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Paleozoic Geology of the Northern Lake Simcoe Area, South-Central Ontario

2000

ONTARIO GEOLOGICAL SURVEY

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by

D.K. Armstrong

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Introduction

GEOGRAPHIC AREA

The north Lake Simcoe study area consists of the area underlain by Paleozoic bedrock between latitudes 44º30′N and 44º53′N, and between longitude 80º09′W and 78º30′W. The study area essentially follows the erosional edge of the Paleozoic bedrock in south–central Ontario from the Penetanguishene Peninsula in southeastern Georgian Bay, eastward towards the town of Bobcaygeon (Figures 1 and 2). This area is covered by 1:50 000 scale National Topographic System (NTS) map sheets 31D/12, 31D/11, 31D/10 and parts of 41A/9, 41A/16, 31D/13, 31D/14, and 31D/15. The study area includes parts of Simcoe, Victoria and Peterborough counties and the northernmost part of the Regional Municipality of Durham. The study area is also covered by Ontario Geological Survey (OGS) Paleozoic bedrock geology maps P.3339, OFM 222, and OFM 235 (Figure 1).

PREVIOUS WORK

The Paleozoic bedrock of south–central Ontario has been the subject of geological investigation since at least the 1842 survey of Alexander Murray (Liberty 1969). The Ordovician strata from the Lake Simcoe area through to Kingston, New York State and the Ottawa area has been studied by numerous geologists and paleontologists in the more than 150 intervening years. Many outcrops and exposures in this region are recognized as “classic” sections. This previous work is well reviewed in Liberty’s (1969) memoir covering the Paleozoic geology of the Lake Simcoe area.

Geological investigations in the Lake Simcoe area since Liberty’s work mainly include studies of sedimentology and diagenesis (e.g., Mukherji 1969; Mukherji and Young 1973; Brett and Brookfield 1984; Brookfield and Brett 1988; Brookfield 1988; Noor 1989; McFarland 1997; McFarland et al. 1997; Grimwood 1998; Grimwood et al. 1999) and of bedrock resource quality (Dolar–Mantuani 1975; Koniuszy and Rogers 1983; Rogers 1985, 1986; Derry Michener Booth and Wahl and Ontario Geological Survey 1989; LeBaron and Williams 1990). There have also been a number of field trip guidebooks that cover this area (e.g., Kobluk and Brookfield 1982; Coniglio et al. 1990; Melchin et al. 1994). Studies in adjacent areas with correlative stratigraphy include mapping to the east by the Ontario Geological Survey (OGS) (Carson 1980a–d, 1981) and graduate theses in the Kingston area (Brown 1997; McFarlane 1992).

PRESENT STUDY

The Middle Ordovician limestones of the Lake Simcoe area are a major source of aggregate in Ontario. During field mapping in 1992–93 there were 11 aggregate and 2 landscaping stone quarries in operation in this area (a list of active and inactive quarries is presented in Appendix 1). Development pressures in the Niagara Escarpment area, traditionally the primary source of aggregate products for the Toronto area, have seen aggregate companies develop new and expand existing quarry operations in the Lake Simcoe area in order to maintain capacity and meet demand for aggregate products.

Certain beds within the Ordovician succession in the Lake Simcoe area have been identified as being alkali–carbonate reactive (Ryell et al. 1974); that is, crushed stone aggregate from these beds react with alkalis in cement causing concrete to expand (Rogers 1985). The main objective of the present study is to regionally delineate alkali–carbonate reactive beds and investigate controls on their origin and distribution.

The present study commenced in 1990 with reconnaissance investigations throughout the Middle Ordovician outcrop belt in south–central to eastern Ontario (Armstrong 1990). The study continued in 1991 with further reconnaissance mapping and the drilling of a deep drill hole north of Highway 7, 3.5 km west of the village of Manilla (Armstrong and Byerley 1991). Detailed mapping followed during the

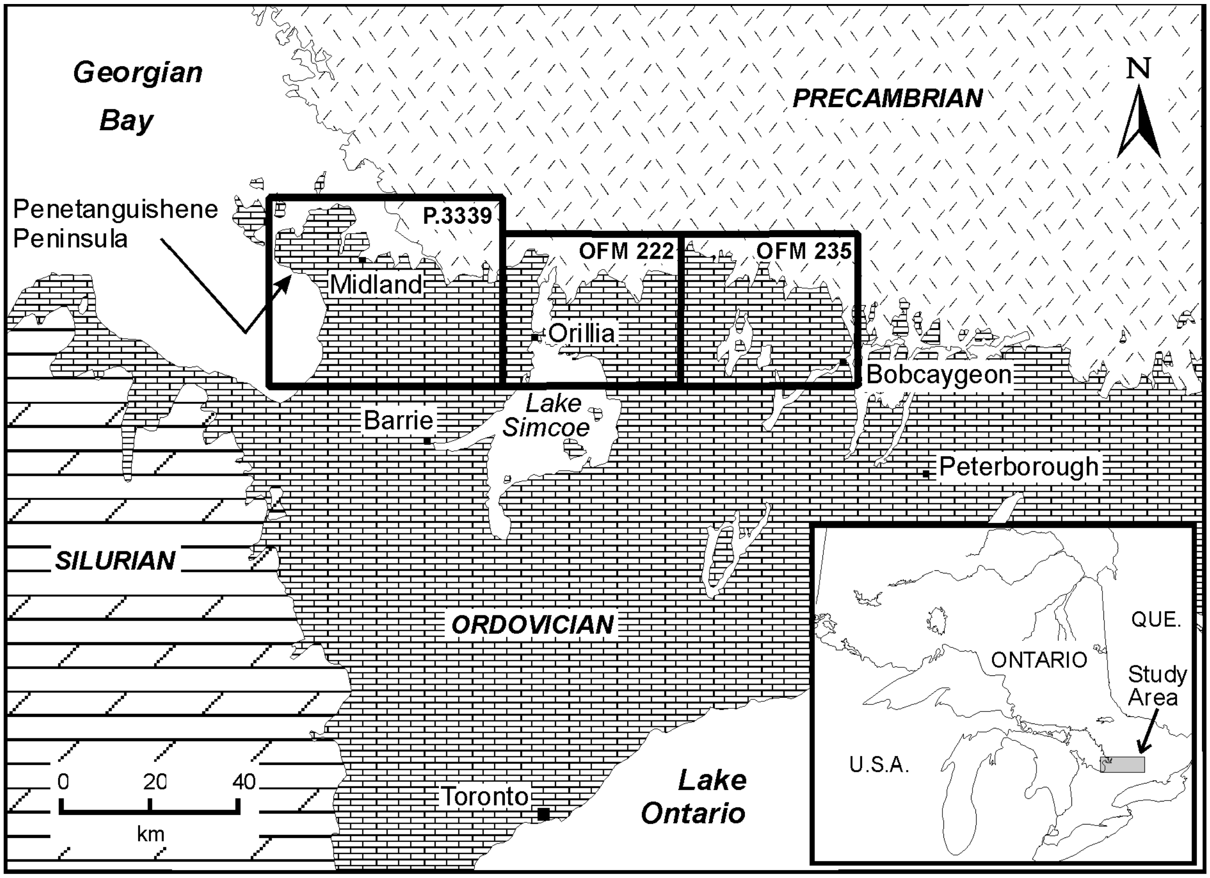


Figure 1: North Lake Simcoe project area (3 boxes) and general bedrock geology of south-central Ontario (modified from Armstrong 1999a and Ontario Geological Survey 1991). Numbered boxes indicate location and number of recent OGS Paleozoic bedrock geology maps (P.3339, Armstrong and Rhéaume 1995; OFM 222, Armstrong and Anastas 1993; OFM 235, Armstrong and Rhéaume 1993b).

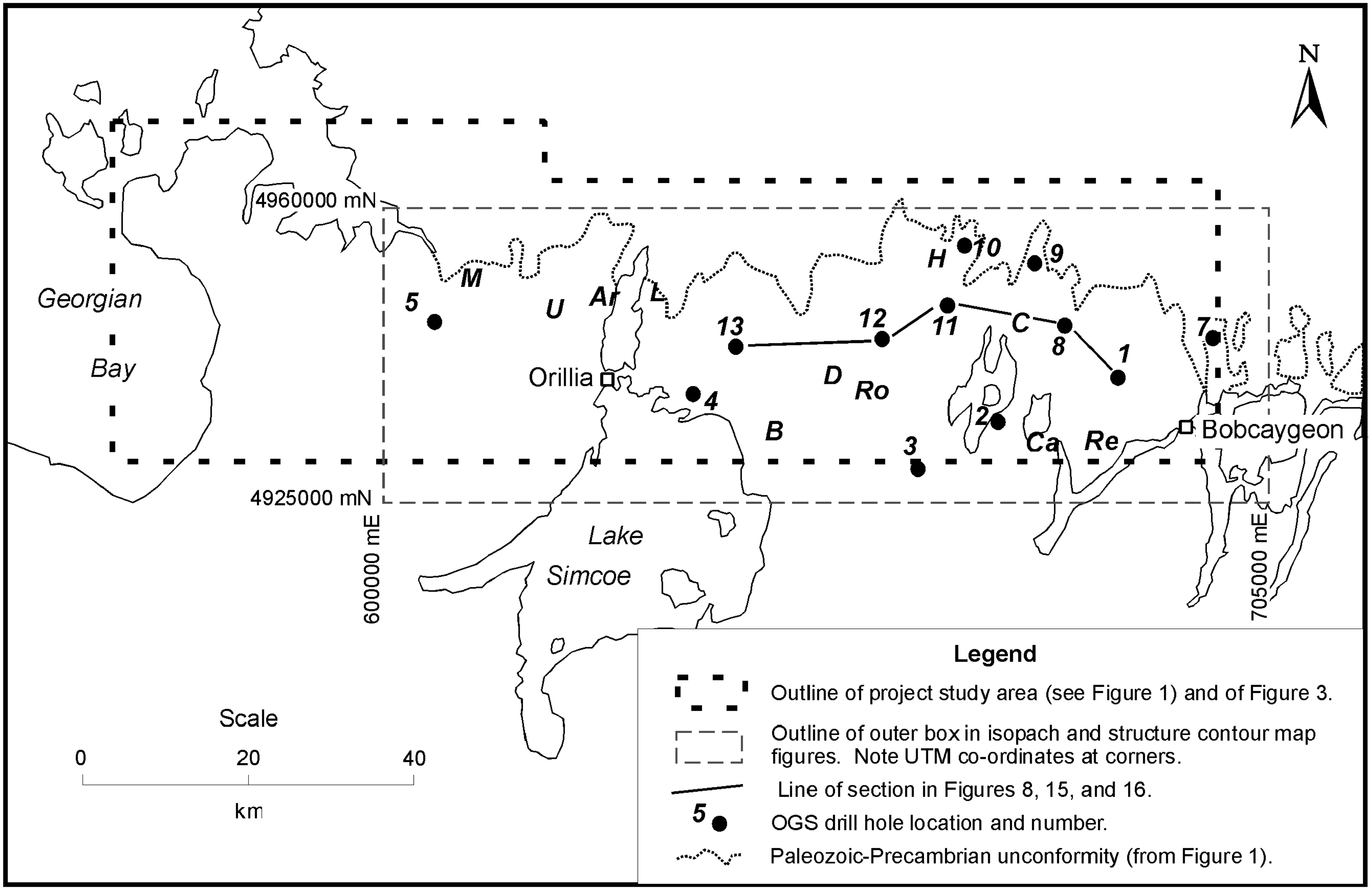


Figure 2: Outline of project study area and location of isopach and structure contour map figures presented in this report. Also shown, are the approximate locations of OGS drill holes, quarries (M = Medonte, U = Uhthoff, L = Longford, B = Brechin, D = Dalrymple, C = Coboconk), outcrops (H = Head Lake roadcut), and Precambrian inliers (Ar = Ardtrea, Ro = Rohallion, Ca = Cameron Lake, Re = Red Rock) used to construct isopach and structure contour figures.

summers of 1992 and 1993 (Armstrong and Anastas 1992; Armstrong and Rhéaume 1993a) with resulting open file and preliminary maps published shortly thereafter (Figure 1; Armstrong and Anastas 1993; Armstrong and Rhéaume 1993b, 1995). Figure 3 is a simplified bedrock geology map for the study area, covering the Penetanguishene–Elmvale (Armstrong and Rhéaume 1995), Orillia (Armstrong and Anastas 1993), and Fenelon Falls map sheets (Armstrong and Rhéaume 1993b).

