[PS]Upper Ordovician Organic-Rich Mudstones of Southern Ontario*

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Abstract

Despite unconventional hydrocarbon exploration activity in Upper Ordovician mudstones of adjacent jurisdictions, these units are not well characterized in Ontario. The Ordovician shale sequence studied for this project consists of the Georgian Bay Formation, the Blue Mountain Formation and its Rouge River Member and the Collingwood Member of the Cobourg Formation, from top to bottom. In 2011, the Ontario Geological Survey drilled a 496.5m deep well in Wellington County, to collect core samples through the Upper Ordovician shale sequence. Samples were analyzed for gas concentration and composition, methane isotope composition, adsorption isotherms, rock mechanics, Rock-Eval® 6 pyrolysis, mineralogy, permeability, porosity and gas, oil and water saturations. The well was also logged geophysically. The interval with the best source rock potential consists of the Rouge River and Collingwood members. In the Wellington well, these members are 13.7m and 10.4m thick, respectively. A thin phosphatic bed is present between the two units. The Rouge River Mb is a highly fissile dark bluish-grey to black, non-calcareous shale, whereas the Collingwood Mb is a dark brown to black, fissile, impure limestone, with very thin bioclastic interbeds. An oil stain was observed near the top of the Collingwood Mb in this core. Results confirm that the Rouge River and Collingwood members represent the most organic-rich interval (up to 4.68 wt%). Rock-Eval® 6 pyrolysis Tmax data (438°C to 442°C) from these units suggests temperatures in the early oil window. Methane isotopes indicate a thermogenic source. The Rouge River Mb has high oil saturation (up to 31.5%) and a mix of type II/III kerogen (HI between 280 and 419) while the Collingwood Mb shows high gas saturation (77.2%) and a type II kerogen (HI between 532 and 650). The Rouge River and Collingwood members present different characteristics for almost all geochemical and geophysical parameters. This project also studied the Ordovician shale sequence across southern Ontario to better define the extent and

thickness of these units. Drill core and cuttings were collected from previously drilled wells and analyzed for mineralogy by X-Ray diffraction and Rock-Eval® 6 pyrolysis. However, to efficiently portray the regional potential of these units as source rocks, additional new core and gas samples should be collected and analyzed for crucial parameters, like porosity, permeability and gas/oil concentrations, compositions and saturations amongst others.

Upper Ordovician Organic-Rich Mudstones of Southern Ontario

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ABSTRACT

Despite unconventional hydrocarbon exploration activity in Upper Ordovician mudstones of adjacent jurisdictions, these units are not well characterized in Ontario. The Ordovician shale sequence studied for this project consists of the Georgian Bay Formation, the Blue Mountain Formation and its Rouge River Member and the Collingwood Member of the Lindsay Formation, from top to bottom.

In 2011, the Ontario Geological Survey (OGS) drilled a 496.5m deep well near Mount Forest in Wellington North County, to collect core samples through the Upper Ordovician shale sequence. Samples were analyzed for gas concentration and composition, methane isotope composition, adsorption isotherms, rock mechanics, Rock-Eval® 6 pyrolysis, mineralogy by X-Ray diffraction, permeability, porosity and gas, oil and water saturations. The well was also logged geophysically. Furthermore, in the summer of 2012, the OGS sampled some previously drilled cores and drill cuttings from 11 wells found throughout southern and eastern Ontario (Figure 1). The samples collected were analyzed for Rock-Eval® 6 pyrolysis and mineralogy by X-Ray diffraction.

The interval with the best source rock potential consists of the Rouge River and Collingwood members. In the Mount Forest well, these members are 13.7m and 10.4m thick, respectively. A thin phosphatic bed is present between the two units. The Rouge River Mb is a highly fissile dark bluish-grey to black, non-calcareous shale, whereas the Collingwood Mb is a dark brown to black, fissile, impure limestone, with very thin bioclastic interbeds. An oil stain was observed near the top of the Collingwood Mb in this core.

