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Upper Ordovician Organic-Rich Mudstones of Southern Ontario: Drilling Project Results

2015

ONTARIO GEOLOGICAL SURVEY

Open File Report 6312

Upper Ordovician Organic-Rich Mudstones of Southern Ontario: Drilling Project Results

by

C. Béland Otis

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Foreword

Natural variations in the quality of groundwater-sourced water supplies have the potential to impact human health and limit the usability of the groundwater resource. Therefore, in 2007, the Ontario Geological Survey Branch (OGS) of the Ministry of Northern Development and Mines initiated the multi-year Ambient Groundwater Geochemistry Project, which involved sampling domestic groundwater wells across southern Ontario. The objective of this geoscience survey was to identify areas of compromised water quality and determine whether these areas are related to variations in rock and soil composition. Most of these variations, including well known regional water-quality problems, can be attributed to definable geological conditions. In 2009, the OGS initiated a complementary three-year geoscience study of gas content in bedrock formations of southern Ontario by undertaking preliminary, science-based analyses of different bedrock units to assess and characterize the presence of gas and the possible implications for groundwater quality. The OGS drilled a bedrock hole as part of this work to obtain fresh samples of rock through the Paleozoic stratigraphy. The data from this current study, presented in this report, is used to 1) inventory and assess gas content in Ordovician rocks in southern Ontario; 2) characterize the gas to better understand its composition and origin; and 3) test for correlation between the natural gas signatures and areas of compromised groundwater quality.

J. A. Fyon
Director
Ontario Geological Survey

November 27, 2015

Contents

FIGURES

PHOTOS

TABLES (in Appendix)

Miscellaneous Release—Data 326

Geological, Geochemical and Geophysical Data from the Ordovician Shales Drilling Program and the Regional Sampling Program, Southern Ontario; by C. Béland Otis.

This data release contains geological, geochemical and geophysical data collected as part of the Ordovician shale drilling program that took place near Mount Forest in 2011 and the regional sampling program conducted throughout southern Ontario in the summer of 2012. The data are being released in conjunction with Open File Report 6312, *Upper Ordovician Organic-Rich Mudstones of Southern Ontario: Drilling Project Results*. The geochemical and geological data are provided in 33 tables as Microsoft® Excel® 2010 (*.xlsx*) files. The geophysical data are presented in 5 Log ASCII Standard (*.las*) files and as graphic logs in 8 *.tif* files.

MRD 326 is available separately from this report.

Abstract

The Ontario Geological Survey (OGS) drilled well OGS-SG11-02, near Mount Forest, to obtain core through the Upper Ordovician shale sequence which contains known organic-rich mudstones. The cored interval consisted of, in ascending order, the upper part of the lower Cobourg Formation, the Collingwood Member of the Cobourg Formation, the Blue Mountain Formation and its Rouge River Member and most of the Georgian Bay Formation. The well reached a depth of 406.50 m and the resulting core was sampled for various parameters, including gas content; adsorption capacity; gas and gas isotopic composition; oil, gas and water saturation; porosity; permeability; total organic carbon; Rock-Eval® 6 pyrolysis products; mineralogy by X-ray diffraction; and rock mechanics. In addition, the well was logged for geophysical parameters.

These new data indicate that 2 units within the Ordovician shale succession, the Collingwood and the Rouge River members, have the greatest hydrocarbon generation potential. This conclusion is based on parameters such as total gas content, gas adsorption, hydrocarbon saturation, total organic carbon content and other pyrolysis parameters such as the quantity of free hydrocarbon in the rock, the amount of hydrocarbons generated through thermal cracking and the type of organic matter, characterized in this report by hydrogen index values. The upper Blue Mountain and Georgian Bay formations may however present better reservoir properties, because of a greater primary porosity associated with their lithologic character. Rock-Eval® 6 pyrolysis data indicate that organic matter in the Collingwood and Rouge River members at this location are within the “oil window” of thermal maturity.

Despite being situated stratigraphically above each other, and both described as black shales, the Collingwood and Rouge River members have significantly different geological and geochemical characteristics. The 2 units are separated by a phosphatic nodular bed in this particular well and can be readily distinguished on the basis of visual inspection of the core and by their geophysical properties in log. The 2 units reflect different environments of deposition and sources of sediment. The Collingwood Member seems associated with a more open marine setting, indicated by the type of organic matter and its calcite-dominated mineralogy, making it a shaly limestone or calcareous mudstone. The Rouge River Member, on the other hand, shows a higher proportion of terrestrially derived clays, suggesting that deposition was mainly influenced by the influx of siliciclastic sediments during the Taconic Orogeny. Rock-Eval® 6 pyrolysis analysis indicates that the Rouge River Member contains Type II-III organic matter (i.e., gas and oil prone) and the Collingwood Member contains oil prone Type II (oil prone) organic matter.

The hydrocarbon generation potential of these Upper Ordovician black shales, as indicated by data obtained from well OGS-SG11-02, compare favourably with correlative units in adjacent jurisdictions. However, the Rouge River and Collingwood members have significantly less gas or oil saturation values when compared to equivalent but deeper units in adjacent jurisdictions. This is likely due to the lower maturity level of these units in southern Ontario. Additionally, regional-scale data are required to determine the regional variability of these units, their thermal maturity and hydrocarbon generation potential before any assessment of their resource potential can be made.

Upper Ordovician Organic-Rich Mudstones of Southern Ontario: Drilling Project Results

C. Béland Otis[1]

Ontario Geological Survey
Open File Report 6312
2015

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Introduction

In 2009, the Ontario Geological Survey (OGS) initiated a geoscience study of organic-rich, fine-grained bedrock formations in southern Ontario by undertaking preliminary, science-based analyses of known Paleozoic black shale units to determine their natural gas content. Several units were initially identified for this study based upon several criteria: high organic content, established source rock of economic hydrocarbon accumulations, and correlatives to known hydrocarbon-bearing shale units in adjacent jurisdictions of the United States and/or Canada (Barker 1985; Béland Otis 2009, 2010, 2011). These units included the Upper Devonian Kettle Point Formation, the Middle Devonian Marcellus Formation, the Upper Ordovician Georgian Bay and Blue Mountain formations and the Upper Ordovician Collingwood Member of the Cobourg Formation. The lower member of the Blue Mountain Formation is called the Rouge River Member. Throughout this report, this entire succession of units will be abridged as the Upper Ordovician shale succession. Note that the Upper Ordovician Queenston Formation, a succession of green and red shales overlying the Georgian Bay Formation, will not be discussed since it does not show any hydrocarbon generation potential.

In the spring of 2010, the OGS drilled 2 wells through the Devonian Kettle Point Formation in southwestern Ontario to evaluate its natural gas potential. Core samples were collected to measure gas concentration and other key parameters (Béland Otis 2010, 2011, 2013). Similar work was performed in 2011 near Mount Forest in the Wellington North County to assess the hydrocarbon potential of the Upper Ordovician shale succession and some preliminary data have been published by Béland Otis (2012). Furthermore, in the summer of 2012, additional rock samples were collected from this core and analyzed for mineralogy (by X-ray diffraction) and Rock-Eval® 6 pyrolysis products (Béland Otis 2012). Ordovician shales from additional cores and cuttings from wells across southern Ontario were also sampled for mineralogy and pyrolysis analysis. These results will not be discussed in this report. However, this regional data set is part of the Miscellaneous Release—Data 326 publication associated with this report.

Methodology

The OGS planned to core one well through the Upper Ordovician shale sequence down into the Cobourg Formation of the Trenton Group. The selected drilling site was located in the Arthur Township of Wellington County, Lot 6, Concession V. A first attempt, well OGS-SG11-01, was drilled in February 2011 but intercepted a karst zone at a depth of 121.9 m in Silurian rocks and had to be abandoned. It was cemented throughout. Therefore, a second well, OGS-SG11-02, was initiated in April 2011. This well, with co-ordinates latitude 43°57'35.871"N and longitude 80°38'7.249"W, is located approximately 5 km from the municipality of Mount Forest. The location of this well is indicated in Figures 1 and 2.

The well was bored vertically from surface through Quaternary sediments, the Silurian bedrock succession and the Upper Ordovician Queenston Formation to a depth of 303.58 m, just below the top of the Georgian Bay Formation (296.27 m). The well was then continuously cored down to 497.70 m, into the Cobourg Formation of the Trenton Group. These depths were recorded by the drillers. In this interval, core samples were collected and subsequently analyzed for gas content; gas composition; isotopic composition of methane; total organic carbon; oil, gas and water saturation; permeability; porosity; adsorption capacity; and rock mechanics. Subsequent geophysical logging (see below) indicated that depths recorded by the drillers were up to 1.2 m greater than the depths recorded by the logging tools. Therefore, the term “corrected depth” will be used in this report to reference the geophysical logger depths. The core was subsequently sampled for additional parameters (mineralogy by X-ray diffraction, Rock-Eval® 6 pyrolysis products) as part of a regional study (Béland Otis 2012). Only results from this core will be discussed in this report.

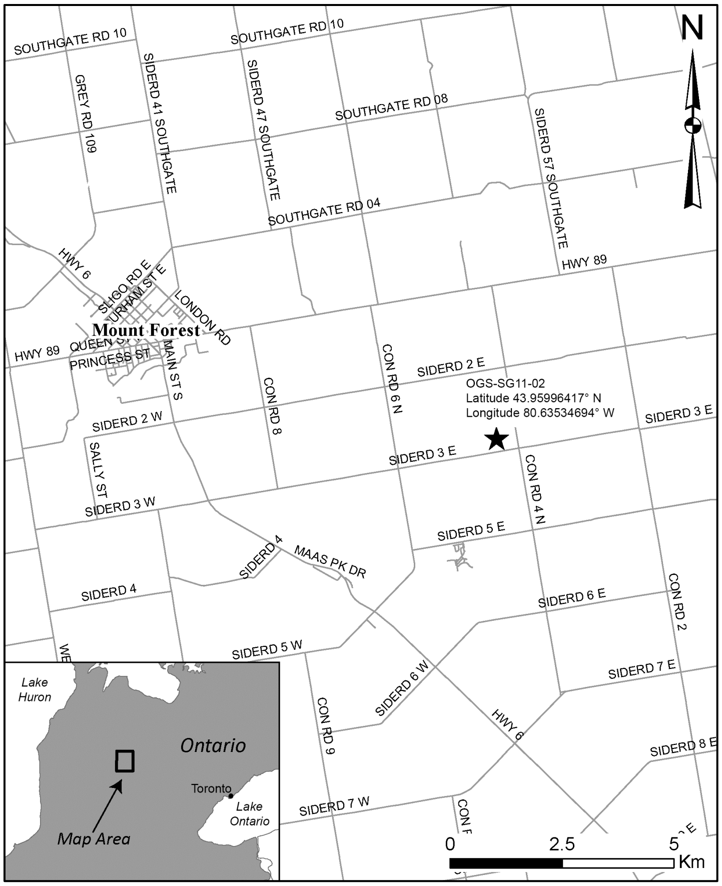

Figure 1. Map showing the location of the OGS-SG11-02 well drilled near Mount Forest, southern Ontario.

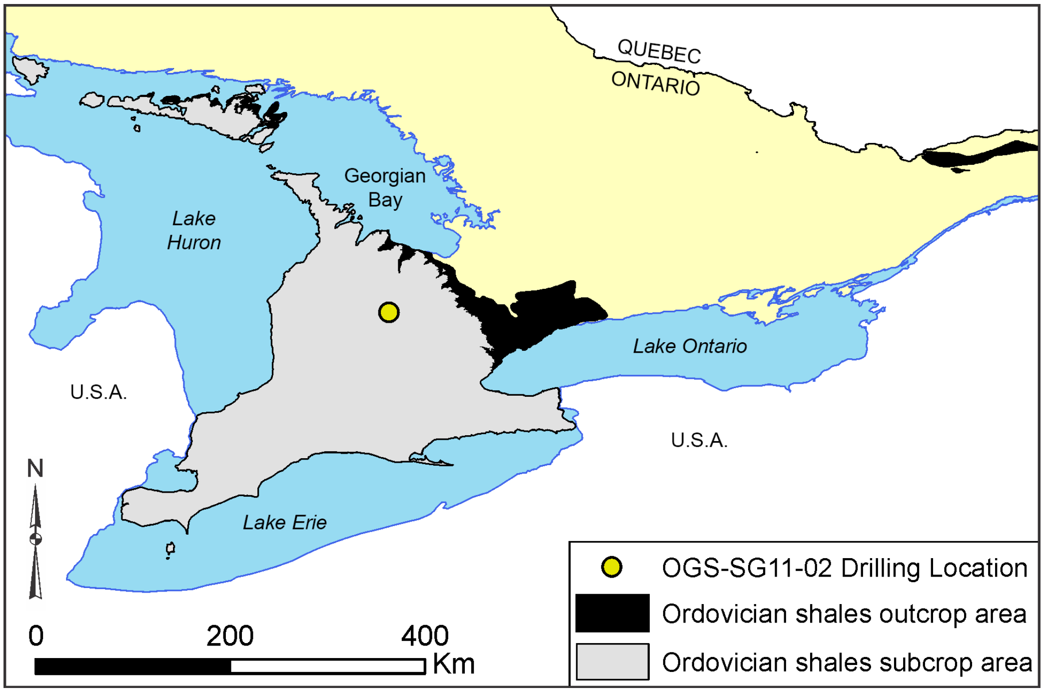

Figure 2. Map showing the subcrop and outcrop areas of the Ordovician shales in southern Ontario, as well as the drill site for the OGS-SG11-02 well.

The main purpose for drilling this new core was to obtain desorbed gas measurements and other important parameters that are only measurable with fresh core. Core samples, 30 cm long, were collected at 2.29 to 18.5 m intervals depending on the lithology. These core samples were put into sealed canisters as soon as the core reached surface (Photo 1) and stored in a water bath at reservoir temperature. Initially, gas content readings were obtained hourly at the drilling site. When drilling was completed, the canisters were sent to Core Laboratories Ltd. in Calgary where readings were taken weekly, until gas measurements became negligible. All canister samples were assigned the term "CAN". The samples were then numbered in sequence from the top to the bottom of the well (CAN-01, CAN-02, etc.). Twenty-four desorption canister samples were obtained from the OGS-SG11-02 well (Table 1; for all tables of data *see* "Appendix").

The quantity of total gas contained in a core sample is the sum of projected lost gas, measured desorbed gas in the canister and projected or measured residual gas. The lost gas content represents the estimated quantity of gas released by the core sample before it was put in the canister. This is an estimated value calculated by Core Laboratories Ltd using a specific algorithm. The measured desorbed gas content corresponds to the measured quantity of gas naturally released by the core sample in the canister over time. The residual gas content represents the gas still in the shale after the measurement

Photo 1. Gas canister used to collect core samples for gas desorption analyses and adsorption isotherms. The height of the canister is approximately 30 cm.

of desorbed gas is completed. To determine residual gas, the core sample is crushed to release the gas still trapped in the rock. Residual gas can also be calculated using an algorithm. Core Laboratories Ltd measured the residual gas content of 15 samples out of the 24 collected and calculated the projected residual gas content for all gas samples. Some of the canister samples were also analyzed by Core Laboratories Ltd. for additional parameters. Twelve samples were analyzed for gas composition and 7 of these were also analyzed for the isotopic composition of methane; although 2 of the samples appear to have been air contaminated. These subsamples were collected directly from the canister. The air contamination identified in the samples CAN-19B and CAN-24B is only observed in the isotopic gas composition suggesting that the contamination occurred when the subsamples were collected from the canister. Finally, 5 samples were analyzed for adsorption capacity, standard Gas Research Institute (GRI) analyses and rock mechanical properties (Guidry, Luffel and Curtis 1996). Table 1 presents all analyses performed for each canister sample.

In October 2011, the OGS-SG11-02 well was geophysically logged by Weatherford International Ltd. The parameters measured were gamma-ray, density, porosity, spontaneous potential, temperature, conductivity, induction sonic and micro-resistivity images collected using the micro-imager. Selected geophysical logs are presented in Figure 3 of this report. All geophysical logs are available as **.las* (Log ASCII Standard) files in MRD 326. Following geophysical logging, both OGS-SG11-01 and OGS-SG11-02 wells were plugged in accordance with the Oil, Gas and Salt Resources of Ontario, Provincial Operating Standards.

Additional core samples were collected from OGS-SG11-02 and analyzed for total organic carbon by Core Laboratories Ltd. These samples are identified in the column “Total Organic Carbon” of Table 2. In addition, samples from OGS-SG11-02 were collected for mineralogy by X-ray diffraction (XRD) and Rock-Eval® 6 pyrolysis (listed in Table 2), which also includes total organic carbon determination. All these rock samples were labelled with the prefix TOC. Two additional samples (CBO-12-1121 and CBO-12-1122) were taken in the summer of 2012. Table 2 lists all samples, depths, and corresponding analyses performed. X-Ray diffraction analyses were performed by Geoscience Laboratories (Geo Labs) in Sudbury while Rock-Eval® 6 pyrolysis analyses were conducted at the Geological Survey of Canada (Organic Geochemistry and Petrology Group) in Calgary.

Previous Work

As stated above, the Queenston Formation shows little hydrocarbon potential and will therefore not be considered in this report. This report focusses on the remaining Upper Ordovician shale sequence which includes, in descending order, the Georgian Bay and Blue Mountain formations, including the Rouge River Member of the Blue Mountain Formation, and the Collingwood Member of the Cobourg Formation. The Upper Ordovician strata of southern Ontario have a long and complicated nomenclatural history which is reviewed elsewhere in this report (*see* “Stratigraphy”). Consequently different names have been assigned to these formations in some previous studies.

Various studies have look at the stratigraphy, sedimentology and paleontology of the Upper Ordovician shale succession of southern Ontario. The Georgian Bay Formation was studied by Foerste (1924), Parks (1925), Montgomery (1930), Caley (1940, 1943), Liberty (1955, 1964, 1969, 1978), Sanford (1961), Liberty and Bolton (1971), Czurda, Winder and Quigley (1973), Russell and Telford (1983) and Byerley and Coniglio (1989, 1991). The Blue Mountain Formation and its Rouge River Member were studied by Raymond (1916), Parks (1928), Caley (1940), Liberty (1955, 1964, 1969, 1978), Sanford (1961) and Russell and Telford (1983). The Collingwood Member of the Cobourg Formation was examined by Raymond (1912, 1916), Parks (1928), Caley (1936), Liberty (1955, 1964, 1969), Sanford (1961) and Russell and Telford (1983). Compilation publications which cover the Upper Ordovician shales include Winder (1961), Beards (1967), Johnston et al. (1992), Hamblin (1999, 2003) and Armstrong and Carter (2006, 2010).

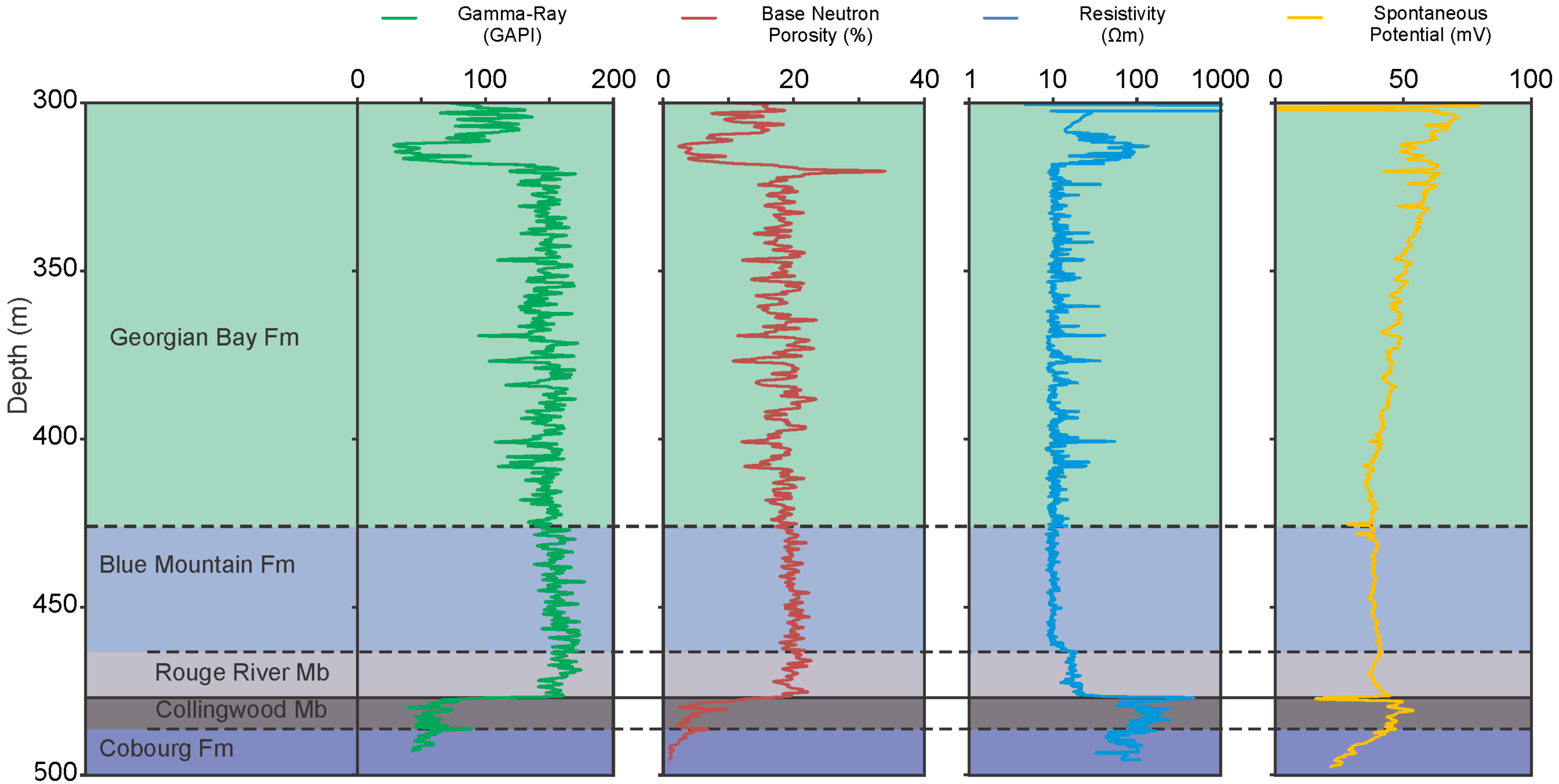

Figure 3. Stratigraphic and geophysical logs for the OGS-SG11-02 well. Gradational contacts are represented by dashed lines. A solid line indicates a sharp contact. Abbreviations: m, metres; Fm, Formation; Mb, Member.

Upper Ordovician shales are also present in eastern Ontario but have been assigned different names. The current stratigraphic nomenclature used is the Eastview Member of the Lindsay Formation, the Billings and Carlsbad formations, which respectively correspond to the Collingwood Member, Blue Mountain and Georgian Bay formations. Wilson et al. (1936), Wilson (1946), Williams (1991) and Williams and Telford (1986) are the most significant studies of Upper Ordovician shale stratigraphy in the Ottawa area. Hamblin (1998) produced a literature review of the Upper Ordovician units in eastern Ontario. Dix and Jolicoeur (2011) and Gbadeyan (2011) also studied Upper Ordovician shales in that area.