Twelve holes were drilled in support of this project in the spring of 1993 (Armstrong 1995). The locations of these drill holes are plotted, along with locations of major quarries in the study area, in Figures 2 and 3. All of the drill holes were continuously cored through the Ordovician bedrock section and into the Precambrian basement. The cores provided unweathered, stratigraphically well–constrained samples for petrographic, geochemical and aggregate quality analysis. The drill holes were also geophysically logged. Lithologic, geochemical and geophysical logs and data for these drill holes are presented in Armstrong (1999a, 1999b). Armstrong (1999a) also reported on the geophysical and geochemical characteristics of the various Paleozoic bedrock units encountered in the drilling.

This report summarizes the findings of the regional mapping, including a synthesis of both surface and subsurface data. This report is intended to accompany Ontario Geological Survey Preliminary Map P.3339 for the Elmvale–Penetanguishene area (Armstrong and Rhéaume 1995), open file maps OFM 222 for the Orillia area (Armstrong and Anastas 1993) and OFM 235 for the Fenelon Falls area (Armstrong and Rhéaume 1993b), and the report of drilling results, OFR 5999 (Armstrong 1999a). A forthcoming report (Armstrong and Williams, in prep.) will present results of aggregate testing of these strata, including alkali–carbonate reactivity testing.

General Geology

The northern Lake Simcoe study area is underlain by both Paleozoic and Precambrian age bedrock. Precambrian igneous and metamorphic rocks of the Grenville Province are exposed in the extreme northern part of the study area and form the basement beneath the Paleozoic strata which underlies that remainder of the study area. The trace of the Paleozoic–Precambrian unconformity trends roughly east–west across the study area (Figures 1, 2 and 3; Ontario Geological Survey 1991).

Paleozoic bedrock in the Lake Simcoe area consists of carbonate and siliciclastic sedimentary rocks of Middle Ordovician (Blackriveran to Trentonian) age. These strata dip gently (at less than 5 m/km) to the south–southwest and progressively younger units are preserved in that direction. The Ordovician section in the study area attains a maximum thickness of about 100 m at the southern boundary of the study area.

Both Precambrian and Paleozoic terrains are unconformably overlain by unconsolidated Quaternary and Recent sediments. This drift cover is generally thin over the Precambrian terrain in the north and over parts of the Paleozoic terrain. Quaternary drift cover is particularly thick and extensive in the western part of the study area. Details of the Quaternary geology of the north Lake Simcoe area are published in maps and reports by Burwasser and Boyd (1974), Finamore and Bajc (1983, 1984), Barnett (1989, 1997), Bajc (1994), and Barnett et al. (1991).

Precambrian Geology

The geology of the Middle Proterozoic Grenville Province in Ontario is reviewed by Easton (1992). Recent maps and reports on the Precambrian geology in the Lake Simcoe area include Easton (1988), Easton and Carter (1994) and Lumbers and Vertolli (2000a, 2000b). In the study area the Grenville Province is subdivided into 2 major belts: the Central Gneiss Belt (CGB) in the west and the Central Metasedimentary Belt (CMB) in the east (Figure 3; Easton 1992).

The CGB consists mainly of quartzofeldspathic gneissic rocks of plutonic origin, with subordinate amounts of metasedimentary gneissic rocks (Easton and Carter 1994). The CMB consists of a "major

Middle Proterozoic accumulation of metavolcanic and siliciclastic and carbonate metasedimentary rocks" (Easton and Carter 1994). These 2 belts are separated by the Central Metasedimentary Belt Boundary Zone (CMBBZ), a major shear zone several kilometres wide, "characterized by strongly deformed rocks with northeasterly–trending, moderately to shallowly southeasterly dipping tectonic layering, and southeast–plunging mineral lineations" (Easton and Carter 1994). The CMBBZ can be traced southward, beneath the Paleozoic cover, with regional magnetic and gravity data (e.g., Gupta 1991a, 1991b). It has been interpreted to be coincident with a magnetic lineament termed the Niagara–Pickering Linear Zone (Wallach 1990). The characterization of the CMBBZ in the subsurface is discussed by Forsyth et al. (1994) and Easton and Carter (1994).

All 12 OGS drill holes were cored into the Precambrian basement (Armstrong 1999a). Most of these holes intersected gneiss ranging from felsic through to intermediate or mafic. One hole, OGS–93–05, intersected metagabbro pseudo–eclogite, and another OGS–93– 07, encountered amphibolite. Felsic pegmatite ranged from a minor to major constituent in most holes. One hole, OGS–93–01, intersected metasediments (graphitic metapelite and dolomitic marble). The top 2 m of the Precambrian interval in this core was also considerably brecciated. Weathering of the uppermost Precambrian ranged from very minor (e.g., slight bleaching, fractures with iron oxide coatings) to up to 2 m deep and the local development of a regolith. A regolith was preserved in only 2 of the drill holes, OGS–93–08 and OGS–93–02.

THE PRECAMBRIAN SURFACE

The Precambrian surface upon which the Ordovician sea transgressed is generally thought of as being a peneplained, gently undulatory surface. This interpretation is perhaps suggested by the Precambrian terrain to the immediate north, which has also been subjected to post–Ordovician erosion. Inliers of Precambrian basement within the Paleozoic occur at a number of locations and stratigraphic levels in the study area (Armstrong and Rhéaume 1993b; Armstrong and Anastas 1993). A structure contour map of the Precambrian surface, generated from OGS drill hole data (Armstrong 1999a), suggests a generally smooth surface gently dipping to the south–southwest at less than 3 m/km. Including the elevations of the Precambrian inliers at Red Rock, Cameron Lake, Rohallion, and Ardtrea, reveals a more irregular Precambrian surface (Figure 4). The effect of this irregular paleotopography on Ordovician sedimentation is discussed in the following sections.

Ordovician Geology

During the Blackriveran Stage of the Middle Ordovician, a major marine transgression, called the Tippecanoe, transgressed over older Cambrian sediments (south of the study area) and the Precambrian Shield in southern Ontario (Johnson et al. 1992). This transgression is reflected in the Middle Ordovician strata of the north Lake Simcoe area by an overall deepening upward succession of basal nearshore siliciclastics, through supratidal and intertidal dolostones and limestones, and subtidal lagoonal and shoal limestones, to deeper shelf, mixed limestones and shales. This succession was subdivided by Liberty (1969) into 4 formations, in ascending order, the Shadow Lake, Gull River, Bobcaygeon, and Verulam formations (Figures 3 and 5). Liberty (1969) assigned all of these formations, except for the siliciclastic–dominated Shadow Lake Formation, to the Simcoe Group. He assigned the Shadow Lake Formation as the uppermost unit of the Cambro–Ordovician Basal Group. Although Cambrian age strata are reported from the subsurface to the south, in the vicinity of Toronto (Liberty 1969), no Cambrian sediments are known to underlie the Shadow Lake Formation in the present study area. Grimwood et al. (1999), following on previous suggestions (e.g., Noor 1989; Melchin et al. 1994; Armstrong 1997) which noted that the Shadow Lake Formation is conformable with and thus genetically linked to the overlying carbonates of the Gull River Formation, assigned the Shadow Lake Formation to the Simcoe Group (Figure 5). The lithologic characteristics of the formations constituting the Simcoe Group in the north Lake Simcoe area are discussed in the following sections.

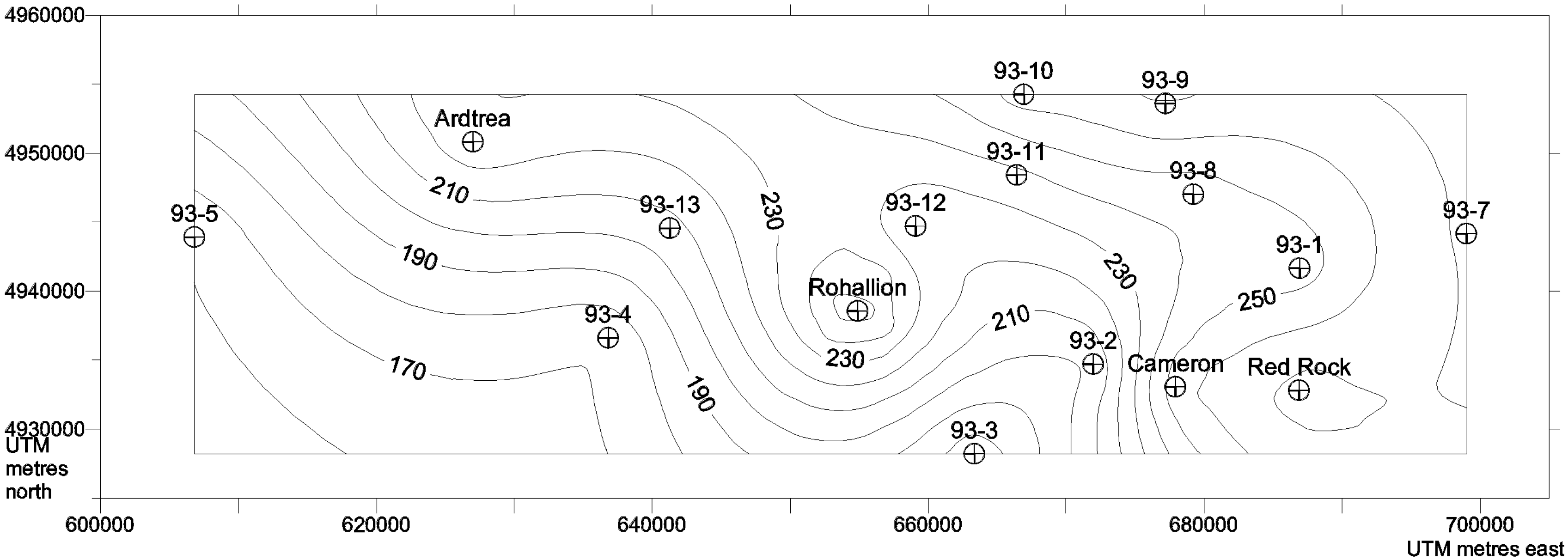
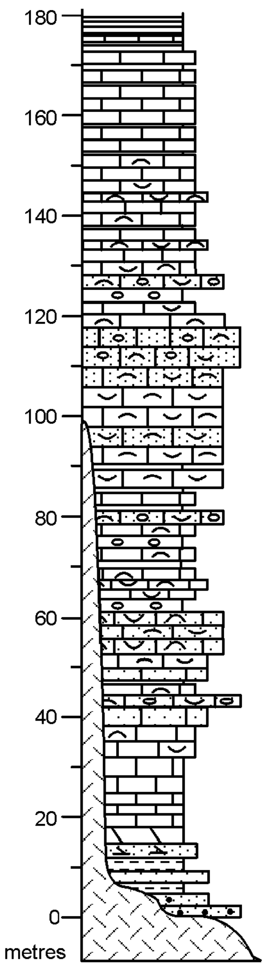


Figure 4: Structure contour of the Precambrian basement surface (metres above sea level). Data points (circled crosses) include numbered OGS drill holes (e.g., 93-5) and Precambrian inliers (Ardtrea, Rohallion, Cameron and Red Rock). See Figure 2 for location of map area. Contour interval = 100 m.



