# PS Depositional Environments of Organic-Rich Calcareous Shale in the Western Anticosti Basin: the Upper Ordovician Macasty Formation, Quebec, Canada\*

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Search and Discovery Article #10571 (2014)\*\*
Posted February 11, 2014

\*Adapted from poster presentation given at AAPG 2013 Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013

### **Abstract**

The Macasty Formation, equivalent to the Utica shale in the United States and southern Quebec, consists of organic-rich black calcareous shale deposited on top of the shallow water Mingan carbonate platform in a foreland basin during the Taconic orogeny. The sharp boundary between the two units suggests an abrupt change in the basin configuration. The Macasty shale is composed of very fine-grained quartz, feldspar and clay minerals cemented by calcite (up to 45%). We examined the entire section of the Macasty shale ( $\sim$  80 m in thickness) in drill hole LGPL on Anticosti Island. The compositions including the mineralogy and major and minor element abundance did not show any significant changes during the deposition of the shale. The siliciclastic components were primarily supplied from granitic rocks of the Grenville province after extensive weathering. These components were deposited in anoxic environments that allowed the accumulation of redox-sensitive elements and organic matter (up to 8 % TOC), and the reduction of marine sulfate to sulfide (0.7 to 1.6 wt% S). The organic matter has  $\delta^{13}C_{PDB}$  values ranging from -29 to -23 ‰, which are similar to those of Ordovician sedimentary rocks in other areas. Sulphur isotope compositions for disseminated fine-grained pyrite range from -11 to +1 ‰, which suggest the deposition in a basin with a slightly restricted supply of open ocean water. The sulfide concentrated chalcophile elements, such as As (up to 13 ppm), Cu (up to 61 ppm), Mo (up to 179 ppm) and Pb (up to 39 ppm). The organic matter was responsible for the reduction of soluble  $U^{6+}$  to  $U^{4+}$  to be fixed in the sediments, leading to high U/Th ratios (up to 3.5) in organic-rich shale. The abundant calcite in the shale shows  $\delta^{13}C$  values from -2.8 -to +1.0 ‰ and  $\delta^{18}O_{PDB}$  from -8.6 to -2 ‰. Combined with the finely crystalline texture of calcite, it is interpreted to have been precipitated at temperatures from 40 to 55 C after the deposition of the siliciclastic material and organics, b

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# Depositional environments of organic-rich calcareous shale in the western Anticosti Basin: the Upper Ordovician Macasty Formation, Quebec, Canada

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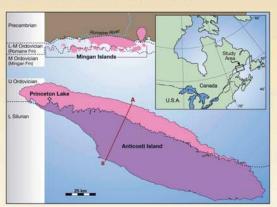
The Macasty Formation, equivalent to the Utica shale in the US and southern Quebec, consists of organic-rich black calcareous shale deposited unconformably on top of the shallow water Mingan carbonate platform in a foreland basin during the Taconic orogeny. The sharp boundary between the two units suggests an abrupt change in the basin configuration. The Macasty shale is composed of very finegrained quartz, feldspar and clay minerals cemented by calcite (up to 45%). We examined the entire section of the Macasty shale (~ 80 m in thickness) in Princeton Lake drill core on Anticosti Island. The compositions including the mineralogy and major and minor element abundance did not show any significant changes during the deposition of the shale. The siliciclastic components were primarily supplied from granitic rocks of the Grenville province after extensive weathering. These components were deposited in anoxic environments that allowed the accumulation of redox-sensitive elements and organic matter (up to 8 % TOC), and the reduction of marine sulphate to sulphide (0.7 to 1.6 wt % S). The organic matter has  $\delta^{13}C_{pop}$  values ranging from -29 to -23 %, which are similar to those of Ordovician sedimentary rocks in other areas. Sulphur isotope compositions for disseminated fine-grained pyrite range from +14 to +27 ‰, which suggest the deposition in a basin with a slightly restricted supply of open ocean water. The sulphide concentrated chalcophile elements, such as As (up to 13 ppm), Cu (up to 61 ppm), Mo (up to 179 ppm) and Pb (up to 39 ppm). The organic matter was responsible for the reduction of soluble U<sup>6+</sup> to U<sup>4+</sup> to be fixed in the sediments, leading to high U/Th ratios (up to 3.5) in organic-rich shale. The abundant calcite in the shale shows  $\delta^{13}$ C values from -2.8 -to +1.0 % and  $\delta^{18}$ O<sub>ppp</sub> from -8.6 to -2 ‰. Combined with the finely crystalline texture of calcite, it precipitated at temperatures from 40 to 55 °C after the deposition of the siliciclastic material and organics, but before any significant compaction. The introduction of this slightly oxidizing diagenetic solution was accompanied by the crystallization of coarsegrained pyrite with variably high  $\delta^{34}$ S values from - 3 to +28 ‰.

