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Ontario Geological Survey
Open File Report 6278

Shale Resources of Southern Ontario: An Update

2012

Ontario

ONTARIO GEOLOGICAL SURVEY

Open File Report 6278

Shale Resources of Southern Ontario: An Update

by

D.J. Rowell

2012

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Miscellaneous Release—Data 301
Geochemical, Mineralogical and Brick Testing Results for Shale Resources of Southern Ontario; by D.J. Rowell. This data release, released in conjunction with Open File Report (OFR) 6278, *Shale Resources of Southern Ontario: An Update*, contains brick testing results for the historical brick and tile manufacturing shale formations, collected and collated by the Ontario Geological Survey (OGS) over many years and at various locations throughout southern Ontario. Also presented in this release are the results of geochemical and mineralogical testing on these same shale formations. The test results are provided in tables in Microsoft® Excel® (*.xls*) format. The release also includes an ESRI® ArcGIS® map that displays the geographic distribution and location of these samples. The map is also provided in portable document (*.pdf*) format. Many of these test results have been published in a variety of OGS reports; however, with the release of OFR 6278, it is important to provide this information digitally and in a single, summarized release. Available on 1 CD.

These data are available separately.

Abstract

The purpose of this report is to identify and delineate potential shale resources that can be used to manufacture brick and tile in southern Ontario. In addition to identifying these resource areas this report will outline physical (e.g., thick overburden cover) and high-level land-use planning constraints that can greatly reduce the potential extraction areas. The aim is to assist decision-makers in protecting the resource and ensuring that an adequate supply of shale remains for future use.

Despite the number of shale formations in Ontario, many of these are, and never were, potential sources of raw material to be used in the manufacture of brick and tile. This is because many of the formations are buried by a thick sequence of Quaternary-age sediments; are overlain by a thick sequence of Paleozoic-age bedrock; have a high organic, sulphur or bituminous content; or failed to pass standard brick tests.

Therefore, historically and in practice, only 3 shale formations have been used extensively to produce brick and tile: the Arkona, Queenston and Georgian Bay formations. Of these 3 formations, it is suggested in this report that only the Queenston Formation remains as a viable source of raw material. Between urban expansion, current land-use planning policies and overburden thickness, the Arkona and Georgian Bay formations are virtually eliminated from future extractive opportunities.

Therefore, it is vitally important to protect areas of the Queenston Formation, overlain by thin drift cover (less than 8 m), as a source of raw material for the manufacture of brick and tile for the foreseeable and distant future. Guillet and Joyce (1987) referred to the Queenston Formation as a resource of provincial significance.

Shale Resources of Southern Ontario: An Update

D.J. Rowell[1]

Ontario Geological Survey
Open File Report 6278
2012

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[1] **Aggregate and Industrial Minerals Geologist, Earth Resources & Geoscience Mapping Section, Ontario Geological Survey**

Introduction

The Ontario Geological Survey of the Ministry of Northern Development and Mines is responsible for the Aggregate Resources Inventory Program, the purpose of which is to provide the basic geological information required to include potential mineral aggregate resource areas in land-use planning strategies and decision making processes. Aggregate Resources Inventory Papers (ARIPs) identify and evaluate aggregate resources (both sand and gravel, and bedrock-derived aggregate) so these important resource areas can be considered during land-use planning discussions. The aim is to assist decision-makers in protecting the public well-being by ensuring that adequate resources of mineral aggregate remain available for future use.

Older ARIPs often identified other important industrial mineral resources that are not "true" aggregate resources. (The term "true" aggregate resources refers to material used in the production of such traditional aggregate products as Granular A, Granular B, Select Sub-base Material (SSM), crushed stone products, hot-laid (asphalt) and concrete aggregate.) For example, ARIP 50 for the Regional Municipality of Hamilton–Wentworth identified the Guelph Formation as a significant Selected Bedrock Resource Area (Ontario Geological Survey 1984). In certain circumstances, the Guelph Formation can be used to produce a variety of "true" aggregate products, but the quality of the aggregate from the Guelph Formation can also fail to meet specification. Extensive testing of the Guelph Formation should be completed to ensure its use in the production of "true" aggregate products. The Guelph Formation is perhaps more important as a significant source of high-purity dolostone (Kelly 1996).

Aggregate Resources Inventory Paper 164, the nonrevised edition of ARIP 165, and ARIP 169 (Regional Municipality of Halton, Regional Municipality of Peel, and the United Counties of Prescott and Russell, respectively) identified significant resources of Queenston Formation shale, used in the manufacture of brick and tile (Golder Associates Limited and Rowell 1996a, 1996b; Rowell 1997). Because of the low load-bearing capacity of the Queenston Formation, this formation is not a source of "true" aggregate material. Later reports do not identify these other important industrial minerals: i.e., ARIP 165—Revised (Peel), ARIP 184 (Halton) and ARIP 181 (City of Hamilton) (Golder Associates and Rowell 2009; Rowell 2009a; Marich 2010).

PURPOSE

Therefore, based on the concern that other important industrial minerals (e.g., high-purity dolostone from the Guelph Formation and shale resources from a variety of formations across southern Ontario) would not be identified during the land-use planning process, it was decided to produce a report and map that would identify important shale resources used in the manufacture of brick and tile. The principles that form the basis of this report are similar to the ARIP reports, including the requirement that the shale resource must be of sufficient quality to be used by the industry. It is hoped that this document and the accompanying map (Figure 1, back pocket) will be used by land-use planners in the same context and manner that ARIPs are.

> The conservation of raw materials for the heavy clay industry is becoming increasingly important in the urban area of southern Ontario. Shales of the Dundas and Queenston formations outcrop mainly in the heavily populated Toronto–Hamilton area where competition for land use is high. The shales of this region are the principal raw material for 92 percent of Ontario's brick industry…Alternative sources of these raw materials are scarce…Deposits of these shales are restricted by nature and must be utilized where found…Municipal planning boards, concerned with optimum land use, should insure that zoning regulations do not prevent utilization of our mineral resources. (Guillet 1967)

> There is, however, at present acute concern among producers that local demands for land use, and environmental restrictions imposed on resource based industries in urban areas, will result in the eventual demise of this basic industry in central Ontario. (Vos 1975)
>
> Access to new shale resources is perhaps the single most serious problem for the industry in Ontario. Protection by certain municipalities of small portions of their shale resources for future extraction needs is essential if the brick industry is to survive. (Guillet 1982)

It is difficult to imagine that 45 years after the first statement was published, the same statement is still applicable.

The second reason for preparing this report is to summarize data that is distributed in a large number of reports. By completing this task it is hoped that this report will become a single quick reference that can be used extensively.

OVERBURDEN THICKNESS

One of the fundamental and underlying principles of the Aggregate Resources Inventory Program is the assumption that aggregate producers can strip up to 8 m of overburden and still produce an economically viable product. The 8 m limit has been a source of debate since the 1970s and, therefore, some discussion on this 8 m limit is warranted.

The question of "How much overburden can be economically removed from a deposit?" has plagued the extraction industry for a number of years. Overburden stripping for shale mining can, and has, varied in southern Ontario, from no overburden to removing "on average" 8 m of overburden. ("On average" refers to properties where the overburden is quite variable from 0 to 14 m, but the average is no greater than 8 m.)

The 8 m limit was established during the development of the document, *A Policy for Mineral Aggregate Resource Management in Ontario* (Ontario Mineral Aggregate Working Party 1977). This document and the recommendations that were contained in it, was the culmination of a great deal of work by the Ontario Mineral Aggregate Working Party members, including public hearings, written submissions, interviews, presentations and public comment. The members of the working party that synthesized the information and presented the recommendations were from a variety of backgrounds, including public and municipal representatives (i.e., municipal politicians, municipal staff, representatives from the Niagara Escarpment Commission and the Conservation Council of Ontario), public servants from a number of provincial ministries, and members from the Aggregate Producers Association of Ontario.

In a presentation before the Ontario Mineral Aggregate Working Party members and the Honourable Leo Bernier, the Clay Brick Association of Canada confirmed that stripping of 8 m of overburden was the maximum amount that could be removed in order to remain economically viable (Ontario Mineral Aggregate Working Party 1977). The 1978 study by Proctor and Redfern, for the Clay Brick Association of Canada, used the 8 m limit as the basis of their calculations of future shale reserves.

The 1988 study by Gartner Lee Limited presented the following facts:

- In 1988, all of the shale extraction operations in Ontario initially started on shale outcrops (i.e., no overburden). Guillet and Joyce (1987) state that surface weathering of shale often results in superior quality of the shale material, which is an added benefit of extracting surface, or close to surface, shale resources.

- In 1988, there were no existing shale extraction operations removing more than 8 m of overburden. If there was stripping of 8 m of overburden, it was usually completed on a small portion of the property only, and it was done in the recognition that this was a temporary measure to meet an immediate need, not a long-term practice.
- General material handling and cost considerations preclude the handling of large quantities of overburden material. Overburden stripping must be minimized. In a cost efficient operation, any overburden that is stripped should only be handled once.
- The most efficient and least expensive way to handle overburden is to place the material directly into berms, in the legal setback portion of the property. In an example provided by Gartner Lee Limited (1988), approximately 1.2 m of overburden from the mineable portion of the property would be required to construct these berms. Additional overburden from the mineable portion of the property could be used for progressive rehabilitation.
- In 1988, a survey of government and industry folks indicated that 3 m or less was the ideal amount of overburden to strip. Five metres was considered a "desperation move".

Rowell (2008) reported that the overburden thickness overlying the Queenston Formation in the Regional Municipality of Halton (a prime shale producing area) can be extremely variable over short distances. The Queenston Formation shale is very susceptible to weathering, erosion and downcutting (Photo 1), resulting in an extremely variable bedrock surface. In addition, many water well drillers, and indeed professional geoscientists, have a difficult time identifying the exact contact between the Queenston Formation bedrock surface and the overlying hard, reddish, clay-rich Halton Till that is present in this area. Therefore, overburden thickness can be quite variable within a single licensed property, leading to greater overburden stripping than the owner/operator may have anticipated.

Photo 1. The erosion and weathering of the Queenston Formation near Cheltenham.

Since 1988, urban sprawl in the traditional brick-manufacturing areas of southern Ontario has sterilized resources and sent land purchase prices soaring. Municipal and provincial land use planning decisions have further reduced the amount of shale resource areas that can be extracted (e.g., *Places to Grow Act 2005, Ontario's Greenbelt Act 2005*). The rising cost of fuel, which is used in machinery required to strip overburden, has also increased the cost of preparing a quarry location for production.

The cost of overburden stripping must be balanced with all other costs involved with producing a brick. If a producer can realize a price benefit or savings in one area of his production cost, they may be able to endure higher than average costs in another aspect of production. The price of production and the price of the commodity greatly influence stripping and production costs. The price of a commodity is extremely important. For example, the amount of overburden removed and the cost of stripping may be much higher and still economically feasible over a high-purity, high-quality dolostone used in the manufacture of metallurgical flux, than the amount of overburden and the cost of stripping over a lower cost aggregate product (e.g., crushed stone used in the production of hot-laid asphalt stone).

In 2008, the maximum or preferred stripping limit of 8 m was reconfirmed verbally and in written correspondence to the author by brick industry representatives. Once again, the stripping of less than 8 m of overburden is certainly preferred but resource areas with less than 8 m of overburden are becoming rare because of urban expansion and restrictive land-use planning policies.

PREVIOUS WORK

The shale resources of southern Ontario have been the focus of a number of studies. Some of this work has focussed primarily on geology, depositional environments, facies and fossil records (Brogly 1984; Brogly and Martini 1990; Brogly, Martini and Middleton 1998). Armstrong (2001a, 2001b), and Armstrong and Sergerie (2002a, 2002b, 2002c) completed studies on the geology and geochemistry of the Queenston Formation. Zoldners and Wilson (1961), Brady and Dean (1966), Kwong, Martini and Narain (1985), Martini and Kwong (1986), Armstrong and Frederic (2001), Rowell (2009b), and Rowell and Brunton (2011) have reported on the brick manufacturing nature of various shale formations. Other studies, such as Guillet (1967, 1977, 1982), Vos (1975), Guillet and Joyce (1987), Rutka and Vos (1993), and Venta (1998) have studied the industry, production, land-use planning, location of the resource, recycling and other aspects of the industry. Some planning studies have been completed by Gartner Lee Limited (1988) and the Clay Brick Association of Canada (1991). Finally, McIlveen (1998) conducted an investigation of the concentration of predominantly metallic cations in, and over, various shale formations.

ACCOMPANYING MAP

The map that accompanies this report (*see* Figure 1) was produced in ESRI® ArcGIS®. The map identifies the important brick-manufacturing shale formations in southern Ontario. It also identifies the overburden thickness overlying these important formations. The overburden thickness is based on a series of Ontario Geological Survey published maps. These maps are either part of the Drift Thickness Series of maps (Cooper 1981; Cooper and Nicks 1981a, 1981b, 1981c; Fitzgerald, Mundry and Storrison 1979; Kelly, Cooper and Styles 1993; Morris and Cousineau 1994a, 1994b; Sado and Faught 1981a, 1981b; Vos 1969) or Aggregate Resources Inventory Papers (Golder Associates Limited and Rowell 2009; Jagger Hims Limited and Rowell 2009; MacNaughton Hermsen Britton Clarkson Planning Limited et al. 2009; Marich 2010; Ontario Geological Survey 1985; Rowell 2009a, 2012a, 2012b; Rowell and Gao 2010).

Locations where geochemical analyses and brick testing results are available are plotted on Figure 1. Sample numbers are available in the ArcGIS® version of Figure 1 (*see* Miscellaneous Release—Data 301 (MRD 301), available separately from this report) and not the printed version since labelling on the printed map would be confusing. The results of these tests are provided in tables in the appendix of this report. **The quality test data refer strictly to a specific sample. Because of the inherent variability of sample collection, care should be exercised in extrapolating such information to the rest of the deposit, particularly where some of the deposits may be quite large. It is therefore highly recommended that where extraction and development is contemplated, that extensive testing be conducted to verify shale quality and quantity. Site specific investigations provide greater detail on the nature of the local deposit.**

There are many Paleozoic rock formations in Ontario that consist of shale beds or shale partings, but are dominated by other lithologies (e.g., limestone or dolostone). Of the predominantly shale-rich formations in southern Ontario, only 3 were used in the production of brick and tile in 1985. Many of the other shale formations are, and never were, potential sources of raw material because many of the formations are 1) buried by a thick sequence of Quaternary-age sediments; 2) overlain and buried deeply by a thick sequence of Paleozoic bedrock; 3) have a high organic, sulphur or bituminous content; or 4) failed to pass standard brick tests. As Vos stated in 1975, "Of the shale formations in southern Ontario only a few are accessible (either exposed at surface or covered by a thin overburden cover) and have the qualities acceptable for use as a raw material."