Results from the drilling program confirm that the Rouge River and Collingwood members represent the most organic-rich interval (up to 4.68 wt%). Rock-Eval® 6 pyrolysis Tmax data (438°C to 442°C) from these units suggests temperatures in the early oil window. Methane isotopes indicate a thermogenic source. The Rouge River Mb has high oil saturation (up to 31.5%) and a mix of type II/III kerogen (HI between 280 and 419) while the Collingwood Mb shows high gas saturation (77.2%) and a type II kerogen (HI between 532 and 650).

As a regional perspective, the Rouge River and Collingwood Mbs are present throughout the wells sampled in southern Ontario, with the exception of the Collingwood Mb which is absent in the Chatham well. However, the thicknesses of the units can vary considerably. The Collingwood Mb tends to have similar mineralogy throughout Ontario though Rock-Eval6 pyrolysis data suggests that source rock potential seems to be higher in the northeast where the thickness is also greater. As for the Rouge River Mb, the mineralogy is also fairly consistent throughout the sampled wells while the thickest interval and the greater hydrocarbon generation seem to occur in the southeast of southern Ontario. Tmax results from samples collected in southern Ontario indicate an early oil window thermal regime while data from the Russell well of eastern Ontario implies late oil window to overmature thermal regime.

The Rouge River and Collingwood members present different characteristics for almost all geochemical and geophysical parameters. This project also studied the Ordovician shale sequence across southern Ontario to better define the extent and thickness of these units by sampling for mineralogy by X-Ray diffraction and Rock-Eval® 6 pyrolysis. However, to efficiently portray the regional potential of these units as source rocks, additional new core and gas samples should be collected and analyzed for crucial parameters, like porosity, permeability and gas/oil concentrations, compositions and saturations amongst others.

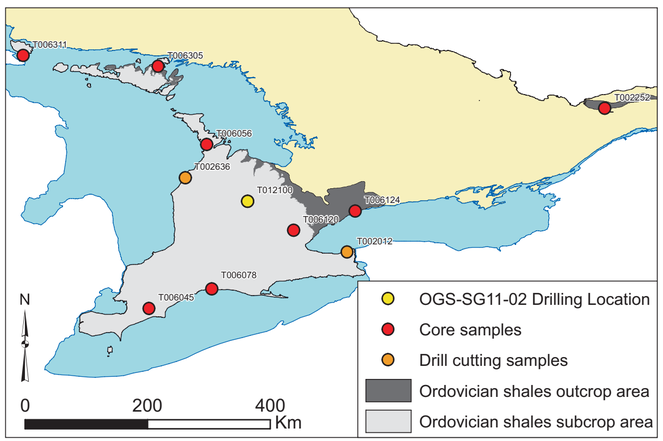

Figure 1: Localization map of subcrop/outcrop areas of Ordovician shales, Mount Forest (OGS-SG11-02) well and other drill holes/drill cuttings used as part of the regional sampling program.

DRILLING PROGRAM

The well drilled near Mount Forest (OGS-SG11-02) intercepted the entire Ordovician succession which is made up of the following stratigraphic units (Figure 2). The Queenston Fm, which is composed of a succession of red and green shales and has low organic content will not be discussed here since it has no shale gas potential.

Georgian Bay Fm (from 296.27 m to 426.00 m):

Bluish - to greenish-grey non-calcareous shale, interbedded with limestone, siltstone and sandstone. The thickness of these beds tends to increase upward. Gas bubbles were observed on the core at about 313 m deep. Its lower contact with the Blue Mountain Formation is gradational.

Blue Mountain Fm (from 426.00 to 476.90 m):

Bluish- to brownish-grey non-calcareous shale with laminations of limestone and siltstone. The lower part of the unit is called the Rouge River Mb.

Rouge River Mb (from 463.3 to 476.90 m):

Dark grey-brown to brownish black noncalcareous shale. Its lower contact with the Collingwood Mb is sharp and is associated with a phosphatic bed of about 1 cm (Photo 1).

Lindsay Fm (from 476.90 to 496.50):

Collingwood Mb (from 476.90 to 486.30):

Dark grey-brown to black, organic-rich, calcareous shale with thin interbeds of bioclastic limestone. Oil stain can be observed on the core (Photo 2).The Collingwood is the upper member of the Lindsay Fm. Its lower contact with the Cobourg Fm is gradational.