### **Anticosti Basin**

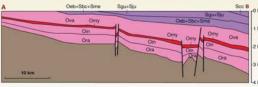
The Anticosti Basin represents the eastern segment of the St. Lawrence platform. The basin is bounded on the north by Precambrian Grenville Province and to the southeast and southwest by thrusted terranes of the Appalachian orogen. The western Anticosti Basin is mostly concealed beneath the waters of the northern part of the Gulf of St. Lawrence and its adjacent estuary, but rises to the surface to form bedrock along the Mingan Islands and on Anticosti Island. There, preserved Lower Ordovician to Lower Silurian strata recorded a transition from a passive-margin setting to a tectonically active foreland basin to a post-Taconic successor basin. The foreland basin was related to the emplacement of Taconic thrust sheets farther to the south over the northern part of the Gaspe Peninsula and over parts of the Goulf St. Lawrence (Pinet et al., 2008). The subsequent post-Taconic successor basin was affected by minor Acadian tectonic stresses (Bordet et al., 2010).

## **Macasty Formation (Princeton Lake Drill Core)**

Earlier petrography and Rock-Eval analysis showed that Upper Ordovician Macasty Formation contains Type II organic matter (TOC, up to 7.1 %; HI, up to 485 mg HC/g; Bertrand, 1987) and has significant potential for oil production. In a more recent study by Petrolia (2013), the shale displayed consistently high TOC (average 4.0 wt%) across the entire thickness (~ 80 m) of the formation and the values are within the oil window



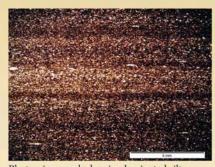
An index map showing the location of the study area in astern North America and a eologic map showing Lower Ordovician to Lower Silurian strata exposed along the Mingan Subsurface data used in this study ore located in the western part of



Structural cross section (AB) showing Lower Ordovician to Lower Silurian strata present below Anticosti Island based on seismic and core correlations (modified Castonguay et al., 2005). Ora = Romaine; Oin = Mingan; Omy = Macasty; Ova = Vaureal; Oeb = Ellis Bay; Sbc = Becscie; Sme = Merrimack; Sgu = Gun River; Sju = Jupiter; Scc = Chicotte



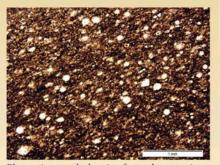
Typical Macasty shale in Princeton Lake drill core showing massive, dark-coloured, fined-grained ithology with poorly developed fissility. Core shown here in 5-feet segments.



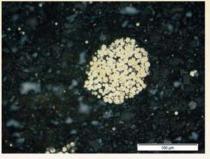
micrograph showing laminated silt bearing Macasty mudstone. Framework grains are quartz with rare sponge spicules. Matrix is



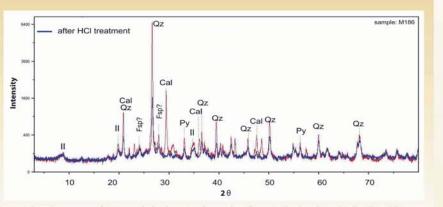
Photomicrograph showing cone-in-cone horizontal structure within the Macasty mudstone with concentric cones nested inside each other and thin layers of clay trapped between cones. These features formed by expansive mineral growth of cone-shaped aggregates of fibrous calcite. Scale bar is 1 mm.