In 1987, 90% of all of Ontario's brick and tile production came from the Queenston and Georgian Bay formations. Since that time, the Georgian Bay Formation is no longer used to produce brick and tile, meaning that the Queenston Formation is the last, main resource of raw material.

REPORT FORMAT

Since this is a geological and technical report, this study will focus its attention on the most important, historical brick and tile manufacturing shale formations, as well as the Cabot Head and Blue Mountain formations, each of which have been suggested as alternative sources of raw material. Information on each formation will include geographic distribution, lithology, depositional environment, geochemistry, mineralogy and suitability of brick manufacturing. The final part within each section presents a very high-level discussion on the chances of developing the resource. It must be clearly stated, that the current report is a geological one and not a planning document, so detailed planning principles and policies have not been applied nor will they be discussed. However, high-level, regional planning constraints will be noted in order to convey a realistic picture as to whether a shale resource area can be licensed and extracted.

In Table A1 (Geochemical Results—Major Oxides, *see* Appendix), there is a column referred to as the "Number of Analyses". Many of the geochemical results are from drill holes, specifically, from various depths along the drill-hole core. For the purpose of this report, however, only an average of all the drill-hole results are provided (for individual test results, consult the original publication). Therefore, N is equal to the number of geochemical results within that drill hole or along a quarry face. This averaging approach is actually quite useful for this study since a quarry owner and/or operator would extract the material as part of a bench or lift, which is a "blending" of these various depths anyways.

SOME BASIC TERMINOLOGY

Clay is an unconsolidated material of a particular size range: "a rock or mineral fragment or a detrital particle of any composition (often a crystalline fragment of a clay mineral), smaller than a very fine silt grain, having a diameter less than 1/256 mm (4 microns)" (Bates and Jackson 1987). When moistened, clay becomes plastic and can be molded or fashioned into any desirable shape, a shape that is preserved upon drying. Furthermore, if heated to redness or slightly above redness, the substance fuses and upon cooling assumes a rock-like consistency. The quality of the clay is determined by its physical and chemical properties. Clay is often used in the production of drainage tile. Clay resources will not be discussed in this report.

Shale is compacted or consolidated clay. Shales in Ontario were deposited long ago in marine environments and the clay particles consolidated over long periods of time. The deposits are generally extensive, thick and of relative uniformity. Because of their extent and consistency they have replaced clay as the preferred raw material for the manufacture of brick and tile.

Clay minerals are often formed as a result of weathering processes and alteration of primary silicate minerals such as feldspars, pyroxenes and amphiboles. Clay minerals are loosely defined as a complex group of fine-crystalline, metacollodial, or amorphous hydrous silicates, essentially of aluminum and sometimes magnesium and iron (Bates and Jackson 1987). The chlorite group of minerals belong to the phyllosilicates. Generally, the chlorite group of minerals may be viewed as consisting of 2 layers of talc separated by a brucite- or gibbsite-like octahedral layer with a general formula of:

$$(Mg, Fe)_3 (Si, Al)_4 O_{10} (OH)_2 \bullet (Mg, Fe)_3 (OH)_6$$

Both the clay mineral group (e.g., kaolinite, talc, pyrophyllite) and the mica group minerals (e.g., muscovite, phlogopite, biotite, etc.) also belong to the phyllosilicates (Table 1, below).

Table 1. Clay and mica mineral groups (*after* Klein and Hurlbut 1985).

Clay Mineral Group		**Mica Group Minerals**	
Kaolinite	$Al_2Si_2O_5(OH)_4$	Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$
Talc	$Mg_3Si_4O_{10}(OH)_2$	Phlogopite	$KMg_3(AlSi_3O_{10})(OH)_2$
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$

Illite is a general term for the mica-like clay minerals. Illite differs from the micas, however, in having less substitution of Al for Si, having K partly replaced by Ca and Mg, and containing more water (Klein and Hurlbut 1985). Clay minerals have the ability and capacity to absorb water and exchange cations in response to changes in the environment.

NATURE OF A SHALE QUARRY

It is the experience of licensed operators involved with the manufacture of brick and tile that a proposed quarry operation excites the same opposition among prospective neighbours as a "true" aggregate operation. The common objections of truck traffic, noise, dust, vibration and water issues are cited. The reality is that the operations are significantly different.

If a brick and tile manufacturing company can quarry and manufacture at the same site, the traffic is a mere fraction of a "true" aggregate operation. The volume of material that is removed from a shale operation is substantially less than most large aggregate operations and, as a result, the areal extent and depth of the extraction of the operation is substantially reduced. Shale extraction in Ontario has remained fairly consistent at approximately 2 million tonnes per year. By comparison, aggregate extraction averages about 160 million tonnes per year.

Noise and vibrations are less of an issue because shale operations generally do not blast. The softer shale lends itself to extraction via front-end loaders. Dust can be controlled using standard Ministry of the Environment (MOE) approved operating procedures.

Arkona Formation

GEOGRAPHIC DISTRIBUTION

The Arkona Formation is a member of the Devonian-age Hamilton Group of limestones and shales located in southwestern Ontario. The Hamilton Group extends across southwestern Ontario from approximately Ipperwash Beach on Lake Huron, southeastward to the Port Glasgow area on Lake Erie (*see* Figure 1). Natural exposures of the Arkona Formation occur along the banks of the Ausable River east of Arkona (Hungry Hollow area) and at Decker Creek north of Thedford. The unit is also exposed in quarries at Thedford, Hungry Hollow and Parkhill.

The Hamilton Group is disconformably underlain on the northwest side of the Algonquin Arch—a structural high trending northeasterly through the southwestern Ontario peninsula—by the fossiliferous, micritic limestones of the Dundee Formation. On the southeastern side of the Algonquin Arch the Hamilton Group is underlain by the black, bituminous shales of the Marcellus Formation – a shale formation that has no potential for the manufacture of brick and tile. The black, fissile, bituminous shales of the Upper Devonian-age Kettle Point Formation conformably overlie the Hamilton Group (Armstrong and Carter 2010). The Kettle Point Formation has no potential as a source of raw material for the brick and tile industry because of its high organic content and the presence of pyrite, leading to poor firing characteristics and scumming.

The Hamilton Group forms a small part of the Devonian stratigraphic succession, which in southwestern Ontario has a maximum thickness of about 305 m (Sanford 1968). The Hamilton Group itself has a maximum thickness of about 90 m and consists of the following formations listed in descending stratigraphic order (Armstrong and Carter 2010):

- the Ipperwash Formation is about 13 m thick and consists of grey-brown, fine- to coarse-grained, argillaceous and bioclastic limestone with shaly interbeds;
- the Widder Formation is approximately 21 m thick and consists of calcareous shale interbedded with argillaceous, crinoidal and nodular limestone;
- the Hungry Hollow Formation is about 2 m thick and consists of interbedded fossiliferous shale and bioclastic limestone;
- the Arkona Formation is predominantly shale with occasional thin limestone lenses;
- the Rockport Quarry Formation is about 5 to 6 m thick and consists of grey to brown, fine-grained, argillaceous limestone with occasional shale interlayers; and,
- the Bell Formation is generally a soft, blue-grey, calcareous shale with a thickness of about 14 to 15 m.

LITHOLOGY AND DEPOSITIONAL ENVIRONMENT

The Arkona Formation consists of up to 37 m of soft, blue-grey, easily weathered, calcareous to noncalcareous shale with occasional thin, laterally discontinuous, argillaceous limestone lenses, particularly in the lower and middle parts of the unit (Armstrong and Carter 2010). In general, the formation is fossil poor; however, it contains local, thin concentrations of well-preserved fossils, primarily brachiopods with minor bryozoans, crinoids and tentaculids (Martini and Kwong 1986). The Arkona Formation has a gradational contact with the underlying Rockport Quarry Formation.

Martini and Kwong (1986) describe the Arkona Formation from a borehole and exposure in the Hungry Hollow area just east of Arkona, as consisting of a lower calcareous shale facies with occasional isolated fossils or fossiliferous layers displaying intense pyritization; a middle shale facies with abundant, thin bioclastic interlayers composed mostly of brachiopods; and an upper unit characterized by light grey shale with occasional thin fossiliferous layers. More detail on the Arkona Formation is available in Sanford (1969), Guillet (1977), Uyeno, Telford and Sanford (1982), Martini and Kwong (1986) and Guillet and Joyce (1987).

The Arkona Formation forms a small and distal part of a thick and extensive terrigenous clastic wedge known as the Catskill Delta Complex, which was shed into the Appalachian Basin from highlands produced during the Middle Devonian-aged Acadian Orogeny (Faill 1985). The Catskill Delta deposition was largely confined to the central portion of the Appalachian Basin, in Pennsylvania, central New York, eastern Ohio and West Virginia; however, pulses of fine-grained sediment, particularly during the Late Devonian, managed to spill out into the outer margins of the basin and over the Algonquin Arch to mix with carbonate-rich sediments of the Michigan Basin. The shales of the Arkona Formation were deposited in warm, muddy, shallow subtropical seas. Organisms flourished at times, resulting in thin biostromal deposits (Martini and Kwong 1986).

GEOCHEMISTRY AND MINERALOGY

Table A1 (Geochemical Results—Major Oxides) shows the results of geochemical analyses performed on the Arkona Formation in the Thedford and Hungry Hollow areas. Figure A1 (*see* Appendix) compares the Arkona Formation's SiO_2, Al_2O_3, MgO and CaO content with that of other shale formations discussed in this report. As noted earlier, some of the results are averages of a number of geochemical analyses. In general, the major oxide data are fairly consistent, with the exception of the Brady and Dean (1966) Sample 15, which has a significantly higher calcium carbonate content, and therefore less SiO_2 and Al_2O_3.

Samples from a 2008 OGS drill hole were submitted for semi-quantitative XRD analysis (Rowell 2009b). Sample powders were pulverized with an agate mortar and pestle. Samples were run with Co radiation at 40 kV and 45 mA. In general, the Arkona Formation consists primarily of illite, quartz, chlorite and calcite. Guillet (1977) reports that the shale appears to contain a higher proportion of clay minerals (66%) than most Ontario shales. Brady and Dean (1966) report, from their mineralogical analysis, that the Arkona Formation may have a slightly lower quartz content, approximately 19%, compared with other southern Ontario shale formations, which contain roughly 25%. Previous mineralogical work also indicates the presence of minor amounts of interlayered clay minerals, such as vermiculite, and elevated levels of pyrite (Table A4, *in* Appendix).

BRICK TESTING RESULTS

In the past, the Arkona Formation has been used for the manufacture of brick and tile. Today, the formation is primarily used for the production of tile and rarely used for the manufacture of brick. Brick produced from the upper part of the Arkona Formation has a tendency to scum and effloresce (Table A5, *in* Appendix). This may be due to a greater accumulation of soluble salts (Martini and Kwong 1986) or the presence of pyrite. Scumming can be controlled with the addition of as little as 0.25% barium carbonate.

Rowell (2009b) reports that the Arkona Formation near Hungry Hollow had medium plasticity and was easy to extrude. The carbonate content ranged from 8 to 15%, which produced a red fired body except for drill-hole interval 27.43 to 30.21 m. This interval had a 27% carbonate content leading to a buff-coloured fired body. There was some evidence of pyrite in the top portion of the drill hole and lime-popping was observed from 10.21 to 18.56 m. The optimum firing range was 1050 to 1075°C to produce properties that met the requirements of CSA A82-06. Above 1075°C the fired sample showed visible bloating and glazing because of overfiring (*see* Table A5 and Rowell 2009b).

Rutka and Vos (1993) tested a sample in the Thedford area which had medium plasticity and was easily extruded. The carbonate content ranged from 6 to 16% leading to a red fired body except at the 27.13 to 30.15 m interval. This interval had a carbonate content of 30% and resulted in a buff fired body. Scumming was observed in the 0 to 5.94 m drill hole interval.

Brady and Dean (1966) concluded that the Arkona Formation has a suitably long firing range for the manufacture of dense clay products; however, the firing shrinkage is inclined to be high and this may cause problems unless firing conditions and temperatures are uniform. They believe this is due to the low percentage of free quartz. Martini and Kwong (1986) concluded that the firing range of the Arkona Formation is relatively short for the manufacturing of dense products. The results of the optimum firing range (1050 to 1075°C, Rowell 2009b) would tend to favour Martini and Kwong’s (1986) conclusion.

POTENTIAL RESOURCE DEVELOPMENT

Despite the historical production of brick and tile from the Arkona Formation, and despite the reasonably positive brick manufacturing test results reported in various publications (e.g., Rutka and Vos 1993; Rowell 2009b), it is unrealistic to assume that the Arkona Formation will be a major and significant source of raw material for future brick and tile production. This statement is made for the following reasons.

First, the area of Arkona Formation that is identified on Map 1 (*see* Figure 1) is actually the Hamilton Group. The mapping of the Hamilton Group has not been subdivided into the 6 formations that comprise the group, as noted above. This means that the actual areal extent of the Arkona Formation would be significantly less than the area noted on Map 1.

Second, as noted on Map 1, the overburden cover overlying the Arkona Formation is generally greater than 15 m. There are only a few, relatively small areas where the overburden is between 1 and 8 m thick. This factor alone means that the economic viability of extracting the Arkona Formation is, at best, questionable (*see* “Overburden Thickness”). In addition, the Arkona Formation is the 4th formation from the top in the Hamilton Group. This would mean that one would not only have to strip the unconsolidated overburden to extract the formation, but would also have to remove the 3 rock formations that cover the Arkona Formation (a potential thickness of 36 m of rock).

Finally, the areas where the overburden thickness is between 1 to 8 m, and therefore a potential economically viable extraction area, are generally located along deeply cut river valleys (e.g., the Ausable River). A host of planning constraints—possibly including environmental issues, source water protection and protection of fish habitat—would almost certainly ensure that these areas would not be available for licensing and extraction. Therefore, it is unrealistic to expect any new extraction of the Arkona Formation for the manufacture of brick and tile in southwestern Ontario.

Cabot Head Formation

GEOGRAPHIC DISTRIBUTION

The Lower Silurian Cabot Head Formation has been suggested by some as an alternate source of raw material for expanded lightweight aggregate material and/or the manufacture of brick and tile. The formation is regionally extensive in the subsurface of southwestern Ontario; however, the formation does not crop out extensively in Ontario. In fact, the only mappable outcrops of the Cabot Head Formation are along the face of the Niagara Escarpment (Hewitt 1971), generally in the Niagara Falls area and along the Bruce Peninsula (western shoreline of Georgian Bay). The formation continues onto Manitoulin Island. The fact that the Cabot Head Formation is essentially buried in southwestern Ontario, overlain by younger Paleozoic formations, is reflected on Map 1 (*see* Figure 1) by the absence of a mappable Cabot Head Formation unit.