CHARACTERISTIC LITHOLOGIES	DEPOSITIONAL ENVIRONMENTS	South-central Ontario (a)		Southwestern Ontario (b)		N. American Stages (c)
petroliferous, argillaceous lime mudstone	DEEP SHELF	SIMCOE GROUP	COLLINGWOOD MB.		COLLINGWOOD FM.	MAYSVILLIAN
bioclastic lime mudstone-wackestone	DEEP SHELF		L LINDSAY FORMATION	TRENTON GROUP	COBOURG FORMATION	EDENIAN
bioclastic wackestone-packstone, bioclastic grainstone	SHALLOW SHELF					
intra-bioclastic grainstone	SHALLOW SHOAL		U VERULAM FORMATION		VERULAM FORMATION	
bioclastic packstone-grainstone	SHOAL-SHALLOW SHELF		L			TRENTONIAN
bioclastic wackestone-grainstone, calcareous shale	DEEP SHELF					
bioclastic grainstone	SHALLOW SHELF		U BOBCAYGEON FORMATION		U KIRKFIELD FORMATION	
wacke-grainstone + shale			M		L	
intra-peloidal wacke-grainstone bioclastic wackestone	SHOAL		L	BLACK RIVER GP.	COBOCONK FM.	BLACKRIVERAN
lime mudstone dolostone	LAGOON - TIDAL FLAT		U / L GULL RIVER FORMATION		GULL RIVER FORMATION	
arkosic siltstone, argillaceous sandstone conglomerate	NEARSHORE-SUPRATIDAL		SHADOW LAKE FORMATION		SHADOW LAKE FORMATION	
	PRECAMBRIAN SHIELD					

Figure 5: Lithostratigraphy, chronostratigraphy and depositional environments of the Simcoe Group in south-central Ontario (modified after Grimwood et al. 1999; Melchin et al. 1994; Brookfield and Brett 1988). South-central Ontario nomenclature (column a) as proposed by Grimwood et al. (1999) and Armstrong (1997). Southwestern Ontario nomenclature (column b) after Winder and Sanford (1972) and Johnson et al. (1985). North American Ordovician stages (column c) are as modified by Melchin et al. (1994), after Barnes et al. (1981). Key: U = upper member; M = middle member; L = lower member.

SHADOW LAKE FORMATION

The oldest Paleozoic strata in the north Lake Simcoe area consist of the mainly siliciclastic sediments of the Shadow Lake Formation. These strata lie unconformably and sharply on the Precambrian Grenville basement, however, this basal contact is rarely exposed. The Shadow Lake Formation is poorly exposed, typically occurring in small isolated outcrops along a low escarpment capped by the more resistant carbonate beds of the overlying Gull River Formation. Trending roughly east–west across the study area and ringing Paleozoic outliers, this escarpment marks the edge of the Paleozoic outcrop belt (Figure 3).

The Shadow Lake Formation consists of non–fossiliferous, red, maroon and green, poorly sorted, argillaceous, arkosic sandstones and conglomerates, arenaceous (sandy) siliciclastic mudstones (shales) and siltstones, and minor argillaceous dolostones and limestones. These rock types are commonly interbedded and gradational with each other.

The Shadow Lake Formation, originally named by Okulitch (1939) based on outcrops north of Coboconk, was redefined by Liberty (1969). Okulitch included dolomitic limestones in the top of Shadow Lake Formation, whereas Liberty assigned these strata to the overlying Gull River Formation (Liberty 1969, page 22). The present study follows the latter convention.

The siliciclastic sediments of the Shadow Lake Formation are gradationally overlain by impure carbonates of the Gull River Formation. The upper contact of the Shadow Lake Formation is placed where its mainly siliciclastic sediments give way to mainly carbonate sediments (typically argillaceous dolostones) of the lower Gull River Formation. Natural weathering accentuates this contact, making it appear sharp in outcrop, whereas in drill core this contact can be difficult to pick out.

In the study area the Shadow Lake Formation ranges from 0 to almost 10 m in thickness, and averages approximately 6 m in thickness. An almost complete section, 6 m thick, of the formation is exposed in the sump at the Waubaushene Quarry (locality 93DKA–443[1]), located 4 km northeast of Waubaushene. The basal contact is not clearly exposed here, however, large blocks of the underlying Precambrian basement have been dug up in the bottom of the sump. Two other exposures in the study area expose almost 6 m of the Shadow Lake Formation: 5.78 m in a roadcut on the west side of Head Lake (locality 92DKA–148) and 5.8 m in a creekbed outcrop (locality 92DKA–109) located approximately 3.35 km east–northeast from Highway 169 and 2 km south–southeast of the Head River. Both of these locations expose the sharp upper contact of this formation with the overlying argillaceous dolostones of the Gull River Formation. Neither of these outcrops expose the basal contact of the Shadow Lake Formation. Another relatively thick (5 m) outcrop of this formation is located on the northwest shore of Quarry Island (locality 93DKA–346), a Paleozoic outlier in Georgian Bay, 11 km northeast of Midland.

Other significant outcrops (including its upper contact) of the Shadow Lake Formation in the north Lake Simcoe area include: an almost 3 m high outcrop on the shoreline of Georgian Bay at Waubaushene (locality 93DKA–341); approximately 2 m in the lower lift of Grass Lake Quarry (locality 92DKA–200) located 2.5 km northwest of Lake St. George; and 2.25 m in a roadcut southwest of Beech Lake (locality 93DKA–412).

The type section of the Shadow Lake Formation (Okulitch 1939; Liberty 1969) is located on the west side of Highway 35, approximately 6.4 km north of the town of Coboconk and 0.4 km west of Shadow Lake (locality 93DKA–418). At the time of mapping (1992 and 1993), the section was severely slumped and overgrown. Recent road improvements have resulted in a much cleaner section. Approximately 2 m of Shadow Lake Formation is now exposed in this outcrop. The basal contact with the underlying Precambrian basement is not exposed at this or any other locality in the study area.

All 12 holes drilled by the OGS in the north Lake Simcoe study area intersected the Shadow Lake Formation (Armstrong 1999a). The thickness of this formation in these holes ranges from 1.63 m to 9.15 m

[1] locations of cited map localities are presented in Appendix 2

and averages 5.89 m (Appendix 3). An isopach map of the formation (Figure 6) illustrates the complicating effect of the irregular basement paleotopography and, when compared with the structure contour of the Precambrian surface (Figure 4), the in–filling nature of the Shadow Lake.

Across the study area, trends in colour and grainsize in the Shadow Lake Formation are not obvious. However, some generalizations can be made. The uppermost strata of this formation are commonly dolomitic argillaceous sandstones or shales, or a very argillaceous sandy dolostone or limestone. The basal beds of the Shadow Lake Formation, typically a half metre or more thick, commonly consist of a coarse sandstone or conglomerate. The formation's basal contact is typically sharp and irregular and small clasts of the underlying Precambrian basement are common in the basal sandstones and conglomerates. In 2 OGS drill holes, OGS–93–2 and OGS–93–8, a regolith was developed beneath the Shadow Lake. And in a few other holes the uppermost Precambrian rocks are slightly weathered or contain weathered (e.g., iron oxide coated) fractures. A yellow–orange mineral (probably a form of iron oxide) is common within the basal few metres of the Shadow Lake Formation. In drill hole OGS–93–13, patches of salmon–red K–feldspar alteration occur in the basal 0.55 m (Armstrong 1999a). Other general characteristics observed in the cores include: burrows (including some vertical burrows up to 30 cm long) and colour–mottling, possibly after burrows; occasional gypsum nodules; and sub–horizontal gypsum–filled fractures. These characteristics are consistent with interpretations (Grimwood et al. 1999; Melchin et al. 1994) of the Shadow Lake Formation as consisting of basal transgressive lag sediments deposited in near–shore marine environments and filling in depressions on the Precambrian surface.

GULL RIVER FORMATION

The Gull River Formation is characterized by sparsely to moderately fossiliferous, thin– to medium–bedded, micritic to fine–grained limestones, dolomitic limestones and dolostones. These predominantly carbonate–rich strata conformably overly the mainly siliciclastic sediments of the Shadow Lake Formation. Although this contact is gradational, natural weathering of the softer siliciclastics accentuates the contact in outcrop. Exposures of this contact in the study area are discussed in the preceding Shadow Lake Formation section.

The Gull River Formation was originally named by Okulitch (1939) based on outcrops located north of Coboconk along the Gull River. Liberty (1969) redefined the formation and subdivided it into 3 informal members, lower, middle, and upper (Figure 5). During the course of the present study it was observed that Liberty's upper member (approximately equivalent to the Moore Hill Formation of Okulitch, 1939) has stronger affinities to the overlying Bobcaygeon Formation than to the Gull River Formation. It was therefore proposed (Armstrong and Anastas 1992; Armstrong and Rhéaume 1993a; Armstrong 1997; Grimwood et al. 1999) that the upper member of Liberty's Gull River Formation be assigned to the lower member of the Bobcaygeon Formation and that the remaining Gull River strata be subdivided into 2 informal members, lower and upper. Thus, the lower member of the Gull River Formation is approximately equivalent to Liberty's original lower member, and the upper member is approximately equivalent to Liberty's middle member (Figure 5).

No single outcrop in the study area exposes the entire Gull River Formation section. Significant outcrops of this formation are reported in the following sections of this report. Complete sections of the Gull River Formation were encountered in all OGS drill holes, except OGS–93–05 (where the upper part of the formation was removed by post–Ordovician erosion). In these cores the Gull River Formation ranges from 10.83 m to 22.58 m in thickness, averaging 18.18 m (Appendix 3). An isopach map of the formation, constructed using these subsurface data and zero values for Precambrian inliers that penetrate the formation (estimated 11 m of Gull River Formation overlying the Ardtrea inlier) is presented in Figure 7. This map illustrates the continuing effect of the inliers on the lateral variability in formation thickness. The Gull River Formation is thickest in the northeast and northwest parts of the study area, in the vicinity of drill holes OGS–93–08 and –09, and the Uhthoff Quarry, respectively.