The Upper Ordovician shales outcrop over a wide area and therefore are found on numerous geological maps, including Liberty (1972a, 1972b, 1972c, 1972d), Johnson and Telford (1985a, 1985b, 1985c), and Russell (1985). Bailey Geological Services Ltd. and Cochrane (1988) mapped the Upper Ordovician shales on Manitoulin and St. Joseph islands. Other maps in southern Ontario showing the Upper Ordovician shale include those by Telford and Bond (1974), Telford, Bond and Liberty (1974a, 1974b, 1974c), Bond, Liberty and Telford (1976), Bond and Telford (1976), Liberty, Bond and Telford (1976a, 1976b), Telford (1976) and Armstrong (1993a, 1993b). In eastern Ontario, these units appear on maps by Williams, Rae and Wolf (1984, 1985a, 1985b, 1985c). The Upper Ordovician shale units are also displayed in the most recent Paleozoic geology compilation map for southern Ontario by Armstrong and Dodge (2007).

Ami (1906), Foerste (1924), Copper (1978), Barnes, Telford and Tarrant (1978), Ludvigsen (1978, 1979), Verma (1979), Tuffnell and Ludvigsen (1984), Kerr and Eyles (1991), Bolton (1994), Rudkin et al. (1998), Brett et al. (2006) and Zhang, Tarrant and Barnes (2011) focussed on the paleontology of the Upper Ordovician shale succession.

The hydrocarbon potential and organic geochemistry of the Upper Ordovician shales have been the subject of numerous studies, including Macauley (1981, 1984, 1987), Macauley and Snowdon (1984), Powell et al. (1984), Snowdon (1984), Macauley et al. (1990), Obermajer (1997), Obermajer et al. (1996) and Obermajer, Fowler and Snowdon (1999a, 1999b). In the 1980s, the Ontario Geological Survey investigated the oil shale potential of the Upper Ordovician shales, focussing especially on the Collingwood Member. This project produced a large number of publications (Barker 1985; Barker et al. 1983a, 1983b, 1983c; Churcher 1986; Churcher et al. 1991; Harris 1984a; Johnson 1983; Johnson, Russell and Telford 1983a, 1983b, 1985; Stromquist, Dickhout and Barker 1984). Hamblin (2006) included the Upper Ordovician shales of southern Ontario in his review of potential shale gas plays across Canada. Preliminary shale gas potential studies of these units were reported by Carter, Fortner and Clark (2008) and Béland Otis (2011, 2012). Finally, the hydrocarbon potential of the Blue Mountain Formation and its Rouge River Member was considered by Greentree Gas and Oil Ltd. (2006) when the company drilled a well and sampled sidewall core for Rock-Eval® 6 pyrolysis and gas composition analysis.

The Nuclear Waste Management Organization (NWMO) studied a site in the southern Bruce Peninsula for the construction of a Deep Geologic Repository (DGR). They propose that the DGR be situated below the Upper Ordovician shales, in the lower Cobourg Formation. This project has generated numerous geological, geochemical and hydrogeological studies, especially focussing on the physical properties of the Ordovician shales overlying the proposed repository level. The main findings were published in reports by Intera (2011a, 2011b).

The Upper Ordovician shales of southern Ontario were also studied for their brick and ceramic resource potential. Key studies related to this aspect are Baker (1906), Keele (1924), Brady and Dean (1966), Guillet (1964, 1967, 1977), Vos (1975), Telford and Narain (1980), Kwong, Martini and Narain (1985), Martini and Kwong (1986), Guillet and Joyce (1987), Rutka and Vos (1993) and Armstrong and Sergerie (2002).

Academic studies include Brett et al. (2006) who looked at the sedimentology and paleoecology of the Upper Ordovician shales, Rancourt (2009) who petrophysically characterized the Collingwood Member and Sweeney (2014) who studied the allostratigraphy of the Blue Mountain Formation. The last study had not been published in time to be included in this review.

Geological Setting

The Upper Ordovician shale sequence occurs over most of southern Ontario (*see* Figure 2) and therefore is a part of 3 main regional tectonic components: the Michigan Basin in the northwest, the Appalachian Basin in the southeast and the northeast-southwest trending inter-basinal Algonquin Arch. The Michigan Basin is a circular intracratonic basin centered over Michigan and is associated with carbonate and evaporite deposition. The Appalachian Basin is a foreland basin dominated by siliciclastic sediments, that are derived from orogenic events that occurred along the eastern margin of this basin. The Algonquin Arch is a basement high that separates the 2 basins. Its vertical and lateral positions have probably shifted over time because of tectonic activity (*see* Johnson et al. 1992).

The oldest unit discussed in this report is the Collingwood Member of the Cobourg Formation. It is a dark grey to black, highly calcareous shale with some fossiliferous interbeds (Johnson et al. 1992; Armstrong and Carter 2010). It is organic-rich and relatively thin, with a maximum thickness of about 10 m (Johnson et al. 1992). Zhang, Tarrant and Barnes (2011) consider its age to be early Richmondian (previously considered Maysvillian). The Collingwood Member gradationally overlies the limestones of the lower Cobourg Formation. In southwestern Ontario, the Cobourg Formation is the subsurface equivalent of the Lindsay Formation (Johnson et al. 1992). The Collingwood Member also occurs in Michigan and may be the equivalent of the Point Pleasant Formation of Ohio (Ruedemann and Ehlers 1924; Obermajer, Fowler and Snowden 1999b). It has been proposed that the Collingwood Member was deposited in a shallow shelf environment or represents the initial drowning of a carbonate ramp (Brookfield and Brett 1988; Coniglio, Melchin and Brookfield 1990; Johnson et al. 1992; Rancourt 2009). Russell and Telford (1983) and Churcher et al. (1991) suggest that the unit is restricted in Ontario, to an area spanning from Toronto to the Bruce Peninsula and Manitoulin Island.

The Blue Mountain Formation overlies the Collingwood Member or the lower member of the Cobourg Formation. Its sharp basal contact, sometimes marked by a phosphatic horizon, suggests a disconformable relationship with the underlying units and possibly predepositional erosion of the Collingwood Member where it is absent (Russell and Telford 1983; Churcher et al. 1991; Johnson et al. 1992). The Blue Mountain Formation consists mostly of fissile, blue to dark grey, noncalcareous shales that can reach a thickness of 60 m (Johnson et al. 1992). The lower part of this formation, consisting of dark brown to black shale, is called the Rouge River Member (Russell and Telford 1983; Armstrong and Carter 2010). The remainder of the formation is informally referred to as the upper member. The Blue Mountain Formation is stratigraphically equivalent to the lower part of the Churchill River Group of the Hudson Platform, and the Dawson Point Formation, New Liskeard Group, in the Lake Timiskaming outlier and to the Billings Formation in eastern Ontario (Johnson et al. 1992; Dix and Jolicoeur 2011). The stratigraphic equivalent unit in Quebec and the United States is thought to be the Utica shale (Hamblin, 2006; Patchen et al. 2006; Lavoie et al. 2008). The Blue Mountain Formation has been interpreted to represent the onset of siliciclastic deposition during the Taconic Orogeny, below storm wave base in an open marine setting (Johnson et al. 1992; Hamblin 1999; Russell and Telford 1983).

The Georgian Bay Formation is the uppermost unit studied in this project. It consists of greenish-grey to bluish-grey shales with some siltstone, sandstone and limestones interbeds (Johnson et al. 1992; Armstrong and Carter 2010). The thickness of the unit ranges between 125 to 200 m (Johnson et al. 1992). It is considered to be stratigraphically equivalent to the upper Churchill River Group in the Hudson Platform, and the Dawson Point Formation of New Liskeard Group in the Lake Timiskaming area and to the Carlsbad Formation in eastern Ontario (Johnson et al. 1992). The Georgian Bay Formation is also the probable stratigraphic equivalent of the Lorraine Group in Quebec and in New York State (Caley and Liberty 1957; Patchen et al. 2006; Lavoie et al. 2008; Thériault 2009). Its gradational contact with the underlying Blue Mountain Formation is marked by an upward increase in number and thickness of limestone beds. This suggests upward shallowing deposition to a storm-dominated shelf environment for the Georgian Bay Formation.

STRATIGRAPHY

The stratigraphy of the Upper Ordovician shales in Ontario has been studied for over a century. This section presents a review of the various propositions in regards to the stratigraphy and nomenclature of each unit. The stratigraphic nomenclature used in this report is presented in Figure 4.

Collingwood Member of the Cobourg Formation

The Collingwood Member was initially referred to as the Collingwood Formation by Raymond (1912, 1916) to describe the thin interval of interbedded blue limestones and brown shales overlying the Trenton Group. Caley (1936) correlated this Collingwood Formation found on Manitoulin Island to the Eastview Formation of the Ottawa area. Parks (1928) studied the fauna of this Collingwood Formation and subdivided it into 3 units: the Blue Mountain shale, the upper Collingwood black shale and the lower Collingwood limestone. He recognized a sharp break between the upper Collingwood and the Blue Mountain shales. Later, Liberty (1955) incorporated the Collingwood strata into the Whitby Group,

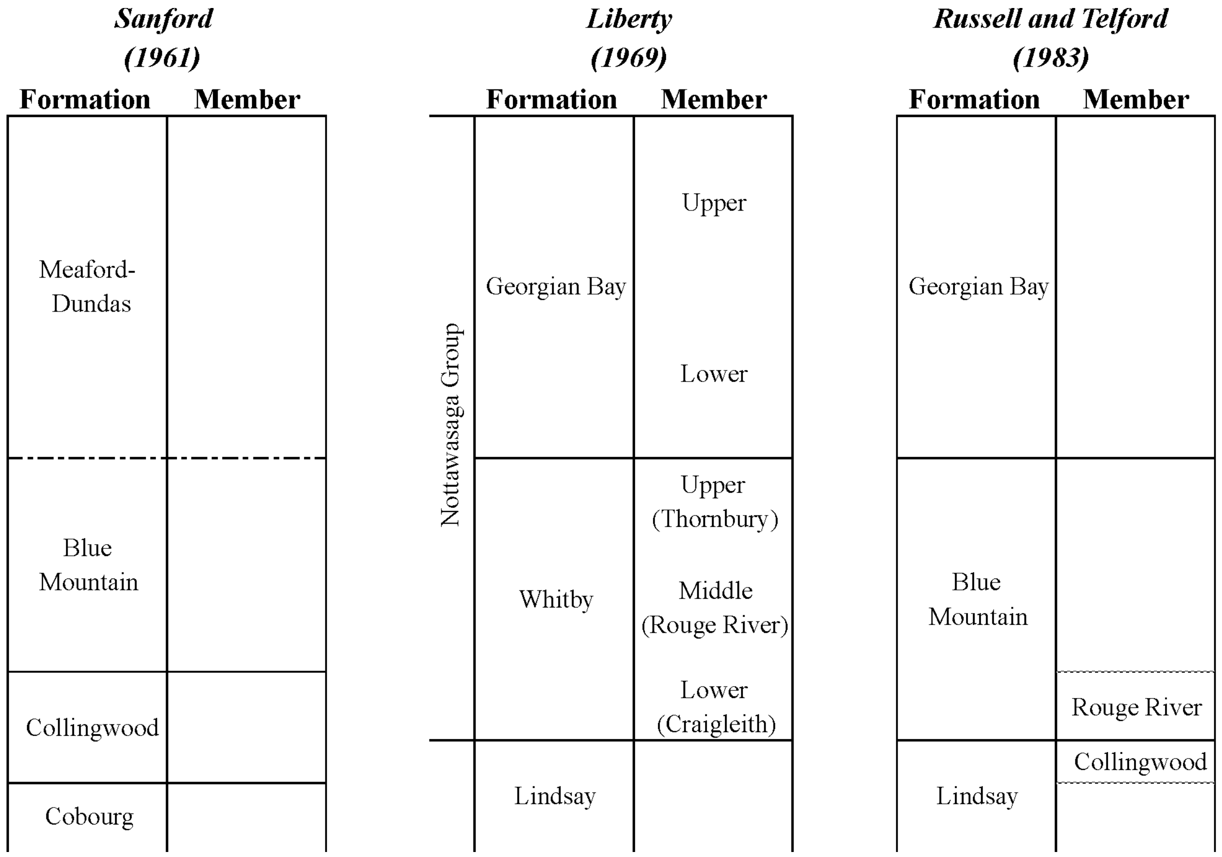

Figure 4. Evolution of the Ordovician shale stratigraphic nomenclature.

which he defined as all shales between the Lindsay Formation (lower limestone unit) and the Nottawasaga Group. He later changed the assignment of the Whitby from a group to a formation and included within the Nottawasaga Group, which then included all shales overlying the Lindsay Formation limestones and underlying the red shales of the Queenston Formation (Liberty 1964, 1969). The term Craigleith Member (of the Whitby Group) was initially used to distinguish the calcareous shales but was later changed to "Lower Member" (Liberty 1955, 1964, 1969). Sanford (1961) grouped the Gloucester shales (now known as the Rouge River Member) within the underlying calcareous shale and identified those strata as the Collingwood Formation.

More recently, Russell and Telford (1983) redefined the Collingwood Member of the Lindsay Formation, as the organic-rich, interbedded shale and limestones overlying the limestones of the Lindsay Formation (equivalent of the Cobourg Formation) and underlying noncalcareous shales of the Blue Mountain Formation. They stated that this Collingwood Member had more affinities with the underlying limestone and should therefore be part of the Lindsay Formation. More recently, Rancourt (2009) divided the Collingwood Member into 2 facies zones. The first one is characterized as a fine-grained organic-rich mudstone with rare bioturbation and the second is a biomicrite/wackestone. The Eastview Member of eastern Ontario is the stratigraphic equivalent of the Collingwood Member (Williams and Telford 1986; Gbadeyan 2011; Dix and Jolicoeur 2011).

Blue Mountain Formation and Rouge River Member

Strata presently assigned to the Blue Mountain Formation were initially referred as the Gloucester Formation by Raymond (1916). Parks (1928) was the first to propose the name Blue Mountain Formation. However, Caley (1940) applied the name Billings, which was used at the time for roughly equivalent strata in the Ottawa area by Wilson (1946). The upper Billings of Caley (1940) also included the Sheguiandah Formation on Manitoulin Island. Liberty (1955) reinstated the Blue Mountain Formation, as part of the Nottawasaga Group. The term "Rouge River" was then used to describe the upper member of the Whitby Group (Liberty 1955). Sanford (1961), working in the subsurface, used the term Blue Mountain Formation but recognized that these blue shales were very difficult to separate from the overlying Meaford–Dundas Formation and suggested that these units should be logged as a single unit. Later, Liberty (1964, 1969) re-assigned the blue shales associated with the Blue Mountain Formation as the upper member of the Whitby Formation, part of the Nottawasaga Group. The Whitby Formation was therefore subdivided it into 3 members (Craigleith, Rouge River, and Thornbury) based on the colour of the shales (black, brown, and blue). Sanford (1978), applied the term Sheguiandah beds for the shales on Manitoulin Island that he interpreted as being equivalent to the upper member of the Whitby Formation. Russell and Telford (1983) reinstated the Blue Mountain Formation to separate it from the underlying calcareous Collingwood Member shales and the overlying Georgian Bay Formation. They also recognized the presence of the Rouge River Member of Liberty (1969) but suggested it is of limited extent. Williams and Telford (1986) suggested that the Billings Formation of eastern Ontario is the correlative unit of the Blue Mountain Formation.

Georgian Bay Formation

The term Meaford was initially used by Foerste (1924) to refer to strata of Waynesville age. Parks (1925) used the term Dundas Formation for the shales situated between the lower Utica Formation and the upper Queenston Formation and subdivided the unit into 4 members (Rosedale, Danforth, Humber and Credit members) based on fossil content. The Georgian Bay shales were first referred as Lorraine shales by Montgomery (1930). These were then subdivided into the Meaford and Dundas shales by Caley (1940) who also later logged them as a single unit (Caley 1943). The Dundas Formation was defined as a series of shales and interbedded limestones and sandy beds while the Meaford Formation was described as fissile shales with interstratified hard layers (Caley 1940). Liberty (1955) proposed the term Dundas–

Meaford Formation, as part of the Nottawasaga Group, for all strata under the red shales of the Queenston Formation and above the brown bituminous shales of the Whitby Group. Sanford (1961) also combined the 2 units but did not refer to the Nottawasaga Group of Liberty (1955). The term Georgian Bay Formation was then introduced by Liberty (1964, 1969) to resolve the conflict created by the previously used terms Meaford and Dundas, which were now replaced by a lower and an upper member. The Georgian Bay Formation was assigned to the Nottawasaga Group, which then included the underlying shales, down to the Lindsay Formation (Liberty 1964, 1969; Liberty and Bolton 1971). On Manitoulin Island, Sanford (1978) divided the Georgian Bay Formation into 2 members: the lower Wekwemikongsing beds and an unnamed upper member. He divided the upper member into 2 submembers: the lower Meaford beds and the upper Kagawong beds. Russell and Telford (1983) used the term Georgian Bay Formation but did not refer to the Nottawasaga Group or to any members. Byerley and Coniglio (1989, 1991) studied the Georgian Bay Formation on Manitoulin Island and the Bruce Peninsula. They referred to the divisions established by Sanford (1978). However, they referred informally to the upper member submember as the Lookout upper submember and the Sextant Falls lower submember. The Georgian Bay Formation is thought to be the stratigraphic equivalent of the Carlsbad Formation of eastern Ontario (Williams and Telford 1986).

Hydrocarbon Potential – Previous Studies

The Upper Ordovician shales, especially the Collingwood and Rouge River members, have been studied for their hydrocarbon potential by various authors, *see* “Previous Work”.

The total organic carbon content of the Collingwood Member is documented to increase northwestward from the Toronto–Pickering area to the Collingwood area, Manitoulin and St. Joseph islands (Barker et al. 1983a; Barker 1985; Macauley and Snowden 1984; Churcher et al. 1991; Obermajer 1997; Obermajer, Fowler and Snowdon 1999b). The average total organic carbon content of the shales for the Toronto area is approximately 2.5 weight %, whereas values in the northwest range between 4 to 7 weight %. This suggests shallower depositional conditions, associated with higher organic productivity, to the northwest (Harris 1984b).

The total organic carbon content tends to be lower in the Blue Mountain Formation than in the Collingwood Member (Obermajer 1997). However, the highest values (up to 2.69 weight %) are usually observed in the lower 15 m of the unit which correlates to the Rouge River Member. Finally, Obermajer (1997) also identified a regional trend suggesting that the values tend to be higher in the western part than in the eastern part of southern Ontario.

Kerogen can be classified into 4 types (I, II, III and IV), mainly based on the provenance of organic matter (Bend 2008; McCarthy et al. 2011). All types present various hydrogen, oxygen and carbon contents which influence the type of hydrocarbon generated. Type I, mainly associated with algal material from lacustrine environment, has the highest hydrogen content and is oil prone. Type II kerogen is marine-derived and has high hydrogen content and modest oxygen content. It generates both oil and gas. Type III kerogen is derived from terrestrial plant source material and produces mainly gas. Type IV, usually associated with reworked material is nonproducing.

Barker et al. (1983a, 1983b) and Macauley and Snowdon (1984) determined the organic matter in the Collingwood Member to be of Types I and II. Obermajer (1997) interpreted the organic matter type for the Collingwood to be Type I-II or II and Type II organic matter for the Blue Mountain Formation. Also, Obermajer (1997) and Obermajer, Fowler and Snowdon (1999b) interpreted the hydrocarbon potential of most of the Ordovician samples they analyzed to be good to excellent.

Initial data from Legall, Barnes and Macqueen (1981) suggest that the Paleozoic strata of southwestern Ontario were buried at much greater depth than at present—required for hydrocarbon generation. Thermal maturity levels for the Collingwood Member vary throughout southern Ontario. The Blue Mountain Formation samples are thermally mature for oil generation throughout southern Ontario, whereas the Collingwood Member is thermally mature only in the Toronto area and mature to overmature in the Ottawa area (Barker et al. 1983a, 1983b; Obermajer 1997; Obermajer, Fowler and Snowdon 1999b). There is also an increase in the production index for the Collingwood Member towards the southeast (Obermajer 1997).

Oil yield for the Collingwood Member, which is proportional to the total organic carbon, is higher on Manitoulin and St. Joseph islands and in the Collingwood area than for the Toronto–Pickering region. The maximum average oil yield for the Collingwood Member was 30 L/t (Barker 1985).

More recent studies on the Upper Ordovician shales in the southern Bruce Peninsula were completed by the Nuclear Waste Management Organization (NWMO) (Jackson 2009; Intera 2011a, 2011b). They conclude from Rock-Eval® pyrolysis analysis that the Collingwood Member and the Blue Mountain Formation, including its Rouge River Member, contains Type II kerogen of marine origin. They found that organic matter in the Georgian Bay Formation is considered Type III kerogen which is gas prone and generally associated with a terrestrial setting (Jackson 2009; Intera 2011b; McCarthy et al. 2011). Finally, oil stains, micro-seeps and other hydrocarbon indicators were recorded in the cores collected from the Ordovician shale interval at the Bruce Peninsula site (Intera 2011a, 2011b).

Greentree Gas and Oil Ltd. (2006) analyzed some sidewall core samples collected from the lower Blue Mountain Formation in a well it drilled near Port Dover. These samples were analyzed for Rock-Eval® 6 pyrolysis and gas composition, including isotopic composition of methane, ethane and propane. Rock-Eval® 6 pyrolysis results indicate 1) that the samples contain a mix of Type II/III kerogen, 2) the "oil window" has been reached and 3) an average production index of 0.3. Since the methane content represents only between 58.9% and 83.9% of the hydrocarbons in the samples, the gas can be characterized as wet. The isotopic composition indicates that the gas has a thermogenic origin.

Results of OGS Drilling Project

LITHOLOGY AND GEOPHYSICAL RESPONSES

The stratigraphy of OGS-SG11-02 well is illustrated in Figure 3 along with select geophysical logs. The exact depth and thicknesses of the stratigraphic units can be found in Table 3. The well was bored through Quaternary deposits, Silurian bedrock, the Queenston Formation and 7.8 m of the Georgian Bay Formation, to a depth (i.e., corrected depth; *see* "Methodology") of 302.0 m. The well was then cored through another 124.0 m of Georgian Bay Formation, 50.9 m of Blue Mountain Formation and 19.6 m of Cobourg Formation. In this well, the Rouge River Member of the Blue Mountain Formation and the Collingwood Member of the Cobourg Formation are 13.6 m and 9.4 m thick, respectively. Bedding was horizontal throughout the core.