LITHOLOGY AND DEPOSITIONAL ENVIRONMENT

The type location for the Lower Silurian Cabot Head Formation is the cliff exposure west of Rocky Bay, a few kilometres west of Cabot Head, at the north end of the Bruce Peninsula. The Cabot Head Formation consists of grey to green to maroon, thin- to medium-bedded, poorly fossiliferous, noncalcareous shale with minor subordinate sandstone and carbonate interbeds. A few thin, bryozoan-rich shale and argillaceous limestone beds are present. The grey shales of the Power Glen Formation of the Niagara Peninsula are considered to be part of the Cabot Head Formation (Armstrong and Carter 2010). The formation displays an overall shallowing-upward succession culminating in sabkha-like and gypsum-bearing units (Brintnell et al. 2009). It has therefore been suggested that the formation was deposited in a shallow water to restricted marine depositional environment.

The formation thickness is variable, from approximately 40 m thick under west-central Lake Erie and thinning to approximately 12 m over the Algonquin Arch in south-central Ontario. The formation thickens again in the Owen Sound area to about 36 m. Drill results from the Bruce Nuclear site indicate a Cabot Head Formation thickness of 23.8 m (Raven et al. 2009), whereas the formation was 31.14 m in the subsurface at the Cyprus Lake drill hole (Rowell and Brunton 2011). The Cabot Head Formation is disconformably overlain by the Dyer Bay Formation and overlies the Manitoulin and Whirlpool formations.

GEOCHEMISTRY AND MINERALOGY

Since there are relatively few exposures of the Cabot Head Formation, and since the potential to license and extract this formation is limited, it is not surprising to discover that there are few geochemical analyses available for this formation. Table A1 shows the major oxide results for the Cabot Head Formation, which appear to be reasonably consistent. SiO_2, Al_2O_3, MgO and CaO content and how it compares to that of the other shale formations is shown in Figure A1.Trace element data for a single Cabot Head Formation sample is presented in Tables A2 and A3 in the Appendix. The trace element data would appear to be fairly consistent with the data provided for the Queenston and Georgian Bay formation samples. While some elements appear to be slightly elevated (e.g., lithium and barium) and others appear to be slightly lower (e.g., cadmium), one should be very cautious because of the extremely limited data for all 3 formations.

The same caution should be used when examining the mineralogical data presented in Table A4. The limited data can best be used to suggest that the mineralogy of the Cabot Head Formation is similar to other shales in southern Ontario, specifically with respect to the presence and abundance of illite, chlorite, quartz and other trace minerals.

BRICK TESTING RESULTS

Rowell and Brunton (2011) submitted a sample of Cabot Head Formation for brick testing (09OGS-DDH-15, Table A5). The sample was obtained from a drill core in the Cyprus Lake area of the Bruce Peninsula. The sample had medium plasticity and was easily extruded. The carbonate levels were in the 18% range, leading to a salmon-fired body. The optimum firing temperature was 1110ºC to produce properties that met the requirements of CSA A82-06, *Fired Masonry Brick Made from Clay or Shale*. The salt content was moderate, leading to some scumming on the fired bars. Table A5 presents additional brick testing results for the Cabot Head Formation.

POTENTIAL RESOURCE DEVELOPMENT

Based on the brick testing results and limited geochemical analyses, it is perhaps most unfortunate that the Cabot Head Formation is not a realistic source of raw material to the brick and tile industry. The problem with trying to develop this resource is the following:

First, the Cabot Head Formation generally does not crop out extensively in southern Ontario as noted above. The formation is exposed along the rugged cliff face along the western shoreline of Georgian Bay and in the Niagara Falls area. Generally, the formation is located in the subsurface of southern Ontario below a thick sequence of unconsolidated Quaternary-age sediments and a number of Paleozoic (rock) formations.

Second, the Cabot Head Formation is a rock unit that is generally exposed along the face of the Niagara Escarpment. Therefore, where the formation may crop out is within the Niagara Escarpment Development Plan (NEDP) area. The NEDP would impose a substantial planning constraint upon the licensing and extraction of this formation. Many areas where the Cabot Head Formation may crop out along the Bruce Peninsula are also within Provincial and National park boundaries.

Queenston Formation

GEOGRAPHIC DISTRIBUTION

The Upper Ordovician-age Queenston Formation trends roughly northwestward throughout south-central Ontario and forms the base of the Niagara Escarpment (Hewitt 1971). It is conformably underlain by the greenish to bluish-grey shales and interbedded limestones of the Georgian Bay Formation. The Queenston Formation is unconformably overlain by the sandstones of the Whirlpool Formation or the dolostones of the Manitoulin Formation. The Whirlpool and Manitoulin formations, as well as a number of other Lower Silurian-age formations (e.g., the Cabot Head Formation, Reynales Formation), comprise the Clinton and Cataract groups, which form the face of the Niagara Escarpment.

The Queenston Formation is exposed or subcrops under surficial sediments along the base and to the east of the Niagara Escarpment (*see* Figure 1, Map 1). The width of the outcrop belt is greatest from just north of Georgetown to the Hamilton–Burlington–Oakville area. The formation narrows in a northerly direction and is exposed in deeply incised river valleys in the Thornbury–Meaford area (e.g., the Beaver Valley). The formation pinches out completely along the south end of the Bruce Peninsula. The formation reappears on Manitoulin Island.

A small area of Queenston Formation crops out southeast of the City of Ottawa, in the United Counties of Prescott and Russell (*see* Figure 1, Map 2). This deposit has been extracted in the past for the production of brick and tile; however, the manufacturing facility has been shut down and the quarry is predominantly water filled.

LITHOLOGY AND DEPOSITIONAL ENVIRONMENT

The Queenston Formation consists of brick red to maroon, noncalcareous to calcareous shale with subordinate amounts of green shale, siltstone and limestone. Gypsum can occur as locally abundant nodules and thin subhorizontal fracture in-fillings. Carbonate content, both of the shale and in terms of the abundance and thickness of the limestone beds, tends to increase to the northwest (Armstrong and Carter 2010). The Queenston Formation ranges in thickness from about 50 m at the north end of Bruce County to over 300 m beneath Lake Erie (Armstrong and Carter 2010). Recent drilling at the Bruce Nuclear site intersected 70.4 m of Queenston Formation at that location (Raven et al. 2009), 434.8 m below ground surface.

The Queenston Formation maintains a fairly uniform lithological and sedimentological character, both vertically and laterally (Rutka and Vos 1993). Recent work completed by Armstrong (2001a) and Armstrong and Sergerie (2002a) has suggested that the Queenston Formation can actually be subdivided into 3 parts: an upper part consisting mainly of massive red shale; a middle part consisting of varying proportions of red and green shale, light green and light red siltstone, sandstone, limestone and intraclastic conglomerate; and a lower part consisting of the same components as the middle unit but with thinner bedding and locally laminated (Armstrong 2001a). Contacts between the 3 parts are gradational and are rarely exposed in a single outcrop. Brogly, Martini and Middleton (1998) suggest that this subdivision represents fluctuations in relative sea level. Where no bedrock or overburden cover exists, the rapidly weathering shales can lead to striking topography and badland development on a small scale (*see* Photo 1).

Because of its red colour, apparent absence of fossils and stratigraphic position at the top of a large siliciclastic wedge (which includes the Blue Mountain, Georgian Bay and Queenston formations) that formed in front of the Taconic Highlands, the Queenston Formation has long been interpreted as a subaerial deposit associated with deltaic deposition. More recent sedimentological work (Brogly 1984; Martini and Kwong 1986; Brogly and Martini 1990; Hamblin 2003) indicates that the Queenston Formation, at least in Ontario, was likely deposited under warm, seasonally arid climatic conditions in a prograding, storm-influenced, muddy shelf to shoreline environment. Periodic emergence due to differential sediment supply from the Taconic Orogeny and possible glacio-eustatic changes in sea level resulted in the local development of intertidal and supratidal mudflat areas where evaporitic deposits were formed. The top of the Queenston Formation is sharp and mud cracked, and indicates a considerable period of subaerial exposure prior to deposition of the fluvial sandstones of the Whirlpool Formation (Rutka and Vos 1993).

GEOCHEMISTRY AND MINERALOGY

The Queenston Formation has been analysed and reported on extensively throughout southern Ontario by previous researchers (Brady and Dean 1966; Guillet 1967, 1977, 1983; Guillet and Joyce 1987; Kwong, Martini and Narain 1985; Martini and Kwong 1986; Rutka and Vos 1993; Armstrong 2001a, 2001b; Armstrong and Frederic 2001; Armstrong and Sergerie 2002a, 2002b, 2002c; Rowell 2009b; Rowell and Brunton 2011). Table A1 presents the major oxide results of many of these chemical analyses, while Figure A1 shows the Queenston's SiO_2, Al_2O_3, MgO and CaO content relative to the other shale units.

The grey-green interlayers in the Queenston shale tend to have a higher lime (CaO) content and are harder than the red shale layers. Lime content, commonly varying proportionally to the percentage of grey-green shale interlayers in the section, generally increases toward the middle of the formation and, on a regional scale, towards the northwest (Sanford 1961; Guillet 1967, 1977; Kwong, Martini and Narain 1985). Generally very little variation, either vertically or laterally, occurs in the chemical and mineral composition of the red shales.

The mineral composition of the Queenston Formation has been reviewed by Guillet (1967, 1977), Kwong, Martini and Narain (1985) and Martini and Kwong (1986). The formation consists of about 60% clay minerals (primarily illite and chlorite) and 40% nonclay minerals (predominantly quartz and calcite). X-ray diffraction analyses indicate that the expanding clay mineral vermiculite is often present in small quantities. Quartz constitutes approximately 25% of the formation, with calcite averaging about 10%. Additional minor minerals include dolomite and plagioclase feldspar. Rowell (2009b) indicates similar mineralogical results, with the formation consisting primarily of illite, quartz, chlorite and calcite. Rowell (2009b) had a sample (08DJR-0010) analysed on the scanning electron microscope (SEM), where subordinate phases of apatite, potassic feldspar and strontium barite were identified.

BRICK TESTING RESULTS

The Queenston shales have a low load-bearing capacity and are therefore unsuitable for use as a construction aggregate. However, the Queenston Formation is well suited for the production of structural clay products such as brick and tile, and is a resource of provincial significance for these products (Guillet and Joyce 1987). Shale has been extracted from quarries at the base of the Niagara Escarpment for this purpose since the late 1800s and early 1900s.

The presence of gypsum ($CaSO_4.2H_2O$) within the Queenston Formation can cause scumming or efflorescence on the brick surface; therefore, gypsum is an undesirable constituent. Sulphates of magnesium and iron, alkalies, chlorides, and soluble vanadium and molybdenum compounds can also cause scumming and efflorescence (Guillet 1967; Rutka and Vos 1993). Fortunately, previous testing of the Queenston Formation has indicated a reasonably low percentage of gypsum. The gypsum tends to occur as nodules generally less than 2.5 cm in diameter or as small fracture in-fillings (Rowell 2009b). Selective quarrying or the addition of barium carbonate can render gypsum insoluble and therefore of little consequence.

Previous brick and ceramic work on the Queenston Formation has concluded that the colour of the brick depends upon the lime (CaO) content. Lime generally occurs in the minerals calcite and dolomite, and as a lime cement (Martini and Kwong 1986). It has been demonstrated that a calcite content of less than 10% will generally produce red coloured bricks, while a calcite content of 10 to 15% will produce buff-coloured bricks. The percentage of calcite increases with the presence of the grey-green shale layers, and the middle part of the formation, as defined by Armstrong (2001a), has a higher lime content. The formation tends to become more calcareous to the north. In some locations, the Queenston Formation can be excessively hard and brittle and may result in large quarry blocks that are difficult to handle and with insufficient plasticity, even when finely ground. Weathering of the shale in a stockpile prior to use will reduce the percentage of calcite. In addition, the brick industry is adept at dealing with minor variations in the shale geochemistry.

POTENTIAL RESOURCE DEVELOPMENT

As Guillet and Joyce (1987) stated, the Queenston Formation is a resource of provincial significance. It is the single-most important shale formation that has been used extensively in the past, and indeed today, to produce brick and tile. The resource is under a great deal of pressure from urban expansion in the Stoney Creek to Georgetown area. Provincial planning decisions and policies have also reduced the size of the resource area for licensing and extraction.

The Queenston Formation does exist in Grey County of southern Ontario but many of the areas where the shale is exposed are part of deeply incised river valleys and re-entrants (e.g., Beaver Valley area). Such locations may have other important planning constraints placed upon them. The Niagara Escarpment Development Plan is also a planning constraint that limits the licensing and development of the Queenston Formation in some locations along its geographic distribution.

Georgian Bay Formation

GEOGRAPHIC DISTRIBUTION

The outcrop belt of the Georgian Bay Formation trends parallel to the Queenston Formation in southern Ontario, east of the Niagara Escarpment. The formation has its greatest surface exposure (in an east-west direction) along the Lake Ontario shoreline, extending from eastern Toronto westward to Oakville. The formation then narrows parallel to the Niagara Escarpment and disappears under Georgian Bay in the Meaford area (*see* Figure 1, Map 1). The Georgian Bay Formation then reappears as outcrops along the eastern end of Manitoulin Island. The formation is approximately equivalent to the Carlsbad Formation in eastern Ontario (Johnson et al. 1992).

The Georgian Bay Formation is generally covered by a thick succession of Quaternary-age sediments. Areas of thin drift occur immediately west and northwest of Toronto (up to about 20 km north of the Lake Ontario shoreline), and along the shore of Georgian Bay between Collingwood and Owen

Sound (e.g., northwest of Meaford and near Christie Beach). Small areas having a thin cover of drift occur near Creemore, and west of Alliston in the Rosemont area.

LITHOLOGY AND DEPOSITIONAL ENVIRONMENT

Strata presently assigned to the Georgian Bay Formation were previously assigned to the Dundas and Meaford formations (Liberty and Bolton 1971). The Georgian Bay Formation is characterized by noncalcareous, greenish to bluish grey shale, interbedded with limestone, siltstone and sandstone (hard beds). The abundance and thickness of these hard beds decrease stratigraphically downward. The sandstone and siltstone beds are commonly calcareous and are typically fossiliferous, with bryozoans, crinoids and brachiopods being the most common fossils.

The formation is conformably overlain by the Queenston Formation and conformably overlies the Blue Mountain Formation. The contact between the Georgian Bay and Queenston formations represents a gradual transition from a subtidal marine depositional environment to an intertidal marginal marine environment. Limestone and calcareous sandstone beds are common to both formations, increasing in frequency in the middle and lower Queenston (as noted earlier) and being quite prevalent in the upper Georgian Bay Formation. Therefore, the actual contact between the formations is often quite arbitrary and is sometimes chosen at the first appearance of red, mottled shale beds.

The formation thickness varies from 125 to 200 m (Johnson et al. 1992). Raven et al. (2009) intersected 90.90 m of Georgian Bay Formation at the Bruce Nuclear site, south of Port Elgin, at approximately 505.2 m below surface. The formation is approximately 180 m thick in the Toronto area and thins northward.