Cobourg Fm (from 486.30 to 496.50):

Fine-grained fossiliferous light grey to dark grey nodular limestone interbedded with light grey to grey-brown shale. The Cobourg Fm is the lower member of the Lindsay Fm. The lower contact of the unit was not intercepted in the drill hole.

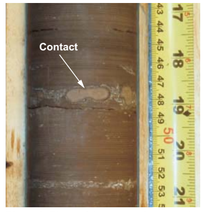

Photo 1: Photo of the contact between the Rouge River Mb (above) and the Collingwood Mb (under) in the Mount Forest well (OGS-SG11-02).

Photo 2: Photo of an oil stain observed in the Collingwood Mb of the Mount Forest well (OGS-SG11-02) at a depth of 479.74m. It is associated to a vertical fracture.

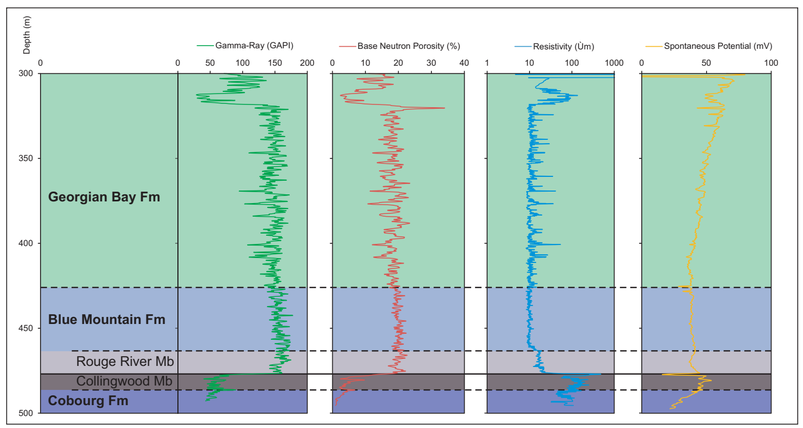

Figure 2: Stratigraphic and geophysical logs of the Mount Forest well (OGS-SG11-02).

RESULTS

Gas Content and Composition

Gas desorption data clearly indicate that the Rouge River and Collingwood members are the stratigraphic units with the most gas content (Figure 3). Some higher than expected gas content values can be observed in the Georgian Bay Formation. These values are probably associated to greater porosity and does not indicate higher source rock potential. Low adsorbtion values for the Collingwood Member suggest a high proportion of free gas in this unit.

Gas composition does show a slight increase in heavier hydrocarbons in the Rouge River and Collingwood members.

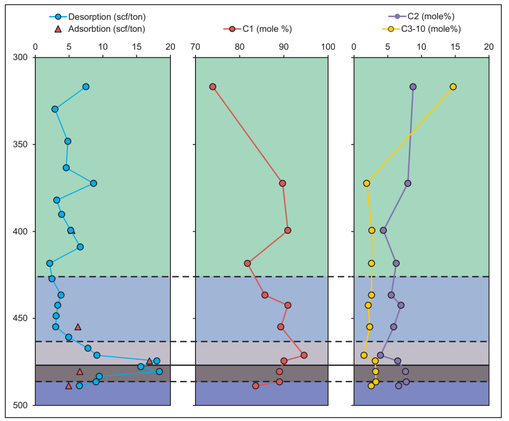

Figure 3: Gas desorption/ adsorbtion and gas composition logs of the Mount Forest well (OGS-SG11-02). See stratigraphy in Figure 2.

Gas Research Institute (GRI) Parameters

The GRI parameters indicate that the porosity and permeability are greater in the Georgian Bay and Blue Mountain formations which can be explained by the higher proportion of siltstone, sandstone and fossiliferous beds.

The Rouge River and Collingwood members have the best hydrocarbon saturation values (Figure 5). However, the 2 stratigraphic units present different trends. The Rouge River Mb shows the best oil saturation value (31.5%) while the Collingwood Mb shows the best gas saturation value (77.2%).