Photomicrograph showing featureless massive Macasty mudstone, Framework grains are quartz and calcispheres. Matrix composed of fine-grained carbonate, clays, and organic

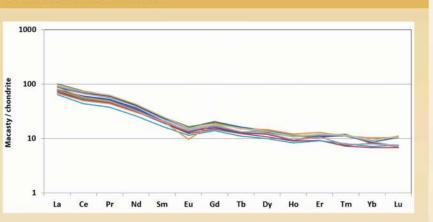


Photomicrograph in reflected light showing framboidal pyrite with roughly spherical aggregates of discrete equi-regular euhedral microcrystallites. Scale bar is 100 μm.

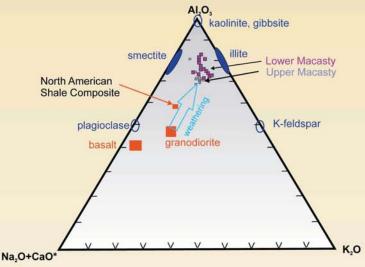


Typical XRD pattern of Macaty shale showing the peaks of quartz (Qz), calcite (Cal), illite (II), pyrite (Py), and feldspar (Fsp). Combined with XRF data, the mineralogy is estimated to be  $\alpha = -40-50\%$ ; calcite = -30-40%; illite = -15% and others = -5%.

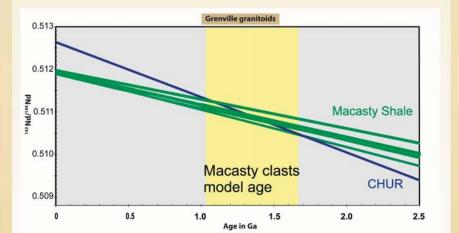
## **Sediment Provenance**



Chondrite-normalized REE pattern of the Macasty shale showing an enrichment of light REE and negative Eu anomalies. The data suggest that the provenance is mostly from evolved felsic rocks.

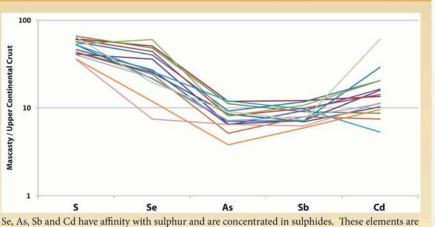


Ternary plot of the bulk rock composition of Macasty shale. Low alkalis and alkali-earth elements suggest that the framework grains of these shales experienced intense weathering at the source. Granodiorite and basalt values from Taylor and McLennan (1985). North American Shale Composite (NASC) values from Gromet et al. (1984). Note that CaO in the Macasty shale is assumed to be in calcite. Therefore CaO\* (CaO in silicates) is zero in the calculation.

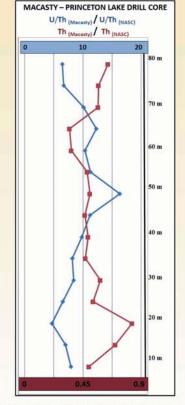


Macasty shale Nd isotopic evolution (green lines) compared to chondritic uniform reservoir (CHUR) (blue line). The Nd model ages, weighted average of the provenance of these shales, range from 1.05 to 1.6 Ga, and are similar to the ages of granitoids in the Grenville Province. The Nd isotope data were obtained by Pedro (2011). CHUR values from Allegre et al. (1983).