Similar to the Queenston Formation, the Georgian Bay Formation is believed to have been deposited as part of a large siliciclastic wedge that formed in front of the Taconic Highlands. Deposition occurred on a shallow, warm, muddy, storm-influenced, middle to outer shelf (Martini and Kwong 1986).

GEOCHEMISTRY AND MINERALOGY

Table A1 provides the results of major oxide analyses completed on a number of Georgian Bay Formation samples. The Georgian Bay Formation generally has a higher percentage of SiO_2, Al_2O_3, Na_2O, TiO_2 and Fe_2O_3 than the Queenston Formation, and generally has a lower concentration of CaO (*see* Figure A1). Data from Closs (1979) indicates that the Georgian Bay Formation has slightly elevated concentrations of Cr, Cu, Ni, V and Zn when compared to the Queenston Formation and slightly lower levels of Mn and Pb. Caution is advised when comparing this data since the number of analyses is limited.

Mineralogical analyses are provided in Table A4. The results indicate that the Georgian Bay Formation has a similar mineralogy to the Queenston Formation; specifically, the most abundant mineral is illite, generally followed in abundance by chlorite and quartz, with trace levels of calcite, dolomite, feldspars, vermiculite and other mixed layered clay minerals. Czurda, Winder and Quigley (1973) report that the carbonate content is fairly consistent at 4 to 5%, with an increase to 20 to 25% in the southwestern part of the Georgian Bay Formation's geographic distribution (Table 2, below). The increase is attributed to an increase in dolomite content. Another trend that Czurda, Winder and Quigley (1973) noted was an increase in the quartz content to 35 to 40% in the northern part of the belt, compared to 10 to 15% in the south. They believe that the source of this quartz in the northern part of the belt is from the Canadian Shield. This shale formation is predominantly a compacted shale (i.e., not cemented).

Table 2. Mineralogy of the Georgian Bay Formation (*after* Czurda, Winder and Quigley (1973)).

Mineral	Toronto Area	Meaford Area	Windsor Area
Illite	55 – 60%	35 – 45%	50 – 55%
Quartz	15 – 18%	40%	7 – 15%
Chlorite	10 – 15%	10 – 15%	5 – 10%
Carbonate	4%	6%	10 – 25%
Vermiculite	3 – 5%	3 – 5%	5 - 10%
Heavy Minerals*	2 – 4%	2 – 4%	

*Predominantly pyrite

BRICK TESTING RESULTS

The formation has been used extensively in the past as a source of raw material for manufacturing bricks and tile in the Toronto and Mississauga area (Guillet 1977). Table A5 shows that the Georgian Bay Formation can produce hard to very hard bricks. There is some evidence of scumming with some of the samples tested. Improved performance is achieved by reducing or eliminating hard beds, either by mechanical means or by manual methods (e.g., selective extraction). Minor amounts of gypsum and pyrite require neutralizing to prevent scumming and efflorescence.

There has been a succession of small companies that have tried to manufacture a variety of drainage tiles and brick in the Meaford area (quarry located close to Meaford and the plant was located at Meaford). It is unclear as to why these facilities are no longer in operation. Whether it was due to the nature of the Georgian Bay Formation raw material or economics of the operation remains uncertain. Either way, there is no longer any extraction of the Georgian Bay Formation in southern Ontario for the manufacture of brick and tile.

POTENTIAL RESOURCE DEVELOPMENT

As noted earlier, the outcrop belt of the Georgian Bay Formation is largely covered by a thick sequence of Quaternary-age sediments. In the Simcoe County area, from Georgian Bay trending southeastward to Lake Ontario is one of the largest buried bedrock valleys in Ontario, the Laurentian Buried Valley. In 1890, J.W.W. Spencer (cited in Wilson 1901) proposed that a major drainage valley existed between Georgian Bay and Lake Ontario. The valley is approximately 100 km long and 25 km wide. This concept was based on the depth of many water well records in the area and the resulting pattern that they formed. Wilson (1901) and Deane (1950) have suggested changes, provided additional information and modified Spencer’s original work – but neither have discounted the concept and have only provided support for the idea. Studies by Davies, Holysh and Sharpe (2008), and Bajc and Rainsford (2010) have reconfirmed the presence of the buried valley, and are trying to delineate the actual river channels more accurately, the latest attempt using a geophysical gravity survey. The buried valley is covered with several tens of metres of overburden.

In the southern part of Simcoe County and northern portion of the Greater Toronto Area (GTA) is the Oak Ridges moraine, reaching elevations in excess of 350 m asl. The moraine is built on a regional erosional surface consisting of the Newmarket Till and tunnel valleys. This pre-moraine surface partially controlled the distribution and thickness of the sediments that form the moraine (Barnett et al. 1998). As the Laurentide Ice sheet began to melt and retreat from southern Ontario, it split into a number of glacial lobes that behaved semi-independently. The moraine formed where the Simcoe and Lake Ontario lobes separated during deglaciation, several kilometres north of the present day Lake Ontario shoreline. As the ice lobes melted, a re-entrant in the ice was created that acted as a focal point for meltwater flow and sediment deposition.

The depositional history of the Oak Ridges moraine is complex and is the result of the readvance and retreat of one or both ice margins bounding the moraine. Overall, deposition occurred in 4 stages: 1) subglacial sedimentation; 2) subaqueous fan sedimentation; 3) fan to delta sedimentation and; 4) ice-marginal sedimentation (Barnett et al. 1998). The moraine sediments represent proximal (high energy) to distal (low energy) environments ranging from subglacial to proglacial lake environments. The Quaternary-age sediments that comprise the moraine form a thick package of sediment that has buried the Georgian Bay Formation.

For these reasons, extraction of the Georgian Bay Formation for the manufacture of brick and tile in the central part of the formation's geographic distribution would be uneconomic. Earlier discussion on the economically viable 8 m limit would obviously preclude the stripping of the sediments in this area. The Carlsbad Formation in eastern Ontario is generally not available for extraction because of overburden thickness and sterilization by urban developments in and around the City of Ottawa.

Blue Mountain Formation

GEOGRAPHIC DISTRIBUTION

The Blue Mountain Formation's outcrop belt lies to the east of that of the Georgian Bay Formation and trends parallel to it. In this area, the formation is generally covered by a thick succession of Quaternary-age sediments (*see* "Potential Resource Development" of the Georgian Bay Formation above for a complete explanation of the thickness of the overburden cover). Small areas with thin drift cover are known to occur east of Toronto, along the Lynde and Duffins creek areas and along the Rouge River. In a hole drilled by Ontario Power Generation (OPG) just south of these exposures, there was approximately 40 m of overburden covering the Blue Mountain Formation. Outcrops of the Blue Mountain Formation have been mapped in the Collingwood–Thornbury–Meaford area.

LITHOLOGY AND DEPOSITIONAL ENVIRONMENT

The Blue Mountain Formation consists of 40 to 60 m of blue-grey to grey-brown to greyish black, poorly fossiliferous, noncalcareous shale, with thin, minor interbeds of limestone and siltstone (Johnson et al. 1992). Raven et al. (2009) intersected 38.10 m of the Blue Mountain Formation in the Bruce Nuclear drill core, at a depth of 595.92 m below ground surface. The Blue Mountain Formation is approximately equivalent to the Billings Formation in eastern Ontario.

The lower part of the formation shows a downward gradation from grey to greenish grey shale to the very dark grey to black noncalcareous shales of the Rouge River Member (Russell and Telford 1983). The contact with the underlying shales of the Collingwood Member of the Lindsay Formation is sharp. It has been suggested that the Collingwood Member was eroded prior to deposition of the Blue Mountain Formation (Russell and Telford 1983), thus forming this sharp contact. The upper contact between the Blue Mountain and Georgian Bay formations cannot be chosen consistently or reliably. Carbonate beds in the upper part of the Blue Mountain Formation are generally less than 5 cm thick. It has therefore been suggested that the arbitrary contact between the 2 formations is the lowest significant carbonate bed of the Georgian Bay Formation (>5 cm thick).

Similar to the Queenston and Georgian Bay formations, the Blue Mountain Formation was deposited as part of the large siliciclastic wedge that formed in front of the Taconic Highlands. The depositional environment has been interpreted to be a deep shelf environment below storm wave base. Clastic sediments were believed to have been supplied by erosion of the Taconic Highlands to the southeast.

GEOCHEMISTRY AND MINERALOGY

Based on a limited number of analyses provided in Table A1, the Blue Mountain Formation would appear to be very similar geochemically to the Georgian Bay Formation, with slightly elevated Al_2O_3, K_2O and S. It has slightly lower concentrations of CaO and Na_2O. The Blue Mountain Formation is reported to have a higher organic-carbon content. No trace element data is available for the Blue Mountain Formation (*see* Tables A2 and A3). Mineralogically, the formations are similar, with the predominant minerals being illite, chlorite, and quartz, with trace amounts of calcite, dolomite and feldspars (*see* Table A4).

BRICK TEST RESULTS

The limited brick testing that has been completed on the Blue Mountain Formation would suggest that it can be used to manufacture brick. The formation appears to have good plasticity and burns to a dense, red, hard body at about 1005°C. There appears to be less frequent and thinner hard beds than in some parts of the Queenston and Georgian Bay formations. Martini and Kwong (1986) noted some scumming in their test results. Density and fired modulus of rupture (MOR) appear to be quite reasonable. Higher concentrations of sulphur and organic-carbon have been reported and may be of concern.

POTENTIAL RESOURCE DEVELOPMENT

The availability of the Blue Mountain Formation for licensing and extraction is extremely limited. The formation is covered by a thick succession of Quaternary-age sediments, including areas covered by the Oak Ridges moraine and part of the Laurentian buried valley. The southern part of the Blue Mountain Formation belt is covered by urban sprawl in the Pickering area and an overburden cover of about 40 m, as noted earlier.

Some potential for development may exist in the Collingwood to Thornbury area, but much of the resource area is located near Georgian Bay and would be limited by recreational housing and activities, and land-use planning policies. There are no quarry records, nor historical production facilities, to suggest that the Blue Mountain Formation has been used to manufacture brick and tiles commercially in the past. The Billings Formation in eastern Ontario is generally not available for extraction because of overburden thickness and sterilization by urban developments in and around the City of Ottawa.

Summary

Despite the number of shale formations in Ontario, many of these shale formations are, and never were, potential sources of raw material to be used in the manufacture of brick and tile. This is because many of the formations are buried by a thick sequence of Quaternary-age sediments; are buried deeply by

Paleozoic-age bedrock; have a high organic, sulphur or bituminous content; or failed to pass standard brick tests.

Therefore, historically and in practice, only 3 shale formations have been used extensively to produce brick and tile: the Arkona, Queenston and Georgian Bay formations. Of these 3 formations, it is suggested in this report that only the Queenston Formation remains as a viable source of raw material. Between urban expansion, current land-use planning policies and overburden thickness, the Arkona and Georgian Bay formations are virtually eliminated from future extractive opportunities.

Therefore, it is vitally important to protect areas of the Queenston Formation, overlain by thin drift cover (less than 8 m), as a source of raw material for the manufacture of brick and tile for the foreseeable and distant future. Guillet and Joyce (1987) referred to the Queenston Formation as a resource of provincial significance.

As Vos stated in 1975, "Sequential land use will be a major tool in keeping this industry alive. To date the potential of this tool has neither been appreciated nor utilized." Almost 40 years after this statement was published, are we utilizing this land-use planning tool effectively?

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Appendix

Test Results

Table A1. Geochemical results—major oxides.

Sample No.	Number of Analyses	SiO_2 (%)	Al_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	TiO_2 (%)	Fe_2O_3 (%)	LOI (%)	Total (%)	S (%)	CO_2 (%)	H_2O+ (%)	H_2O- (%)
Arkona Formation																	
OGS89-11 [1]	N = 10	49.51	16.14	0.13	2.41	7.64	0.31	3.97	0.15	0.76	6.24	10.89	98.13	0.53	7.69	-	-
08DJR-0011 [2]	N = 10	51.55	16.65	0.13	2.60	6.31	0.34	4.33	0.15	0.80	6.35	9.93	99.13	0.42	6.14	4.13	0.55
Brady and Dean Sample 15 [3]	N = 1	43.25	14.14	-	2.95	14.20	0.19	3.47	-	0.76	5.01	15.63	99.60	0.13	12.24	3.81	0.3
Martini Lab No. 5 [4]	N = 1	51.44	16.73	0.10	2.33	2.88	0.25	4.27	0.15	0.84	6.53	14.47	100.00	0.28	6.97	-	-
Martini Lab No. 8 [4]	N = 1	56.21	15.35	0.14	2.53	5.88	0.37	3.87	0.19	0.83	6.16	8.48	100.00	0.36	4.77	-	-
Cabot Head Formation																	
09OGS-DDH-15 [5]	N = 1	54.92	17.70	0.06	3.93	2.25	0.14	5.81	0.10	0.86	5.37	8.33	99.47	0.16	3.03	4.75	0.60
Shelburne Hole 1	N = 3	55.63	17.17	0.07	4.13	2.35	0.29	5.70	0.06	0.83	5.23	5.93	100.47	0.19	5.00	3.21	0.64
Martini Lab No. 3 [4]	N = 1	51.72	14.46	0.06	3.28	2.81	0.29	4.92	0.19	0.71	7.37	14.20	100.00	0.03	2.93	-	-
Queenston Formation																	
00DKA-001 [6]	N = 27	50.64	13.45	0.11	3.38	8.80	0.52	3.91	0.15	0.70	5.66	12.13	99.44	0.15	7.43	-	-
00DKA-002 [6]	N = 17	45.59	10.43	0.14	2.75	15.73	0.75	2.84	0.16	0.59	4.23	16.84	100.04	0.03	13.25		
00DKA-003 [6]	N = 10	47.35	11.99	0.11	3.21	13.27	0.37	3.51	0.15	0.64	4.60	13.41	98.61	0.58	10.08	-	-
00DKA-004 [6]	N = 13	49.55	13.70	0.11	3.54	9.61	0.24	4.09	0.14	0.70	5.31	12.65	99.65	0.01	8.56	-	-
00DKA-005 [6]	N = 4	42.68	11.72	0.12	2.68	16.11	0.41	3.45	0.14	0.58	4.73	16.81	99.42	0.02	13.20	-	-
00DKA-006 [6]	N = 6	51.24	14.19	0.11	3.94	7.56	0.13	4.43	0.14	0.72	5.75	11.59	99.80	0.01	7.40	-	-
00DKA-007 [6]	N = 13	57.75	13.53	0.10	2.62	6.24	0.81	3.78	0.15	0.75	5.36	8.82	99.91	0.01	5.13	-	-
00DKA-008 [6]	N = 11	50.67	14.55	0.10	3.79	7.75	0.14	4.41	0.14	0.72	5.79	11.82	99.89	0.01	7.25	-	-
00DKA-010 [6]	N = 5	41.67	8.75	0.10	2.28	14.83	0.37	2.63	0.12	0.54	4.38	18.15	99.61	0.02	14.88	-	-
00DKA-011 [6]	N = 6	46.13	9.18	0.15	2.94	16.74	0.78	2.61	0.16	0.58	3.36	17.09	99.72	0.02	14.58	-	-
00DKA-012 [6]	N = 1	53.41	14.24	0.10	2.52	7.29	0.60	3.88	0.14	0.73	6.60	10.18	99.67	0.01	5.94	-	-
00DKA-013 [6]	N = 3	55.46	12.52	0.10	2.38	8.53	0.82	3.47	0.13	0.67	5.46	10.48	100.03	0.01	6.77	-	-
00DKA-014 [6]	N = 13	49.20	13.45	0.12	3.20	10.36	0.28	4.01	0.15	0.68	5.25	12.93	99.63	0.08	8.87	-	-
00DKA-015 [6]	N = 1	49.52	12.62	0.10	2.46	12.15	0.27	3.59	0.15	0.67	4.06	14.02	99.61	0.02	10.30	-	-
00DKA-016 [6]	N = 1	52.74	15.00	0.09	3.11	6.39	0.11	4.53	0.14	0.76	6.62	10.38	99.86	0.01	5.82	-	-
00DKA-017 [6]	N = 5	52.78	15.21	0.09	3.10	6.07	0.15	4.57	0.14	0.76	6.74	10.38	99.99	0.01	5.65	-	-
00DKA-018 [6]	N = 11	52.47	14.49	0.10	3.10	7.48	0.16	4.40	0.14	0.73	5.79	11.05	99.91	0.01	6.62	-	-
00DKA-019 [6]	N = 1	49.06	14.12	0.07	4.72	7.56	0.14	4.41	0.21	0.68	5.48	11.85	98.31	1.35	8.72	-	-
00DKA-020 [6]	N = 5	42.28	10.80	0.09	5.75	14.06	0.14	3.60	0.16	0.53	4.13	18.41	99.96	0.02	15.08	-	-