Lower Member, Gull River Formation

The lower member of the Gull River Formation consists of up to 15 m of grey, light green and brown, fine–grained argillaceous dolomitic limestone, dolostone, and limestone. Characteristics such as evaporite

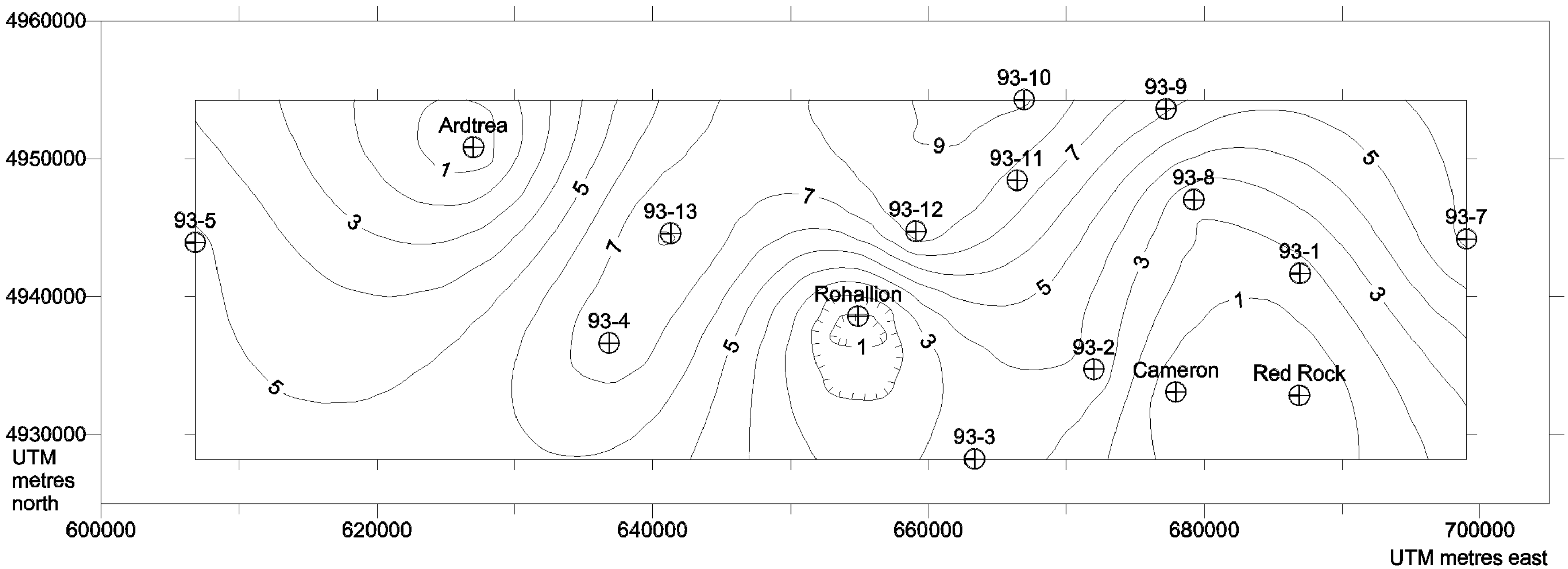


Figure 6: Isopach of Shadow Lake Formation. Data points (circled crosses) include numbered OGS drill holes (e.g., 93-5) and Precambrian inliers (Ardtrea, Rohallion, Cameron and Red Rock). See Figure 2 for location of map area. Contour interval = 1 m.

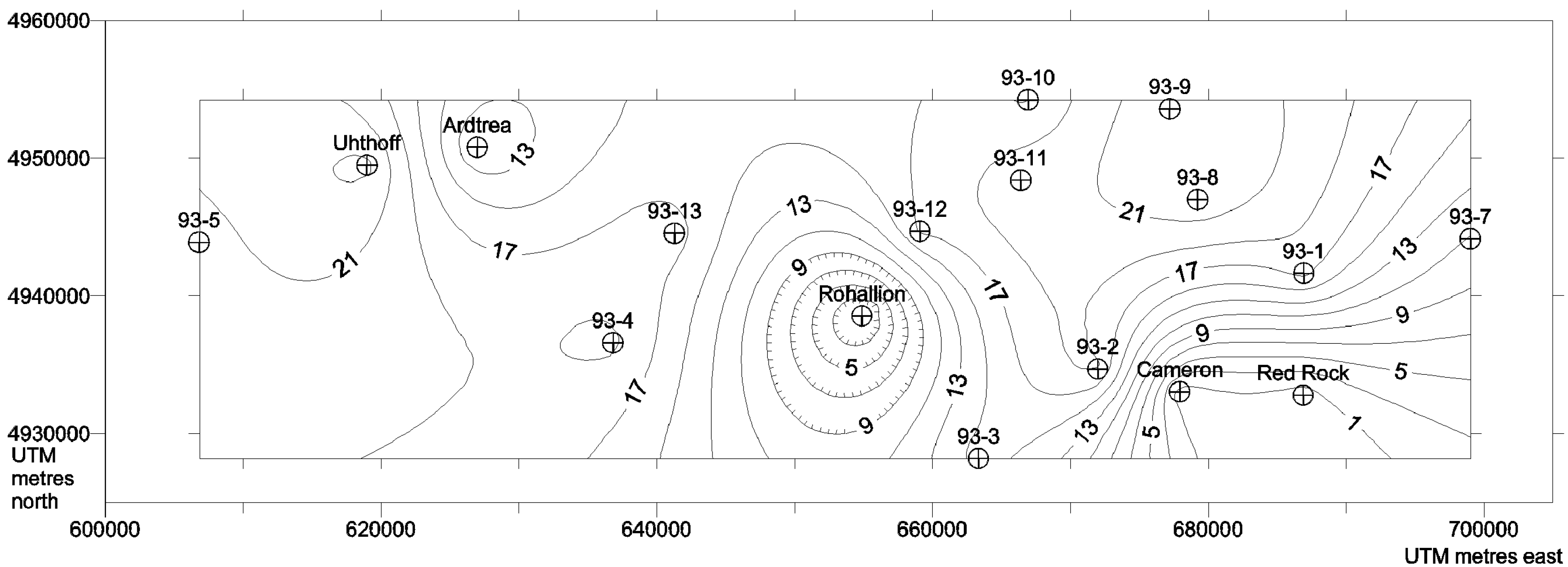


Figure 7: Isopach of Gull River Formation. Data points (circled crosses) include numbered OGS drill holes (e.g., 93-5) and Precambrian inliers (Ardtrea, Rohallion, Cameron and Red Rock). Estimated values used for drill hole OGS-93-05 (20.31 m), Ardtrea inlier (11 m) and Uhthoff Quarry (23.5 m). See Figure 2 for location. Contour interval = 2 m.

mineral casts and nodules, sparse fossil content and local desiccation cracks indicate restricted, intertidal to supratidal depositional environments (Grimwood et al. 1999) over much of the study area. However, in the western part of the study area, the middle part of this member contains fossiliferous limestone beds that are indicative of subtidal lagoonal environments in that area.

Fossiliferous beds in the lower member include fossiliferous wackestones and packstones, peloidal, bioclastic pack–grainstones and oolitic grainstones. The oolitic grainstone beds are exposed in a roadcut located along Highway 169, 2.6 km south of the Head River (locality 92DKA–115) and were encountered in drill hole OGS–93–05. Perhaps the most striking of the fossiliferous beds is an up to 4.60 m interval of brown, burrow–mottled wackestones and packstones, informally called the "burrow–mottled beds". In the western part of the study area the burrow–mottled beds form the caprock of a topographically low escarpment. They are also the uppermost beds in the Waubaushene (locality 93DKA–443), Grass Lake (locality 92DKA–200), and Rama (now Ramara) Township (locality 92DKA–102). The burrow–mottled beds, and other fossiliferous strata in the lower member, thin to the east, eventually pinching out in the vicinity of Coboconk. The eastward thinning of the burrow–mottled beds is illustrated in the schematic cross–section in Figure 8.

Generally, the fauna of the lower member is sparse, consisting mainly of ostracods and trilobites. In fossiliferous beds, such as the burrow–mottled beds, the fauna is more diverse and includes pelecypods, trilobites, gastropods, brachiopods, ostracods and cephalopods. In the burrow–mottled beds fossils which were originally aragonite have been glauconitized. Glauconite also occurs as a small branching form, which may be a burrow–lining, and vertical fracture surfaces. The fracture–coating form of glauconite suggests a late stage origin for this mineral.

During the course of this project an ophiuroid (type of starfish) was discovered in the limestone beds immediately underlying the burrow–mottled beds at the Uhthoff Quarry. This specimen was determined to be a new species of the genus *Euzonosoma* and the first Ordovician record of the ophiuroid family Encrinasteridae in North America (Hotchkiss et al. 1995).

The top of the lower member is marked by a distinctive light green, argillaceous dolomitic limestone or dolostone, informally called the "green marker bed" (GMB). The green marker bed is commonly 1.5 m thick and occurs throughout the study area. Grimwood et al. (1999) interpreted the green marker bed to have been deposited in a supratidal environment. Its widespread occurrence suggests a regional shallowing event at the end of lower Gull River time.

No outcrop in the study area exposes a complete section of the lower member. The thickest outcrop sections are: 10.50 m at the Uhthoff Quarry (locality 92DKA–203); 9.25 m in a roadcut along Highway 69/400 north of Waubaushene (locality 93DKA–339); 8.70 m in the Grass Lake Quarry (locality 92DKA–200); and 8.50 m in a roadcut along Highway 503 west of Dongola (locality 92DKA–152). Combining the nearby and overlapping Uhthoff and Grass Lake quarry sections yields a composite thickness for the lower member of 15.2 m in this area.

Complete sections of the lower member of the Gull River Formation were intersected in all but one of the OGS drill holes; drill core of OGS–93–05 began at a stratigraphic level just below the green marker bed (Armstrong 1999a). In the OGS cores the lower member ranges from 9.19 to 14.09 m in thickness, averaging 12.35 m (Appendix 3). An isopach map of the lower member, constructed from drill hole data and the estimate (calculated above) from the Uhthoff and Grass Lake quarries (Figure 9), illustrates the effect of the Precambrian inliers. Figure 9 shows that the lower member is thickest (approximately 13 m) in the northeastern and western parts of the study area, away from the inliers.