The Georgian Bay Formation was bored for the first 7.8 m. Therefore, its upper contact with the Queenston Formation was not cored and cannot be described here. The cored section of the unit started at 302.0 m. The top of the cored unit is characterized by a dark bluish-grey highly fossiliferous limestone with some calcareous shale interbeds. The limestone beds are approximately 5 cm to 15 cm thick while the shale interbeds are approximately 8 cm thick. At approximately 318.4 m, the rock type is mostly dark greenish-grey to dark bluish-grey calcareous shale with some siltstone, sandstone and fossiliferous limestone beds (or "hard" beds). Calcareous content of the shale matrix decreases with depth, as does the thickness and recurrence of hard (limestone, sandstone or siltstone) interbeds. The maximum thickness of hard beds is around 15 cm and the minimum is about 2 mm. Gypsum and pyritic beds were also observed. Bioturbation is present, as well as rippled, laminated siltstone beds. Throughout the unit, some horizontal fractures were observed while very few vertical fractures were identified. The horizontal fractures were not confirmed in the images taken with the micro-imager logging tool and therefore may have been induced mechanically by drilling operations. During drilling of this formation, few gas shows were noticed. At a depth of 310.5 m, small gas bubbles could be observed coming from one of the shale interbeds and at 406.3 m, a gas kick was strong enough to shut down the blow-out prevention system. In addition, a petroliferous odor was reported around the drill rig during drilling of this upper section of this unit.

The lower contact of the Georgian Bay Formation with the Blue Mountain Formation is gradational and difficult to determine. In core, some lithologic indications can be identified. These include a subtle downward colour change from bluish and greenish-grey shale to a more brownish colour, a decrease in siltstone and limestone beds and the disappearance of sandstone beds. Since these changes are continuous and gradational through the core, a precise contact is difficult to resolve. In this case, geophysical logs were useful in helping to determine a specific contact depth (*see* Figure 3). Changes in the responses of various geophysical logs can be used to identify the contact. The contact corresponds to the beginning of an overall downward increase in the gamma-ray log response and the start of a general upward increase in the spontaneous potential log. For the other logs, neutron, sonic and induction, this contact corresponds to a sharp decline in variability from the Georgian Bay Formation to the Blue Mountain Formation.

The Blue Mountain Formation was intercepted in the well between the depths of 426.0 m and 476.9 m, giving it a thickness of 50.9 m. The lower part of the unit, between 463.3 m and 476.9 m, is identified as the Rouge River Member and will be described below. Throughout this report, the term “upper Blue Mountain Formation” will be used to describe the part of the Blue Mountain Formation which does not include the Rouge River Member. It consists of dark brownish grey alternating to lighter grey, noncalcareous shale with some thin siltstone and limestone interbeds. As with the Georgian Bay Formation, the quantity and thickness of the siltstone and limestone interbeds tend to decrease with depth.

The contact between the upper Blue Mountain Formation and the Rouge River Member is gradational. The main lithologic differences between the 2 units are a downward darkening of the shale and the disappearance of limestone and siltstone interbeds upper into the Rouge River Member. Since the contact is very difficult to accurately determine in core, geophysical logs were used to help constrain its position (*see* Figure 3). The gamma-ray log, which shows a slight downward increase through the upper Blue Mountain Formation, exhibits a slightly elevated plateau at its base, followed by a decrease into the Rouge River Member. The spontaneous potential curve, while almost flat for the upper Blue Mountain Formation shows a downward decrease into the Rouge River Member followed by a similar increase in the lower Rouge River. Resistivity logs display a sharp increase from the upper Blue Mountain into the Rouge River. A concordant, but more subtle increase can also be observed on the sonic log.

The Rouge River Member is 13.6 m thick in this well and represents the lowest part of the Blue Mountain Formation. It consists of dark grey to brownish black noncalcareous shale. It is generally very homogenous and contains some pyrite nodules and thin calcite laminations.

The lower contact of the Rouge River Member with the Collingwood Member of the Cobourg Formation is sharp. In core, it is marked by a phosphatic nodule bed of about 1 cm thick (Photo 2). This contact is also easily identified on all geophysical logs (*see* Figure 3). The gamma-ray and base neutron porosity curves exhibit significant downward decreases associated with the Collingwood Member. Inversely, there is a definite downward increase for the sonic and induction curves. Though, there is a sharp negative spike in the spontaneous potential log at the contact. The spontaneous potential values for the Collingwood Member are actually higher than those for the Rouge River Member.

The Collingwood Member of the Cobourg Formation is a dark-grey brown to black, highly fossiliferous biomicrite, with fossils dominated by trilobites and brachiopods. In this core, it is interbedded with some pale grey to white, bioclastic limestone beds. The well intercepted this unit between 476.9 m and 486.3 m. In the OGS-SG11-02 well, an oil stain was noted at a depth of 478.8 m along a vertical fracture (Photo 3).

The frequency and thickness of the limestone beds increase with depth, as the Collingwood grades into the "lower Cobourg Formation" (this term will be used for the lower part of the Cobourg Formation that does not include the Collingwood Member). The gradational nature of this lower contact makes placement of a contact in core somewhat arbitrary. Geophysical logs can be used to define the contact, but they are similarly gradational in nature. The sonic and neutron porosity logs exhibit troughs in their curves at the contact, which is coincident with a decrease in resistivity. The spontaneous potential curve exhibits an elevated plateau for the Collingwood Member and then a steady decrease into the lower Cobourg Formation.

The lower Cobourg Formation consists of light to dark grey, nodular, fossiliferous limestone interbedded with some black, calcareous micrite (shale). For the interval cored, the quantity and thickness of shale beds decreased with depth. The OGS-SG11-02 well only intercepted the top 10.2 m of the lower Cobourg and therefore the lower contact of this unit was not observed. The thickness of the lower Cobourg Formation in other wells in this area is approximately 40 m (Armstrong and Carter 2010).

MINERALOGY BY X-RAY DIFFRACTION

Mineralogical data are presented in Table 4 and Figures 5, 6 and 7. The main components observed down core from the Georgian Bay Formation to the Rouge River Member are clays (62.4 to 70.6 weight %) and quartz (19.2 to 24.7 weight %). The exception is one limestone sample from the top of the cored Georgian Bay Formation interval, that is primarily composed of carbonate minerals (calcite, 62.4 weight %; dolomite and ankerite, 21.1 weight %). Clays in the units are mostly composed of illite (aluminum 2:1 clay) and magnesium chlorite. Other minerals found in these units are calcite (≤8.9 weight %), dolomite and ankerite (≤8.9 weight %), plagioclase (≤3.3 weight %), pyrite (≤2.5 weight %) and potassium feldspar (≤1.0 weight %).

The upper contact of the Cobourg Formation (equivalent to the top of the Collingwood Member) is marked by a sharp decrease in quartz, clay and pyrite content, balanced by an increase in calcite content. The Collingwood Member consists mainly of calcite (50.0 to 58.5 weight %) and clays (29.3 to 35.5 weight %). Additional minerals include quartz (≤11.0 weight %), dolomite and ankerite (≤2.2 weight %), potassium feldspar (≤1.0 weight %) and pyrite (≤0.5 weight %). Plagioclase was not found in the Cobourg Formation samples. The lower Cobourg Formation can be differentiated from the Collingwood Member by the former's lower clay (13.5 to 26.9 weight %) and quartz (3.7 to 7.6 weight %) content and greater calcite (56.7 to 81.4 weight %) and dolomite and ankerite content (1.2 to 8.0 weight %). Potassium feldspar (≤0.6 weight %) and pyrite (≤0.3 weight %) contents are mostly similar. Clay composition in the Cobourg Formation seems be similar to that in the Georgian Bay Formation down to the Rouge River Member interval. A mineralogy ternary diagram plot (*see* Figure 7) confirms that the mineralogical composition of the Upper Ordovician shales varies mostly in carbonate content, while quartz and clay contents stay mostly proportionally constant.

Photo 2. The phosphatic nodule bed corresponds to the contact between the Rouge River (above) and the Collingwood (below) members at a depth of 476.90 m. The top of the core corresponds to the top of the photo.

Photo 3. An oil stain is observed at a depth of 478.80 m in the Collingwood Member in the OGS-SG11-02 core. The top of the core corresponds to the top of the photo.

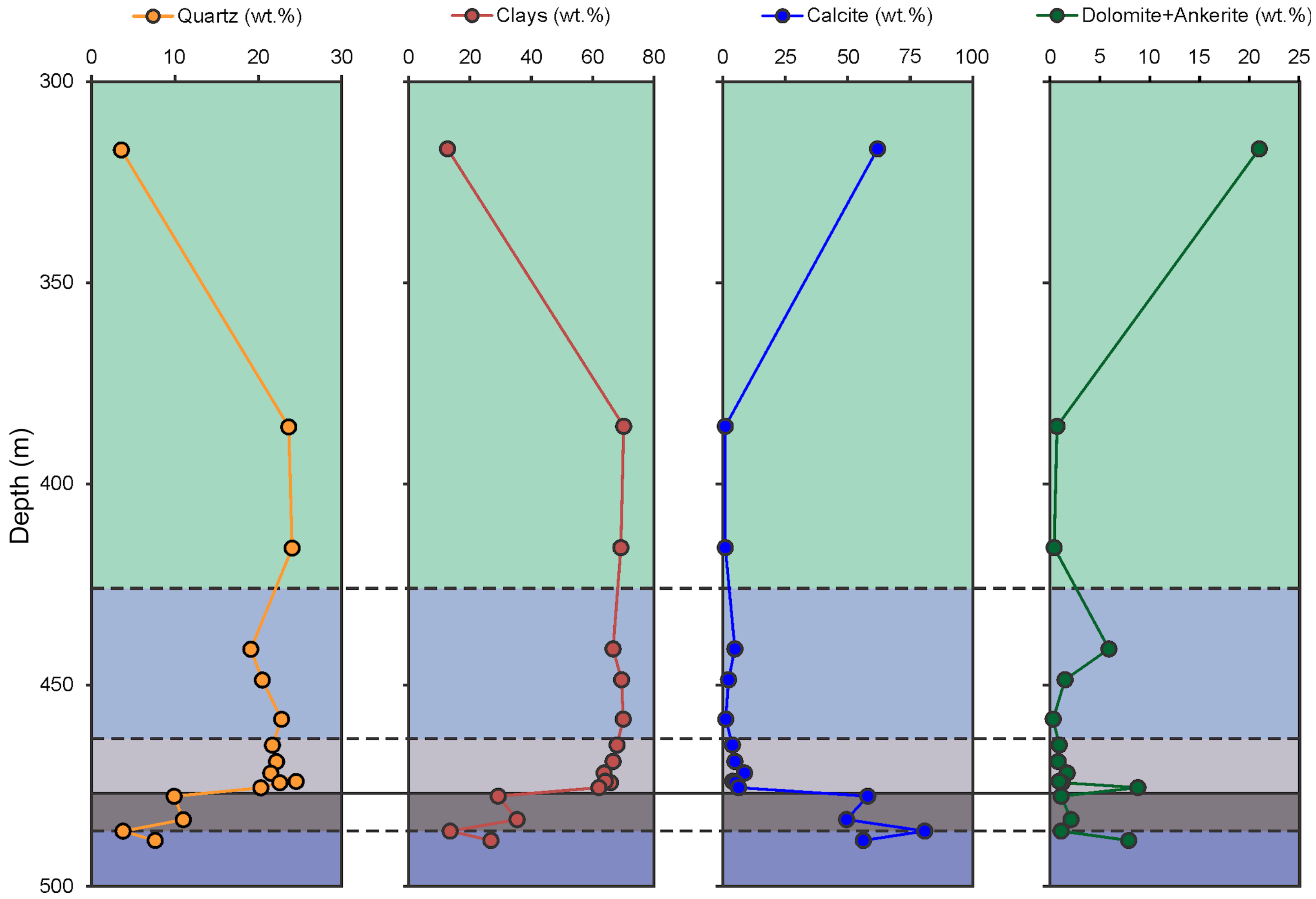

Figure 5. Mineralogy (XRD) logs (quartz, clays, calcite, dolomite + ankerite) for the OGS-SG11-02 core samples; *see* stratigraphy of the well in Figure 3. Abbreviations: m, metres; wt. %, weight percent.

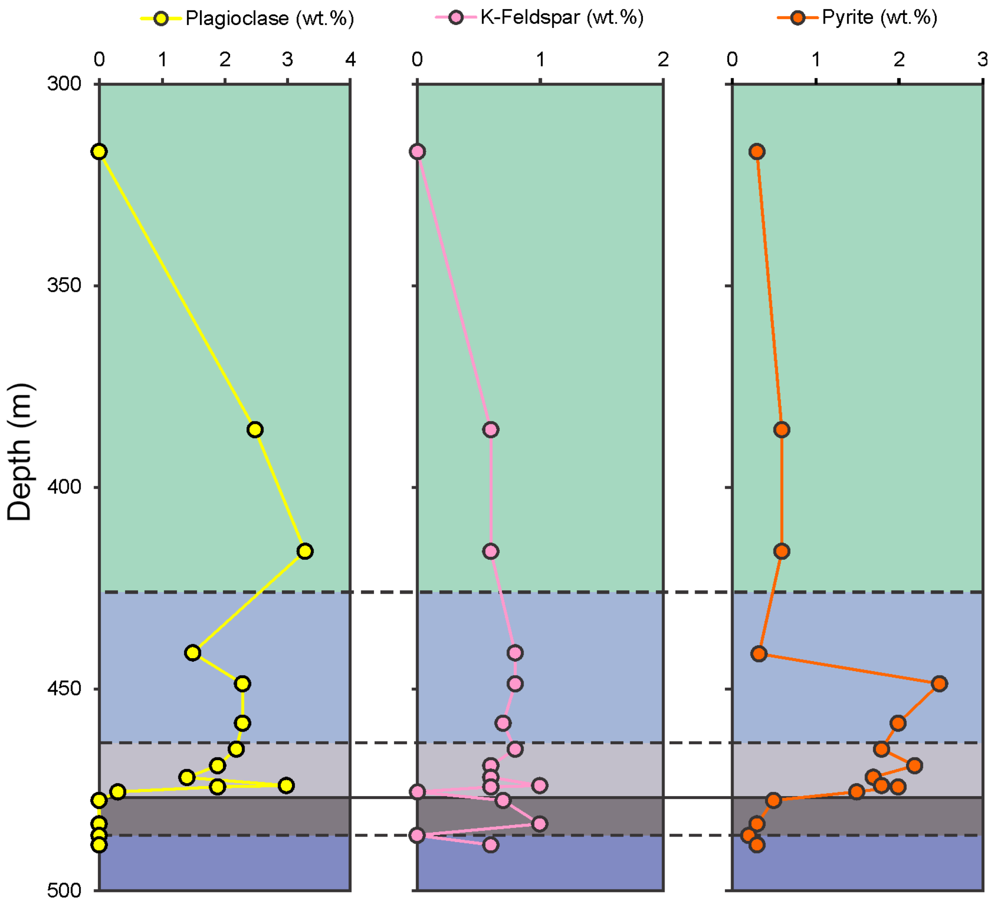

Figure 6. Mineralogy (XRD) logs (plagioclase, potassium feldspar, pyrite) for the OGS-SG11-02 core samples; *see* stratigraphy of the well in Figure 3. Abbreviations: m, metres; wt. %, weight percent, K-Feldspar, potassium feldspar.

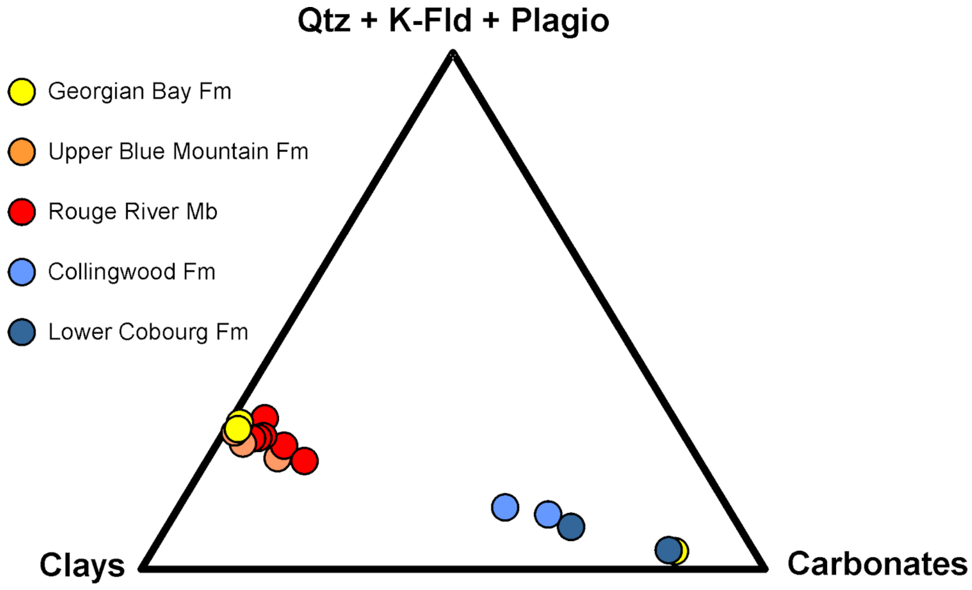

Figure 7. Ternary plot of mineralogical data (by XRD) for the OGS-SG11-02 core samples. Abbreviations: Fm, Formation; Mb, Member; Qtz, quartz; K-Fld, potassium feldspar; Plagio, plagioclase.

TOTAL ORGANIC CARBON CONTENT AND ROCK-EVAL® 6 PYROLYSIS

Results for total organic carbon content and Rock-Eval® 6 pyrolysis are presented in Tables 5 through 8 and Figures 8 through 11. The Collingwood Member has the highest total organic carbon values at 4.68 weight % while the Rouge River Member has a maximum total organic carbon content value of only 2.18 weight %. Other important parameters used to characterize source rock potential are the amount of free hydrocarbon in the sample, designated as S1, and the amount of hydrocarbons generated through thermal cracking of nonvolatile organic matter, referred to as S2. The higher the values of S1 and S2, the greater the potential of hydrocarbon accumulations in the source rock. The highest S1 and S2 values in the OGS-SG11-02 well are 2.25 $mg_{hydrocarbon}/g_{rock}$ and 30.42 $mg_{hydrocarbon}/g_{rock}$, respectively, and they were both measured in the Collingwood Member. The Rouge River Member yielded much lower S1 and S2 values, with its highest values being 1.17 $mg_{hydrocarbon}/g_{rock}$ and 7.33 $mg_{hydrocarbon}/g_{rock}$, respectively.

Parameters such as the production, hydrogen and oxygen indices are calculated from S1, S2 and total organic carbon (TOC). If these values are low (TOC <0.3 weight %, S1 and/or S2 <0.2 $mg_{hydrocarbon}/g_{rock}$), the indices may not be reliable (Peters 1986; Osadetz, Snowdon and Obermajer 2003). Therefore, in Figure 8, samples with questionable data are indicated while in Figure 10 they are simply omitted. These samples are mostly found in the Georgian Bay and Blue Mountain formations.

Rock-Eval® 6 pyrolysis can help determine the source of organic matter, which can influence the type of hydrocarbons produced. Samples of the Collingwood Member and lower Cobourg Formation plot in the Type II organic matter field in a plot of S2 versus total organic carbon (*see* Figure 9). Type II organic matter is usually associated with marine source and is considered to be oil prone. It also corresponds to hydrogen index (HI) values between 350 $mg_{hydrocarbon}/g_{TOC}$ and 700 $mg_{hydrocarbon}/g_{TOC}$. The HI refers to the amount of hydrogen relative to the amount of total organic carbon and is a measure of the organic matter's richness. The Rouge River samples have HI values between 200 $mg_{hydrocarbon}/g_{TOC}$ and 300 $mg_{hydrocarbon}/g_{TOC}$. Most samples of the Rouge River Member plot in the Type II/III field (*see* Figure 9) indicating the organic matter is both oil and gas prone. Type III organic matter is generally interpreted as having a terrestrial source. However, this is problematic for Ordovician source rocks because land plants had not yet evolved. In this case, the hydrogen index values were probably diminished by some degradation (Wielgoz and Bend 2014). The origin of organic matter in samples of the Georgian Bay and upper Blue Mountain formations, is more difficult to determine since the organic content in these units is much lower and therefore generates less reliable indices. Both appear to contain mostly Type III organic matter (*see* Figure 9). Hydrogen index values for these units, which again are questionable due to low organic content, are all lower than 133 $mg_{hydrocarbon}/g_{TOC}$, except in one sample where it reaches 234 $mg_{hydrocarbon}/g_{TOC}$. This Type III organic matter signature is probably, like for the Rouge River Member, associated to degradation of organic matter. With regard to source rock potential, the Collingwood Member has a better hydrocarbon generation potential than the Rouge River Member because it contains higher total organic carbon, S1, S2 and hydrogen index values.

Thermal maturity of the Upper Ordovician shales may be evaluated by studying the Tmax parameter: values of Tmax correspond to the maximum temperature of the S2 peak. Depending on the type of organic matter, onset of oil generation corresponds generally to Tmax values between 435 and 445°C (McCarthy et al. 2011). As stated before, Tmax is considered reliable only when total organic carbon is greater than 0.3 weight %, and S1 and S2 are greater than 0.2 $mg_{hydrocarbon}/g_{rock}$. In the samples collected from the OGS-SG11-02 well, only those from the Rouge River Member, Collingwood Member and the lower Cobourg Formation met these criteria. As observed in Figure 11, all those samples fall into the early oil window with Tmax values between 438 and 442°C.