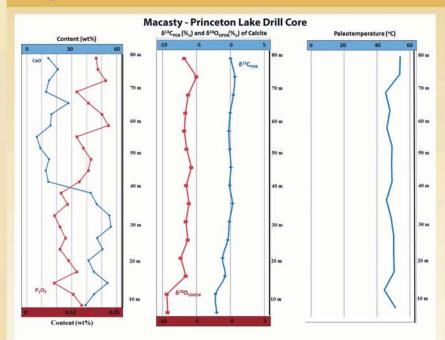
## **Depositional Environment**



enriched in the Macasty shale. Upper continental crust values from Taylor and McLennan (1985).



Princeton Lake Drill Core (~80 m thick Macasty Formation). In blue is (U/Th) in Macasty sample/ (U/Th) in NASC; in red is Th in Macasty sample/ Th in NASC. The high ratio of (U/Th) indicates high organic content and hence reducing conditions. NASC values from Gromet et al. (1984).



In blue is CaO in wt %; in red P<sub>2</sub>O<sub>5</sub> in wt %. The high (>20%) in the lower Macasty, but lower in the upper Macasty with a few exceptions.

of calcite. The values of  $\delta^{13}C_{PDB}$  at ~0 % indicate that calcite present in Macasty shale is an early diagenetic component.

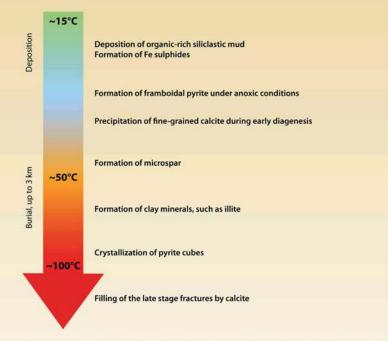
In blue is  $\delta^{13}C_{pDB}$  (‰) trend and in red is  $\delta^{18}O_{pDB}$  (‰) trend and in r present in the Macasty shale calculated by the equation  $t (^{\circ}C) = 16.0 - 4.2(\delta c - \delta w) +$ 0.13(δc-δw)2 (Faure, 1986). Assuming  $\delta w = 0\%$ , the average paleotemperature was

The framework grains of the Macasty shale are composed of very finegrained quartz, clay minerals, and feldspars. Abundant post-depositional calcite is also present in the Macasty shale; resulting into a more brittle lithology.

The major elements, when compared with the NASC, show a typical signature of shales, but higher content of carbonate and phosphate. The REE show a slight depletion, when compared to NASC, and no significant enrichment or depletion, when compared to the upper crust, but an enrichment of light REE and negative Eu anomalies, when normalized to chondrites, indicating a felsic provenance. Based on its location and tectonic setting, our data suggest a sediment provenance mainly from granitic rocks of the Grenville Province. The Macasty samples show considerable depletion in Na<sub>2</sub>O and K<sub>2</sub>O content when compared to the upper continental crust indicating that the source was highly weathered.

Se, As, Sb and Cd show high concentrations, when compared to the upper continental crust, being likely incorporated in pyrite. The high U/Th ratios (up to 16), when compared to NASC, indicate anoxic depositional conditions.

The  $\delta^{13}C_{pdB}$  isotope values of the calcite are close to 0 % indicating that calcite was precipitated from marine waters. Their  $\delta^{18}O_{PDR}$  values are  $\sim$  -6 % suggesting at low-medium temperature after some burial or incursion of meteoric



- · Macasty sediment derived from a felsic source in the Proterozoic Grenville
- No significant change in the source during the Macasty deposition.
- Source rocks underwent intense weathering, probably under hot humid climatic conditions.
- Abundant organic matter (up to 8 wt% in TOC), pyrite, and redox-sensitive elements indicate that the depositional environment was anoxic.
- High  $\delta^{34}$ S for sulphides suggest a limited supply of open ocean water, probably stratified water column or irregular basin paleotopography.
- Carbon and oxygen isotope compositions in calcite indicate a supply of marine carbonate during early diagenesis at temperatures of ~ 50°C.

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## Acknowledments

The Natural Sciences and Engineering Research Council (NSERC) of Canada provided research support. The Ministère