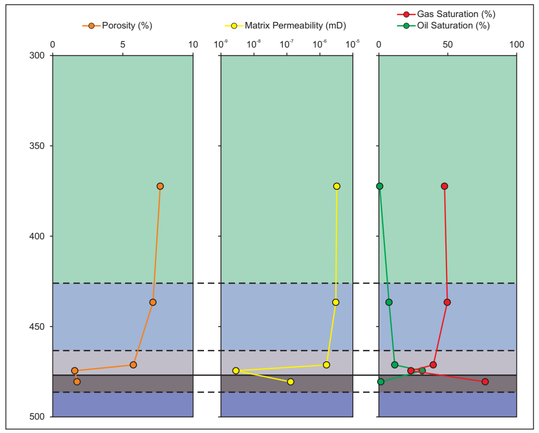

Figure 5: Gas Research institute logs for the Mount Forest well (OGS-SG11-02). See stratigraphy in Figure 2.

Gas Isotopes

Samples for methane isotopes were collected throughout the entire Ordovician shale succession. All of them support a thermogenic origin (Figure 4). This conclusion is also supported by the presence of heavier hydrocarbons (Figure 3)

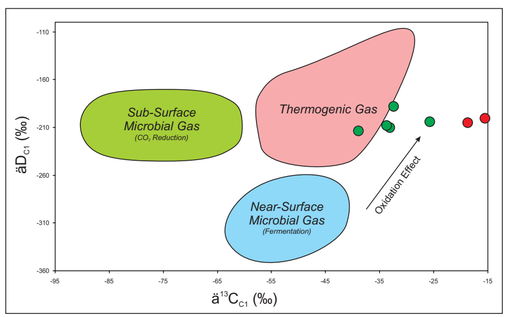

Figure 4: Isotopic signature of methane of the Ordovician shales of the Mount Forest well (OGS-SG11-02). The red dots indicate probable contaminated samples.

Organic Matter and Maturity

Rock-Eval® 6 pyrolysis data indicate that the organic-rich shales of the Collingwood and the Rouge River members are in the oil window. Organic matter found in the Rouge River member results from a mix of terrestrial and marine origin while matter from the Collingwood Member seems to have a unique marine origin (Figure 6). Additional Rock-Eval® 6 pyrolysis data are discussed on the next panel.

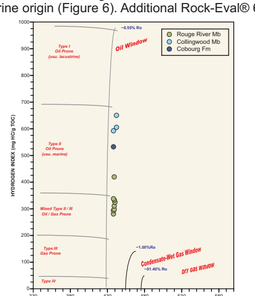

Figure 6: Hydrogen Index versus Tmax for the samples of the Mount Forest well (OGS-SG11-02). Samples from the Georgian Bay and Blue Mountain formations are not shown due to questionable data related to low S1 and S2 (see Figure 7).

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REGIONAL SAMPLING PROGRAM

The main objective of the regional sampling program (2012) was to refine, if possible, the stratigraphy of the Ordovician shale succession and to establish correlation with adjacent jurisdictions.

The Ordovician shale succession is characterized by a series of gradational changes in lithology which makes it very difficult to pick tops of geological units. In fact, the Oil, Gas and Salt Resources database currently does not allow to subdivide the Georgian Bay-Blue Mountain formations, which also include the Rouge River Mb. Furthermore, historically, the Rouge River Mb has mistakenly been recongnized as the Collingwood Mb which makes it impossible to create regional maps from the geological information of the database.

High resolution geophysical logs, when available, can definitely facilitate the task to distinguish the various units (Figure 2) but the quantity of those logs in southern Ontario is limited. Therefore, it was decided that drilled cores and cuttings from 11 previously drilled wells would be sampled and analyzed for Rock-Eval® 6 pyrolysis and mineralogy by X-Ray diffraction (XRD). Location of the wells sampled is illustrated in Figure 1.

Based on Rock-Eval® 6 pyrolysisl and mineralogy data, geological contacts between units have been defined for the 11 wells.