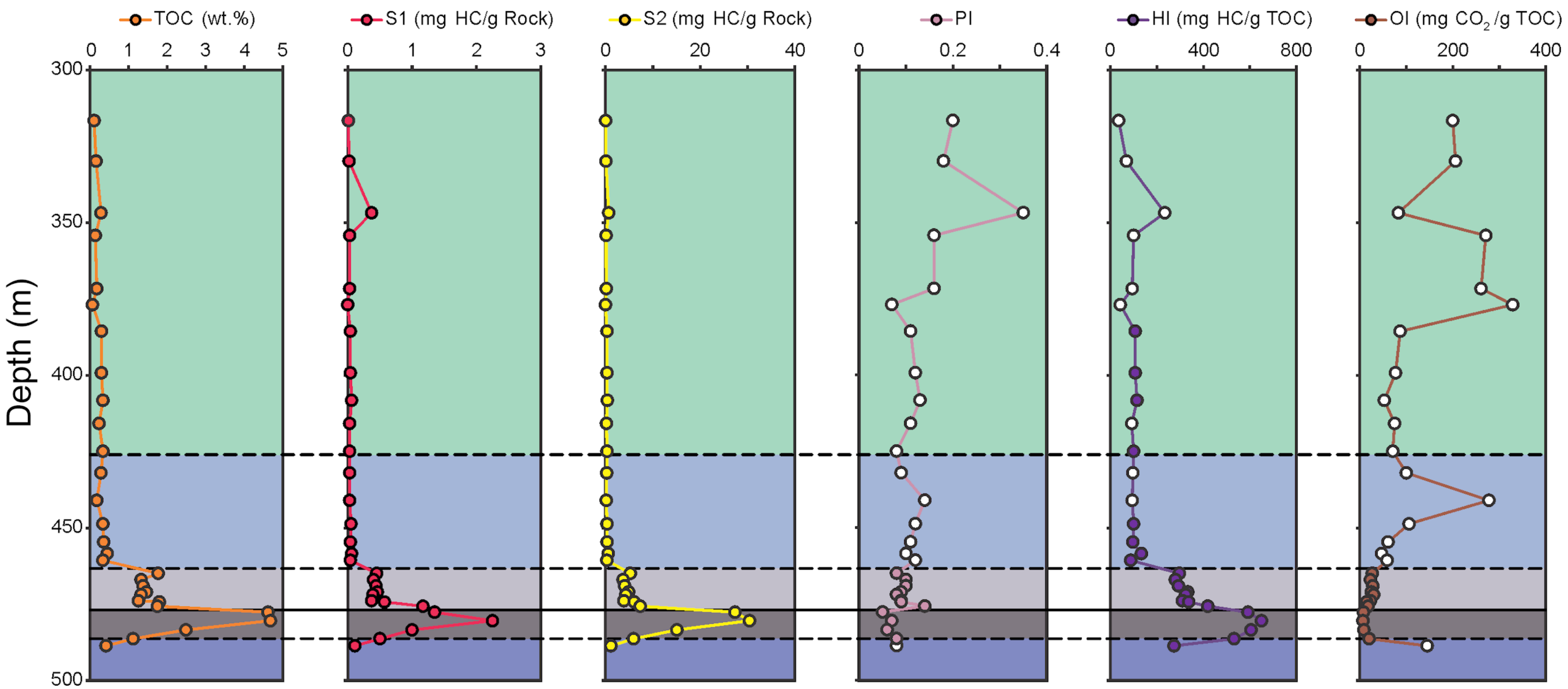

Figure 8. Rock-Eval® 6 pyrolysis logs (TOC, S1, S2, PI, HI, OI) for core samples from the OGS-SG11-02 well. White-filled dots indicate questionable data due to low TOC, S1 and/or S2, *see* stratigraphy of the well in Figure 3. Abbreviations: m, metres; TOC, total organic carbon; wt. %, weight percent; HC, hydrocarbon; PI, production index; HI, hydrogen index; OI, oxygen index; CO_2, carbon dioxide.

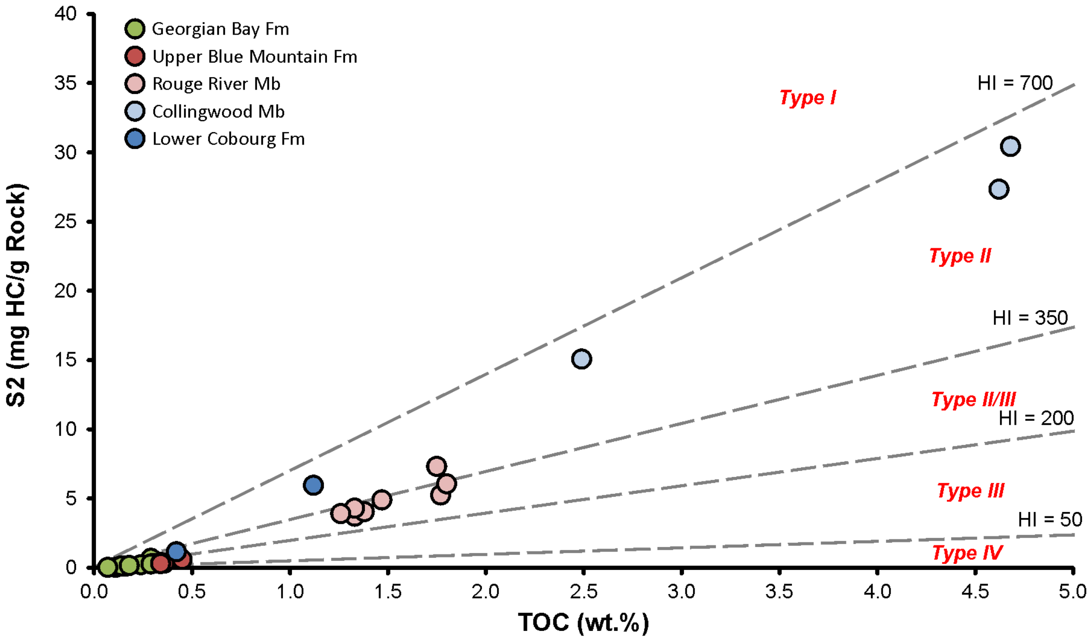

Figure 9. A plot of S2 versus total organic carbon (TOC) for the core samples from the OGS-SG11-02 well; *see* text for explanation of S2 and the fields (Jarvie 2014). Abbreviations: HC, hydrocarbon; HI, hydrogen index; TOC, total organic carbon; wt. %, weight percent; Fm, Formation; Mb, Member.

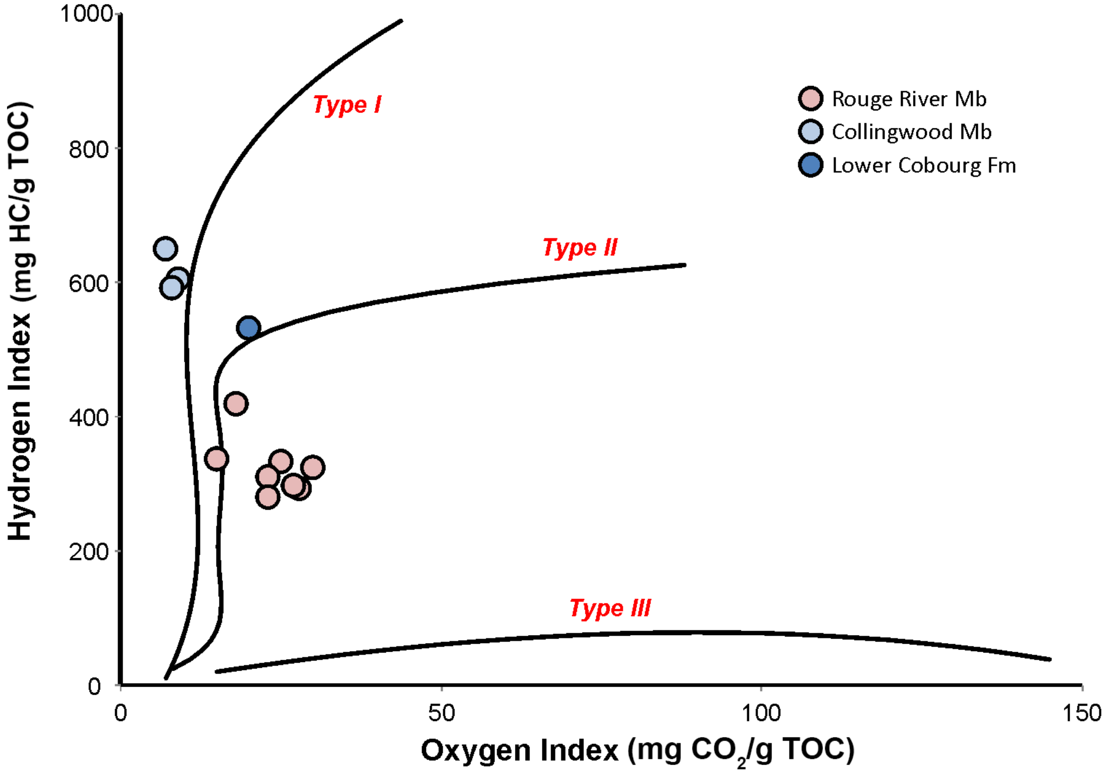

Figure 10. A modified Van Krevelen diagram showing hydrogen index versus oxygen index plot for the OGS-SG11-02 core samples. Samples from the Georgian Bay and Blue Mountain formations are not shown since all data from these units are questionable (*see* Figure 8); *see* text for explanation of the fields (Obermajer 1997). Abbreviations: HC, hydrocarbon; TOC, total organic carbon; CO_2, carbon dioxide; Fm, Formation; Mb, Member.

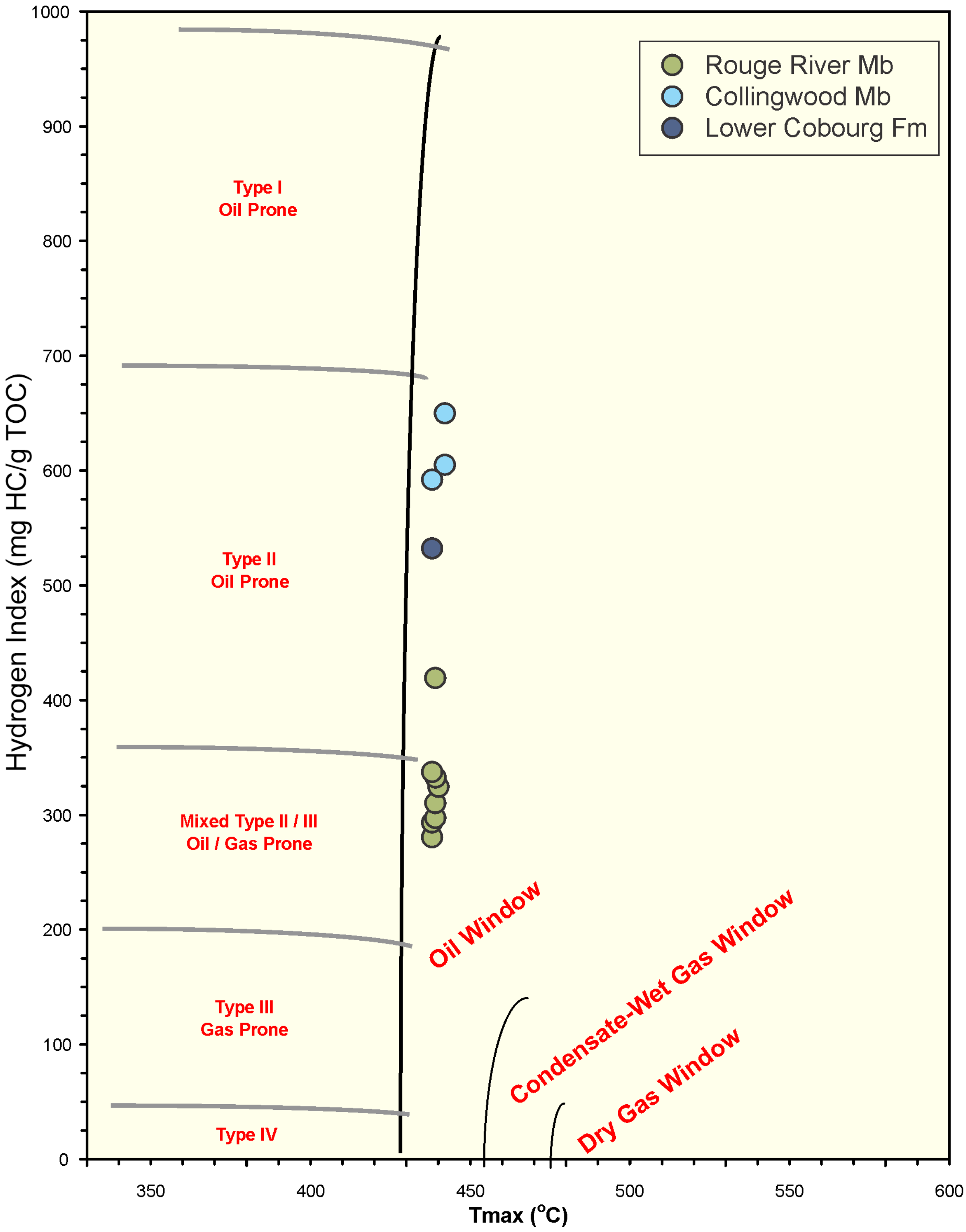

Figure 11. Hydrogen index versus Tmax plot for the OGS-SG11-02 core samples. Samples from the Georgian Bay and Blue Mountain formations are not shown since all data from these units are questionable (*see* Figure 8); *see* text for explanation of the various fields (modified from Greentree Gas and Oil Ltd. 2006). Abbreviations: HC, hydrocarbon; TOC, total organic carbon; Fm, Formation; Mb, Member.

TOTAL GAS CONTENT AND GAS ADSORPTION

Gas content results are presented in Table 9 and Figure 12, and were determined from the gas desorption experiments in sealed canisters, *see* "Methodology". The Georgian Bay Formation has total gas content values between 2.1 and 8.6 scf/ton (standard cubic feet per ton) , with an average of 5.0 scf/ton. The upper Blue Mountain Formation has slightly lower values (2.5 to 4.9 scf/ton, average 3.9 scf/ton), whereas the Rouge River Member has higher values (4.9 to 18.0 scf/ton, average 10.0 scf/ton). The highest values were obtained from samples of the Collingwood Member, with an average total gas content of 14.5 scf/ton (minimum 9.5 scf/ton, maximum 18.4 scf/ton). Gas content values for the lower Cobourg Formation range between 6.5 and 9.0 scf/ton, with an average of 7.8 scf/ton.

The total gas content profile (*see* Figure 12) increases exponentially through the upper Blue Mountain Formation, into the Rouge River Member, peaking near its contact with the Collingwood Member. This may be explained by the greater proportion of shaly and organic material in the Rouge River Member, which acts as the gas source rock. Gas content values for the Georgian Bay Formation samples do not follow the same trend and are more variable. This variation is probably linked to the changing mineralogy and therefore organic content. Indeed, frequent limestone, sandstone and siltstone

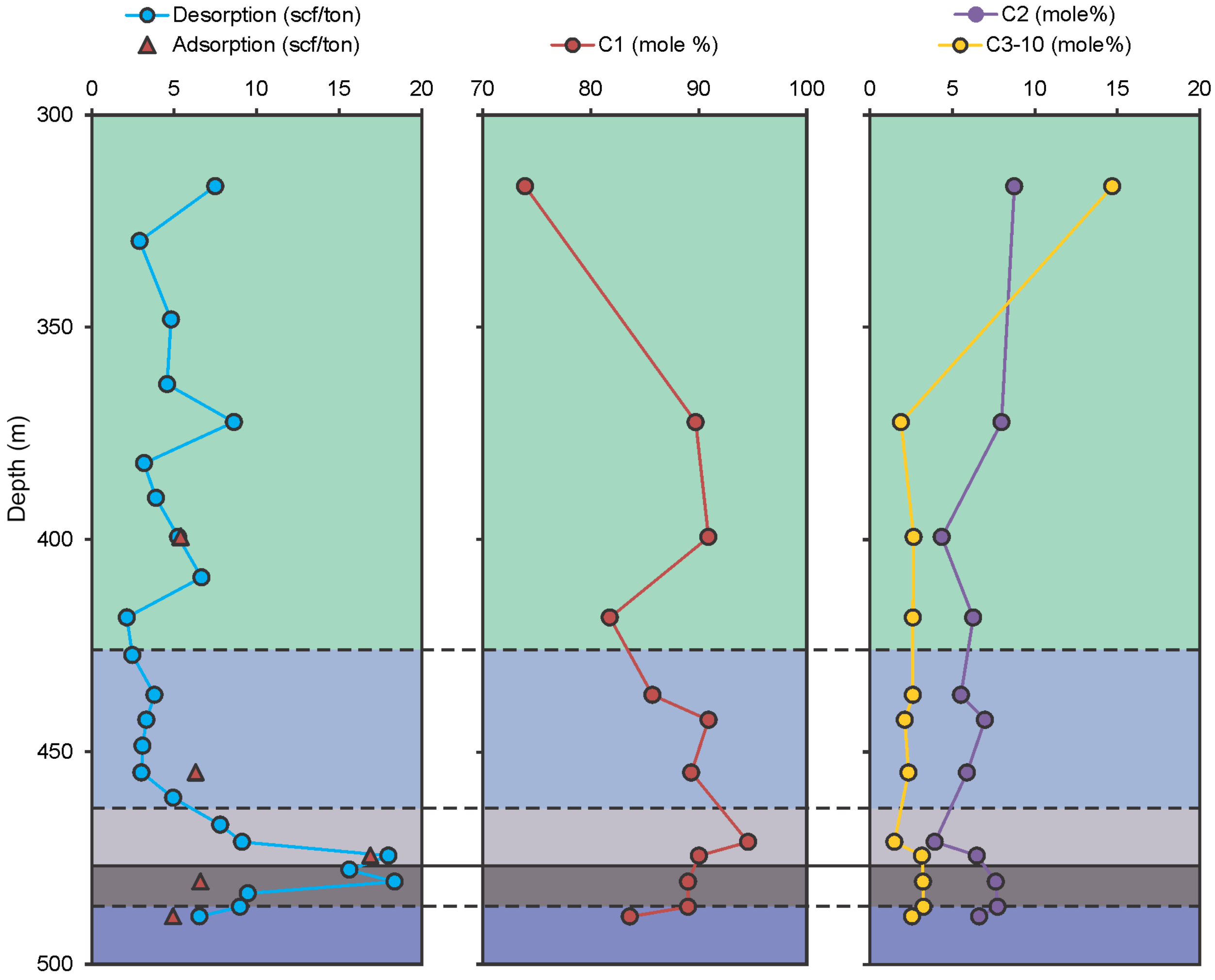

Figure 12. Gas desorption/adsorption and composition logs for the OGS-SG11-02 well, *see* stratigraphy of the well in Figure 3. Abbreviations: m, metres; scf/ton, standard cubic feet per ton; C1, methane; C2, ethane; C3-10, propane and heavier hydrocarbons.

beds are present throughout the unit. These generally show greater porosity and lower hydrocarbon potential values than clay. Similarly, the decrease in gas content observed from the top of the Collingwood down to the lower Cobourg Formation may also be explained by a downward decrease in shale and organic content.

Table 10 and Figure 12 present the results for methane adsorption. The Georgian Bay and upper Blue Mountain formations have gas storage capacity values of 5.40 scf/ton and 6.31 scf/ton, respectively. The Rouge River Member shows the highest value at 16.90 scf/ton followed by the Collingwood at 6.59 scf/ton. The lower Cobourg Formation has the lowest gas storage capacity value at 4.94 scf/ton.

There is a downward increase of storage capacity from the Georgian Bay Formation down to the top of the Cobourg Formation. From the upper biomicrite (Collingwood Member) to the lower limestone (lower Cobourg Formation) units, the storage capacity decreases significantly.

For the Collingwood Member, the total gas content is much greater than the methane storage capacity (*see* Figure 12), suggesting a large proportion of free gas. Inversely, total gas content and methane storage capacity values are similar for the Rouge River Member, indicating that most of the gas is adsorbed. This will be discussed later.

GAS COMPOSITION AND METHANE ISOTOPES

Gas compositions are presented in Table 11 and Figure 12. Methane, represented as C1, accounts for the majority of the gas, ranging from 73.92 mole % in the Georgian Bay Formation up to 94.57 mole % in the Rouge River Member. Heavier hydrocarbons (C2 and greater) account for an average of 10.07 mole %. The methane proportion increases with depth from the Georgian Bay Formation down to the Rouge River Member. The trend then reverses in the Collingwood Member where heavier hydrocarbons proportion increases downward.

The isotopic composition (δD, for deuterium (^2H) and $\delta^{13}C$) of methane was determined for samples from all stratigraphic units and is given in Table 12 and Figure 13. These data are presented in delta notation as δD_{C1} and $\delta^{13}C_{C1}$ and the values, in per mil (‰),were calculated relative to international standards V-PDB for carbon and V-SMOW for hydrogen. Some samples with low carbon isotope values (e.g. CAN-19B and CAN-24B) appear to be air contaminated. This contamination may be associated with the low volumes in the sampling syringe analyzed. Methane isotope data (*see* Figure 13) support a thermogenic origin for the gas. This agrees with ratios of $C1/(C2+C3)<100$, which also indicates a thermogenic origin (Martini et al. 1996). Since methane is probably co-generated with oil, as suggested by the presence of oil stain and the measured Tmax values, this gas was probably produced at temperatures below 150 to 160ºC (Stolper et al. 2014).

GAS RESEARCH INSTITUTE CORE ANALYSIS

Gas Research Institute (GRI) core analyses are presented in Table 13 and Figure 14. Results are divided into 2 sets of analyses: one for samples "as-received" (bulk density, matrix permeability and gas-filled porosity) and the other for samples at dry and "Dean Stark" extracted conditions (grain density, matrix permeability, porosity and gas, oil and water saturations). Both bulk and grain densities tend to decrease from the Georgian Bay Formation down to the Rouge River Member, but increase again in the Collingwood Member, where the matrix is made up mostly of calcite instead of clays. Porosity and permeability are much higher in the Georgian Bay and upper Blue Mountain formations. This is probably due to the presence of numerous sandstone, siltstone and limestone interbed and less shaly material. Matrix permeability values decrease by several orders of magnitude in the Rouge River Member due to the high proportion of clay content (*see* Figure 5). The Collingwood Member shows a significant higher permeability value than the Rouge River Member, again probably related to the higher clay content of the latter.

The Rouge River and Collingwood members show different trends in hydrocarbon saturation. The units above the phosphatic bed display an increase in oil saturation with depth countered by an important decrease in gas saturation and a slight diminution in water saturation. Therefore, in the Rouge River Member, oil fills 31.5% of the porosity while gas only fills 23.3%. The Collingwood Member, however, exhibits gas saturation up to 77.2 % while oil saturation is as low as 1.4%. Water saturation in the Collingwood Member (21.4%) is less than half of that in the Rouge River Member (45.2%). Since an oil stain was observed in a subvertical fracture within the Collingwood Member, one may expect higher oil saturation values for this unit. A possible explanation would be that the oil is confined to secondary porosity (e.g., fractures) and was therefore not measured by the GRI analyses which are executed on small unfractured core plug samples.

MECHANICAL PROPERTIES AND BRITTLENESS

Rock mechanical properties are presented in Tables 14, 15, and Figure 15. For triaxial analyses, the results vary only slightly between the different stratigraphic units, except for the Rouge River Member which has a somewhat higher Young's modulus (3.04×10^6 psi). Otherwise, all Young's modulus values fall between 1.13×10^6 and 1.95×10^6 psi and the Poisson's ratios are between 0.23 and 0.26. As for the dynamic tests, there is more variation between the stratigraphic units. Again, the Rouge River Member shows the highest Young's modulus values, followed by the Georgian Bay Formation, the Collingwood Member, the lower Cobourg Formation and finally the upper Blue Mountain Formation. Poisson's ratio (0.21–0.28) does not vary greatly between the units.

