavoie, 2008). Based on hand specimen observations, the Lower Silurian sandstones of the Val Brillant Formation have 5 to 10% of mm-sized dissolution pores and the Lower Silurian hydrothermal dolostones of the Sayabec Formation have between 5 to 30% of mm- to cm-sized dissolution and fracture pores (Lavoie, 2009). Extensive petrophysical data for the Upper Gaspé Limestones and Gaspé Sandstones can be found in Hu and Lavoie (2008).

Traps and seals. The geology of the Gaspé Belt is complex and thus there is potential for various traps and seals (Lavoie et al., 2008, 2009). Stratigraphic seals are likely in nearshore coarse-grained clastic units (Val Brillant Formation, Gaspé Sandstones) where rapid facies transition from porous channel/ deltaic wedges to mud dominated facies are known. The Late Silurian-Early Devonian West Point reefs are surrounded by siliciclastic muddy facies. Diagenetic seals are expected for hydrothermal dolostones for all Gaspé Belt carbonates. Finally, the Late Silurian (Salinic) unconformity provides an excellent seal for the porous Val Brillant and Sayabec formations. Over the years, industry drilling has targeted surface expressions of anticlines, but the recent interpretation of potential fold and thrust belt thin-skinned tectonics in the subsurface allows for other types of structural traps. Finally, combined tectonic-diagenetic processes might have generated other traps as shown by the Galt gas field in Devonian limestones.

Exploration plays. Two major groups of plays are proposed, hydrothermally-altered carbonates and nearshore clastics (Lavoie et al., 2008, 2009). The hydrothermal dolostones are found in the Lower Silurian (Sayabec and La Vieille formations; Lavoie and Morin, 2004; Lavoie and Chi, 2010), in the Upper Silurian West Point reefs (Lavoie et al., 2008, 2009), in the lowermost Devonian West Point Pinnacles (Lavoie et al., 2008, 2009, 2010) and in the Lower Devonian Upper Gaspé Limestones (Lavoie et al., 2008; 2009). These hydrothermal dolostone plays are all associated with extensional to transtensional faulting in the Gaspé Belt with the inception of faulting occurring in late Early Silurian (Desaulniers, 2005; Lavoie and Chi, 2010). Hydrocarbons were likely derived from the underlying Ordovician black shales with a possible contribution from local Lower Devonian poorer source rocks. The second type of plays are the clastic ones, they include the nearshore Lower Silurian sands of the Val Brillant Formation and the fluvial to marginal marine sandstones of the Lower Devonian York River Formation (Gaspé Sandstones). Secondary dissolution porosity within the Val Brillant Formation is filled with bitumen- and dead oil (Lavoie and Chi, 2002; Lavoie et al., 2008, 2009); whereas for the York River Formation, the oil is found in primary pore space (Lavoie et al., 2009). In both cases, stratigraphic and tectonic closures are expected.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the review of this report by Keith Dewing (GSC-Calgary). The dataset presented here is the synthesis of over 30 years of sample collection and analyses; we would like to acknowledge the contribution of various governmental and academic researchers and GSC technicians involved at various stages in the construction of this dataset. Amongst those involved in the collection of field samples, special thanks to Rudolf Bertrand and Stéphanie Roy from INRS-ETE, also to Daniel Brisebois from the MRNQ and our colleague Esther Asselin from GSC-Q.