Upper Member, Gull River Formation

The upper member of the Gull River Formation consists of up to 10 m of micritic, white to light grey to brown, medium–bedded, sparsely fossiliferous, limestone (lime mudstone and thin intraclastic packstones

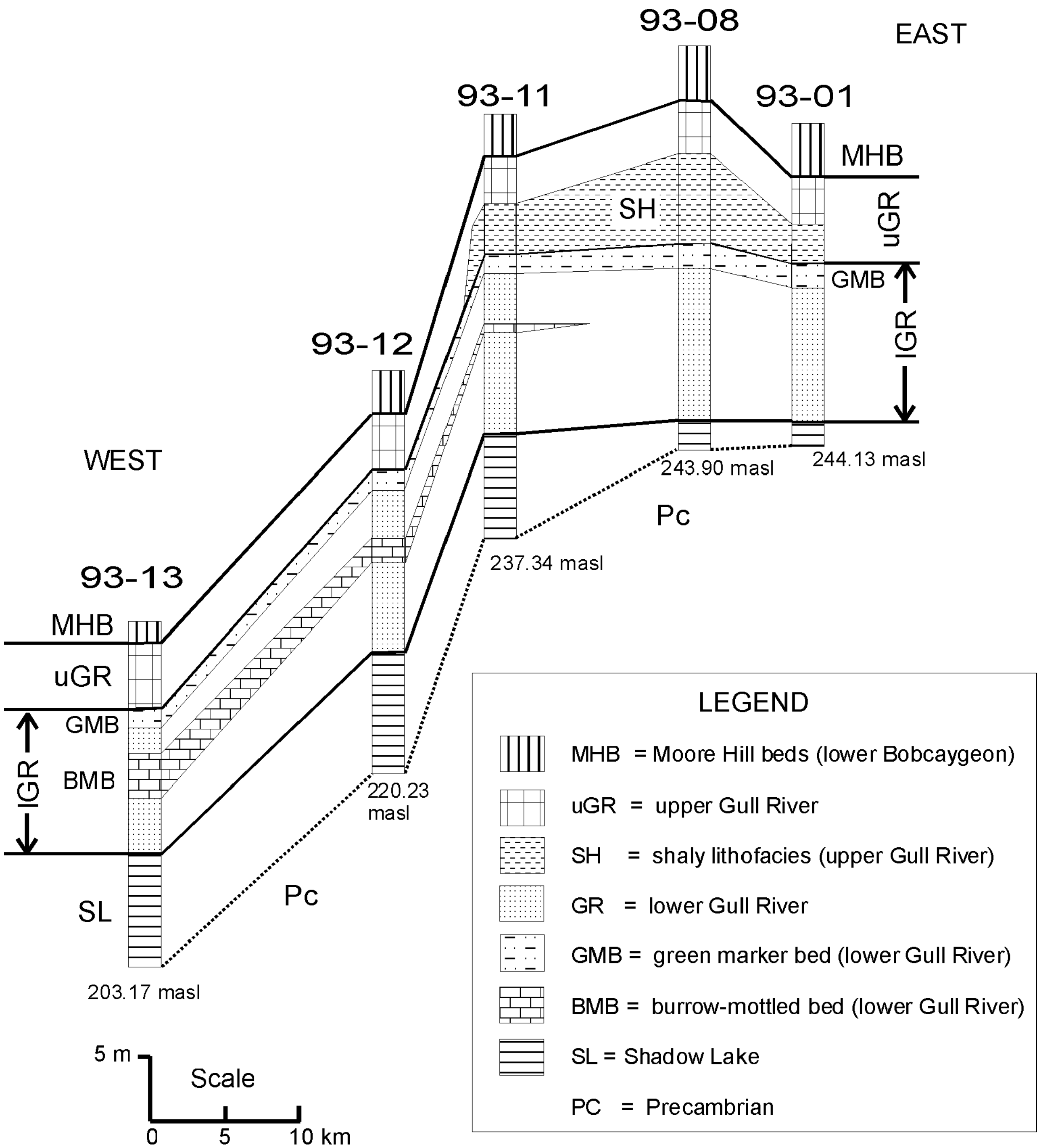


Figure 8: True elevation schematic east-west cross-section of Moore Hill bed and lower units across study area (see Figures 2 and 3 for locations of drill holes). Elevations of base of Shadow Lake Fm. are indicated in metres above sea level (masl).

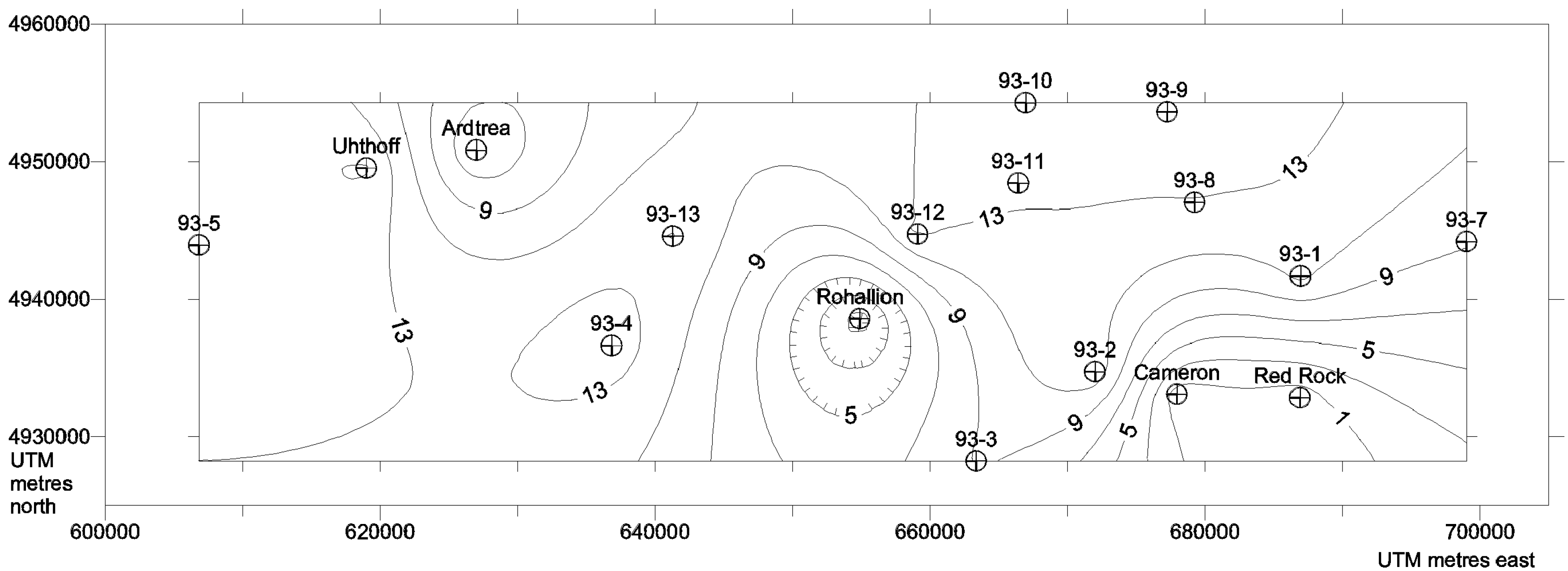


Figure 9: Isopach of lower member of Gull River Formation. Data points (circled crosses) include numbered OGS drill holes (e.g., 93-5), Precambrian inliers (Ardtrea, Rohallion, Cameron and Red Rock). and Uhthoff Quarry. Estimated values for Adtrea inlier (5 m), drill hole 93-05 (13.51 m), and Uhthoff Quarry (15.2 m). See Figure 2 for location. Contour interval = 2 m.

and grainstone). The sparse fauna is dominated by ostracods, but also includes trilobites and rare occurrences of brachiopods. Other characteristics include fenestral fabric ("birds–eyes" filled with sparry calcite), vertical burrows (typically filled with sparry calcite), local mudcracks, and intraformational conglomerates (Melchin et al. 1994). This unit is interpreted to have been deposited in a tidal flat to very shallow, subtidal environment (Grimwood et al. 1999).

Complete sections of the upper member of the Gull River Formation include: 7.63 m in the Medonte Quarry (locality 93DKA–440); 8.30 m in the Uhthoff Quarry (locality 92DKA–203); 6.05 m in the Woods–Longford Quarry (locality 92DKA–103); 4.50 m in the Highway 503 roadcut southeast of Head Lake (locality 92DKA–149); and 9.50 m in the Dudman Quarry 2.5 km east of Burnt River (locality 93DKA–326). Throughout the study area there are also numerous partial sections of the upper member. These commonly expose the uppermost 1 to 2 m of the member and its contact with the overlying Moore Hill beds of the lower Bobcaygeon Formation.

Other significant outcrops of the upper member include: 6.70 m in a roadcut (locality 92DKA–212) and 5.85 m in an inactive quarry (locality 92DKA–214), both in the Hampshire Mills area; 5.75 m in a roadcut (locality 92DKA–228) on the east side of Dalrymple Lake, 0.6 km north of the village of Dalrymple; 7.70 m in a roadcut (locality 93DKA–327) along Somerville Township Road 5, 2.3 km south of Burnt River; and 6.05 m in a large roadcut (locality 92DKA–155) along Highway 649, approximately 15 km north of Bobcaygeon.

In the eastern part of the study area the basal few metres of the upper member contains siliciclastic clay, silt and minor sand grains. Outcrops of this shaly lithofacies occur in the Highway 649 roadcut (2.3 m; locality 92DKA–155), the Dudman Quarry (2.9 m; locality 93DKA–326) and the Somerville Township 5 roadcut (3.65 m; locality 93DKA–327) south of Burnt River. The limestone associated with this lithofacies includes argillaceous, locally sandy, peloidal and intraclastic lime mudstone, wackestone, packstone and minor grainstone.

The shaly lithofacies was encountered in 7 OGS holes drilled in the eastern part of the study area (Appendix 3; Armstrong 1999a). An isopach map of the shaly lithofacies constructed using the drill hole data (Figure 10) illustrates the limited distribution of this unit. It is restricted to the eastern part of the study area with a thin tongue extending to the southwest between the Rohallion and Cameron Lake inliers.

Although the lower contact of the upper member is sharp, at the abrupt change to the light green argillaceous dolostone of the green marker bed, the upper contact of the upper member is gradational and locally interbedded with the Moore Hill beds of the lower Bobcaygeon Formation. The nature of this contact is more thoroughly discussed in the next section of the report.

All of the OGS drill holes, except OGS–93–05, intersected the upper member of the Gull River Formation. The member ranges in thickness from 1.64 m in drill hole OGS–93–07 to 9.43 m in OGS–93–08, with an average of 5.83 m over the study area. Including outcrop data (complete section thicknesses listed above), the average thickness for the upper member (including the shaly lithofacies) of the Gull River Formation in the Lake Simcoe area is 6.26 m. An isopach map of the upper member (including the shaly lithofacies) constructed from drill hole data and outcrop data (Medonte, Uhthoff and Longford quarries) in the western part of the study area (where subsurface data are sparse) is presented in Figure 11.