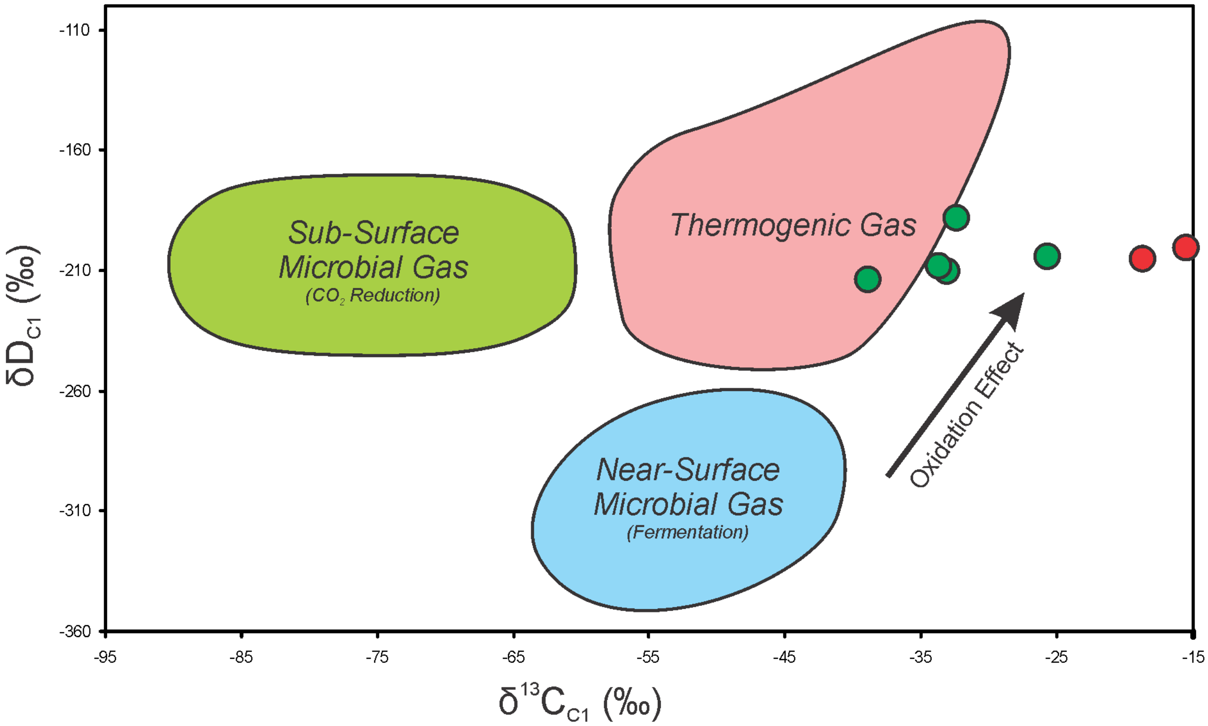

Figure 13. Isotopic composition of methane (δD (for deuterium, ^2H) and $\delta^{13}C$; in per mil (‰), relative to international standards V-PDB for carbon and V-SMOW for hydrogen) in the Ordovician shales of the OGS-SG11-02 well. This diagram, *modified* from Coleman et al. (1995), discriminates different sources of gas based on their isotopic signature. The red dots indicate probable contamination in samples. Abbreviation: C1, methane.

Rock mechanical parameters can be used to evaluate brittleness and can sometimes be preferred to a mineralogical analysis despite the fact that the latter usually influences the former (Slatt and Abousleiman 2011). A brittle rock is usually characterised by a high Young's modulus and a low Poisson's ratio. Samples of the Upper Ordovician shale succession have low Young's moduli and intermediate Poisson's ratios (Tables 14 and 15). Generally, shales with a Young's modulus less than 3×10^6 psi are considered non-prospective (Britt and Shoeffler 2009). As observed in Figure 15, the Upper Ordovician shale samples fall close to the brittle-ductile line. Dynamic values generally fall in the brittle field while static results fall correspond to the ductile area. A brittleness index can also be calculated with static rock mechanical parameters (Rickman et al. 2008). Their equations have been simplified to the following:

$$BI = 50 \times \left[\frac{Y-1}{7} + \frac{0.4-P}{0.25} \right] \qquad (1)$$

Where, BI is the brittleness index (%),

Y is static Young's modulus (×10^6 psi),

P is Poisson's ratio

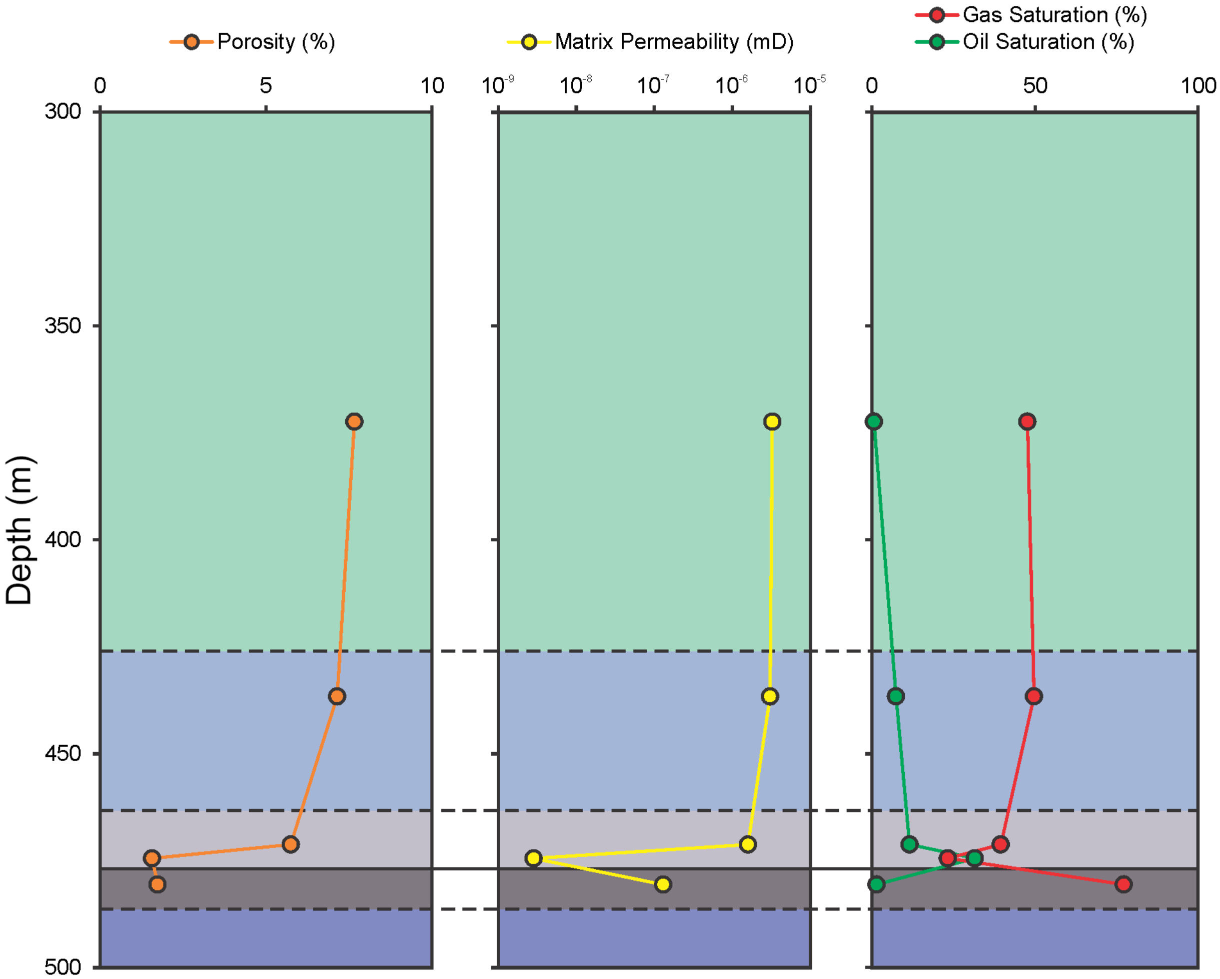

Figure 14. Graphic logs showing Gas Research Institute (GRI) parameters (porosity at dry and Dean Stark extracted conditions, matrix permeability for as-received samples, gas and oil saturation at dry and Dean Stark extracted conditions) for the OGS-SG11-02 well; *see* stratigraphy of the well in Figure 3. Abbreviations: m, metres; mD, milliDarcy.

Using Equation 1, calculated values for brittleness indices (BI) vary from 28.93 to 46.57% in the OGS-SG11-02 well (Table 14). These values are considered low to medium (Buller 2010; Hall 2010). The large proportion of clays, especially in the Georgian Bay and Blue Mountain formations probably causes these low values.

STRUCTURAL ANALYSIS (FRACTURES)

Many horizontal fractures were observed in the OGS-SG11-02 core immediately following retrieval to surface. A micro-imager log was run to determine whether the fractures were natural or drilling induced. Since most fractures in the core were not detected down hole by the micro-imager log, they are assumed to be mechanically induced by the drilling operations. Figures 16 through 20 present the structural features of each stratigraphic unit on a stereonet as measured by the micro-imager log (i.e., natural and not drilling induced).

The vast majority of the bedding is horizontal, which is especially noticeable in the Blue Mountain Formation and its Rouge River Member (*see* Figures 17 and 18). The micro-imager log identified small scale faults (less than one metre offsets), healed fractures, partially opened fractures and other structural features throughout the stratigraphy. Within the Georgian Bay and Blue Mountain formations, including the Rouge River Member, no structural feature with a dip greater than 60° was recorded. However, subvertical open fractures are observed in the Collingwood Member and the lower Cobourg Formation. These features probably increase secondary porosity within these units.

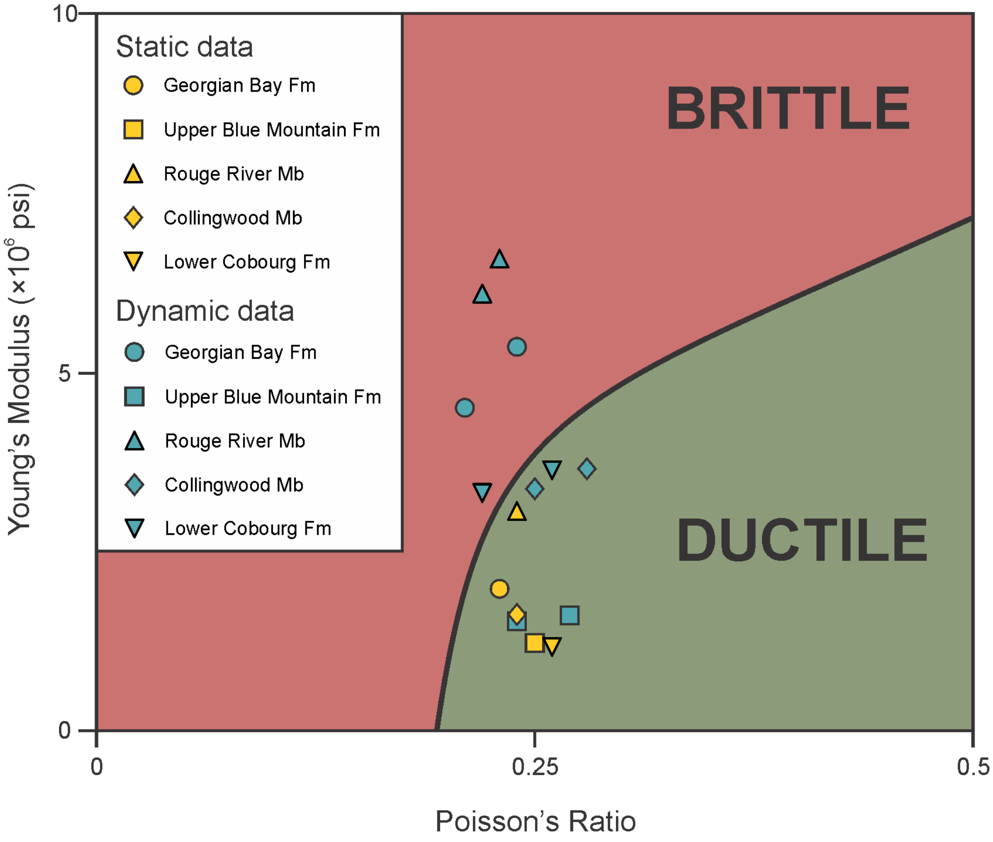

Figure 15. A cross-plot of Poisson's ratio and Young's modulus indicating brittle and ductile areas for OGS-SG11-02 samples (*modified* from Grieser and Bray 2007).

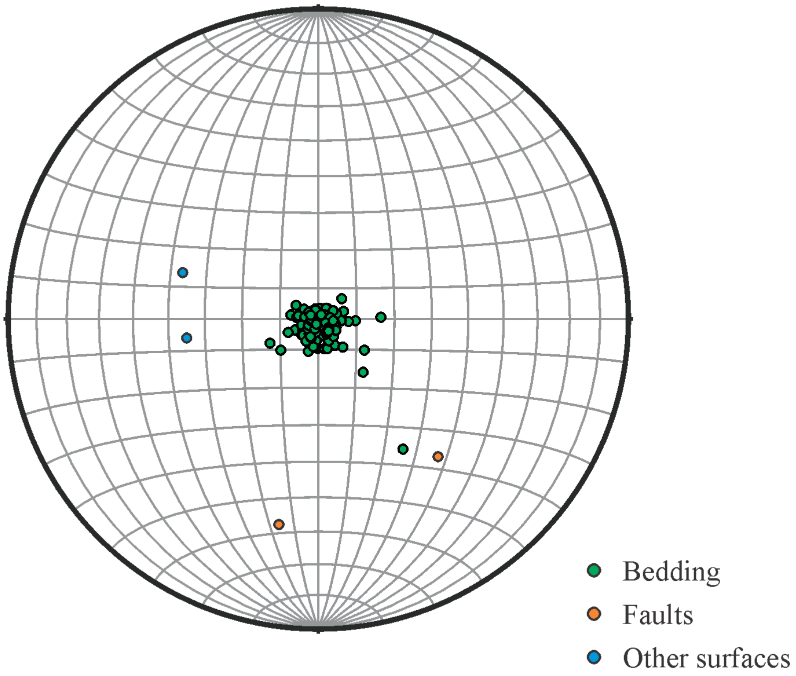

Figure 16. Various structural measurements collected by the micro-imager within the Georgian Bay Formation (OGS-SG11-02 well, Mount Forest, Ontario), plotted on a stereonet. These planar structures are represented by their poles.

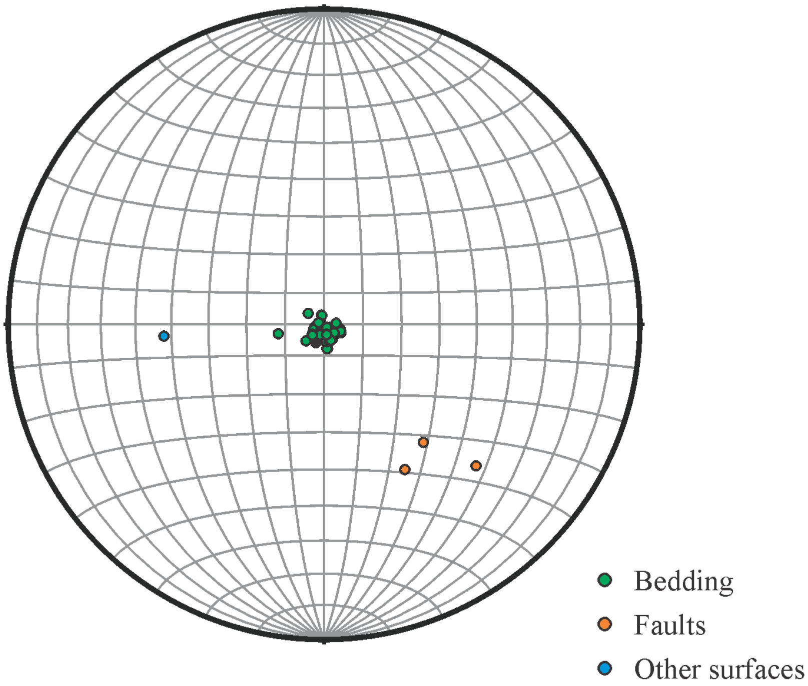

Figure 17. Various structural measurements collected by the micro-imager within the Upper Blue Mountain Formation (OGS-SG11-02 well, Mount Forest, Ontario), plotted on a stereonet. These planar structures are represented by their poles.

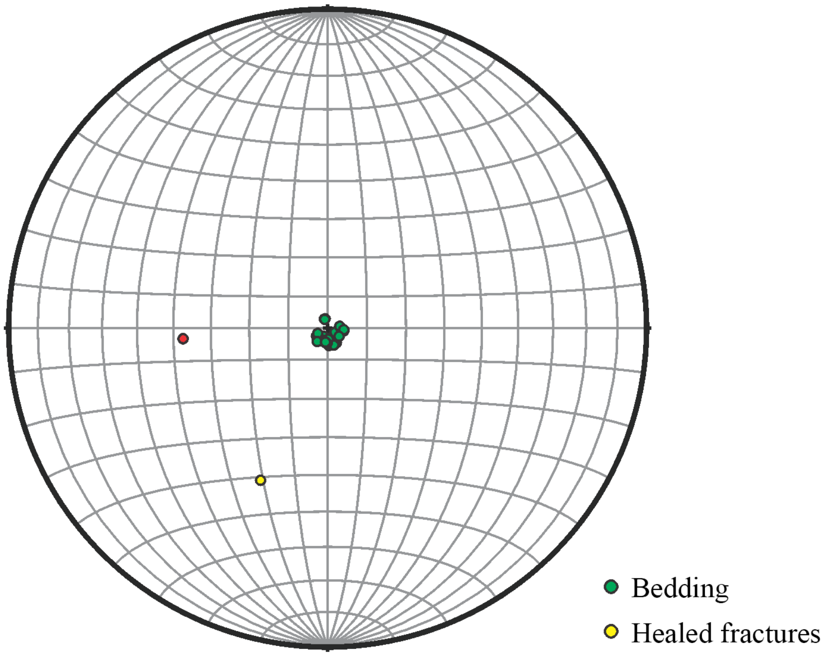

Figure 18. Various structural measurements collected by the micro-imager within the Rouge River Member (OGS-SG11-02 well, Mount Forest, Ontario), plotted on a stereonet. These planar structures are represented by their poles.

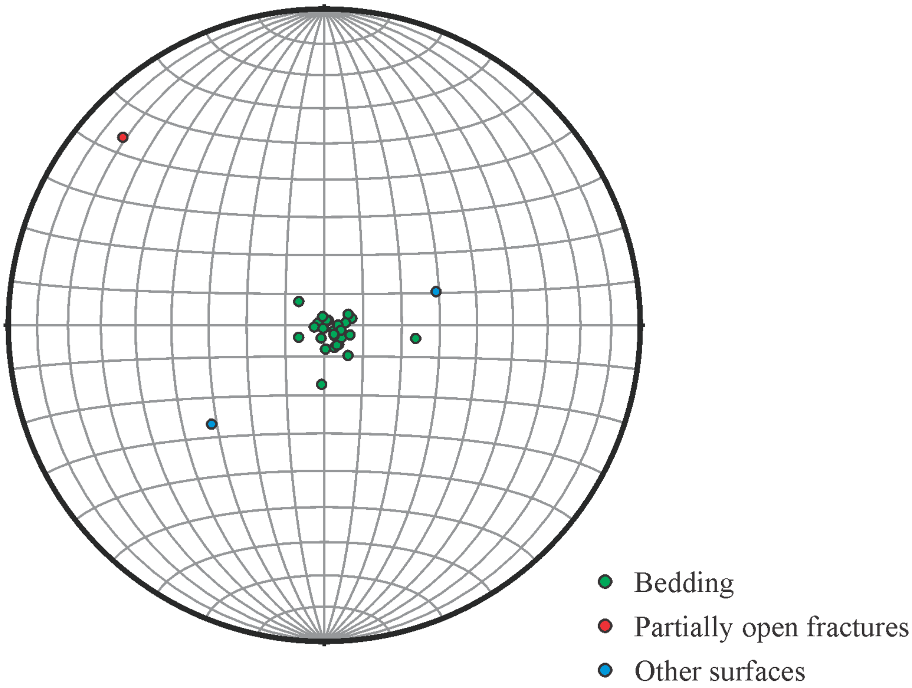

Figure 19. Various structural measurements collected by the micro-imager within the Collingwood Member (OGS-SG11-02 well, Mount Forest, Ontario), plotted on a stereonet. These planar structures are represented by their poles.

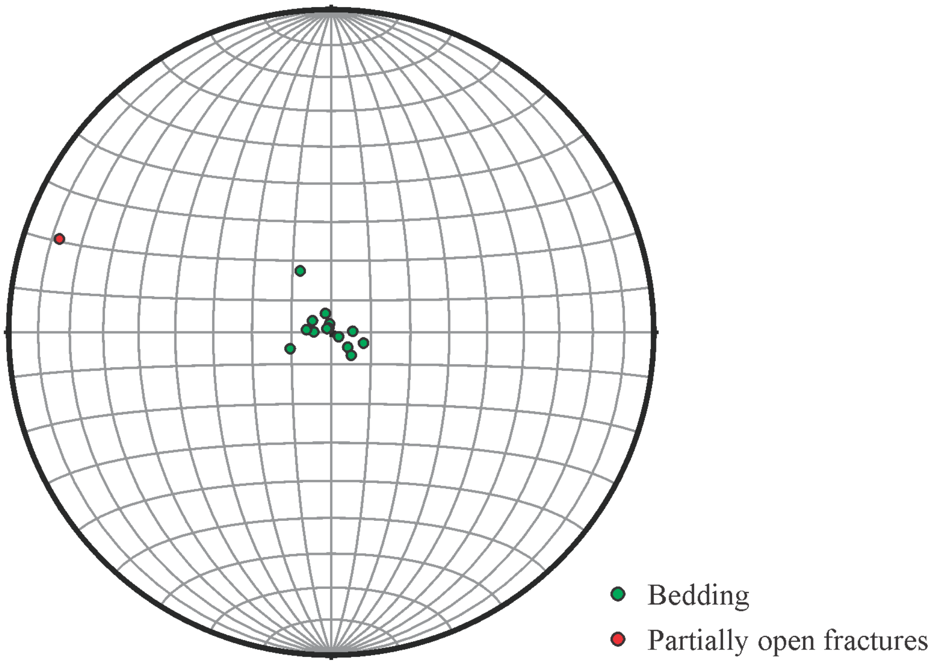

Figure 20. Various structural measurements collected by the micro-imager within the lower Cobourg Formation (OGS-SG11-02 well, Mount Forest, Ontario), plotted on a stereonet. These planar structures are represented by their poles.

Discussion

SOURCE ROCK POTENTIAL

The stratigraphic units in this study with the highest hydrocarbon generation potential as source rocks are the Rouge River and Collingwood members, based on gas content, hydrocarbon (oil and gas) saturation, total organic carbon, free hydrocarbon in the rock (S1), generated hydrocarbons through thermal cracking (S2) and hydrogen index. The organic-poor Georgian Bay and upper Blue Mountain formations do contain some higher than expected gas content values. However, its occurrence is probably related to the presence of sandstone or limestone beds with higher porosity and permeability and therefore greater conventional reservoir properties. This is suggested by the high porosity determined by the neutron geophysical log (CAN-01) and the actual GRI porosity and permeability measurements made on sample CAN-05. Since the source rock potential of these rocks is low, gas migration (possibly from the Rouge River or Collingwood members) is proposed as a mechanism to enrich these units.

Collingwood Member of the Cobourg Formation

Data collected as part of this project agree with conclusions from the authors of previous studies (Macauley 1981, 1984, 1987; Macauley and Snowdon 1984; Macauley, Snowdon and Ball 1985; Macauley et al. 1990; Snowdon 1984; Churcher et al. 1991; Obermajer 1997; Obermajer, Fowler and Snowden 1999a, 1999b; Obermajer et al. 1996). Total organic carbon values range from 2.49 to 4.68 weight % and organic matter plots in the Type II field (*see* Figures 9 and 11), suggesting a marine-type organic matter and environment. The low OI values could indicate a Type I organic matter but in this case (*see* Figure 10), the observed HI should be higher (Obermajer 1997).