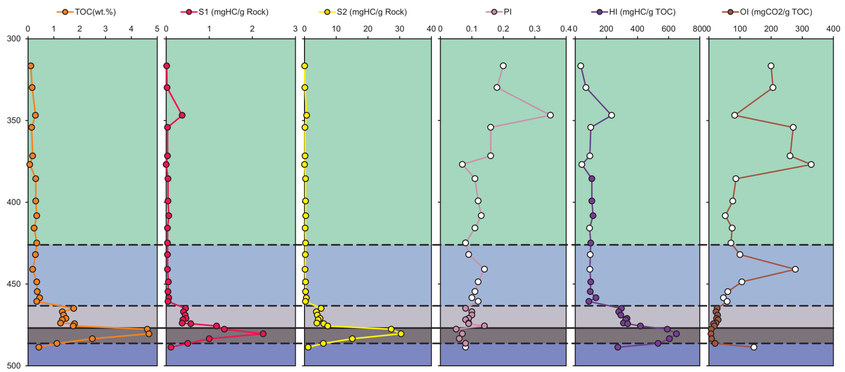

Figure 7: Rock-Eval® 6 pyrolysis logs for the Mount Forest well (OGS-SG11-02). White-filled dots indicate questionable data due mainly to either low TOC, S1 or S2.

ROCK-EVAL® 6 RESULTS

Rock-Eval® 6 data relate to source rock potential. Figure 7 presents various logs from the OGS-SG11-02 well. In this case, the Collingwood Mb seems to have the best source rock potential, based on higher TOC, S1, S2 and Hydrogen Index. However, in some other wells the Rouge River Mb may have the best potential. A series of maps (Figure 8) presents the various parameters throughout southern Ontario.

In general, one can conclude that in the southeast of the study area, the Rouge River Mb has the best source rock potential and inversely in the northwest, it is the Collingwood Mb. Compared throughout southern Ontario, the Collingwood Mb presents better values for Rock-Eval® 6 parameters (H1, S1, S2, TOC) which are indicative of a Type I or II organic matter, while the Rouge River Mb seems to be associated to a Type II or II/III.

Tmax values indicate an early oil window thermal regime, except in the case of the Russell well (T002252) in eastern Ontario, where the data suggest late oil generation or overmature (Tmax up to 440°C). In southern Ontario, a slight increase in Tmax can be noticed from the northwest (Tmax up to 445°C) towards the southeast Tmax up to 493°C).