Sample No.	Number of Analyses	SiO$_2$ (%)	Al$_2$O$_3$ (%)	MnO (%)	MgO (%)	CaO (%)	Na$_2$O (%)	K$_2$O (%)	P$_2$O$_5$ (%)	TiO$_2$ (%)	Fe$_2$O$_3$ (%)	LOI (%)	Total (%)	S (%)	CO$_2$ (%)	H$_2$O+ (%)	H$_2$O- (%)
00DKA-025 [6]	N = 9	36.15	9.69	0.10	5.81	18.26	0.11	3.22	0.11	0.47	4.48	21.51	99.91	0.08	18.58	-	-
00DKA-026 [6]	N = 7	40.15	11.94	0.08	5.55	14.12	0.15	3.91	0.15	0.54	4.72	18.47	99.78	0.06	14.76	-	-
00DKA-027 [6]	N = 6	36.56	13.01	0.09	3.52	15.77	0.15	3.48	0.13	0.49	4.82	21.51	99.53	0.02	14.05	-	-
00DKA-028 [6]	N = 1	41.84	12.48	0.11	4.90	11.90	0.10	3.35	0.12	0.55	4.32	19.96	99.64	0.02	12.50	-	-
00DKA-029 [6]	N = 1	49.40	12.84	0.10	3.19	9.10	0.20	3.78	0.14	0.66	6.79	13.78	99.99	0.01	7.96	-	-
00DKA-030 [6]	N = 2	42.19	14.35	0.08	3.07	10.68	0.12	3.84	0.13	0.60	6.12	18.26	99.41	0.01	9.29	-	-
00DKA-031 [6]	N = 5	42.06	12.59	0.10	2.95	14.54	0.13	3.61	0.14	0.59	5.36	17.73	99.80	0.02	12.22	-	-
00DKA-032 [6]	N = 6	46.26	13.63	0.10	3.23	11.36	0.13	4.21	0.14	0.65	5.70	14.32	99.71	0.01	9.73	-	-
00DKA-033 [6]	N = 2	58.13	12.63	0.13	2.26	7.01	1.06	3.38	0.15	0.71	5.30	8.98	99.70	0.02	5.61	-	-
00DKA-034 [6]	N = 1	58.79	14.00	0.08	2.66	4.26	0.92	3.99	0.15	0.78	6.44	7.77	99.83	0.01	3.41	-	-
00DKA-036 [6]	N = 2	37.49	9.39	0.15	2.74	21.29	0.45	2.99	0.16	0.49	3.92	20.68	99.73	0.04	17.70	-	-
00DKA-037 [6]	N = 6	54.00	11.59	0.15	2.25	10.07	0.95	3.01	0.14	0.64	4.93	11.95	99.69	0.01	8.21	-	-
00DKA-038 [6]	N = 1	54.84	15.70	0.07	3.06	4.80	0.49	4.58	0.14	0.79	6.92	8.45	99.83	0.01	3.88	-	-
00DKA-040 [6]	N = 11	45.18	10.66	0.14	2.75	15.72	0.71	2.92	0.15	0.58	4.36	16.38	99.53	0.03	13.30	-	-
00DKA-041 [6]	N = 3	54.47	14.57	0.11	4.91	4.53	0.13	4.73	0.14	0.77	5.67	10.30	100.33	0.01	6.07	-	-
00DKA-042 [6]	N = 10	57.32	15.15	0.09	3.46	3.63	0.23	4.76	0.15	0.81	6.14	8.15	99.87	0.03	3.57	-	-
00DKA-043 [6]	N = 27	56.50	13.66	0.11	2.66	6.50	0.96	3.68	0.15	0.77	5.18	9.60	99.76	0.09	5.29	-	-
00DKA-145 [6]	N = 17	47.14	11.63	0.12	2.74	13.10	0.85	3.21	0.15	0.63	4.92	14.58	99.07	0.05	10.85	-	-
00DKA-146 [6]	N = 17	51.57	12.63	0.12	2.80	9.92	0.84	3.44	0.15	0.69	5.19	11.73	99.07	0.02	8.20	-	-
00DKA-147 [6]	N = 19	49.44	12.13	0.12	2.75	11.57	0.84	3.26	0.15	0.66	4.93	13.11	98.96	0.06	9.41	-	-
00DKA-148 [6]	N = 14	44.29	11.54	0.11	2.85	14.68	0.52	3.37	0.15	0.59	4.71	15.89	98.70	0.16	12.41	-	-
00DKA-149 [6]	N = 8	47.32	12.74	0.12	3.22	11.82	0.34	3.77	0.15	0.66	5.03	14.04	99.19	0.08	10.08	-	-
00DKA-150 [6]	N = 6	42.39	10.84	0.11	2.77	16.94	0.55	3.20	0.14	0.56	4.69	17.22	99.40	0.03	14.18	-	-
00DKA-151 [6]	N = 24	42.19	12.19	0.10	3.48	14.85	0.16	3.86	0.14	0.57	5.00	16.61	98.95	0.09	12.68	-	-
00DKA-152 [6]	N = 8	47.29	11.94	0.11	3.50	12.31	0.27	3.65	0.14	0.60	5.04	14.54	99.39	0.06	11.10	-	-
00DKA-153 [6]	N = 25	40.92	12.07	0.09	4.78	13.26	0.22	3.81	0.13	0.55	5.28	17.46	98.56	0.46	12.88	-	-
00DKA-154 [6]	N = 29	35.04	11.41	0.10	5.11	17.86	0.22	3.50	0.12	0.47	4.93	20.40	99.16	0.16	17.27	-	-
01DKA-009 [7]	N = 6	52.32	14.53	0.09	3.02	7.98	0.28	4.32	0.12	0.74	6.11	10.52	100.04	0.01	6.36	-	-
01DKA-010 [7]	N = 4	58.10	14.75	0.11	2.83	4.98	0.46	4.24	0.15	0.81	5.75	7.86	100.02	0.01	4.11	-	-
01DKA-014 [7]	N = 8	51.52	13.02	0.11	2.81	9.73	0.32	3.76	0.13	0.67	5.96	12.13	100.15	0.01	7.58	-	-
01DKA-015 [7]	N = 7	45.73	13.52	0.10	3.10	12.42	0.13	4.10	0.14	0.64	5.86	14.14	99.86	0.01	9.90	-	-
01DKA-016 [7]	N = 9	40.14	11.09	0.11	3.17	17.70	0.18	3.54	0.13	0.52	4.70	18.16	99.44	0.02	14.42	-	-
01DKA-017 [7]	N = 7	45.52	14.00	0.09	3.49	12.04	0.09	4.01	0.13	0.64	5.45	14.21	99.66	0.01	10.12	-	-

Sample No.	Number of Analyses	SiO_2 (%)	Al_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	TiO_2 (%)	Fe_2O_3 (%)	LOI (%)	Total (%)	S (%)	CO_2 (%)	H_2O+ (%)	H_2O- (%)
01DKA-025 [7]	N = 5	37.81	11.40	0.10	2.81	18.79	0.15	3.64	0.13	0.50	5.03	18.87	99.22	0.02	14.16	-	-
01DKA-026 [7]	N = 2	37.96	12.54	0.08	5.01	15.06	0.15	3.83	0.14	0.51	5.58	18.41	99.24	0.01	13.80	-	-
01DKA-027 [7]	N = 5	38.42	11.35	0.11	6.99	14.38	0.14	3.56	0.13	0.50	4.83	19.52	99.94	0.02	15.12	-	-
01DKA-028 [7]	N = 4	39.19	13.06	0.09	3.83	16.07	0.16	3.86	0.15	0.56	5.58	17.62	100.16	0.02	12.90	-	-
01DKA-029 [7]	N = 4	39.23	10.62	0.12	6.58	14.79	0.13	3.39	0.14	0.50	4.57	19.63	99.70	0.02	15.25	-	-
08DJR-0009 [2]	N = 7	52.38	13.84	0.11	3.27	6.85	0.29	4.56	0.16	0.76	6.08	10.94	99.24	0.05	5.93	3.41	0.77
08DJR-0010 [2]	N = 10	48.00	11.15	0.13	2.79	12.64	0.71	3.38	0.16	0.67	4.81	14.92	99.36	0.07	10.16	2.66	0.68
09OGS-DDH-15 [5]	N = 1	50.20	11.29	0.12	2.96	10.69	0.26	3.65	0.15	0.69	5.39	14.09	99.50	0.01	9.03	4.84	1.79
10DJR-0021 [8]	N = 1	41.67	12.20	0.10	2.79	13.85	0.04	3.97	0.14	0.64	5.92	17.88	99.22	0.02	11.10	4.46	2.12
10DJR-0022 [8]	N = 1	47.18	11.45	0.12	3.91	10.64	0.11	3.87	0.14	0.70	5.53	15.62	99.26	0.01	9.44	4.09	1.74
10DJR-0024 [8]	N = 1	50.20	11.29	0.12	2.96	10.69	0.26	3.65	0.15	0.69	5.39	14.09	99.50	0.01	9.03	4.84	1.79
Brady and Dean Sample 4 [3]	N = 1	48.36	14.28	-	4.07	9.29	0.12	4.30	-	0.78	4.38	12.10	99.63	0.02	8.52	-	-
Brady and Dean Sample 5 [3]	N = 1	50.49	15.32	-	3.77	7.31	0.24	4.56	-	0.77	4.65	10.22	99.67	0.02	6.71	-	-
Brady and Dean Sample 6 [3]	N = 1	45.10	11.90	-	2.63	14.30	0.81	2.99	-	0.67	4.57	-	-	0.32	12.47	-	-
Guillet Milton Quarry [9]	N = 1	55.00	14.00	-	3.23	7.25	0.90	3.23	-	0.72	6.17	-	-	0.20	5.81	-	-
Guillet Diamond [9]	N = 1	50.91	14.90	-	4.40	7.41	0.36	4.02	-	0.73	6.53	-	-	0.27	6.67	-	-
Guillet Brampton [9]	N = 1	49.00	14.09	-	2.14	11.52	0.62	3.50	-	0.58	3.74	12.86	99.48	-	9.81	-	-
Kwong-85 [10]	N = 5	54.17	13.98	0.10	3.83	5.69	0.32	4.25	0.15	0.77	6.89	9.86	100.00	-	-	-	-
Kwong-85-L4 [10]	N = 1	50.64	14.01	0.10	3.23	9.19	0.18	4.38	0.18	0.74	5.52	11.84	100.00	-	-	-	-
Kwong-85-L5 [10]	N = 2	50.27	12.39	0.10	3.53	11.52	0.36	3.86	0.18	0.69	4.28	12.83	100.00	-	-	-	-
Kwong-85-L6 [10]	N = 1	58.96	12.24	0.11	2.12	7.10	0.86	3.50	0.17	0.66	5.43	8.88	100.01	0.03	1.62	-	-
Martini Lab No. 1 [4]	N = 1	52.45	16.57	0.09	3.84	2.86	0.21	5.06	0.23	0.79	7.43	10.46	100.00	0.05	1.61	-	-
Martini Lab No. 13 [4]	N = 1	47.97	14.49	0.09	3.79	7.17	0.15	4.53	0.15	0.65	7.04	13.97	100.00	0.04	7.00	-	-
Martini Lab No. 15 [4]	N = 2	51.58	14.13	0.11	4.03	5.77	0.32	4.42	0.15	0.70	6.49	12.34	100.00	0.06	5.81	-	-
Martini Lab No. 4 [4]	N = 1	56.20	15.09	0.07	2.87	3.04	0.41	4.26	0.14	0.77	7.24	9.90	100.00	0.05	1.36	-	-
OGS89-05A [1]	N = 9	47.06	11.97	0.11	2.37	12.79	0.65	3.35	0.15	0.64	5.20	14.03	98.31	0.13	10.22	-	-
OGS89-06 [1]	N = 8	53.29	14.07	-	3.66	6.03	-	-	-	-	5.91	-	-	0.12	-	-	-
OGS89-08 [1]	N = 5	50.86	12.54	0.10	2.70	9.79	0.71	3.43	0.17	0.65	5.37	11.90	98.24	0.04	8.06		
OGS89-09 [1]	N = 9	56.76	14.88	-	2.59	4.53	-	-	-	-	6.50	-	-	0.24	-	-	-
Georgian Bay Formation																	
01DKA-001 [7]	N = 1	56.39	17.76	0.08	3.49	1.92	0.70	4.59	0.25	0.92	7.76	6.15	100.03	0.30	2.12	-	-
01DKA-002 [7]	N = 2	59.98	16.42	0.10	3.19	1.65	0.90	4.30	0.20	0.93	6.88	5.73	100.25	0.13	1.78	-	-