The Collingwood Member shows the highest gas content values with a maximum of 18.4 scf/ton. However, the only adsorption isotherm available for this sample shows a much lower value at 6.59 scf/ton. This suggests that a large proportion of free gas is probably associated with secondary porosity (Figure 21). Vertical fractures have been identified in the Collingwood Member by examining the core and the micro-imager log (*see* Figure 19). These fractures, not detected by GRI analyses, increase the secondary porosity, allowing for greater reservoir properties to hold the free gas. High gas saturation (77%) also implies a comparatively large amount of free gas in the Collingwood Member. Also, the highest calculated lost gas content values in this study were recorded in the Collingwood Member, suggesting high effective permeability values (*see* Table 9).

Finally, Figure 22 shows the relationship between total organic carbon and gas content for the Cobourg and Blue Mountain formations, including their respective members. For the Blue Mountain Formation, the trendline gas content intercept is close to null (0.6 scf/ton). This suggests that organic matter is needed to get significant gas content values, either from gas generation or adsorption. For the Cobourg Formation trendline, the gas content intercept is much higher (5.3 scf/ton). This again supports higher free gas content in the calcareous unit that is not necessarily correlated to total organic carbon.

In Michigan, the Collingwood Member has been identified as a productive unit (Harrison 2010; Rock, Harrison and Barranco 2010). Limited pyrolysis data indicate that it is thermally mature and produces dry gas and condensate (Banas 2012). However, the Collingwood Member occurs at a much greater depth in Michigan (over 3000 m) than in Ontario (just over 1050 m) and the proximity of the midcontinental rift system may raise thermal maturity (Harrison 2010; Rock, Harrison and Barranco 2010; Banas 2012; Churcher 1991; Hamblin 2003). Correlation of hydrocarbon generation potential from Michigan should therefore be limited.

Rouge River Member of the Blue Mountain Formation

Many previous studies have focussed on the hydrocarbon generation potential of the Collingwood Member, but very few have considered the Blue Mountain Formation. This, despite the fact it has been correlated to the Utica shale, a hydrocarbon productive unit in the United States and the province of Quebec (Obermajer 1997; Obermajer, Fowler and Snowden 1999a, 1999b; Obermajer et al. 1996; Lehmann et al. 1995; Kirschbaum et al. 2012; Lavoie et al. 2008). Based on source rock evaluation data obtained in this drilling project, the Rouge River Member has fair to good source rock quality (McCarthy et al. 2011). Oil saturation values also suggest good oil potential. These conclusions agree with those of Obermajer, Fowler and Snowdon (1999b). Supplementary data obtained on sidewall core samples from the GGOL #67 well (MNR license # T011574, Greentree Gas and Oil Ltd. 2006) show that it has organic matter of Type II/III and Type III, confirming that the Rouge River Member has good hydrocarbon generation potential (Figure 23). The Rouge River Member at this location has slightly lower hydrogen index values than in the OGS-SG11-02 well. The Tmax values from the GGOL #67 well (433 to 444°C) indicate that temperatures have reached the "oil window", and compare favourably with the OGS-SG11-02 data and Obermajer's (1997) conclusions.

The gas in the Rouge River Member seems to be mostly adsorbed on organic matter. This is indicated by similar gas content and storage capacity values and good correlation between total organic carbon and gas content (*see* Figures 12 and 22).

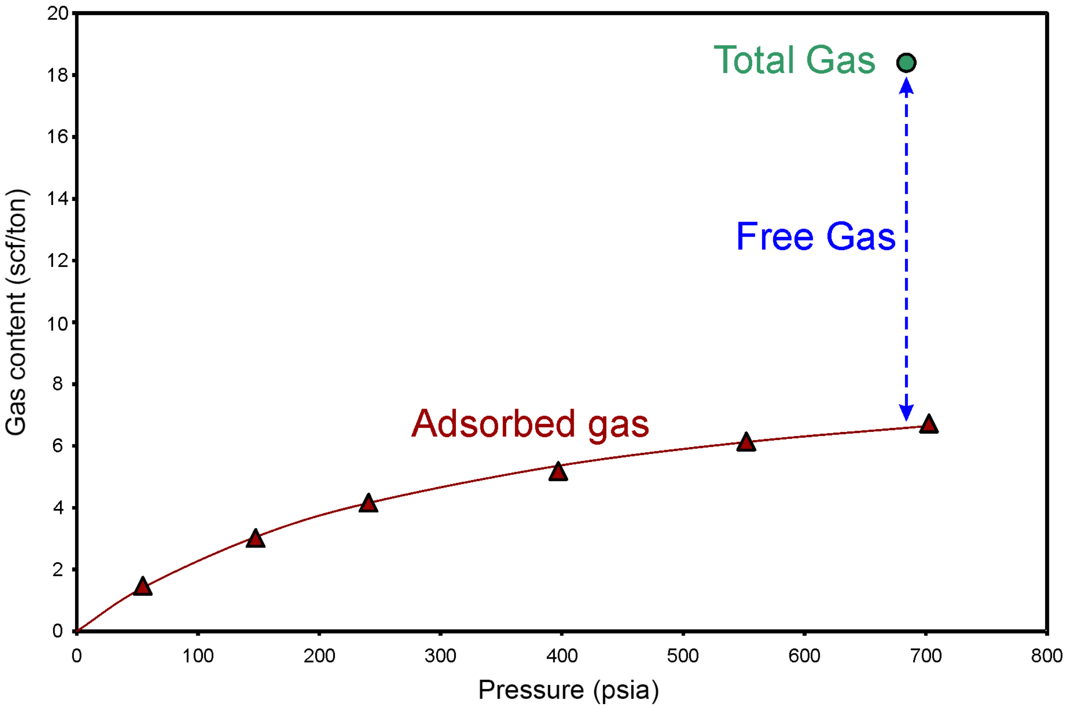

Figure 21. The adsorption isotherm (red line) for the sample CAN-21 (Collingwood Member) is compared to the measured total gas content (green dot). The high total gas content value indicates the possible presence of a large proportion of free gas in the sample. Abbreviations: scf/ton, standard cubic feet per ton; psia, pounds per square inch absolute.

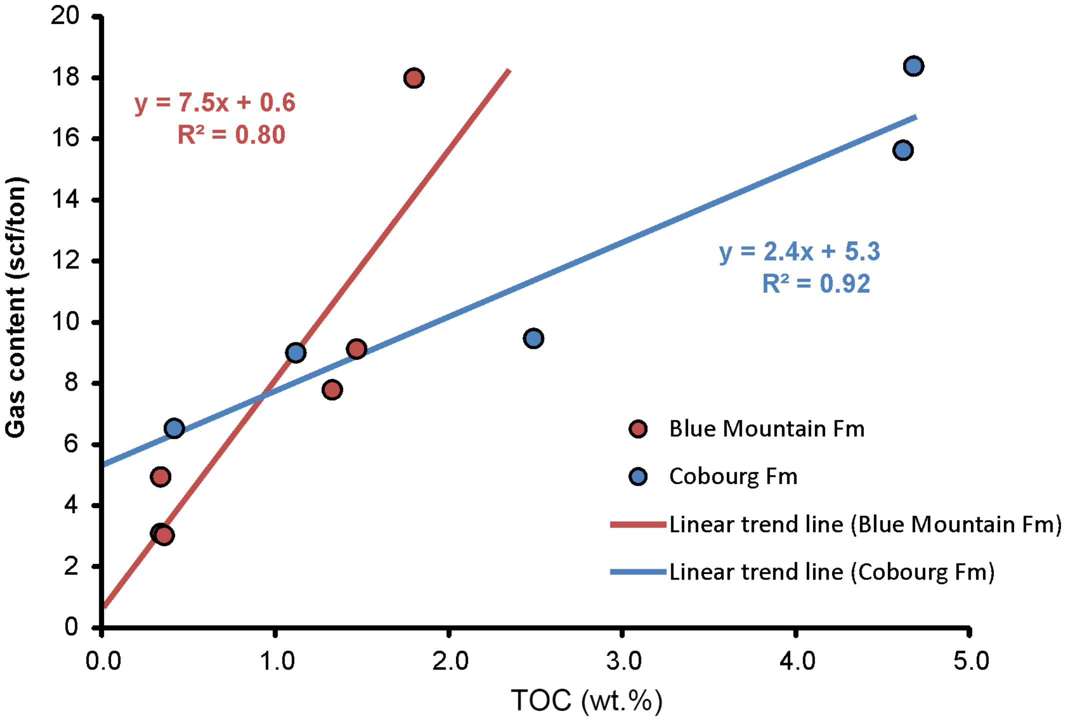

Figure 22. Total organic carbon versus gas content plot for the Cobourg and Blue Mountain formations. The Blue Mountain Formation includes the Rouge River Member and the Cobourg Formation includes the Collingwood Member. Abbreviations: scf/ton, standard cubic feet per ton; TOC, total organic content; wt.%, weight percent.

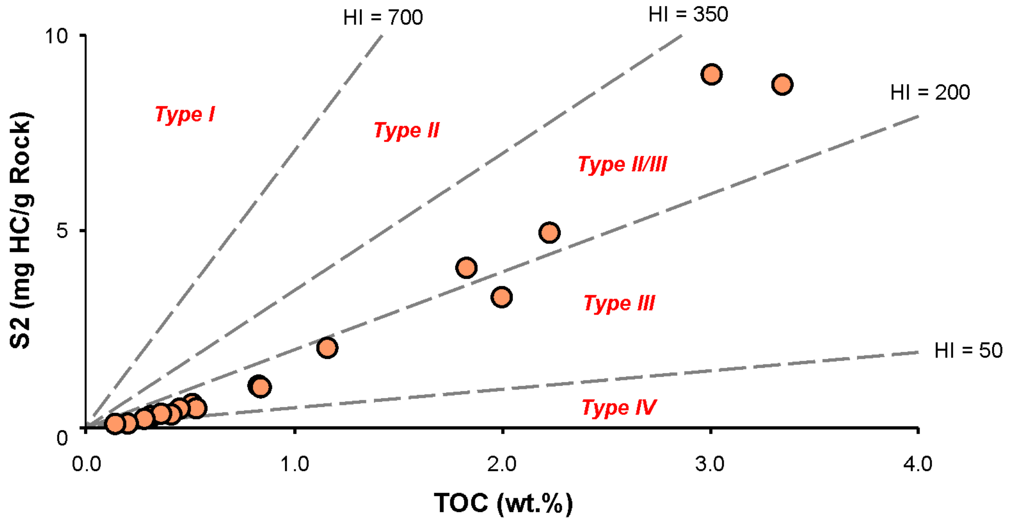

Figure 23. A plot of S2 versus total organic carbon (TOC) for samples collected by Greentree Gas and Oil Ltd. from the GGOL #67 well (Greentree Gas and Oil Ltd. 2006). Abbreviations: HC, hydrocarbon; HI, hydrogen index; wt. %, weight percent.

ENVIRONMENT OF DEPOSITION

Before Russell and Telford (1983) redefined the units, the Collingwood and Rouge River members were sometimes grouped together in a single stratigraphic unit. This is still done by most of the industry when reporting to the Ministry of Natural Resources and Forestry. However, these 2 units have fundamental differences in geological and geochemical parameters such as gas adsorption, hydrocarbon saturations, organic matter type, mineralogy and structural features. All of these parameters relate in some degree to the respective depositional environments of these units. Therefore, the units are essential to define.

Collingwood Member of the Cobourg Formation

The Collingwood Member is the uppermost unit of the Cobourg Formation. It has been interpreted to be formed from sediments deposited on a deep shelf setting under tropical conditions (Harris 1984b; Johnson et al. 1992). To preserve the organic matter, Harris (1984b) suggested that anoxic conditions developed at that time during stratification of the water column. Melchin et al. (2013) suggested the Collingwood Member was deposited during maximum transgression at the top of the Upper Ordovician carbonate platform, and that the overlying phosphatic lag bed represents sediment-starved conditions related to the maximum flooding surface. Rancourt (2009) agreed that the Collingwood Member corresponds to an upward deepening of the basin, based on microfacies, biostratigraphy and geophysical logs. A similar interpretation has been made in eastern Ontario for the correlative Eastview Member (Gbadeyan 2011). In Michigan, Hiatt (1985) proposed that the Collingwood Member was instead deposited in a lagoonal environment. Conversely, the possible stratigraphic equivalent in Ohio, the Point Pleasant Formation, has been associated with a sub-basin, which was open-marine and for which deposition took place below the wave base (Riley and Baranoski 2011; Perry 2012). Smith (2014) argues that the Point Pleasant Formation must have been deposited in a shallow environment due to the presence of storm beds and burrows. However, the relationship between the Collingwood Member and the Point Pleasant Formation is still unclear. Indeed, a phosphatic bed similar to the one observed in most of southern Ontario above the Collingwood Member and in northern Michigan is reported in Ohio at both the bottom and top of the Point Pleasant Formation (Huck 2013). Additional stratigraphic work would be needed to determine which unit in Ohio, if any, could be correlated to the Collingwood Member of Ontario and Michigan. Previous work on the Collingwood Member, found in both of these jurisdictions, points toward a strong relationship between them (Churcher et al. 1991; Rancourt 2009; Rock, Harrison and Barranco 2010). These studies are mainly based on petrophysics, geophysics and biostratigraphy. Further geographic correlation at this point is speculative.

The data obtained by this study support the idea that the Collingwood Member was deposited in a low-energy marine setting associated with anoxic conditions which could represent both shallow and deep settings. Indeed, the high organic carbon content (up to 4.68 weight %) implicates some mechanisms to preserve organic matter which are usually either a high primary production or anoxic bottom water conditions (Sharma, Dix and Riva 2003; Pedersen and Calvert 1990). Previous studies supported the idea that the Collingwood Member was characterized by sediment starvation and that anoxic conditions were present during the Collingwood deposition (Brett et al. 2006; Sharma, Dix and Riva 2003). The presence of fine lamination usually corroborates the absence of burrows. These 2 facts support the likelihood of an anoxic depositional environment for the Collingwood Member. Also, hydrogen index values from the OGS-SG11-02 well indicate organic matter in the Collingwood Member is Type II kerogen which is interpreted to originate from a marine source (*see* Figure 11). Furthermore, the Collingwood Member gradationally overlies the limestones of the Cobourg Formation, which has been associated with a shallow shelf or shoal environment (Johnson et al. 1992). Mineralogical data also support this idea with a gradational upward decrease in carbonate content offset by an increase in quartz and clay content up to the disconformable contact with the overlying Rouge River Member (*see* Figure 7). Biostratigraphic work done by Rancourt (2009) and Brett et al. (2006) also support a deep water environment. The possibility that the Collingwood Member was deposited in a relatively small restricted basin, as suggested by Riley and Baranoski (2011) and Perry (2012) for the Point Pleasant Formation in Ohio, cannot be supported for the Collingwood Member if one considers the geographic distribution of this unit and its stratigraphic equivalents, including Michigan, Ohio, Ontario (Brett et al. 2006; Rock, Harrison and Barranco 2010; Churcher et al. 1991). Indeed, Churcher et al. (1991) suggested that the Collingwood had limited extent in southern Ontario but more recent core examination by Hamblin (2003) may confirm the presence of a more widespread thin interval of this unit in southwestern Ontario. Data from this drilling project cannot confirm nor refute the latest ideas suggested for the Collingwood in Ontario and surrounding jurisdictions concerning shallow or deep water deposition (Rancourt 2009; Riley and Baranoski 2011; Smith 2014).

The upper contact of the Collingwood Member with the Blue Mountain Formation is characterized by a phosphatic bed a few centimetres thick. Harris (1984b) suggested that the stratification of the water column explains the high P_2O_5 concentration observed in the Collingwood Member. Churcher et al. (1991) proposed that the phosphatic bed was associated with an erosional surface due to subaerial exposure (Churcher 1986). Conversely, Melchin et al. (2013), Sharma, Dix and Riva (2003) and Brett et al. (2006) suggested that the disconformity at the top of the Collingwood Member is associated with a maximum flooding surface. Alternatively, Rancourt (2009) proposed that the phosphatic bed resulted from a down dip transport from shallower waters. Neither Rancourt (2009) nor Wilson, Budai and Sengupta (2001) report evidence of a subaerial exposure in the Michigan Basin. In Michigan, Rock, Harrison and Barranco (2010) interpreted the phosphatic bed to originate from a hardground representing a maximum flooding surface. This hardground was later replaced by phosphatic minerals and then ripped up by storm events. A discordant contact has been identified between the Utica and the Lorraine shales in Quebec but no origin has been suggested (Thériault 2008; Lavoie et al. 2014). Finally, in Ohio a similar phosphatic bed has been observed locally by Huck (2013) above and below the Point Pleasant Formation. His hypothesis was that the beds were the result of condensed sections arising from low rates of sedimentation and a sea level rise.

The phosphatic bed was not specifically studied as part of this project, and so data from this study remain equivocal concerning its origin. However, there was no evidence in the OGS-SG11-02 core that indicate subaerial exposition. Nonetheless, this bed separates 2 different rock types with contrasting parameters, indicating 2 different depositional processes, likely separated by a period of no sedimentation and probably some degree of erosion. Yet, in the Toronto–Pickering area, especially in the Pickering well (OGS-83-3), the contact between the Collingwood and the Rouge River members is gradational (Johnson 1983). This was also locally observed in Ohio and New York (Russell and Telford 1983; Churcher et al. 1991; Riley and Baranoski 2011; Huck 2013). Additional regional work would be needed to map the extent of the phosphatic lag bed, so that its origin and implications for depositional controls on the Collingwood and Rouge River members can be adequately determined.

Blue Mountain and Georgian Bay Formations

The Blue Mountain Formation corresponds to the initial phase of deposition of Taconic Orogeny-derived clastics (Johnson et al. 1992). This is supported by mineralogical data that indicate the Blue Mountain and Georgian Bay formations are composed of more clay, quartz and plagioclase than the underlying carbonate-dominated Cobourg Formation (including Collingwood Member) (*see* Figures 5 and 6). The proportion of clays versus quartz and feldspar content (*see* Figure 7) is relatively constant from the Cobourg Formation up to the Georgian Bay Formation, suggesting that all noncalcareous content originates from the same source. Various cross sections from Armstrong and Carter (2010) demonstrate an increase in thickness of the Blue Mountain and Georgian Bay formations towards the southeast. It also indicates that the Taconic uplands (ancestral Appalachian Mountains) were the main source of siliciclastic sediments for the Upper Ordovician shales.

Most previous authors agree that the initial Upper Ordovician shale deposition represented in southern Ontario by the Blue Mountain Formation (and Rouge River Member) occurred in a deep shelf environment (Johnson et al. 1992; Obermajer 1997). More recently, in New York,, Smith and Leone (2011) and Smith (2014) have proposed that the Utica shale was instead deposited in a shallow anoxic environment. No evidence was found in this study for shallow water deposition of the Blue Mountain Formation. Upward through the shale succession (upper Blue Mountain to Georgian Bay formations), an increase in grain size and abundance of sedimentary features such as cross bedding indicates an upward evolution to shallower environments with higher energy levels.

COMPARISON WITH ORDOVICIAN SHALES IN ADJACENT JURISDICTIONS

One of the objectives of this project was to assess the unconventional hydrocarbon generation potential for the Ordovician shales of southern Ontario. The actual potential is difficult to evaluate at this point, because of the geographically limited availability of data. However, Ontario shales can be compared to publicly available data for equivalent units in adjacent jurisdictions.

Current depth is a significant parameter for unconventional resources since it influences many other factors, such as reservoir pressure and gas content amongst others. The organic-rich shales in the OGS-SG11-02 well occur at a much shallower depth (about 500 m) than most active or proven unconventional hydrocarbon plays in Quebec and northern United States. For example, the Utica shale can reach depths up to 2500 m in Quebec and even more than 4000 m in the United States and the Collingwood Member in Michigan can reach depths up to 3000 m (Thériault 2009; Marcellus Center for Outreach and Research 2014a; Harrison 2010; Rock, Harrison and Barranco 2010; Banas 2012). These units mainly produce gas at those depths. The deepest Ordovician shales in Ontario occur in the Chatham Sag area and at approximately 900 m depth (Armstrong and Carter 2010).

Depth can also influence the type of hydrocarbons generated. Since the shales in Ontario occur more shallow and are less thermally mature, one would expect heavier hydrocarbons (wet gas, condensate, or oil) to be generated. This is supported by drilling results of Greentree Gas and Oil Ltd. (2006) in the Port Dover area, north of Lake Erie. Their well (GGOL #67) documented the presence of wet gas in the basal

Ordovician shale interval (equivalent to the Rouge River Member). Rock-Eval® 6 pyrolysis data from the OGS-SG11-02 well confirm that the Ordovician shales in the Mount Forest area have reached the early oil window of thermal maturity. In addition, oil saturation values for the Rouge River Member in OGS-SG11-02 are also relatively high (31.5 %). It is also important to remember that the current depth of the Ontario Ordovician shales, even if not as great as for the surrounding jurisdictions, may not characterize conditions in the past. In fact, various studies estimated that the Paleozoic rocks of southwestern Ontario were one probably 800 to 2000 m deeper, which can explain how the Ordovician source rocks reached the oil window (Legall, Barnes and Macqueen 1981; Coniglio et al. 1994).

Another depth-related parameter to consider is reservoir pressure. Indeed, increased reservoir pressure usually enables the hydrocarbons to flow more easily to the well bore. Hydrocarbon production at under-pressured conditions is more challenging. Not much data are available concerning the pressure present in the Ontario Ordovician shales. In the Bruce County, Intera (2011a) reports mostly under-pressured values for this interval.

One feature which definitely does not favour hydrocarbon potential of the Ontario Ordovician shales is the relative thinness of the organic-rich section. The combined thickness of the Collingwood and Rouge River members, which correspond to the section with the greatest hydrocarbon potential, is only 23.0 m in the OGS-SG11-02 well. A reasonable estimate of maximum thickness for this interval in southwestern Ontario is no more than 60 m. In comparison, the thickness of the Utica shale alone can be as much as 150 m in the northern United States and 300 m in Quebec (Marcellus Center for Outreach and Research 2014b; Jarvie 2012; Lavoie et al. 2014). The maximum thickness of the Collingwood Member in Michigan is approximately 13 m which is comparable to what is observed in Ontario (Wilson, Budai and Sengupta 2001; Rock, Harrison and Barranco 2010; Banas 2012).