BOBCAYGEON FORMATION

The Gull River Formation is overlain by the generally more fossiliferous and coarser grained limestones of the Bobcaygeon Formation. Liberty (1969) subdivided the Bobcaygeon Formation into 3 informal members, lower, middle and upper (Figure 6). Liberty's 3–fold subdivision is retained here, except that, as discussed in the previous section, the Moore Hill beds (previously Liberty's upper member of the Gull River Formation) are included in the lower member of the Bobcaygeon Formation. The informal

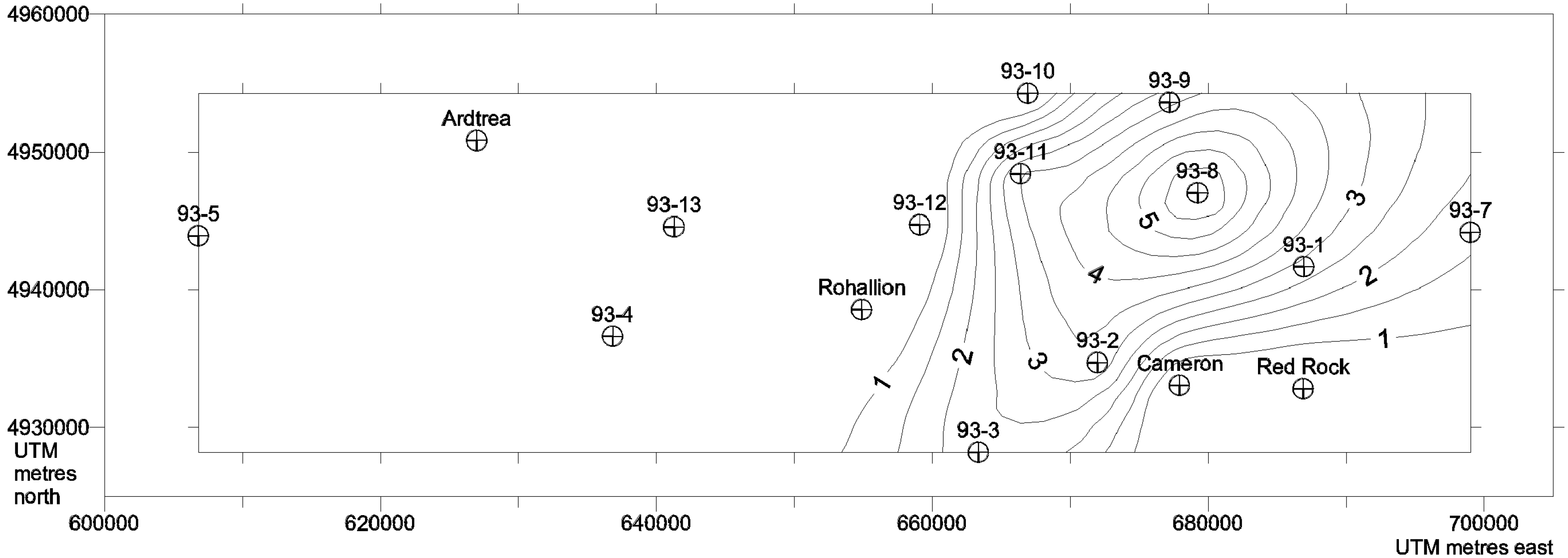


Figure 10: Isopach of the shaly lithofacies, upper Gull River Formation. Data points (circled crosses) include numbered OGS drill holes (e.g., 93-3) and Precambrian inliers (Ardtrea, Rohallion, Cameron and Red Rock). See Figure 2 for location. Contour interval = 0.5 m.

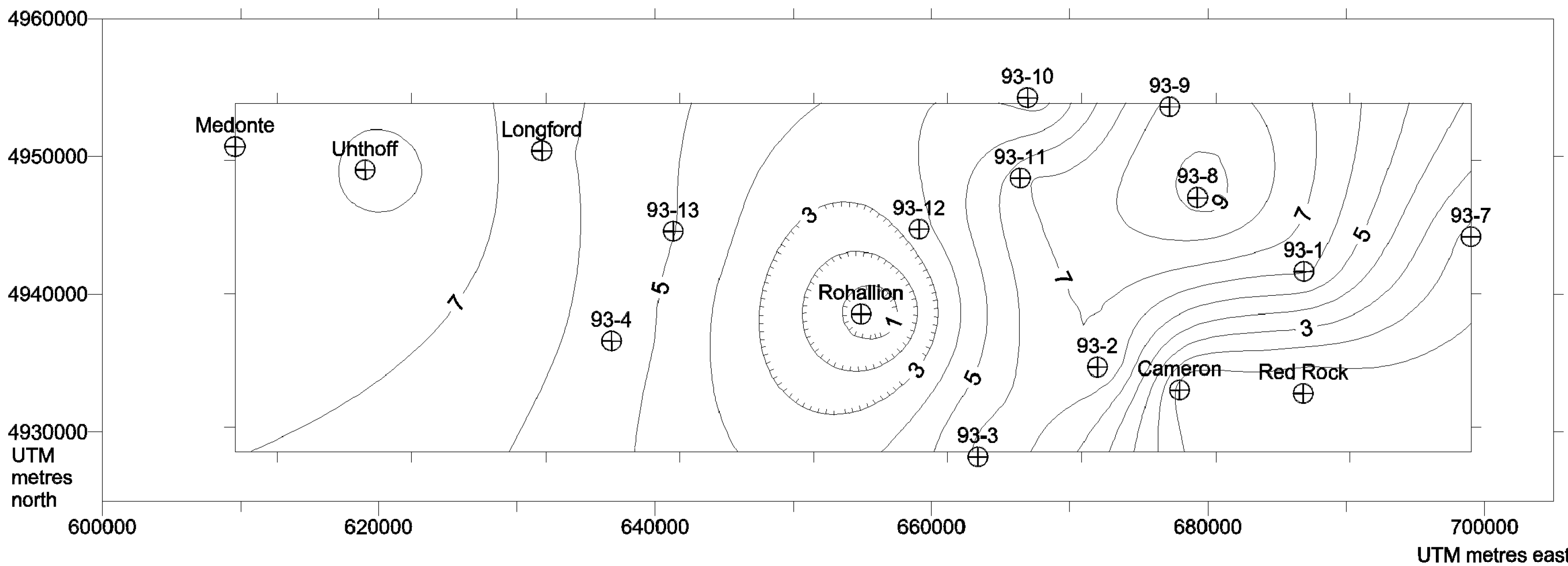


Figure 11: Isopach of the upper member, Gull River Formation. Data points (circled crosses) include numbered OGS drill holes (e.g., 93-4), Precambrian inliers (Ardtrea, Rohallion, Cameron and Red Rock) and Medonte, Uhthoff, and Longford quarries. See Figure 2 for location. Contour interval = 1m.

designation, “Moore Hill beds”, is retained here to distinguish these beds from the remaining overlying strata of the lower member.

Lower Member, Bobcaygeon Formation

The lower member consists of 2 parts, a lower part informally called the Moore Hill beds and an upper part approximately equivalent to the lower member as defined by Liberty (1969). The main difference between these 2 is that the matrix grainsize is significantly coarser in the upper part.

MOORE HILL BEDS

The Moore Hill beds are approximately equivalent to the Moore Hill Formation of Okulitch (1939) and to the upper member of the Gull River Formation of Liberty (1969). They typically consist of dark brown, very fine– to fine–grained, bioturbated, fossiliferous, medium– to very thick–bedded, peloidal limestones (bioclastic peloidal wackestones). Fossils include tabulate corals (especially *Tetradium*), gastropods, trilobites, cephalopods, bryozoans, bivalves and brachiopods. The diverse fauna and its bioturbated nature indicates that this unit was deposited in a subtidal environment, in a less restricted marine setting than the underlying Gull River Formation. The very fine– to fine–grain size suggests it was deposited in a protected lagoonal environment (Melchin et al. 1994; Grimwood et al. 1999).

The basal contact of the Moore Hill beds with the upper member of the Gull River Formation is sharp and planar, and commonly coincident with a hardground surface. Interbeds of grey, micritic limestone, similar to the underlying upper Gull River, occur locally within the Moore Hill beds. Hardgrounds commonly form the bounding surfaces of beds in this unit. The upper contact of the Moore Hill beds with the remaining strata of the lower member varies from sharp and coincident with a hardground, to gradational, with interbeds of overlying strata occurring locally.

The Moore Hill beds range from less than 1 m to over 5 m in thickness in the outcrop belt. Complete sections of this unit include quarry sections at: Medonte (1.30m; locality 93DKA–421); Uhthoff (1.80 m; locality 92DKA–203); Woods–Longford (2.60m; locality 92DKA–103); and Brechin (1.55 m; locality 92DKA–232). Complete roadcut and natural outcrop sections include the: Coboconk east roadcut (3.65 m; locality 92DKA–144); Highway 649 roadcut (5.00 m; locality 92DKA–155); Highway 35 roadcut north of Coboconk (0.53 m; locality 93DKA–421); Highway 503 roadcut southeast of Head Lake (0.70 m; locality 92DKA–149); Hampshire Mills (1.75 m; locality 92DKA–214); Highway 503 south of Sebright (2.40 m; locality 92DKA–226); and the east side of Lake Dalrymple (1.90 m; locality 92DKA–228). Locally, such as in the Coboconk area, there are rapid lateral thickness variations.

In the subsurface of the study area, complete sections of the Moore Hill beds were intersected in 11 OGS drill holes (Appendix 3; Armstrong 1999a). In these cores this unit ranges from 1.05 to 7.75 m in thickness and averages 3.56 m. In general, this unit thickens to the east, however, as shown in an isopach map of this unit (Figure 12), they locally have a relatively complex thickness distribution pattern. This complex pattern appears to be due to more than just the effect of the known Precambrian inliers.

LOWER K–BENTONITE BED

Locally, the Moore Hill beds contain a thin (less than 10 cm) clayey shale bed that is interpreted to be a K–bentonite, correlative with the widespread volcanic ash bed called the Deicke K–bentonite (Trevail 1990; Kolata et al. 1996). Liberty (1969) termed this the “MH bentonite”. Four samples of approximately stratigraphically equivalent K–bentonite beds, 2 from the Brechin Quarry and 1 each from the Uhthoff and Woods–Longford quarries, were submitted to the Ontario Geoscience Laboratories for mineralogical (XRD and SEM) and geochemical analysis (major and trace elements) analysis. Mineralogically the clay mineral component consists of mixed layer illite–smectite clays in ratios ranging from 70/30 to 85/15

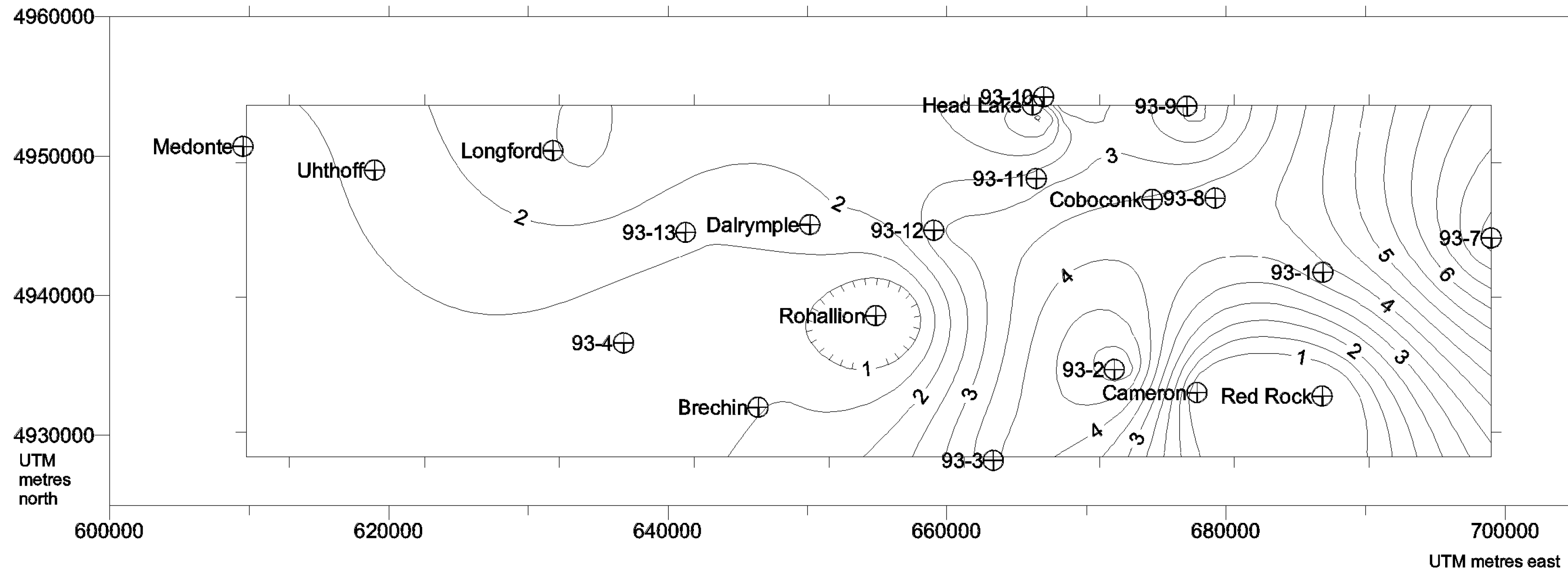


Figure 12: Isopach of Moore Hill beds, lower Bobcaygeon Formation. Data points (circled crosses) include numbered OGS drill holes (e.g., 93-4), Precambrian inliers (Rohallion, Cameron and Red Rock), Medonte, Uhthoff, Longford and Brechin quarries and mapped localities (roadcuts south of Dalrymple, southeast of Head Lake and at Coboconk). See Figure 2 for location. Contour interval = 0.5 m.