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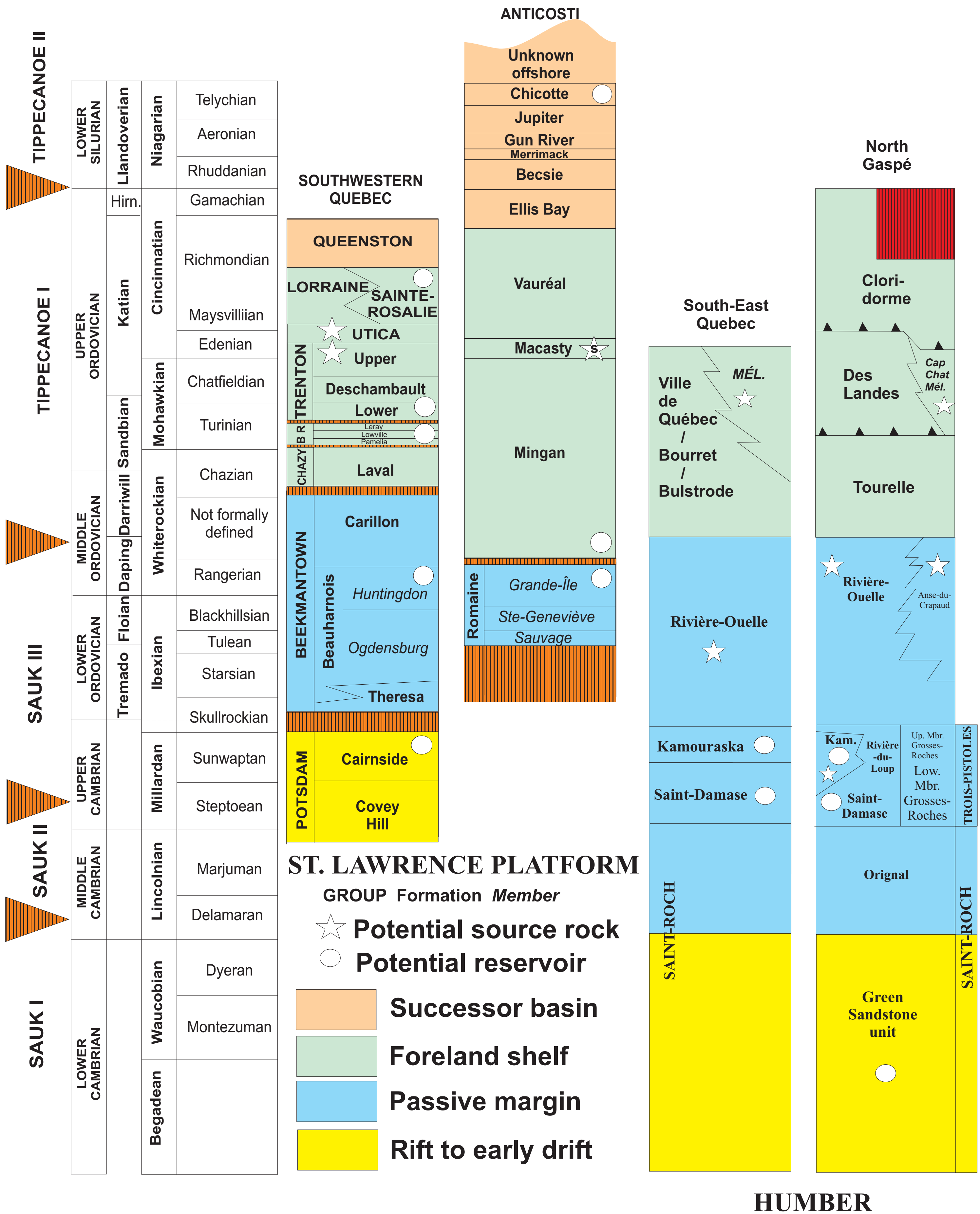

Figure 1. Stratigraphic correlation chart for Cambrian - Lower Silurian strata of the St. Lawrence Platform and Humber Zone, Quebec.

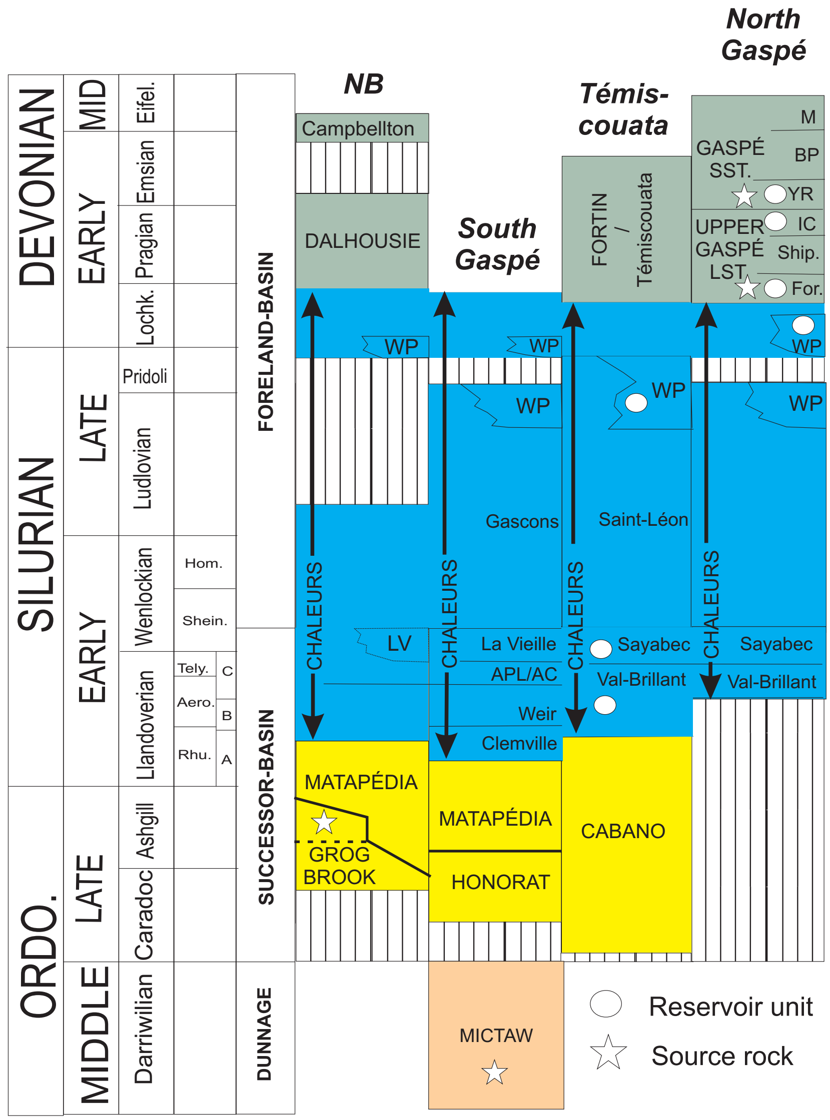

Figure 2. Stratigraphic correlation chart for Middle Ordovician - Middle Devonian strata of the Gaspé Belt, Quebec and New Brunswick.