Gas content of the organic-rich Ordovician shales is considerably less than values reported for productive equivalent units in adjacent jurisdictions. In the OGS-SG11-02 well, the maximum gas content values are 18.4 scf/ton for the Collingwood Member and 18.0 scf/ton for the Rouge River Member. By comparison, the Utica shale in Quebec is reported to have gas content up to 89 scf/ton and storage capacity up to 70 scf/ton (Chatellier 2013; Karlen 2007; Jarvie 2012). The main difference can again mainly be attributed to the depth of the shales. Storage capacity, as with reservoir pressure, is also usually depth dependant. Also, higher thermal maturity, again associated with depth, tends to produce more gas. Since data is not available for deeper shales in Ontario, it is currently difficult to completely compare with other jurisdictions. However, one shallow well was drilled near Quebec City at Saint-Augustin-de-Desmaures in 2008 by Junex Inc. The depth of the shales were less than 560 m and gas content from the Utica and Lorraine reached about 20 scf/ton, similar to what was obtained for the OGS-SG11-02 well (Dorrins 2009). With stimulation, this well produced wet gas with some oil.

Mineralogy can have a great impact on the shale porosity, permeability and the ability to fracture. The Collingwood Member of Ontario, which mainly consists of calcite, can be compared to other Ordovician shales in the surrounding jurisdictions. For example, it is mineralogically similar to the Quebec Lower Utica of Thériault (2012) which is composed of about 11.3 weight % quartz, 4.4 weight % feldspar, 52.5 weight % calcite, 4.7 weight % dolomite and 25.8 weight % clay. The Rouge River Member, however, has higher clay content (almost up to 70%) than equivalent units in Quebec and the northern United States for which clay content typically does not exceed 50% (Martin et al. 2008; Harrington 2012; Thériault 2012). In an unconventional shale reservoir, it is generally preferred to have a minimal clay component since increased clay content negatively affects porosity, effective permeability and the brittleness of the rock and the quantity of fractures. For example, in the OGS-SG11-02 well, the Collingwood Member, with a maximum clay content of 35.5 weight %, has more well-developed vertical fractures than the Rouge River Member with a maximum clay content of 68.4 weight %.

The mineralogical differences between the Collingwood and Rouge River members, in addition to differences in other parameters, would complicate their treatment as a combined reservoir for hydrocarbon extraction.

Conclusion

In southern Ontario, the Upper Ordovician shale units with the greatest hydrocarbon generation potential are the Collingwood Member of the Cobourg Formation and the Rouge River Member of the Blue Mountain Formation. This is based on determination of total gas content, gas adsorption, hydrocarbon saturations, total organic carbon and other pyrolysis parameters such as the quantity of free hydrocarbon in the rock (S1), the amount of hydrocarbons generated through thermal cracking (S2) and the type of organic matter.

The upper Blue Mountain and Georgian Bay formations have some gas content values higher than expected and gas shows were reported during drilling. However, these are probably due to their better reservoir than source rock properties.

Although the stratigraphically adjacent Collingwood and Rouge River members represent the greatest hydrocarbon generation potential in this succession, they have totally distinct geological and geochemical characteristics that are largely associated with differences in their depositional environments. Composed mostly of calcite and containing marine-type organic matter, the Collingwood Member is associated with deposition on a deepening carbonate platform environment. Conversely, the Rouge River Member is clay-dominated reflecting deposition during the initial phase of the Taconic Orogeny into a deep shelf environment. The organic matter types in the Rouge River Member indicate a mixture of marine and terrestrial sources, however no terrestrial plants are known for the Ordovician. A nodular phosphatic bed that separates these 2 units indicates a period of nonsedimentation (likely linked to a maximum flooding surface) and possible erosion. No evidence of subaerial exposure was found at this contact.

Mineralogy of the shales also affects their reservoir properties. Subvertical fractures occurring only in the more brittle, calcareous Collingwood Member, act to increase its secondary porosity which could explain its comparatively high apparent free gas content.

A thorough determination of the hydrocarbon generation potential of the Ordovician shale succession in southern Ontario requires a more geographically widespread data set. Most of the data presented in this report originate from a single well. Sophisticated analysis of these very fine-grained units necessitated acquisition of fresh core samples that this well afforded.

Additional data are required, especially in areas where these units are found at greater depths, in order to determine the maturity levels reached. Also, additional regional-scale stratigraphic work is required to correlate these units with the apparently equivalent units in the surrounding jurisdictions and more fully characterize the various depositional environments and controls on hydrocarbon generation. Organic petrographic analysis of the organic matter in the Rouge River and Collingwood members would help in explaining the different types of organic matter that characterize these units. This would definitely help in characterizing the environment of deposition and future exploration work. Finally, the subvertical open fractures seem to play an important role, especially when it concerns the free gas content. Additional regional studies should definitely be conducted because there is a general lack of knowledge regarding the structural history a d character of structures in the Paleozoic rocks of Ontario.

In conclusion, the Upper Ordovician shales of Ontario include organic-rich, hydrocarbon prospective units. However, they have some characteristics that could limit their hydrocarbon generation potential. These relate mainly to the high clay content, especially of the Rouge River Member, which reduces porosity, permeability and brittleness of the rock. Also, both the Collingwood and Rouge River members are relatively thin in Ontario as compared to equivalent productive units in the United States and Quebec. Furthermore, the current reservoir pressure of the shales may be much lower compared to surrounding jurisdictions, because the units are found at much shallower depths in Ontario.

The maturity level determined for the well in this study indicates that the Rouge River and Collingwood member strata have reached the "oil window", suggesting that oil (and some related liquids) generation is favoured over gas, at least in the shallower parts of the Ordovician in southern Ontario. A more regional-scale maturation analysis would help in evaluating whether hydrocarbon generating potential and type changes significantly where the Ordovician shales occur deeper.

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Appendix

Tables

Table 1. List of canister samples collected from the OGS-SG11-02 well with stratigraphy, depth and analyses performed.

Sample CAN-	Stratigraphy	Depth Interval Corrected (m)	Total Gas				Gas Composition		GRI	Adsorption Isotherms	Rock Mechanics
			Lost	Desorbed	Measured Residual	Projected Residual	Average	Isotopes			
01	Georgian Bay Fm	316.53-316.83	X	X	X	X	X				
02	Georgian Bay Fm	329.81-330.09	X	X	X	X					
03	Georgian Bay Fm	347.85-348.15	X	X		X					X
04	Georgian Bay Fm	363.04-363.34	X	X		X					
05	Georgian Bay Fm	372.33-372.64	X	X	X	X	X	X	X		
06	Georgian Bay Fm	381.48-381.78	X	X		X					
07	Georgian Bay Fm	390.01-390.32	X	X	X	X					
08	Georgian Bay Fm	399.23-399.51	X	X	X	X	X			X	
09	Georgian Bay Fm	412.08-412.39	X	X		X					
10	Georgian Bay Fm	418.20-418.51	X	X	X	X	X				
11	Upper Blue Mountain Fm	427.30-427.60	X	X	X	X					
12	Upper Blue Mountain Fm	436.47-436.77	X	X		X	X		X		X
13	Upper Blue Mountain Fm	442.56-442.87	X	X		X	X	X			
14	Upper Blue Mountain Fm	448.66-448.96	X	X	X	X					
15	Upper Blue Mountain Fm	454.68-454.98	X	X	X	X	X			X	
16	Upper Blue Mountain Fm	460.65-460.95	X	X		X					
17	Rouge River Mb	467.00-467.30	X	X		X					
18	Rouge River Mb	471.04-471.34	X	X	X	X	X	X	X		X
19	Rouge River Mb	474.28-474.58	X	X	X	X	X	X	X	X	
20	Collingwood Mb	477.62-477.93	X	X	X	X					X
21	Collingwood Mb	480.41-480.73	X	X	X	X	X	X	X	X	
22	Collingwood Mb	483.41-483.71	X	X	X	X					
23	Lower Cobourg Fm	486.33-486.63	X	X	X	X	X	X			
24	Lower Cobourg Fm	488.61-488.92	X	X		X	X	X		X	X

Abbreviations: Fm, Formation; Mb, Member; m, metres; GRI, Gas Research Institute.

Table 2. List of rock samples collected from the OGS-SG11-02 well with stratigraphy, depth and analyses performed.

Sample	Stratigraphy	Depth Interval Corrected (m)	Total Organic Carbon	Rock-Eval® 6 pyrolysis*	X-Ray Diffraction (Mineralogy)
TOC-01	Georgian Bay Fm	316.53	X	X	X
TOC-03	Georgian Bay Fm	329.81		X	
TOC-05	Georgian Bay Fm	346.78		X	
TOC-07	Georgian Bay Fm	354.20		X	
TOC-09	Georgian Bay Fm	371.60		X	
TOC-10	Georgian Bay Fm	372.33	X		
TOC-11	Georgian Bay Fm	376.90		X	
TOC-13	Georgian Bay Fm	385.59		X	X
TOC-15	Georgian Bay Fm	399.21	X	X	
TOC-17	Georgian Bay Fm	408.20		X	
TOC-19	Georgian Bay Fm	415.79		X	X
TOC-20	Georgian Bay Fm	418.20	X		
TOC-21	Georgian Bay Fm	424.89		X	
TOC-23	Upper Blue Mountain Fm	431.97		X	
TOC-24	Upper Blue Mountain Fm	436.47	X		
TOC-25	Upper Blue Mountain Fm	440.99		X	X
TOC-27	Upper Blue Mountain Fm	448.66		X	X
TOC-28	Upper Blue Mountain Fm	454.65	X	X	
TOC-29	Upper Blue Mountain Fm	458.41		X	X
TOC-30	Upper Blue Mountain Fm	460.63		X	
TOC-31	Rouge River Mb	464.89		X	X
TOC-32	Rouge River Mb	467.00		X	
TOC-33	Rouge River Mb	468.98		X	X
TOC-34	Rouge River Mb	471.04	X	X	
TOC-35	Rouge River Mb	471.88		X	X
TOC-36	Rouge River Mb	473.88		X	X
TOC-37	Rouge River Mb	474.26	X	X	X
CBO-12-1121	Rouge River Mb	475.51		X	
CBO-12-1122	Rouge River Mb	475.51			X
TOC-38	Collingwood Mb	477.62		X	X
TOC-39	Collingwood Mb	480.41	X	X	X
TOC-40	Collingwood Mb	483.41		X	X
TOC-41	Lower Cobourg Fm	486.33		X	X
TOC-42	Lower Cobourg Mb	488.61	X	X	X

Abbreviations: Fm, Formation; Mb, Member; m, metres.
**includes additional total organic carbon analysis.*

Table 3. Stratigraphy, thickness and depth of top of stratigraphic units intercepted in the OGS-SG11-02 well.

Stratigraphic unit	**Depth logger (m)**	**Thickness (m)**
Quaternary deposits	0.00	36.10
Silurian bedrock	36.10	164.90
Queenston Formation	201.00	93.20
Georgian Bay Formation	294.17	131.80
Blue Mountain Formation	426.00	50.90
Rouge River Member	*463.30*	*13.60*
Cobourg Formation	476.90	19.60*
Collingwood Member	*476.90*	*9.40*
Lower Cobourg Formation	*486.30*	*10.20**
Total vertical depth	496.50	

**This number represents a minimum thickness since the lower contact of the unit was not intercepted in the well.*
Italicized numbers denote member subunits within the formations.
Abbreviation: m, metres.

Table 4. Mineralogy results by X-ray diffraction for the OGS-SG11-02 core samples.

Sample	Stratigraphy	Corrected Depth (m)	Quantitative Mineralogy (wt. %)									Qualitative Clay Component		
			Quartz	Calcite	Dolomite + Ankerite*	Plag	K-spar	Pyrite	Other	Total Clay*	Sum	Al 2:1 Clay	Mg-Chlorite	Kaolin
TOC-01	Georgian Bay Fm	316.53	3.5	62.4	21.1	0.0	0.0	0.3		12.6	100.0	present	present	absent
TOC-13	Georgian Bay Fm	385.59	23.8	1.1	0.8	2.5	0.6	0.6		70.6	100.0	present	present	absent
TOC-19	Georgian Bay Fm	415.79	24.2	1.1	0.5	3.3	0.6	0.6		69.6	100.0	present	present	absent
TOC-25	Upper Blue Mountain Fm	440.99	19.2	5.0	6.0	1.5	0.8	0.3		67.1	100.0	present	present	absent
TOC-27	Upper Blue Mountain Fm	448.66	20.6	2.4	1.6	2.3	0.8	2.5		69.9	100.0	present	present	absent
TOC-29	Upper Blue Mountain Fm	458.41	22.9	1.3	0.4	2.3	0.7	2.0		70.4	100.0	present	present	absent
TOC-31	Rouge River Mb	464.89	21.8	4.0	1.0	2.2	0.8	1.8		68.4	100.0	present	present	absent
TOC-33	Rouge River Mb	468.98	22.3	5.0	0.9	1.9	0.6	2.2		67.1	100.0	present	present	absent
TOC-35	Rouge River Mb	471.88	21.6	8.9	1.8	1.4	0.6	1.7		64.1	100.0	present	present	absent
TOC-36	Rouge River Mb	473.88	24.7	4.1	1.0	3.0	1.0	1.8		64.5	100.0	present	present	absent
TOC-37	Rouge River Mb	474.26	22.7	5.2	1.3	1.9	0.6	2.0		66.2	100.0	present	present	absent
CBO-12-1122	Rouge River Mb	475.51	20.4	6.5	8.9	0.3	0.0	1.5		62.4	100.0	present	present	absent
TOC-38	Collingwood Mb	477.62	9.9	58.5	1.2	0.0	0.7	0.5		29.3	100.0	present	present	absent
TOC-39	Collingwood Mb	480.41	No quantitative mineralogy available due to a number of unidentified peaks									n.d.	n.d.	n.d.
TOC-40	Collingwood Mb	483.41	11.0	50.0	2.2	0.0	1.0	0.3		35.5	100.0	present	present	absent
TOC-41	Lower Cobourg Fm	486.33	3.7	81.4	1.2	0.0	0.0	0.2		13.5	100.0	present	present	absent
TOC-42	Lower Cobourg Fm	488.61	7.6	56.7	8.0	0.0	0.6	0.3		26.9	100.0	present	present	absent

Abbreviations: Fm, Formation; Mb, Member; m, metres; wt. %, weight percent; Plag, plagioclase; K-spar, potassium feldspar; n.d., not determined.
Dolomite + Ankerite: Due to significant peak overlaps, the accuracy of discrete dolomite and/or ankerite analyses cannot be determined without extensive testing on synthesized standards.*
The presence of a broad peak at ~ 2.9 Å in many of the samples suggests the presence of both minerals and this has been confirmed through SEM investigation.
The data reported here represent a summed analysis for an optimal Rietveld fit.
*Total Clay** represents the total clay fraction plus any amorphous/organic component and may also include any minor phases not identified during analysis.*

Table 5. Total organic carbon content results for the OGS-SG11-02 core samples.

Sample	**Stratigraphy**	**Depth Corrected (m)**	**Total Organic Content (wt. %)**
TOC-01	Georgian Bay Fm	316.53	0.09
TOC-10	Georgian Bay Fm	372.33	0.26
TOC-15	Georgian Bay Fm	399.21	0.37
TOC-20	Georgian Bay Fm	418.20	0.60
TOC-24	Upper Blue Mountain Fm	436.47	0.57
TOC-28	Upper Blue Mountain Fm	454.65	0.80
TOC-34	Rouge River Mb	471.04	1.92
TOC-37	Rouge River Mb	474.26	2.18
TOC-39	Collingwood Mb	480.41	4.55
TOC-42	Lower Cobourg Mb	488.61	0.46

Abbreviations: Fm, Formation; Mb, Member; m, metres; wt. %, weight percent.

Table 6. Rock-Eval® 6 pyrolysis results (S1, S2, PI, S3, Tmax, Tpeak) for the OGS-SG11-02 core samples.

Sample	**Stratigraphy**	**Depth Corrected**	**Qty**	**S1**	**S2**	**PI**	**S3**	**Tmax**	**Tpeak**
		(m)	**(mg)**	**(mgHC/gRock)**	**(mgHC/gRock)**	**-**	**($mgCO_2$/gRock)**	**(°C)**	**(°C)**
TOC-01	Georgian Bay Fm	316.53	70.3	0.01	0.04	0.20	0.22	430	468
TOC-03	Georgian Bay Fm	329.81	69.9	0.02	0.11	0.18	0.33	466	504
TOC-05	Georgian Bay Fm	346.78	70.9	0.37	0.68	0.35	0.24	315	353
TOC-07	Georgian Bay Fm	354.20	70.6	0.03	0.14	0.16	0.38	439	477
TOC-09	Georgian Bay Fm	371.60	70.4	0.03	0.17	0.16	0.47	434	472
TOC-11	Georgian Bay Fm	376.90	70.8	0.00	0.03	0.07	0.23	505	543
TOC-13	Georgian Bay Fm	385.59	70.5	0.04	0.32	0.11	0.26	434	472
TOC-15	Georgian Bay Fm	399.21	70.7	0.04	0.32	0.12	0.23	433	471
TOC-17	Georgian Bay Fm	408.20	70.6	0.06	0.39	0.13	0.18	431	469
TOC-19	Georgian Bay Fm	415.79	70.7	0.03	0.22	0.11	0.18	434	472
TOC-21	Georgian Bay Fm	424.89	70.8	0.03	0.34	0.08	0.24	431	469
TOC-23	Upper Blue Mountain Fm	431.97	69.9	0.03	0.28	0.09	0.29	436	474
TOC-25	Upper Blue Mountain Fm	440.99	70.3	0.03	0.17	0.14	0.50	436	474
TOC-27	Upper Blue Mountain Fm	448.66	70.5	0.05	0.34	0.12	0.36	435	473
TOC-28	Upper Blue Mountain Fm	454.65	70.8	0.04	0.35	0.11	0.22	436	474
TOC-29	Upper Blue Mountain Fm	458.41	70.3	0.06	0.60	0.10	0.21	437	475
TOC-30	Upper Blue Mountain Fm	460.63	70.7	0.04	0.30	0.12	0.20	433	471
TOC-31	Rouge River Mb	464.89	70.7	0.45	5.26	0.08	0.48	439	477
TOC-32	Rouge River Mb	467.00	70.1	0.40	3.73	0.10	0.31	438	476
TOC-33	Rouge River Mb	468.98	70.7	0.44	4.05	0.10	0.38	438	476
TOC-34	Rouge River Mb	471.04	70.1	0.46	4.90	0.09	0.37	439	477
TOC-35	Rouge River Mb	471.88	70.9	0.39	4.31	0.08	0.40	440	478
TOC-36	Rouge River Mb	473.88	70.3	0.37	3.91	0.09	0.29	439	477
TOC-37	Rouge River Mb	474.26	70.2	0.57	6.07	0.09	0.27	438	476
CBO-12-1121	Rouge River Mb	475.51	70.1	1.17	7.33	0.14	0.32	439	477
TOC-38	Collingwood Mb	477.62	70.8	1.35	27.34	0.05	0.38	438	476
TOC-39	Collingwood Mb	480.41	70.4	2.25	30.42	0.07	0.31	442	480
TOC-40	Collingwood Mb	483.41	70.7	1.00	15.07	0.06	0.23	442	480
TOC-41	Lower Cobourg Fm	486.33	70.5	0.50	5.96	0.08	0.22	438	476
TOC-42	Lower Cobourg Fm	488.61	70.8	0.11	1.15	0.08	0.61	438	476

Abbreviations: Fm, Formation; Mb, Member; m, metres; Qty, quantity of rock sample analyzed; mg, milligrams; g, grams; S1, hydrocarbons volatilized at 300℃; S2, hydrocarbons evolved from kerogen at 300℃ to 600℃; PI, production index; S3, organic carbon dioxide generated from 300℃ to 390℃; Tmax, maximum temperature at S2 peak (converted from Tpeak); Tpeak, temperature at peak generation on the S2 pyrolysis curve.

Table 7. Rock-Eval® 6 pyrolysis results (S3CO, PC, TOC, RC, HI, OICO, OI) for the OGS-SG11-02 core samples.

Sample	Stratigraphy	Depth Corrected	S3CO	PC	TOC	RC	HI	OICO	OI
		(m)	(mgCO/gRock)	(wt. %)	(wt. %)	(wt. %)	(mgHC/gTOC)	(mgCO/gTOC)	(mgCO$_2$/gTOC)
TOC-01	Georgian Bay Fm	316.53	0.02	0.01	0.11	0.10	36	18	200
TOC-03	Georgian Bay Fm	329.81	0.01	0.02	0.16	0.14	69	6	206
TOC-05	Georgian Bay Fm	346.78	0.03	0.10	0.29	0.19	234	10	83
TOC-07	Georgian Bay Fm	354.20	0.01	0.03	0.14	0.11	100	7	271
TOC-09	Georgian Bay Fm	371.60	0.03	0.03	0.18	0.15	94	17	261
TOC-11	Georgian Bay Fm	376.90	0.01	0.01	0.07	0.06	43	14	329
TOC-13	Georgian Bay Fm	385.59	0.02	0.04	0.30	0.26	107	7	87
TOC-15	Georgian Bay Fm	399.21	0.04	0.04	0.30	0.26	107	13	77
TOC-17	Georgian Bay Fm	408.20	0.03	0.05	0.34	0.29	115	9	53
TOC-19	Georgian Bay Fm	415.79	0.02	0.03	0.24	0.21	92	8	75
TOC-21	Georgian Bay Fm	424.89	0.03	0.04	0.34	0.30	100	9	71
TOC-23	Upper Blue Mountain Fm	431.97	0.01	0.04	0.29	0.25	97	3	100
TOC-25	Upper Blue Mountain Fm	440.99	0.03	0.04	0.18	0.14	94	17	278
TOC-27	Upper Blue Mountain Fm	448.66	0.03	0.05	0.34	0.29	100	9	106
TOC-28	Upper Blue Mountain Fm	454.65	0.04	0.04	0.36	0.32	97	11	61
TOC-29	Upper Blue Mountain Fm	458.41	0.05	0.06	0.45	0.39	133	11	47
TOC-30	Upper Blue Mountain Fm	460.63	0.03	0.04	0.34	0.30	88	9	59
TOC-31	Rouge River Mb	464.89	0.13	0.50	1.77	1.27	297	7	27
TOC-32	Rouge River Mb	467.00	0.08	0.36	1.33	0.97	280	6	23
TOC-33	Rouge River Mb	468.98	0.07	0.39	1.38	0.99	293	5	28
TOC-34	Rouge River Mb	471.04	0.07	0.47	1.47	1.00	333	5	25
TOC-35	Rouge River Mb	471.88	0.08	0.41	1.33	0.92	324	6	30
TOC-36	Rouge River Mb	473.88	0.06	0.37	1.26	0.89	310	5	23
TOC-37	Rouge River Mb	474.26	0.11	0.57	1.80	1.23	337	6	15
CBO-12-1121	Rouge River Mb	475.51	0.08	0.72	1.75	1.03	419	5	18
TOC-38	Collingwood Mb	477.62	0.17	2.42	4.62	2.20	592	4	8
TOC-39	Collingwood Mb	480.41	0.13	2.74	4.68	1.94	650	3	7
TOC-40	Collingwood Mb	483.41	0.10	1.36	2.49	1.13	605	4	9
TOC-41	Lower Cobourg Fm	486.33	0.05	0.55	1.12	0.57	532	4	20
TOC-42	Lower Cobourg Fm	488.61	0.03	0.13	0.42	0.29	274	7	145

Abbreviations: Fm, Formation; Mb, Member; m, metres; mg, milligrams; g, grams; wt %, weight percent; S3CO, carbon monoxide from organic and mineral sources; PC, pyrolyzable carbon; TOC, total organic carbon; RC, residual carbon; HI, hydrogen index; OICO, oxygen index for carbon monoxide; OI, oxygen index for carbon dioxide; CO, carbon monoxide; HC, hydrocarbon; CO$_2$, carbon dioxide.