Sample No.	Number of Analyses	SiO_2 (%)	Al_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	TiO_2 (%)	Fe_2O_3 (%)	LOI (%)	Total (%)	S (%)	CO_2 (%)	H_2O+ (%)	H_2O- (%)
01DKA-003 [7]	N = 3	57.62	14.00	0.13	3.11	5.03	0.87	3.58	0.16	0.77	6.76	7.74	99.76	0.45	4.57	-	-
01DKA-004 [7]	N = 2	50.78	11.11	0.18	3.01	12.11	0.87	2.89	0.14	0.59	4.85	13.53	100.04	0.03	10.26	-	-
01DKA-008 [7]	N = 6	62.80	12.42	0.14	2.91	3.98	1.31	2.91	0.17	0.76	5.52	6.93	99.83	0.18	4.34	-	-
01DKA-013 [7]	N = 4	55.22	14.70	0.13	2.61	6.32	0.70	3.86	0.18	0.79	6.42	9.09	100.01	0.04	4.90	-	-
01DKA-019 [7]	N = 29	56.75	15.58	0.10	3.43	4.14	0.59	4.53	0.19	0.84	6.40	7.63	100.19	0.35	4.32	-	-
01DKA-022 [7]	N = 10	56.60	15.96	0.09	3.40	3.99	0.39	4.96	0.20	0.81	6.29	7.44	100.13	0.37	4.11	-	-
10DJR-0020 [9]	N = 1	52.91	15.50	0.09	2.84	4.39	0.42	4.40	0.24	0.85	6.93	10.49	99.06	0.01	3.39	5.86	3.00
10DJR-0023 [9]	N = 1	51.22	6.96	0.17	3.11	14.78	0.67	2.25	0.12	0.49	2.95	17.47	100.20	0.01	12.80	1.90	0.63
Martini Lab No. 6 [4]	N = 1	55.27	15.99	0.08	2.95	2.88	0.55	4.52	0.21	0.83	7.21	9.50	100.00	0.46	2.42	-	-
Martini Lab No. 7 [4]	N = 1	50.64	16.15	0.09	3.18	1.93	0.39	4.74	0.20	0.79	7.13	14.76	100.00	0.45	1.50	-	-
Blue Mountain Formation																	
01DKA-007 [7]	N = 4	55.36	17.52	0.12	3.18	2.63	0.72	4.39	0.21	0.84	7.21	7.49	99.66	0.87	5.27	-	-
Martini Lab No. 2 [4]	N = 1	55.28	16.34	0.12	3.30	2.92	0.24	4.42	0.19	0.82	7.16	9.21	100.00	0.69	2.71	-	-

Notes:

Sample numbers represent a drill hole, and in some cases, a quarry face, that were sampled along the length of the core or exposed quarry face, respectively. "N", therefore, equals the total number of samples obtained and tested from that drill hole or quarry face. See "Report Format" for further explanation.

[1] *Rutka and Vos (1993)*

[2] *Rowell (2009b)*

[3] *Brady and Dean (1966)*

[4] *Martini and Kwong (1986)*

[5] *Rowell and Brunton (2011)*

[6] *Armstrong (2001a)*

[7] *Armstrong and Sergerie (2002a)*

[8] *Rowell (2012b)*

[9] *Guillet (1977)*

[10] *Kwong, Martini and Narain (1985)*

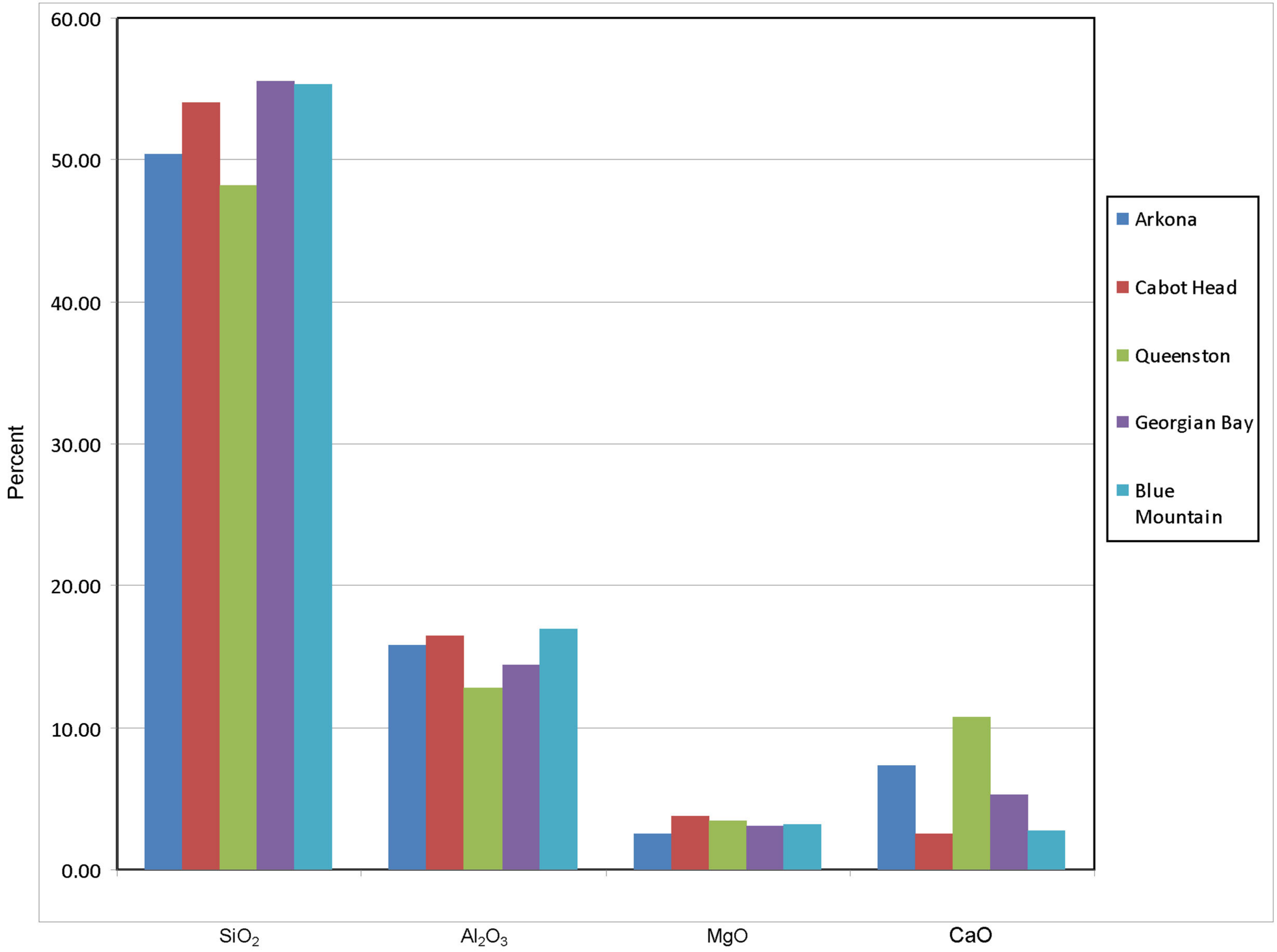

Figure A1. Major oxide comparisons.

Table A2. Trace elements results—atomic absorption (flame) spectroscopy analyses.

	Cd ppm	Co ppm	Cu ppm	Li ppm	Ni ppm	Pb ppm	Zn ppm
Cabot Head Formation							
09OGS-DDH-15 [1]	<5	48	13	95	37	<12	101
Queenston Formation							
09OGS-DDH-15 [1]	<5	34	25	50	25	<12	71
10DJR-0022 [2]	<5	36	13	49	30	<12	69
10DJR-0024 [2]	<5	35	28	52	32	<12	68
10DJR-0021 [2]	<5	39	11	54	31	<12	70
Georgian Bay Formation							
10DJR-0020 [2]	<5	44	24	63	36	<12	90
10DJR-0023 [2]	<5	30	33	39	18	<12	45

[1] *Rowell and Brunton (2011)*

[2] *Rowell (2012b)*

[3] *Armstrong (2001a)*

Table A3. Trace elements results—inductively coupled plasma mass spectroscopy analyses.

	Ba ppm	Be ppm	Bi ppm	Cd ppm	Ce ppm	Co ppm	Cr ppm	Cs ppm	Cu ppm	Dy ppm	Er ppm	Eu ppm	Ga ppm	Gd ppm	Hf ppm
Cabot Head Formation															
09OGS-DDH-15 [1]	490.2	2.88	0.15	0.028	91.75	17.48	85	8.858	13.3	5.484	3.337	1.305	24.33	5.285	3.99
Queenston Formation															
09OGS-DDH-15 [1]	319.0	1.74	0.21	0.075	73.89	14.16	59	4.974	25.5	5.375	3.083	1.357	15.25	5.716	5.96
10DJR-0022 [2]	318.4	1.72	0.19	0.052	71.53	14.21	60	5.361	12.9	4.951	2.869	1.258	15.71	5.271	4.93
10DJR-0024 [2]	331.6	1.81	0.22	0.069	72.41	14.96	59	5.002	18.9	4.732	2.731	1.297	15.08	5.104	4.52
10DJR-0021 [2]	355.3	1.96	0.23	0.072	70.24	15.62	62	5.652	9.3	4.458	2.492	1.168	16.94	4.792	3.59
00DKA-001 [3]	377.1	2.45	-	-	74.62	15.38	62	6.013	24.2	4.610	2.608	1.342	17.96	5.646	3.56
Georgian Bay Formation															
10DJR-0020 [2]	367.5	2.59	0.24	0.040	87.61	19.81	82	7.402	23.7	5.823	3.324	1.518	22.04	6.438	4.46
10DJR-0023 [2]	225.5	0.80	<0.15	0.047	53.33	9.41	34	1.835	34.7	5.214	2.639	1.347	8.28	5.615	5.14

	Ho ppm	In ppm	La ppm	Li ppm	Lu ppm	Mo ppm	Nb ppm	Nd ppm	Ni ppm	Pb ppm	Pr ppm	Rb ppm	Sb ppm	Sc ppm	Sm ppm
Cabot Head Formation															
09OGS-DDH-15 [1]	1.119	0.076	46.65	80.0	0.489	0.34	16.675	37.59	42.7	8.0	10.427	190.83	0.39	18.7	6.715
Queenston Formation															
09OGS-DDH-15 [1]	1.061	0.060	35.25	38.2	0.429	1.08	13.035	33.23	32.1	10.6	8.709	112.42	0.73	13.3	6.657
10DJR-0022 [2]	0.972	0.062	34.69	40.3	0.401	0.87	13.228	31.75	33.7	7.3	8.398	117.14	0.72	13.4	6.305
10DJR-0024 [2]	0.925	0.052	33.98	44.2	0.416	1.01	12.987	32.86	31.8	9.7	8.612	119.01	0.74	13.7	6.230
10DJR-0021 [2]	0.880	0.065	34.46	43.3	0.362	0.81	11.281	31.11	34.3	10.9	8.361	125.56	0.78	14.2	5.881
00DKA-001 [3]	0.980	-	35.39	59.4	0.394	1.98	12.390	33.54	39.7	12.2	8.939	125.30	0.67	13.2	6.457
Georgian Bay Formation															
10DJR-0020 [2]	1.142	0.078	42.23	51.5	0.459	0.34	16.163	39.06	43.0	4.6	10.438	138.65	0.56	18.1	7.714
10DJR-0023 [2]	0.966	0.046	22.79	26.6	0.349	0.46	8.938	27.92	20.4	3.9	6.929	54.65	0.30	8.0	6.178

Table A3 cont'd. Trace element results — Inductively coupled plasma mass spectroscopy analyses.

	Sn ppm	Sr ppm	Ta ppm	Tb ppm	Th ppm	Ti ppm	Tl ppm	Tm ppm	U ppm	V ppm	W ppm	Y ppm	Yb ppm	Zn ppm	Zr ppm
Cabot Head Formation															
09OGS-DDH-15 [1]	3.80	143.4	1.121	0.867	13.124	5119	0.939	0.497	2.683	125.0	1.46	29.26	3.289	87	146
Queenston Formation															
09OGS-DDH-15 [1]	2.23	118.1	0.908	0.895	9.480	4073	0.477	0.448	2.646	89.5	1.16	29.09	2.919	62	216
10DJR-0022 [2]	2.38	107.2	0.904	0.816	9.974	3943	0.505	0.416	2.660	95.3	1.18	26.76	2.723	64	178
10DJR-0024 [2]	2.29	131.4	0.887	0.826	9.369	3784	0.591	0.402	2.034	88.9	1.15	27.32	2.842	61	186
10DJR-0021 [2]	2.38	154.0	0.820	0.731	9.213	3564	0.551	0.373	1.959	90.9	1.08	23.66	2.428	62	125
00DKA-001 [3]	2.38	195.2	0.940	0.874	9.850	3704	0.640	0.392	2.592	108.5	1.11	25.42	2.631	74	119
Georgian Bay Formation															
10DJR-0020 [2]	3.16	121.3	1.137	0.974	11.924	4914	0.674	0.478	3.185	128.9	1.45	30.74	3.104	85	157
10DJR-0023 [2]	1.12	110.8	0.598	0.874	5.875	2727	0.264	0.373	1.604	47.1	0.74	27.24	2.403	38	190

[1] *Rowell and Brunton (2011)*

[2] *Rowell (2012b)*

[3] *Armstrong (2001a)*

Table A4. Mineralogy test results.