illite/smectite). The coarser than +270 mesh, non–clay fraction, consists of quartz and pyrite, ± calcite and ± feldspar. The geochemistry of these samples is presented in Appendix 4.

Two Samples of the Moore Hill bed K–bentonite bed were submitted to the Royal Ontario Museum for U–Pb geochronology of contained zircons. Zircons were found in the Brechin Quarry sample, however, age dating results were problematic (Davis 1999); they were of various ages and the youngest was younger than the age determined for a sample of K–bentonite obtained from a stratigraphically higher location (discussed in below in section on the upper member).

Thin clayey shale beds which appear to be K–bentonites (not confirmed by analysis) were encountered in 6 OGS drill holes in this approximate stratigraphic position. Possible K–bentonites occur in the Moore Hill beds in OGS–93–10 (depth of 6.80 m) and –12 (depth of 27.72[2] m), in upper Gull River strata in drill holes OGS–93–01 (depth of 31.03 m) and –04 (depth of 27.30 m) and in the shaly lithofacies of the upper Gull River in drill holes OGS–93–02 (depth of 47.62 m) and –08 (depth of 17.73 m). Samples from 3 of these beds (from holes OGS–93–02, –10 and –12) were submitted for major element geochemical analysis (*see* samples 93DKA–0227, 93DKA–1006, and 93DKA–1225, *in* Armstrong 1999a).

UPPER PART OF LOWER MEMBER

The upper part of the lower member of the Bobcaygeon Formation (i.e., lower member strata overlying the Moore Hill beds) consists of up to 7 m of grey–brown, medium– to thick–bedded, fine– to coarse–grained, fossiliferous, limestones (bioclastic peloidal packstones and grainstones). Bioturbation is common, generally imparting a semi–nodular texture. Other common characteristics include, planar, ripple and trough cross–stratification and hardgrounds. Fauna include tabulate corals, stromatoporoids, bryozoans, brachiopods, cephalopods, gastropods, trilobites, calcareous algae and abundant echinoderm debris. This rich and varied fauna, the coarse grain size and sedimentary structures all indicate deposition in a shallow, well–agitated, normal marine setting, likely as a complex of offshore bioclastic sand shoals on a shallow marine shelf (Melchin et al. 1994; Grimwood et al. 1999).

A complete section of the upper (i.e., non–Moore Hill bed) part of the lower member is only exposed at 2 localities in the study area, the Brechin and Dalrymple quarries. The upper part of the lower member is 5.75 m thick at the Brechin Quarry (locality 92DKA–232) and 5.61 m at the Dalrymple Quarry (locality 92DKA–230). Other significant exposures of this strata include: the Coboconk Quarry (7.90 m; locality 93DKA–415); Old Coboconk Quarry (5.85 m; locality 93DKA–420); east side of Four Mile Lake (5.65m; locality 93DKA–431); Highway 503 southwest of Head Lake (5.00m; locality 92DKA–149); and south of Four Mile Lake (4.52 m; locality 93DKA–434). All but the last of these exposes the basal contact of this unit with the underlying Moore Hill beds.

In the subsurface, the upper (i.e., non–Moore Hill bed) part of the lower member of the Bobcaygeon Formation ranges from 5.20 to 9.46 m in thickness (Appendix 3), averaging 6.66 m in the 6 holes with preserved overlying strata. In 5 other cores where the lower member is the uppermost unit, it ranges from 3.33 to 7.50 m. An isopach map of the upper part of the lower member, constructed from drill hole data (complete intervals only), is presented in Figure 13.

Complete intervals of the whole lower member (i.e., including the Moore Hill beds) were intersected in 6 OGS drill holes. In these cores the lower member ranges from 6.25 to 13.33 m, averaging 10.10 m (Appendix 3). In the 5 other holes where the lower member is the uppermost unit, it ranges from 4.87 to 11.79 m in thickness (Appendix 3).

Middle Member, Bobcaygeon Formation

The middle and upper members of the Bobcaygeon Formation are more argillaceous than the lower member. The middle member is characterized by interbedded shale and tabular–bedded limestone that is

[2] The depth of this K–bentonite bed was incorrectly reported on page 84 in Armstrong (1999a), The correct depth range for this bed is 27.72 to 27.75 m.

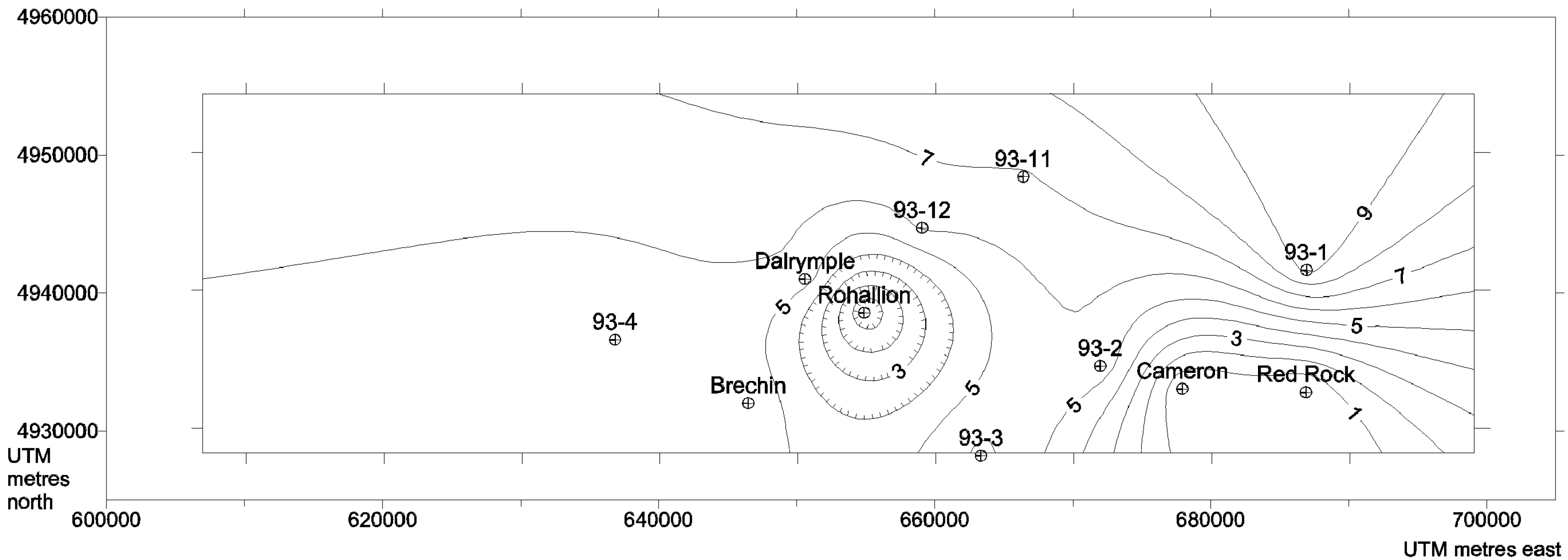


Figure 13: Isopach of upper part of lower member, Bobcaygeon Formation. Data points (circled crosses) include OGS drill holes (e.g., 93-4), Precambrian inliers (Rohallion, Cameron Lake, Red Rock), and Brechin and Dalrymple quarries. See Figure 2 for location of map area. Contour interval = 1 m.

especially well developed in the lower and upper parts of this member. The tabular limestone beds are commonly fine– to medium–grained, grey–brown, sparsely fossiliferous, peloidal grainstones with planar horizontal or low angle lamination. These beds represent storm–influenced deposition and indicate deeper, more open marine shelf conditions (Melchin et al. 1994).

The middle part of this member consists of less argillaceous limestone with characteristics similar to those of the lower member (e.g., thicker bedded, bioturbated). At the Brechin Quarry, abundant oncolites occur in a bed (bioclastic packstone to rudstone) approximately 3 m above the base of the middle member in the middle part of the member. Although not recognized in the nearby Carden and Dalrymple quarries, similar oncolite–rich beds occur in approximately the same stratigraphic position in drill holes OGS–93–04, –12, and –01 (the last being almost 40 km east of the Brechin Quarry occurrence). This oncolite bed may also occur in a rubbly zone 3 m above the base of the middle member in drill hole OGS–93–11. It was not, however, recognized in drill holes OGS–93–03 or OGS–93–02.

The contact between the lower and middle members of the Bobcaygeon Formation has been suggested (e.g., Melchin et al. 1994) to be approximately equivalent to the boundary between the Blackriveran and Trentonian stages (Figure 6). Lithologically, this is consistent with the contact between the Black River and Trenton groups in the subsurface (Figure 5; Beards 1967). In outcrop the basal contact of the middle member is typically sharp and locally erosive. This contact is exposed in the Brechin (locality 92DKA–232), Dalrymple (locality 92DKA–230), Carden (locality 92DKA–229), New Kirkfield (locality 93DKA–404) and Little Bob (locality 93DKA–310) quarries and in an outcrop south of Four Mile Lake (locality 93DKA–434).

The middle member ranges up to approximately 11 m thick in the outcrop belt, but its shaly character typically results in poor natural exposures. Complete sections of this member are exposed in the Brechin (10.35 m; locality 92DKA–232), Carden (9.95 m; locality 92DKA–229), and New Kirkfield (10.10 m; locality 93DKA–404) quarries. Other significant sections include: a roadside natural outcrop south of Four Mile Lake (10.68 m; locality 93DKA–434); the Kirkfield Liftlock (6.65 m; locality 92DKA–250); the Dalrymple Quarry (5.50 m; locality 92DKA–230); and the inactive and overgrown Little Bob Quarry at Bobcaygeon (4.30 m; locality 93DKA–310). The Little Bob Quarry section was designated by Liberty (1969) as this member’s type section.