Table 8. Rock-Eval® 6 pyrolysis results (MINC, S4CO, S4CO2, RCCO, RCCO2) for the OGS-SG11-02 core samples.

Sample	**Stratigraphy**	**Depth Corrected (m)**	**MINC (wt. %)**	**S4CO (mgCO/gRock)**	**S4CO2 ($mgCO_2$/gRock)**	**RCCO (wt. %)**	**RCCO2 (wt. %)**
TOC-01	Georgian Bay Fm	316.53	11.39	0.15	3.21	0.01	0.09
TOC-03	Georgian Bay Fm	329.81	0.60	0.33	4.61	0.01	0.13
TOC-05	Georgian Bay Fm	346.78	0.54	0.74	5.70	0.03	0.16
TOC-07	Georgian Bay Fm	354.20	0.80	0.32	3.56	0.01	0.10
TOC-09	Georgian Bay Fm	371.60	1.50	0.36	4.80	0.02	0.13
TOC-11	Georgian Bay Fm	376.90	11.55	0.01	2.07	0.00	0.06
TOC-13	Georgian Bay Fm	385.59	0.43	1.03	8.05	0.04	0.22
TOC-15	Georgian Bay Fm	399.21	0.35	0.94	8.23	0.04	0.22
TOC-17	Georgian Bay Fm	408.20	0.28	1.27	8.73	0.05	0.24
TOC-19	Georgian Bay Fm	415.79	0.42	0.83	6.25	0.04	0.17
TOC-21	Georgian Bay Fm	424.89	0.34	1.21	9.00	0.05	0.25
TOC-23	Upper Blue Mountain Fm	431.97	0.61	0.95	7.52	0.04	0.21
TOC-25	Upper Blue Mountain Fm	440.99	1.48	0.58	4.30	0.02	0.12
TOC-27	Upper Blue Mountain Fm	448.66	0.75	1.08	8.68	0.05	0.24
TOC-28	Upper Blue Mountain Fm	454.65	0.34	1.54	9.07	0.07	0.25
TOC-29	Upper Blue Mountain Fm	458.41	0.40	1.58	11.87	0.07	0.32
TOC-30	Upper Blue Mountain Fm	460.63	0.30	1.14	9.06	0.05	0.25
TOC-31	Rouge River Mb	464.89	0.95	4.09	40.08	0.18	1.09
TOC-32	Rouge River Mb	467.00	0.75	3.53	30.22	0.15	0.82
TOC-33	Rouge River Mb	468.98	0.87	4.11	29.88	0.18	0.81
TOC-34	Rouge River Mb	471.04	1.21	3.95	30.53	0.17	0.83
TOC-35	Rouge River Mb	471.88	1.61	3.73	28.02	0.16	0.76
TOC-36	Rouge River Mb	473.88	1.02	3.65	26.73	0.16	0.73
TOC-37	Rouge River Mb	474.26	1.18	5.20	36.98	0.22	1.01
CBO-12-1121	Rouge River Mb	475.51	2.16	4.45	30.70	0.19	0.84
TOC-38	Collingwood Mb	477.62	7.89	7.62	68.65	0.33	1.87
TOC-39	Collingwood Mb	480.41	6.08	7.82	58.72	0.34	1.60
TOC-40	Collingwood Mb	483.41	8.96	4.12	34.71	0.18	0.95
TOC-41	Lower Cobourg Fm	486.33	10.67	2.36	17.38	0.10	0.47
TOC-42	Lower Cobourg Fm	488.61	6.06	1.12	8.75	0.05	0.24

Abbreviations: Fm, Formation; Mb, Member; m, metres; wt. %, weight percent; mg, milligrams; g, grams; MINC, mineral carbon; S4CO, organic carbon oxidized into carbon monoxide; S4CO2, organic carbon oxidized into carbon dioxide; RCCO, residual carbon organic calculated from carbon monoxide; RCCO2, residual carbon organic calculated from carbon dioxide; CO, carbon monoxide; CO_2*, carbon dioxide.*

Table 9. Desorption results for the OGS-SG11-02 canister samples.

Sample	Stratigraphy	Depth Interval Corrected (m)	Lost Gas Polynomial Fit[1] (scf/ton)	Measured Desorbed Gas[1] (scf/ton)	Projected Residual Gas[1] (scf/ton)	Measured Residual Gas[1] (scf/ton)	Total Gas[2] (scf/ton)
CAN-01	Georgian Bay Fm	316.53-316.83	2.6 (34%)	2.6 (35%)	0.0 (0%)	2.3 (31%)	7.5
CAN-02	Georgian Bay Fm	329.81-330.09	0.9 (31%)	2.0 (69%)	0.0 (0%)	0.0 (0%)	2.9
CAN-03	Georgian Bay Fm	347.85-348.15	3.1 (65%)	1.7 (35%)	0.0 (0%)	-- --	4.8
CAN-04	Georgian Bay Fm	363.04-363.34	2.7 (58%)	1.9 (42%)	0.0 (0%)	-- --	4.6
CAN-05	Georgian Bay Fm	372.33-372.64	5.4 (62%)	2.2 (25%)	0.0 (0%)	1.1 (13%)	8.6
CAN-06	Georgian Bay Fm	381.48-381.78	1.4 (44%)	1.8 (56%)	0.0 (0%)	-- --	3.2
CAN-07	Georgian Bay Fm	390.01-390.32	1.8 (46%)	2.1 (54%)	0.0 (0%)	0.0 (0%)	3.9
CAN-08	Georgian Bay Fm	399.23-399.51	2.3 (44%)	2.9 (56%)	1.7 (32%)	0.0 (0%)	5.2
CAN-09	Georgian Bay Fm	412.08-412.39	5.3 (79%)	1.4 (21%)	0.0 (0%)	-- --	6.7
CAN-10	Georgian Bay Fm	418.20-418.51	0.4 (19%)	1.6 (76%)	0.6 (27%)	0.1	2.1
CAN-11	Upper Blue Mountain Fm	427.30-427.60	1.2 (50%)	1.2 (48%)	0.0 (0%)	0.0 (0%)	2.5
CAN-12	Upper Blue Mountain Fm	436.47-436.77	1.6 (41%)	2.2 (59%)	0.0 (0%)	-- --	3.8
CAN-13	Upper Blue Mountain Fm	442.56-442.87	1.8 (56%)	1.5 (44%)	0.0 (0%)	-- --	3.3
CAN-14	Upper Blue Mountain Fm	448.66-448.96	1.8 (57%)	1.3 (41%)	0.0 (0%)	0.1 (2%)	3.1
CAN-15	Upper Blue Mountain Fm	454.68-454.98	0.8 (27%)	1.6 (51%)	0.0 (0%)	0.7 (21%)	3.0
CAN-16	Upper Blue Mountain Fm	460.65-460.95	1.0 (21%)	3.2 (64%)	0.8 (15%)	-- --	4.9
CAN-17	Rouge River Mb	467.00-467.30	1.4 (19%)	5.4 (69%)	1.0 (13%)	-- --	7.8
CAN-18	Rouge River Mb	471.04-471.34	1.9 (21%)	5.8 (64%)	1.1 (12%)	1.4 (15%)	9.1
CAN-19	Rouge River Mb	474.28-474.58	3.6 (20%)	7.9 (44%)	0.4 (2%)	6.4 (36%)	18.0
CAN-20	Collingwood Mb	477.62-477.93	2.5 (16%)	8.9 (57%)	5.0 (32%)	4.2 (27%)	15.6
CAN-21	Collingwood Mb	480.41-480.73	7.3 (40%)	7.7 (42%)	2.6 (14%)	3.4 (19%)	18.4
CAN-22	Collingwood Mb	483.41-483.71	1.2 (13%)	4.3 (45%)	1.4 (14%)	4.0 (42%)	9.5
CAN-23	Lower Cobourg Fm	486.33-486.63	2.5 (28%)	5.7 (63%)	3.8 (43%)	0.8 (9%)	9.0
CAN-24	Lower Cobourg Fm	488.61-488.92	2.5 (39%)	2.2 (33%)	1.8 (28%)	-- --	6.5

Abbreviations: Fm, Formation; Mb, Member; m, metres; scf, standard cubic feet.

[1] *Numbers in parentheses refer to the corresponding percentage of the total gas.*

[2] *Total Gas is the sum of lost gas, desorbed gas and measured residual gas, if available. If not, total gas represents the sum of lost gas, desorbed gas and projected residual gas.*

Table 10. Adsorption results for the OGS-SG11-02 canister samples.

		CAN-08	CAN-15	CAN-19	CAN-21	CAN-24
Stratigraphy		**Georgian Bay Formation**	**Upper Blue Mountain Formation**	**Rouge River Member**	**Collingwood Member**	**Lower Cobourg Formation**
Depth Interval Corrected	**(m)**	399.23-399.51	454.68-454.98	474.28-474.58	480.41-480.73	488.61-488.92
Temperature	**(°C)**	12.4	12.8	13.4	13.6	13.8
Corrected Langmuir Storage Capacity	**(scf/ton)**	6.50	7.81	21.08	9.67	6.34
Corrected Langmuir Pressure	**(psia)**	115.61	154.48	167.25	319.72	197.08
Reservoir Pressure (Midpoint)	**(psia)**	569.00	648.00	675.00	684.00	696.00
Adsorbed Phase Methane Density	**(g/cm^3)**	0.372	0.372	0.372	0.372	0.372
Storage Capacity	**(scf/ton)**	5.40	6.31	16.90	6.59	4.94

Abbreviations: m, metres; scf, standard cubic feet; psia, pounds per square inch absolute; g/cm^3*, grams per cubic centimetre.*

Table 11. Gas composition results for the OGS-SG11-02 canister samples.

Sample	Collection Point	Gas Content	Incremental Volume	Gas Analysis (Adjusted for Air)				Calorific Value	
				C_1	C_2	$C_{3\text{-}10}$	CO_2	Dry	Saturated
	(hours)	(scf/ton)	(scf/ton)	(mole %)	(mole %)	(mole %)	(mole %)	(Btu/ft^3)	(Btu/ft^3)
CAN-01*				**73.92**	**8.76**	**14.70**	**2.62**	**1326.0**	**1302.9**
D	965.17	4.8	4.8	72.83	9.11	15.22	2.84	1335.1	1311.8
E	1469.58	5.2	0.4	86.95	4.53	8.52	0.00	1216.8	1195.5
CAN-05*				**89.71**	**7.98**	**1.89**	**0.42**	**1100.8**	**1081.6**
B	74.85	6.7	6.7	90.47	7.94	1.59	0.00	1099.6	1080.4
C	98.85	6.9	0.2	87.59	7.82	3.42	1.17	1118.4	1098.8
D	796.38	7.2	0.3	79.07	9.14	6.29	5.50	1135.7	1115.9
E	1300.75	7.5	0.3	84.79	7.79	3.15	4.27	1082.0	1063.0
CAN-08				**90.90**	**4.37**	**2.65**	**2.09**	**1073.2**	**1054.4**
A	15.30	2.9	2.9	91.28	4.03	1.89	2.80	1048.6	1030.2
B	26.80	3.2	0.3	93.81	4.09	2.10	0.00	1081.7	1062.8
C	42.47	3.4	0.2	89.50	6.30	4.20	0.00	1135.3	1115.4
D	739.90	4.5	1.1	90.10	4.53	3.87	1.50	1105.3	1086.0
E	1244.22	5.0	0.5	89.25	5.34	4.10	1.31	1115.6	1096.1
CAN-10				**81.77**	**6.27**	**2.61**	**9.36**	**1010.6**	**992.9**
A	14.77	1.0	1.0	73.87	6.69	2.95	16.49	948.2	931.6
B	35.25	1.4	0.4	91.43	6.24	2.33	0.00	1100.8	1081.5
C	62.92	1.7	0.3	81.96	8.57	3.57	5.90	1075.2	1056.4
D	506.48	2.0	0.3	95.02	2.60	0.88	1.50	1033.7	1015.6
E	912.58	2.0	0.0	89.79	6.74	2.32	1.15	1092.1	1073.0
CAN-12*				**85.70**	**5.52**	**2.61**	**6.16**	**1038.6**	**1020.4**
A	8.87	2.0	2.0	83.73	4.09	1.40	10.78	960.2	943.4
C	70.48	2.9	0.9	90.56	6.34	2.40	0.70	1096.0	1076.8
D	476.93	3.1	0.2	89.97	7.46	2.57	0.00	1113.7	1094.2
E	882.98	3.6	0.5	83.15	9.00	7.85	0.00	1219.0	1197.7
CAN-13				**90.91**	**6.97**	**2.12**	**0.00**	**1100.3**	**1081.2**
B	34.85			90.91	6.97	2.12	0.00	1100.3	1081.2
CAN-15				**89.31**	**5.89**	**2.34**	**2.46**	**1073.7**	**1055.0**
A	15.65	1.5	1.5	90.63	5.71	1.97	1.69	1073.6	1054.8
B	32.20	1.8	0.3	89.62	7.29	3.09	0.00	1121.7	1102.1
C	38.32	2.2	0.4	85.56	4.57	2.06	7.81	1004.5	986.9
D	361.50	2.3	0.1	83.48	9.70	6.82	0.00	1207.4	1189.2
E	767.58	2.3	0.0	82.81	11.07	5.77	0.35	1195.1	1174.2
CAN-18				**94.57**	**3.94**	**1.49**	**0.00**	**1068.8**	**1048.2**
B	28.82			94.57	3.94	1.49	0.00	1068.8	1048.2
CAN-19				**90.02**	**6.49**	**3.16**	**0.33**	**1113.1**	**1093.6**
A	18.17	5.1	5.1	93.52	4.32	1.72	0.44	1072.3	1053.6
B	35.18	6.0	0.9	90.51	3.65	5.84	0.00	1126.8	1107.2
C	43.08	6.3	0.3	93.35	4.43	1.82	0.40	1075.4	1056.6
D	380.25	9.0	2.7	85.93	9.49	4.32	0.26	1157.3	1137.0
E	883.48	10.7	1.7	85.14	10.13	4.45	0.28	1164.7	1144.3
CAN-21				**89.02**	**7.63**	**3.23**	**0.12**	**1125.4**	**1105.7**
A	14.97	9.4	9.4	90.14	7.06	2.76	0.04	1113.9	1094.4
B	22.97	9.8	0.4	92.09	4.68	3.24	0.00	1095.6	1076.5
C	30.98	10.4	0.6	72.82	15.25	10.68	1.25	1302.0	1279.2
D	376.25	12.9	2.5	89.84	7.14	2.86	0.16	1115.8	1096.3
E	879.28	14.1	1.2	85.59	10.28	3.95	0.18	1157.3	1137.1
CAN-23				**89.01**	**7.74**	**3.25**	**0.00**	**1123.1**	**1103.5**
B	21.10			89.01	7.74	3.25	0.00	1123.1	1103.5
CAN-24				**83.61**	**6.63**	**2.56**	**7.19**	**1036.4**	**1018.3**
A	12.45	3.5	3.5	82.46	5.89	2.60	9.05	1012.6	994.9
B	19.07	3.7	0.2	81.78	18.22	0.00	0.00	1154.4	1134.3
C	24.90	4.0	0.3	87.15	6.76	3.07	3.02	1088.0	1068.9
D	356.23	4.3	0.3	90.05	6.48	2.55	0.92	1097.6	1078.4
E	859.27	4.6	0.3	88.31	7.60	3.32	0.77	1122.9	1103.2

Abbreviations: scf, standard cubic feet; Btu, British thermal units; ft^3, cubic feet; C_1, methane; C_2, ethane; $C_{3\text{-}10}$, propane and heavier hydrocarbons; CO_2, carbon dioxide.

**Samples CAN-01A, CAN-01B, CAN-01C, CAN-05A, CAN-12B were air contaminated.*

Table 12. Isotopic composition of methane gas in the OGS-SG11-02 canister samples.

Sample	Stratigraphy	Depth Interval Corrected (m)	$\delta^{13}C_{C1}$ (‰)	δD_{C1} (‰)
CAN-5B	Georgian Bay Fm	372.33 - 372.64	-32.4	-188
CAN-13B	Upper Blue Mountain Fm	442.56 - 442.87	-25.7	-204
CAN-18B	Rouge River Mb	471.04 - 471.34	-33.1	-210
CAN-19B*	Rouge River Mb	474.28 - 474.58	-15.5*	-200.3*
CAN-21B	Collingwood Mb	480.41 - 480.73	-38.9	-213.5
CAN-23B	Lower Cobourg Fm	486.33 - 486.63	-33.7	-208
CAN-24B*	Lower Cobourg Fm	488.61 - 488.92	-18.7*	-205*

Abbreviations: Fm, Formation; Mb, Member; m, metres; C1, methane.
**Samples CAN-19B and CAN-24B are probably air contaminated.*

Table 13. Gas Research Institute (GRI) parameters for the OGS-SG11-02 canister samples.

	Sample		CAN-05	CAN-12	CAN-18	CAN-19	CAN-21
	Stratigraphy		Georgian Bay Formation	Upper Blue Mountain Formation	Rouge River Member	Rouge River Member	Collingwood Member
	Depth Interval Corrected	**(m)**	372.33 - 372.64	436.47 - 436.77	471.04 - 471.34	474.28 - 474.58	480.41 - 480.73
As Received	**Bulk Density**	**(g/cm^3)**	2.611	2.614	2.601	2.545	2.653
	Matrix Permeability[1]	**(mD)**	3.25×10^{-6}	3.04×10^{-6}	1.59×10^{-6}	2.85×10^{-9}	1.30×10^{-7}
	Gas-filled Porosity	**(%)**	3.65	3.55	2.27	0.37	1.34
Dry & Dean Stark Extracted Conditions[2]	**Gas Saturation**	**(%)**	47.6	49.7	39.5	23.3	77.2
	Grain Density	**(%)**	2.783	2.777	2.723	2.574	2.696
	Matrix Permeability[5]	**(mD)**	6.90×10^{-4}	1.12×10^{-3}	1.27×10^{-3}	1.01×10^{-6}	4.74×10^{-7}
	Porosity	**(%)**	7.66	7.15	5.75	1.58	1.74
	Oil Saturation[3]	**(%)**	0.6	7.4	11.5	31.5	1.4
	Water Saturation[4]	**(%)**	51.7	43.0	49.0	45.2	21.4

Abbreviations: m, metres; g/cm^3, grams per cubic centimetre; mD, millidarcy.
[1] *Matrix Permeability is an effective gas permeability determined from pressure decay results on the fresh, crushed, 20/35 mesh size sample.*
[2] *Dean Stark extracted sample (20/35 mesh size) dried at 110 °C. Porosity and saturations are relative to total interconnected pore space.*
[3] *Oil volume computed assuming an oil density of 0.8 g/cc.*
[4] *Water volume corrected assuming a brine concentration of 30 000 ppm NaCl with an ambient density of 1.018 g/cc.*
[5] *Matrix Permeability is determined from pressure decay results on the extracted, crushed, 20/35 mesh size sample.*

Table 14. Triaxial static Young's modulus, Poisson's ratio and compressive strength results for OGS-SG11-02 canister samples.

Sample		CAN-03	CAN-12	CAN-18	CAN-20	CAN-24
Stratigraphy		Georgian Bay Formation	Upper Blue Mountain Formation	Rouge River Member	Collingwood Member	Lower Cobourg Formation
Depth Interval Corrected	**(m)**	347.85 - 348.15	418.20 - 418.51	471.04 - 471.34	477.62 - 477.93	488.61 - 488.92
Confining pressure	**(psi)**	250	310	330	340	340
Bulk Density	**(g/cm^3)**	2.58	2.55	2.60	2.37	2.44
Compressive Strenght	**(psi)**	16138	9747	15105	16968	10444
Young's Modulus	**(psi)**	1.95×10^{6}	1.19×10^{6}	3.04×10^{6}	1.59×10^{6}	1.13×10^{6}
Poisson's ratio		0.23	0.25	0.24	0.24	0.26
Brittleness Index*	**%**	40.79	31.36	46.57	36.21	28.93

Abbreviations: m, metres; psi, pounds per square inch; g/cm^3, grams per cubic centimetre.
**Brittleness Index is calculated with the following equation: $BI = 50\times[(Y-1)/7+(0.4-P)/0.25]$ where BI is the Brittleness Index (in %), Y is Young's modulus ($\times10^6$ psi) and P is Poisson's ratio.*

Table 15. Rock mechanical properties determined for the OGS-SG11-02 canister samples.

Sample		**CAN-03**		**CAN-12**		**CAN-18**		**CAN-20**		**CAN-24**	
Stratigraphy		Georgian Bay Formation		Upper Blue Mountain Formation		Rouge River Member		Collingwood Member		Lower Cobourg Formation	
Depth Interval Corrected	**(m)**	347.85-348.15		436.47-436.77		471.04-471.34		477.62-477.93		488.61-488.92	
Confining pressure	**(psi)**	250	250	310	310	330	330	340	340	340	340
Axial pressure	**(psi)**	250	8000	310	5000	330	6000	340	8000	340	5000
Bulk Density	**(g/cm^3)**	2.58	2.58	2.55	2.55	2.60	2.60	2.37	2.37	2.44	2.44
Compressional Acoustic Velocity	**(ft/sec)**	12 075	13 499	7184	7550	14 066	14 745	11 207	12 004	10 708	11 588
Shear Acoustic Velocity	**(ft/sec)**	7288	7859	4183	4251	8442	8732	6482	6674	6398	6608
Bulk Modulus	**(×10^6 psi)**	2.61	3.47	0.97	1.13	3.61	4.06	2.22	2.71	1.97	2.50
Young's Modulus	**(×10^6 psi)**	4.49	5.34	1.50	1.58	6.09	6.58	3.35	3.63	3.29	3.61
Shear Modulus	**(×10^6 psi)**	1.85	2.15	0.60	0.62	2.50	2.68	1.34	1.42	1.35	1.43
Poisson's ratio	**-**	0.21	0.24	0.24	0.27	0.22	0.23	0.25	0.28	0.22	0.26

Abbreviations: m, metres; psi, pounds per square inch; g/cm^3, grams per cubic centimetre; ft/sec, feet per second.

Metric Conversion Table

Conversion from SI to Imperial			**Conversion from Imperial to SI**		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
LENGTH					
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
AREA					
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
VOLUME					
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
CAPACITY					
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
MASS					
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton(short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 9**	t
CONCENTRATION					
1 g/t	0.029 166 6	ounce (troy) / ton (short)	1 ounce (troy) / ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights / ton (short)	1 pennyweight / ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors in ***bold*** *type are exact. The conversion factors have been taken from or have been derived from factors given in the* Metric Practice Guide for the Canadian Mining and Metallurgical Industries*, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.*

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