	Quartz	Calcite	Dolomite	Na/Ca Feldspar	K Feldspar	Illite	Chlorite	Hematite	Comments
Arkona Formation									
Brady and Dean Sample 14 [1]	C	D	F	G	-	A	B	-	XRD identified trace pyrite
Brady and Dean Sample 15 [1]	C	C	G	G	-	A	B	-	
Martini Lab No. 5 (<200 µm) [2]	25	10	2	6	-	49	8	-	
Martini Lab No. 5 (<2 µm) [2]	-	-	-	-	-	70	30	-	
Guillet 1977 - Average [3]	26	10	0.2	0.2	0.2	A	A	-	
08DJR-0011 [5]	B	D	-	-	-	A	C	-	
Cabot Head Formation									
Martini Lab No. 3 (<200 µm) [2]	24	-	6	7	-	49	14	-	
Martini Lab No. 3 (<2 µm) [2]	-	-	-	-	-	90	10	-	
Guillet 1977 - 62-415 [3]	18	1	3	<1	<1	A	C	-	
Guillet 1977 - 63-433 [3]	22	-	8	1	1	A	B	-	
Guillet 1977 - 63-426 [3]	32	<.5	<.5	<.5	<.5	A	B	-	
Queenston Formation									
Brady and Dean Sample 3 [1]	B	D	-	E	G	A	B	F	XRD identified vermiculite as a trace expanding clay mineral
Brady and Dean Sample 4 [1]	B	C	E	F	G	B	C	G	XRD identified vermiculite as a trace expanding clay mineral
Brady and Dean Sample 5 [1]	C	D	G	-	-	A	B	G	XRD identified vermiculite as a trace expanding clay mineral
Brady and Dean Sample 6 [1]	B	C	G	G	-	A	B	G	
Kwong 1985 Sample L4 [4]	25	5.5	-	1	1	A	C	-	trace gypsum
Kwong 1985 Sample L5 [4]	26	8	1	1	1	A	C	-	trace gypsum
Kwong 1985 Sample L6 [4]	30	6	1	1	1	A	C	-	trace gypsum
Kwong 1985 Sample L7 [4]	30	5	1	2	1	A	C	-	trace vermiculite and gypsum
Kwong 1985 Sample L8 [4]	25	1	1	1	1	A	C	-	trace vermiculite and gypsum
Kwong 1985 Sample L1 [4]	20	9	1.5	1	1	A	C	-	
Kwong 1985 Sample L2 [4]	25	3	1	1	1	A	C	-	trace vermiculite and gypsum
Martini Lab No. 13 (<200 µm) [2]	25	11	8	2	-	45	8	-	
Martini Lab No. 13 (<2 µm) [2]	10	-	-	-	-	70	20	-	
Martini Lab No. 14 (<200 µm) [2]	33	8	-	4	-	43	12	-	

	Quartz	**Calcite**	**Dolomite**	**Na/Ca Feldspar**	**K Feldspar**	**Illite**	**Chlorite**	**Hematite**	**Comments**
Martini Lab No. 14 (<2 µm) [2]	5	-	-	-	-	75	20	-	
08DJR-0009 [5]	B	D	-	-	-	A	C	-	
08DJR-0010 [5]	C	D	G	G	G	A	B	-	SEM found subordinate phases of apatite and strontium barite
Guillet 1977 - Average [3]	26	11	1.8	1.3	G	A	B	-	trace of expanding clays
Georgian Bay Formation									
Brady and Dean Sample 10 [1]	C	E	G	E	-	A	B	-	
Brady and Dean Sample 11 [1]	C	E	-	E	G	B	C	-	XRD detected vermiculite
Brady and Dean Sample 12 [1]	C	F	-	F	-	A	B	-	XRD detected montmorillonite
Brady and Dean Sample 13 [1]	B	E	F	D	G	A	B	-	XRD detected pyrite
Kwong 1985 Sample L3 [4]	25	0.5	-	1.5	2	A	A	-	
Guillet 1977 - Average [3]	28	3	1	3	0.5	A	B	-	
Blue Mountain Formation									
Guillet 1977 - 66-443 [3]	27	2	0.5	2	-	A	A	-	
Guillet 1977 - 66-411 [3]	21	2	3	-	1	A	A	-	

Notes:

Where percentages are not provided, relative amounts are provided by alpha characters. A = abundant to G = trace.

[1] *Brady and Dean (1966)*

[2] *Martini and Kwong (1986)*

[3] *Guillet (1977)*

[4] *Kwong, Martini and Narain (1985)*

[5] *Rowell (2009b)*

Table A5. Brick testing results.

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	**Water of Plasticity (%)**	**Dry Shrinkage (%)**	**Fired Shrinkage (%)**	**24 Hour Cold (%)**	**Boiled (%)**	**C/B Ratio**	**Density (g/cc)**	**Green MOR (Mpa or psi)**	**Fired MOR (Mpa, psi or Mohs scale of hardness)**	**Efflorescence or Scumming**	**Fired Color**	**Comments**
Arkona Formation												
OGS89-11 Average [1]												
1025°C		4.66	6.59	8.36	9.60	0.87					red	not fired enough, does not pass
1050°C		4.78	6.86	7.45	8.86	0.84					red	borderline properties
1075°C		4.89	7.41	4.33	5.83	0.74					red	proper firing, pass CSA standards
1100°C		4.84	7.68	1.99	3.37	0.59					buff	overfired but passes CSA
08DJR-0011 Average [2]												
1025°C		4.60	6.84	7.35	8.56	0.86					red	borderline properties
1050°C		4.77	7.07	7.28	8.83	0.82					red	borderline properties
1075°C		4.78	7.67	3.77	5.18	0.73					red	proper firing, pass CSA standards
1100°C		4.79	8.56	1.48	1.84	0.81					buff	overfired but passes CSA
Martini Lab No. 5 [3]												
923°C	18.5	2.14	-0.34	15.27	16.63	0.92	1.83	3.28 Mpa	14.24 Mpa	scumming	light brown	
999°C			1.14	10.46	11.80	0.89	1.98		60.00 Mpa	heavy scum	brown	
1060°C			2.21	8.00	8.50	0.94	1.96		59.56 Mpa	heavy scum	med. red-brown	
1101°C			2.15	7.42	7.90	0.94	2.07		59.21 Mpa	heavy scum	med. red-brown	
1120°C			2.69	4.68	4.88	0.96	2.09		48.00 Mpa	heavy scum	med. red-brown	
Martini Lab No. 8 [3]												
923°C	18.7	3.13	-0.07	10.76	13.41	0.80	1.88	3.13 Mpa	13.80 Mpa	scumming	light brown	
999°C			0.81	9.66	12.02	0.80	2.02		31.28 Mpa	scumming	light brown	
1060°C			1.69	8.18	11.06	0.74	2.10		40.21 Mpa	scumming	med. red-brown	
1101°C			1.50	7.22	9.72	0.74	2.09		34.49 Mpa	scumming	med. red-brown	
1120°C			3.41	2.46	2.66	0.92	2.17		52.34 Mpa	scumming	med. red-brown	

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	Water of Plasticity (%)	Dry Shrinkage (%)	Fired Shrinkage (%)	24 Hour Cold (%)	Boiled (%)	C/B Ratio	Density (g/cc)	Green MOR (Mpa or psi)	Fired MOR (Mpa, psi or Mohs scale of hardness)	Efflorescence or Scumming	Fired Color	Comments
Guillet 1977 Average [4]												
1660°F	25.0	4.40	0.00	15.60	16.00	0.98	1.77		almost hard	scumming	pale brown	
1840°F			2.10	10.10	11.30	0.89	1.90		hard	scumming	red brown	
1980°F			3.30	6.50	7.20	0.90	2.00		very hard		dark brown	
Cabot Head Formation												
09OGS-DDH-15 [5]												
1028°C	17.1	4.60	5.88	20.07	21.05	0.95			6.0 Moh		salmon	slight scumming
1047°C			5.52	18.89	20.65	0.91			6.0 Moh		salmon	slight scumming
1064°C			5.47	19.09	20.69	0.92			6.7 Moh		salmon	slight scumming
1073°C			4.26	14.10	17.41	0.81			6.8 Moh		salmon	slight scumming
1110°C			6.96	9.29	13.15	0.71			8.0 Moh		salmon	slight scumming
Martini Lab No. 3 [3]												
923°C	16.5	1.61	-0.67	17.32	19.12	0.91	1.86	1.16 Mpa	9.71 Mpa		brown	
999°C			3.89	7.44	8.60	0.87	2.18		35.40 Mpa		med. red-brown	
1060°C			5.67	5.24	6.01	0.87	2.17		49.62 Mpa		med. red-brown	
1101°C			5.87	3.57	3.94	0.91	2.30		61.62 Mpa		med. red-brown	
1120°C			6.17	1.57	1.97	0.80	2.31		56.98 Mpa		med. red-brown	
1137°C			7.61	0.42	0.28	1.50	2.33		65.57 Mpa		med. red-brown	
Guillet 1977 - 62-415 [4]												
1660°F	26.0	4.50	4.70	9.10	9.60	0.95	2.04		very hard		salmon	
1840°F			8.90	0.40	0.60	0.67	2.35		very hard		dark red	
1980°F			1.00+	0.30	11.30	0.03	1.62		very hard		brown	over fired
Guillet 1977 - 62-433 [4]												
1840°F	17.0	2.80	2.40	8.20	10.20	0.80	2.07		hard	scumming	salmon	
1980°F			2.40	4.00	6.20	0.65	2.08		very hard		pink	slightly over fired

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	**Water of Plasticity (%)**	**Dry Shrinkage (%)**	**Fired Shrinkage (%)**	**24 Hour Cold (%)**	**Boiled (%)**	**C/B Ratio**	**Density (g/cc)**	**Green MOR (Mpa or psi)**	**Fired MOR (Mpa, psi or Mohs scale of hardness)**	**Efflorescence or Scumming**	**Fired Color**	**Comments**
Queenston Formation												
08DJR-0009 Average[2]												
1025°C		2.81	3.36	10.77	12.58	0.86					medium red	not fired enough, does not pass
1050°C		2.94	3.56	10.61	12.65	0.84					medium red	not fired enough, does not pass
1075°C		2.97	4.26	7.21	9.04	0.80					medium red	proper firing, pass CSA standards
1100°C		3.11	5.48	3.51	4.74	0.74					medium red	proper firing, pass CSA standards
08DJR-0010 Average[2]												
1025°C		2.35	1.73	17.07	19.31	0.88					salmon-buff	not fired enough, does not pass
1050°C		2.52	1.84	16.88	20.75	0.81					salmon-buff	not fired enough, does not pass
1075°C		2.64	2.28	15.62	18.36	0.85					salmon-buff	not fired enough, does not pass
1100°C		2.48	3.23	11.50	15.33	0.75					salmon-buff	proper firing, pass CSA standards
09OGS-DDH-15[5]												
1073°C	17.0		2.11	25.84	28.59	0.90			4.2 Moh	minor	buff	high carbonate - requires blending
1082°C			2.10	25.81	28.23	0.91			4.4 Moh	minor	buff	high carbonate - requires blending
1105°C			3.01	24.17	28.16	0.86			5.0 Moh	minor	buff	high carbonate - requires blending
1129°C			3.51	23.99	27.92	0.86			5.0 Moh	minor	buff	high carbonate - requires blending
00DKA-145[6]		0.73	0.35	17.57	20.58	0.85	1.76	186.8 psi	786.8 psi	efflorescence	tan to buff	
00DKA-148[6]		1.67	0.46	19.75	21.28	0.93	1.75	142.7 psi	733.0 psi	efflorescence	pinkish tan	

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	**Water of Plasticity (%)**	**Dry Shrinkage (%)**	**Fired Shrinkage (%)**	**24 Hour Cold (%)**	**Boiled (%)**	**C/B Ratio**	**Density (g/cc)**	**Green MOR (Mpa or psi)**	**Fired MOR (Mpa, psi or Mohs scale of hardness)**	**Efflorescence or Scumming**	**Fired Color**	**Comments**
00DKA-151 [6]		2.90	1.03	13.91	16.85	0.83	1.80	188.7 psi	1257.4 psi	efflorescence	med. pinkish tan	
00DKA-154 [6]		3.12	0.92	15.38	18.08	0.85	1.72	219.5 psi	1238.9 psi	efflorescence	light pinkish tan	
Brady and Dean Sample 4 [7]												
991ºC			0.00						fairly hard		light red	
1040ºC			0.70						fairly hard		light red	
1101ºC			1.30						hard		brown-red	
1117ºC			2.00						very hard		red-brown	
Brady and Dean Sample 5 [7]												
991ºC			0.00						fairly hard		dark salmon	
1040ºC			0.00						hard		dark salmon	
1101ºC			0.30						hard		light red-brown	
Brady and Dean Sample 6 [7]												
991ºC			-0.10						fairly hard		light red	
1040ºC			-0.10						fairly hard		dark salmon	
1101ºC			0.70						hard		brown-salmon	
1117ºC			0.80						hard		brown-salmon	
Guillet - Owen Sound [4]												
1660ºF	21.0	3.30	0.70	17.80	18.60	0.96	1.67		hard		salmon	
1840ºF			0.50	16.00	17.40	0.92	1.66		hard		light salmon	
1980ºF			0.30	15.90	20.70	0.77	1.65		hard		buff	
Guillet - Brampton [4]												
1660ºF	16.0	3.00	0.50	14.30	16.40	0.87	1.85		almost hard		salmon	
1840ºF			1.00	14.10	17.40	0.81	1.81		almost hard		salmon-red	
1980ºF			1.00	12.80	16.60	0.77	1.82		hard		light brown	

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	Water of Plasticity (%)	Dry Shrinkage (%)	Fired Shrinkage (%)	24 Hour Cold (%)	Boiled (%)	C/B Ratio	Density (g/cc)	Green MOR (Mpa or psi)	Fired MOR (Mpa, psi or Mohs scale of hardness)	Efflorescence or Scumming	Fired Color	Comments
Guillet - Milton Quarry[4]												
1660°F	18.0	2.90	0.00	10.90	12.20	0.89	1.95		hard		orange-red	
1840°F			0.30	8.70	11.20	0.78	1.97		very hard		orange-red	
1980°F			1.70	3.00	4.00	0.75	2.04		very hard		brown	
Guillet - National Sewer[4]												
1660°F	18.0	3.70	0.70	14.90	17.20	0.87	1.81		almost hard		salmon	
1840°F			0.50	14.20	17.40	0.82	1.80		almost hard		pink-brown	
1980°F			3.30	6.10	9.80	0.62	1.91		very hard		green-brown	
Guillet - Natco[4]												
1660°F	17.0	2.60	0.30	11.60	13.30	0.87	1.90		almost hard		red	
1840°F			0.30	11.30	14.00	0.81	1.88		almost hard		red	
1980°F			0.30	6.40	9.50	0.67	1.92		very hard		red-brown	
Guillet - Can. Pressed[4]												
1660°F	18.0	4.00	0.30	11.30	12.70	0.89	1.96		almost hard		salmon	
1840°F			1.00	9.30	11.40	0.82	2.00		hard		salmon-red	
1980°F			2.00	5.60	8.10	0.69	2.06		very hard		red-brown	
Guillet - Grimsby[4]												
1660°F	15.0	2.70	0.70	11.10	13.20	0.84	1.95		almost hard		dark salmon	
1840°F			0.90	10.50	13.20	0.80	1.94		almost hard		dark salmon	
1980°F			0.80	5.60	9.00	0.62	2.01		hard		dark red	
Guillet - St. Catharines[4]												
1660°F	18.0	3.60	0.30	12.00	13.40	0.90	1.95		almost hard		salmon	
1840°F			2.30	8.50	10.30	0.83	2.05		hard		salmon-red	
1980°F			4.90	3.20	4.50	0.71	2.26		very hard		red-brown	