Collingwood Mb — Rouge River Mb

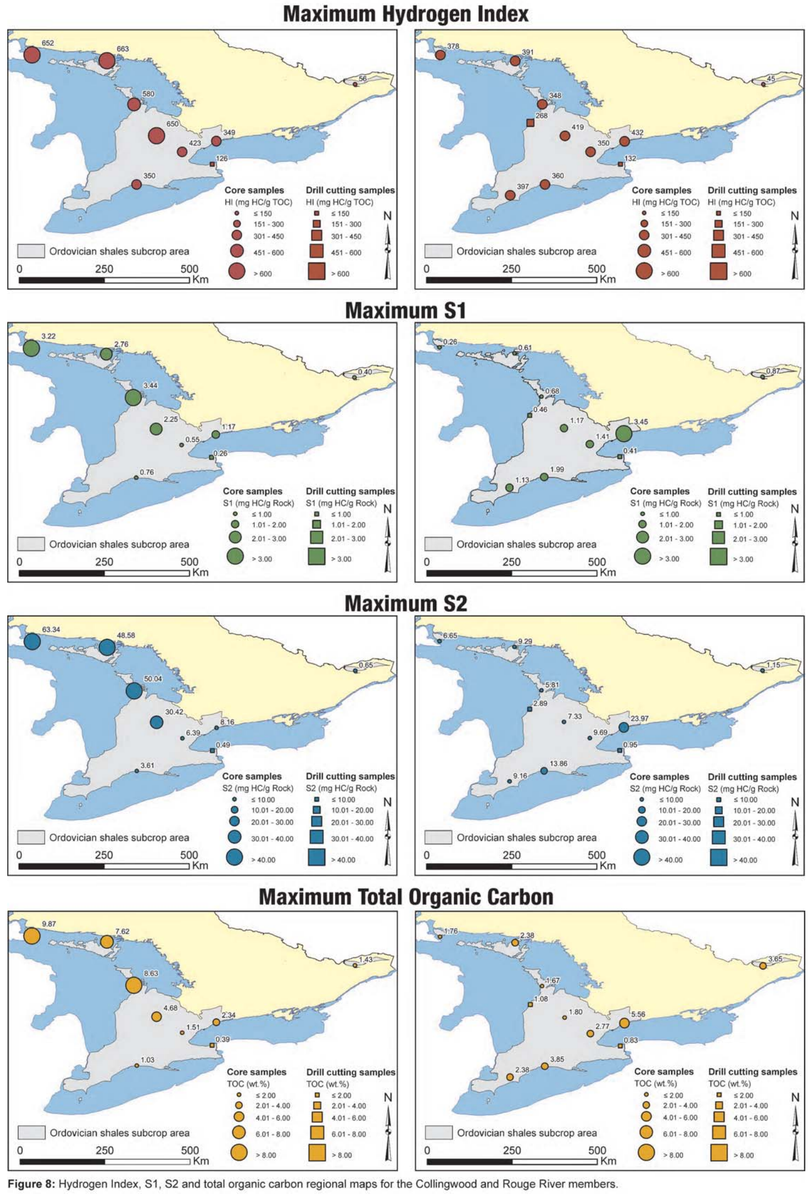

Figure 8: Hydrogen Index, S1, S2 and total organic carbon regional maps for the Collingwood and Rouge River members.

X-RAY DIFFRACTION RESULTS

The mineralogy of the Ordovician shale sequence mostly varies in carbonate content (calcite, dolomite and ankerite) while clay, quartz, feldspath and plagioclase contents seem faily constant (Figure 9). The contact between Rouge River and the Collingwood members is generally presented by a sharp downward increase in carbonate content. Also, the contact is marked by a rise in pyrite content.

No regional mineralogical trend has been observed, except for a slight increase in carbonate content for the Rouge River Mb towards the southeast.

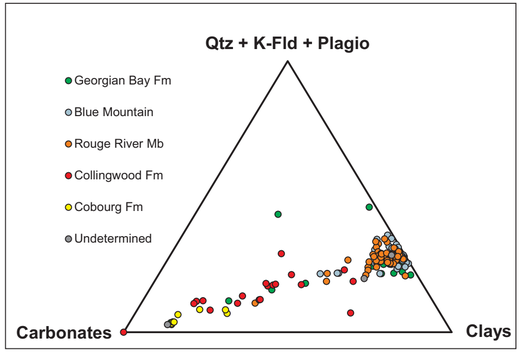

Figure 9: Ternary plot for XRD of all samples collected through the regional sampling program.

CONCLUSION

Here are the main conclusions of the Ordovician shale drilling and sampling projects:

1) The geological contacts between the various stratigraphic units of the Ordovician shale sequence can be difficult to pick, especially due to the fact that the contacts are gradational (except between the Rouge River and Collingwood members).

2) The maximum thickness (37.25m) for the Rouge River Mb can be found in the southeast of the study area while the thickest Collingwood Mb (11.00m) section is observed in the northwest.

3) The Rouge River Mb of the Blue Mountain Formation and the Collingwood Mb of the Lindsay Fm have the best potential as hydrocarbon unconventional resources plays through the Ordovician shale sequence based on:
- Gas desorption/adsorbtion
- Hydrocarbon saturation (GRI data)
- TOC, S1, S2, HI (Rock-Eval® 6 data)

4) Methane isotopes indicate a thermogenic origin.

5) The Collingwood Mb has the highest gas saturation values while the Rouge River Mb shows the highest oil saturation.

6) Based on Rock-Eval® 6 data:
- The Collingwood Mb has the best hydrocarbon generation potential (Type I or II organic matter versus a Type II or II/III for the Rouge River Mb).
- The Collingwood Mb source rock potential seems to increase towards the northwest.
- The Rouge River Mb source rock potential seems to increase towards the southeast.
- Tmax data suggest an early oil window thermal regime, except in eastern Ontario where it seems to be overmature.

7) Based on mineralogical (XRD) data:
- Uniform clay, quartz, feldspath and plagiocalse content throughout southern Ontario for the various stratigraphic units.
- Rouge River/Collingwood members contact:
  - Sharp upward decrease in carbonate content.
  - General increase of pyrite content at the contact.