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	Water of Plasticity (%)	Dry Shrinkage (%)	Fired Shrinkage (%)	24 Hour Cold (%)	Boiled (%)	C/B Ratio	Density (g/cc)	Green MOR (Mpa or psi)	Fired MOR (Mpa, psi or Mohs scale of hardness)	Efflorescence or Scumming	Fired Color	Comments
Kwong-85-L4 [8]												
923°C	15.8	1.30	1.20	14.23	14.85	0.96		0.93 Mpa	13.2 Mpa	efflorescence	reddish brown	
999°C			2.00	13.74	15.14	0.91			13.5 Mpa		light brown	
1060°C			2.67	9.68	12.34	0.78			18.8 Mpa		reddish orange	
1101°C			2.67	9.05	10.85	0.83			17.8 Mpa		reddish orange	
Kwong-85-L5 [8]												
923°C	14.2	2.10	0.54	13.80	14.40	0.96		0.86 Mpa	11.1 Mpa	efflorescence	light brown	
999°C			0.67	13.00	14.48	0.90			12.8 Mpa		light brown	
1060°C			0.54	10.68	12.79	0.84			17.8 Mpa		med. red-brown	
1101°C			3.23	9.35	12.17	0.77			16.6 Mpa		med. red-brown	
Kwong-85-L6 [8]												
923°C	15.1	2.10	0.13	14.32	14.96	0.96		1.07 Mpa	9.1 Mpa	efflorescence	light brown	
999°C			0.54	12.54	14.41	0.87			12.4 Mpa		light brown	
1060°C			0.54	11.08	13.25	0.84			14.1 Mpa		light brown	
1101°C			1.21	11.00	13.23	0.83			16.4 Mpa		red brown	
Kwong-85-L8 [8]												
923°C	14.3	1.90	0.13	11.63	12.27	0.95		0.83 Mpa	9.5 Mpa	efflorescence	brown	
999°C			1.88	8.79	9.96	0.88			18.4 Mpa		light red-brown	
1060°C			3.49	3.90	5.76	0.68			25.1 Mpa		red-brown	
1101°C			3.35	3.63	5.19	0.70			20.8 Mpa		light brown	
Martini Lab No. 1 [3]												
923°C	20.5	2.51	0.27	15.01	16.36	0.92	1.85	2.55 Mpa	12.70 Mpa	scumming	light brown	
999°C			5.45	5.56	5.78	0.96	2.18			scumming	med. red-brown	
1060°C			5.53	4.44	5.08	0.87	2.20		46.64 Mpa	scumming	med. red-brown	
1101°C			6.76	0.65	0.65	1.00	2.40		46.00 Mpa	scumming	dark red-brown	

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	Water of Plasticity (%)	Dry Shrinkage (%)	Fired Shrinkage (%)	24 Hour Cold (%)	Boiled (%)	C/B Ratio	Density (g/cc)	Green MOR (Mpa or psi)	Fired MOR (Mpa, psi or Mohs scale of hardness)	Efflorescence or Scumming	Fired Color	Comments
Martini Lab No. 4 [3]												
923°C	14.0	2.20	-0.13	13.31	14.43	0.92	2.02	1.18 Mpa	6.99 Mpa		med. red-brown	
999°C			1.21	10.70	12.62	0.85	2.11		33.72 Mpa		med. red-brown	
1060°C			1.34	8.79	10.88	0.81	2.18		43.40 Mpa		med. red-brown	
1101°C			2.01	7.64	10.29	0.74	2.23		38.51 Mpa		med. red-brown	
1120°C			1.96	5.32	8.38	0.63	2.14		43.25 Mpa		med. red-brown	
1137°C			3.71	2.22	2.47	0.90	2.36		61.37 Mpa		med. red-brown	
Martini Lab No. 9 [3]												
923°C	15.0	2.40	0.00	15.77	16.33	0.97	1.96	1.19 Mpa	12.70 Mpa	efflorescence	med. red-brown	
999°C			1.08				2.03			efflorescence	med. red-brown	
1060°C			2.29	11.15	12.34	0.90	2.11			efflorescence	med. red-brown	
1101°C			2.97	7.27	8.85	0.82	2.10			efflorescence	med. red-brown	
Martini Lab No. 13 [3]												
923°C	14.1	1.52	0.00	14.93	15.77	0.95	1.86	1.52 Mpa	18.20 Mpa		medium brown	
999°C			0.13	10.37	13.36	0.78	1.96		50.01 Mpa		medium brown	
1060°C			1.26	10.41	12.59	0.83	1.92		48.14 Mpa		light brown	
1101°C			1.26	10.06	12.84	0.78	1.93		50.03 Mpa		light brown	
1120°C			1.60	7.74	8.40	0.92	1.98		48.33 Mpa		light brown	
1137°C			3.46	1.70	2.71	0.63	2.19		64.49 Mpa		brown	
Martini Lab No. 14 [3]												
923°C	14.0	1.59	-0.33	15.06	15.73	0.96	1.96	1.20 Mpa			med. red-brown	drying cracks
999°C			1.47	10.65	12.09	0.88	2.08				med. red-brown	drying cracks
1060°C			1.93	10.30	11.65	0.88	2.13		36.70 Mpa		med. red-brown	
1101°C			2.88	7.47	9.01	0.83	2.26		39.17 Mpa		med. red-brown	
Martini Lab No. 15 [3]												
923°C	16.0	1.47	0.66	10.50	12.26	0.86	2.04	1.82 Mpa	19.88 Mpa	efflorescence	brown	
999°C			2.01	7.84	11.16	0.70	2.11		55.64 Mpa		brown	

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	**Water of Plasticity (%)**	**Dry Shrinkage (%)**	**Fired Shrinkage (%)**	**24 Hour Cold (%)**	**Boiled (%)**	**C/B Ratio**	**Density (g/cc)**	**Green MOR (Mpa or psi)**	**Fired MOR (Mpa, psi or Mohs scale of hardness)**	**Efflorescence or Scumming**	**Fired Color**	**Comments**
1060°C			3.20	5.42	9.47	0.57	2.19		57.29 Mpa		med. red-brown	
1101°C			2.74	5.81	7.98	0.73	2.14		56.34 Mpa		med. red-brown	
1120°C			3.54	4.13	4.81	0.86	2.17		48.45 Mpa		med. red-brown	
1137°C			4.81	0.57	0.63	0.90	2.26		45.15 Mpa		med. red-brown	
Martini Lab No. 16 [3]												
923°C	14.0	1.41	0.07	12.52	13.51	0.93	1.91	1.47 Mpa	17.98 Mpa	efflorescence	brown	drying cracks
999°C			0.40	11.67	15.06	0.77	1.98				medium brown	
1060°C			0.33	11.71	15.65	0.75	1.91				light brown	
1101°C			0.60	10.94	15.37	0.71	1.90		51.48 Mpa		light brown	
1120°C			0.80	9.84	12.87	0.76	1.98				light brown	
1137°C			3.40	2.92	3.06	0.95	2.20		53.42 Mpa		med. red-brown	
OPG Sample												
1080°C	6.31		1.29	8.87	11.22	0.79				scumming		scumming, glazing and bloating
Georgian Bay Formation												
Martini Lab No. 6 [3]												
923°C	16.25	2.26	0.43	13.10	14.16	0.93	2.02	2.76 Mpa	16.21 Mpa		light brown	
999°C			4.90	7.37	8.80	0.84	2.24		38.93 Mpa	scumming	med. red-brown	
1060°C			6.71	2.39	2.79	0.86	2.33		56.81 Mpa	scumming	dark red-brown	
1101°C			7.89	0.41	1.17	0.35	2.50		63.29 Mpa		dark red-brown	
Martini Lab No. 7 [3]												
923°C	16.25	2.84	1.83	13.03	14.03	0.93	1.99	2.22 Mpa	32.82 Mpa	scumming	light brown	
999°C			4.59	7.73	8.29	0.93	2.19		37.87 Mpa	scumming	light brown	
1060°C			8.62	0.01	0.22	0.05	2.46		83.40 Mpa	scumming	dark red-brown	
1101°C			6.97	0.04	0.04	1.00	2.64		83.30 Mpa	scumming	dark red-brown	

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	**Water of Plasticity (%)**	**Dry Shrinkage (%)**	**Fired Shrinkage (%)**	**24 Hour Cold (%)**	**Boiled (%)**	**C/B Ratio**	**Density (g/cc)**	**Green MOR (Mpa or psi)**	**Fired MOR (Mpa, psi or Mohs scale of hardness)**	**Efflorescence or Scumming**	**Fired Color**	**Comments**
Guillet - Ont. Reform [4]												
1660°F	24.0	4.50	0.50	14.20	15.40	0.92	1.88		hard		salmon	
1840°F			2.80	10.10	12.40	0.81	2.00		very hard		salmon-red	
1980°F			6.30	1.50	2.90	0.52	2.31		very hard		dark red	
Guillet - Booth Brick [4]												
1660°F	16.0	2.00	0.00								light salmon	
1840°F			0.30	12.80	15.70	0.82	1.90		almost hard		salmon	
1980°F			0.50	8.00	11.80	0.68	1.90		very hard		brown	
Guillet - Cooksville Area [4]												
1660°F	17.0	2.20	0.00	13.30	14.90	0.89	1.93		hard		light salmon	
1840°F			0.50	11.70	13.60	0.86	1.97		hard		salmon	
1980°F			2.00	5.60	7.80	0.72	2.05		very hard		brown	
Guillet 1977 - Average [4]												
1660°F	18.0	2.30	0.10	13.10	14.60	0.90	1.94		almost hard		pale salmon	
1840°F			0.60	11.70	13.80	0.85	1.97		hard		salmon	
1980°F			2.40	4.30	6.80	0.63	2.20		very hard		dark brown	
Blue Mountain Formation												
Martini Lab No. 2 [3]												
923°C	19	2.15	0.61	12.30	13.63	0.90	2.00	3.62 Mpa	38.70 Mpa		light brown	
999°C			5.37	5.18	5.78	0.90	2.26		52.10 Mpa	scumming	med. red-brown	
1060°C			7.06	1.95	1.89	1.03	2.26		58.74 Mpa	scumming	dark red-brown	
1101°C			6.79	0.27	1.03	0.26	2.50		76.34 Mpa	scumming	dark red-brown	
Guillet 1977 - 66-443 [4]												
1660°F	26.0	5.80	2.00	15.10	15.90	0.95	1.82		almost hard		salmon	
1840°F			5.30	9.10	9.50	0.96	2.05		very hard		red	
1980°F			8.80	0.50	0.60	0.83	2.36		very hard		dark red	

		Shrinkage		Absorption				Strength				
Cone (where applicable) or Temperature	**Water of Plasticity (%)**	**Dry Shrinkage (%)**	**Fired Shrinkage (%)**	**24 Hour Cold (%)**	**Boiled (%)**	**C/B Ratio**	**Density (g/cc)**	**Green MOR (Mpa or psi)**	**Fired MOR (Mpa, psi or Mohs scale of hardness)**	**Efflorescence or Scumming**	**Fired Color**	**Comments**
Guillet 1977 - 62-411 [4]												
1660°F	21.0	3.60	1.70	11.20	13.20	0.85	2.00		very hard		salmon	
1840°F			5.40	4.70	6.90	0.68	2.23		very hard		salmon-pink	
1980°F			4.50	0.50	2.40	0.21	2.09		very hard		brown	

Notes:

C/B ratio = the ratio of 24-hour cold water absorption to the 5-hour boiling absorption. Otherwise referred to as the saturation coefficient.

MOR = modulus of rupture.

[1] *Rutka and Vos (1993)*

[2] *Rowell (2009b)*

[3] *Martini and Kwong (1986)*

[4] *Guillet (1977)*

[5] *Rowell and Brunton (2011)*

[6] *Armstrong (2001a)*

[7] *Brady and Dean (1966)*

[8] *Kwong, Martini and Narain (1985)*

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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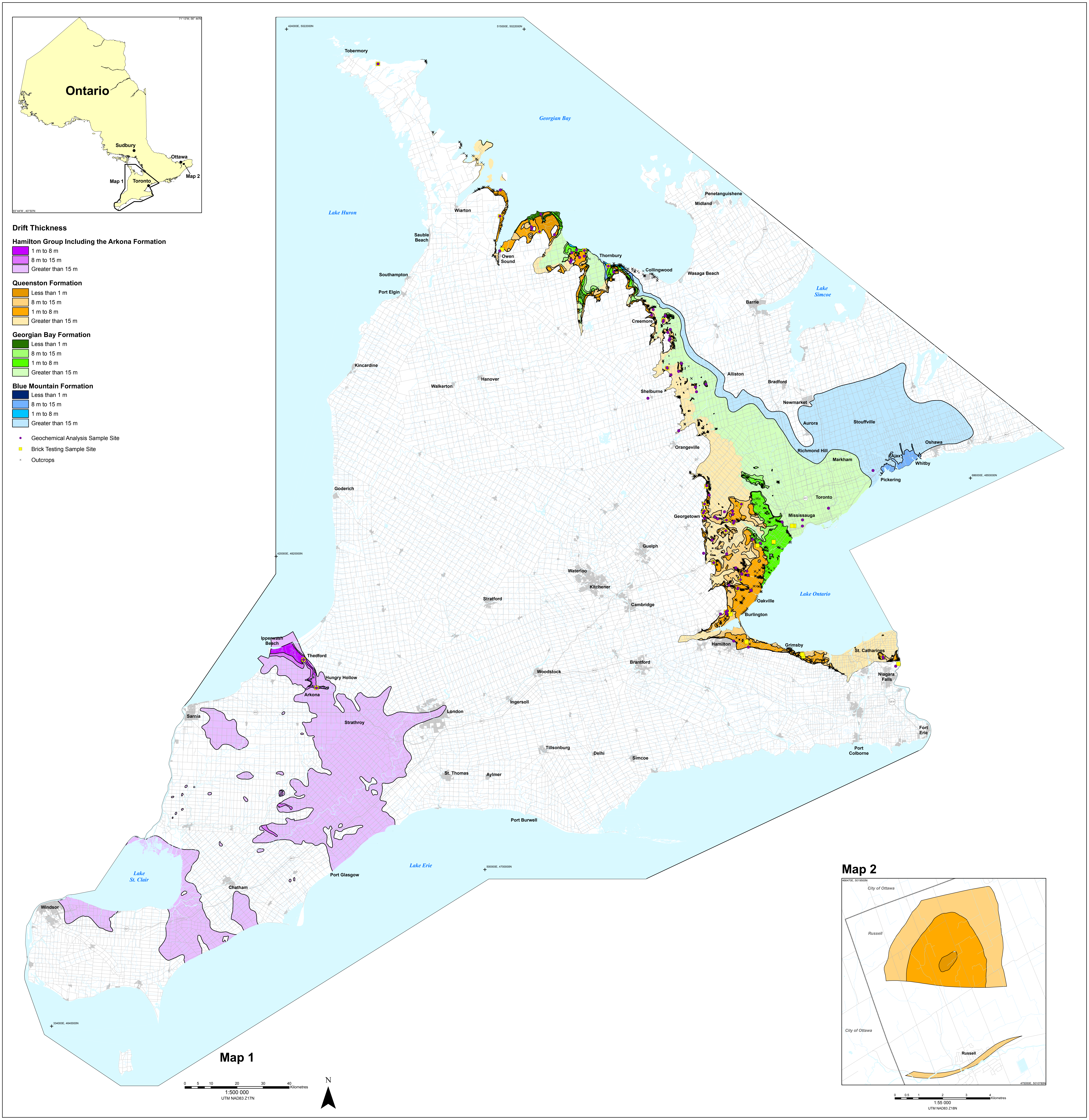

Figure 1. Shale resources of southern Ontario showing drift thickness, and location of geochemical and brick testing sample sites.

Accompanies Open File Report 6278.