Complete sections of the middle member were only intersected in 3 drill holes: OGS–93–1, –2[3] and –3. It ranges from 2.53 to 6.33 m in thickness in these holes (Appendix 3). This unit was the uppermost unit encountered in 3 other drill holes: OGS–93–04, –11 and –12. The thickness of this unit in these holes ranges from 6.23 to 18.91 m (Armstrong 1999a). This erratic lateral variability in thickness is problematic. The upper contact of the middle member with the overlying upper member is placed at the top of the uppermost significant shale bed, yet most other lithologic characteristics are gradational across the contact. Locally, the upper shaly part of the middle member is not well developed and so the upper contact is sometimes placed much lower.

Upper Member, Bobcaygeon Formation

The upper member of the Bobcaygeon Formation consists of up to approximately 14 m of light grey–brown, thin– to medium–bedded, fine– to coarse–grained, fossiliferous limestones with shaly partings and some thin shale beds. Limestone rock types range from bioturbated bioclastic wackestones and packstones, to tabular–bedded, cross–laminated, bioclastic and locally intraclastic grainstones. These are interpreted to represent a complex interplay of inter–shoal and shoal environments on a deepening storm–influenced shelf (Brookfield and Brett 1988; Melchin et al. 1994).

Fossils in the upper member of the Bobcaygeon Formation are dominated by echinoderms and brachiopods, with bryozoans (particularly the domal bryozoan *Prasopora*), trilobites and gastropods.

[3] The depth of the upper contact of the middle member in OGS–93–02 reported in Armstrong (1999a, 1999b) is revised to 24.85 m.

Corals and stromatoporoids are virtually absent in the upper member. Sedimentary structures include large amplitude pararipples which typically cap grainstone beds.

Complete sections of the upper member are only exposed in 2 quarries, the Carden (11.00 m; locality 92DKA–229) and Brechin (10.40 m; locality 92DKA–232). At, and immediately to the south of, the Kirkfield Liftlock (locality 92DKA–250), up to 10.50 m of the upper member are partly exposed between the underlying middle member and overlying lower Verulam Formation. Other significant exposures of the upper member are located: northeast of Brechin (4.75 m; locality 92DKA–125); at Fenelon Falls (9.32 m; locality 93DKA–437); and the New Kirkfield Quarry (2.03 m; locality 93DKA–404). At the last locality its basal contact with the underlying middle member is exposed. At the inactive and mostly water–filled old Kirkfield Quarry (locality 92DKA–248), approximately 2 m (depending on water level) of the upper member is exposed in contact with almost 3 m of the overlying Verulam Formation.

In the subsurface, 2 of the OGS drill holes , OGS–93–2[3] and OGS–93–3, intersected complete intervals (13.00[3] and 13.08 m, respectively) of the upper member (Armstrong 1999a; Appendix 3). Drill hole OGS–93–01 was collared in the upper member and intersected most of the member (12.90 m). There is insufficient subsurface data to comment with certainty on the lateral variability of this unit in the study area. The basal contact of the upper member with the middle member is discussed above.

UPPER K–BENTONITE BED

Locally a thin clayey shale bed occurs in the upper member. This is likely the same bed as the "MR bentonite" of Liberty (1969), which he identified as occurring near the top of the middle member. This bed is particularly noticeable in the Carden Quarry (locality 92DKA–229) as a persistent clay seam which can be traced across the quarry. It is located 11.8 m above the main quarry floor (in 1992) and 4.3 m below the contact with the Verulam Formation. A sample obtained from this locality was submitted to the Royal Ontario Museum for U–Pb geochronology of contained zircons. This sample yielded a small amount of zircon with a high proportion of very fresh grains, from which a precise age of 452.6 ± 0.8 Ma was determined (Davis 1999). This is close to the age of 453.7 ± 1.8 Ma reported for the Millbrig K–bentonite in southeast Missouri (Tucker et al. 1990). Both the Millbrig and Deicke K–bentonites (see previous section) are part of a suite of Middle Ordovician volcanic ash deposits that have been correlated across eastern North America (Kolata et al. 1996).

CAMERON LAKE INLIER

On the south side of Cameron Lake, in the vicinity of Gregory Point, just west of Fenelon Falls, an inlier of crystalline Precambrian basement occurs at the stratigraphic level of the upper member of the Bobcaygeon Formation (locality 93DKA–436; Armstrong and Rhéaume 1993b). An outcrop of the unconformable contact between the limestones of the upper member and the Precambrian basement was discovered during the field season of 1993 (Armstrong and Rhéaume 1993a) and reported on by Armstrong et al. (1993). This outcrop is an excavation (for the foundation of a cottage) about 10 sq. m, exposing about 2 m of section. There is approximately 2 m of paleorelief on the Precambrian surface and its uppermost 1 m or so is bleached with a hematite staining. Small depressions occur on the Precambrian surface filled with fossiliferous wackestone and chert. Overlying this surface is a crudely graded polymictic conglomerate with clasts consisting of large (up to 1 m) rounded Precambrian gneiss boulders, and limestone intraclasts and bioclasts. Interbedded with and overlying the basal conglomerate are bioclastic and peloidal grainstones and rudstones. Armstrong et al. (1993) reported the fauna to include abundant rhodoliths of *Solenopora*, the stromatoporoid *Stromatocerium*, tabulate corals (*Coccoseris*, *Foerstephyllum*, and rare *Tetradium*), some solitary rugosan corals such as *Lambeophyllum*, bryozoans, echinoderm debris, brachiopods (strophomenids and orthids) and graptolites. A thin clayey siltstone produced the brachiopod *Idiopsira*, graptolites and small plant–like fossils. The latter appear to be a type of marine algae, possibly a form of chlorophyceae (P.K. Strother, Boston College, personal communication, 2000).

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[3] The depth of the upper contact of the middle member in OGS–93–02 reported in Armstrong (1999a, 1999b) is revised to 24.85 m.

This outcrop at Cameron Lake represents a rocky shoreline developed on what would have been an island during deposition of all of the older strata. Rocky shorelines are also described (Brookfield and Brett 1988) at 2 other inliers in the study area: at Rohallion, north of Canal Lake (*see* Armstrong and Anastas 1993) and at Red Rock, 7 km east of Fenelon Falls (*see* Armstrong and Rhéaume 1993b).

VERULAM FORMATION

The Verulam Formation ranges from 45 to 60 m thick in south–central Ontario and is subdivided into 2 informal members, lower and upper (Figure 6; Liberty 1969). The lower member consists of over 40 m of interbedded shale and limestone, and the upper member consists of less than 10 m of cross–bedded, bioclastic limestone. Because of its shaly nature the Verulam Formation is not generally well exposed. It's argillaceous content also makes it less desirable for aggregate extraction and so it is exposed in only a few quarries. One of these, the Gamebridge Quarry, is located within the north Lake Simcoe study area (Appendix 1; locality 92DKA–128).

Only 1 OGS drill hole in the north Lake Simcoe area intersected the entire Verulam Formation interval. This drill hole, OGS–93–03, intersected a complete interval (i.e., beneath strata of the overlying Lindsay Formation) of 51.41 m. Another drill hole, OGS–93–02, intersected part of the formation, the basal 9.97 m of the lower Verulam (Appendix 3; Armstrong 1999a).

Lower Member, Verulam Formation

The limestones of the lower member range from micritic, nodular lime mudstones, to coarse–grained, bioclastic packstones and grainstones. These occur as irregular to lenticular, discontinuous beds, interbedded with grey–green calcareous shale. The lower member is very fossiliferous, with both branching and domal (*Prasopora*) bryozoans, echinoderms, brachiopods, trilobites and gastropods.

McFarland (1997) and McFarland et al. (1997) identified 5 lithofacies in the Verulam Formation which are grouped into 2 general depositional environments: shoal deposits and shelf deposits. The shoal deposits consist of crinoidal grainstones and rudstones and are generally restricted to the upper parts of the formation (discussed below in upper member section). The shelf deposits consist of laminated mudstones, shales and calcisiltites, nodular limestones and shell–rich bioclastic limestones (wackestones, packstones, grainstones and rudstones). These deposits, especially the shell–rich bioclastic limestones, contain abundant evidence of deposition under the influence of storms. Storm–generated sedimentary structures in this lower member include scoured bases, basal shell lags, lenticular bedding, normal grading and wave–rippled upper surfaces (McFarland et al. 1997). Laminated fine–grained beds are interpreted to represent deposition by waning storm currents. Other sedimentary structures include abundant hardgrounds, bioturbation, nodular bedding, and dwelling burrows (Melchin et al. 1994).

The upward increase in abundance and thickness of storm beds has been interpreted as a change from distal to proximal storm settings (Brookfield and Brett 1988) and an overall shallowing upwards (Melchin et al. 1994).

The lower member is not well exposed in the study area. Typically, exposures consist of overgrown, slumped roadcuts, no more than a few metres high. The thickest exposures include: 15.00 m at the Gamebridge Quarry (locality 92DKA–128); 17.75 m in a roadside ditch on the side of the hill south of Ancona Point, 6 km west of Bobcaygeon (locality 93DKA–318); and 14.00 m in a similar setting, south of Canal Lake, 2.5 km northeast of Bolsover (locality 92DKA–238).

The basal contact of the lower member, and of the formation, is gradational with the upper member of the Bobcaygeon Formation and is marked by a gradual increase in calcareous shale content. This contact is exposed in the Carden (locality 92DKA–229), Brechin (locality 92DKA–232) and old Kirkfield (locality 92DKA–248) quarries.

Upper Member, Verulam Formation

The upper member consists of up to 10 m of trough cross–stratified coarse–grained, bioclastic limestones (grainstones and rudstones). The dominant allochems are echinoderm fragments, however, locally, brachiopod, fragments of large branching bryozoans and intraclasts are important. The bryozoan fragments commonly occur in lag deposits. Trough cross–bedding is common in the upper member. This unit has been interpreted to represent deposition by shallow shoals and indicates shallowing during latest Verulam Formation time (Brookfield and Brett 1988; Melchin et al. 1994).

The upper member typically occurs capping escarpments east of Lake Simcoe. The best outcrop of this unit is an 8.80 m (partly covered) section (locality 92DKA–242) along County Road 9, located 7 km south–southeast of Kirkfield. Similar outcrops are known to the southeast, south of the study area, in the vicinity of Glenarm and Zion (e.g., Stop 11 *in* Coniglio et al. 1990).

Subsurface Geology

Drilling by the OGS in the north Lake Simcoe area has afforded the acquisition of subsurface geophysical data and unweathered core samples for lithologic and geochemical analysis (Armstrong 1999a and 1999b). The resulting data have enabled higher quality characterization of lithologic units and a better understanding of the lateral variability of these units and their environments of deposition (Armstrong 1997, 1999a).

Structure contour maps of the Precambrian surface (Figure 5) and the top of the Gull River Formation (Figure 14) illustrate the gentle regional dip of Paleozoic strata in the study area. Regional dip ranges from 2.5 to 3.3 m/km and from southwesterly to south–southwesterly in direction.

Including the elevations of mapped Precambrian inliers in the structure contour map of the Precambrian basement (Figure 5), illustrates the irregular surface over which the Middle Ordovician Tippecanoe Sea transgressed. Including these inliers as data–points in isopach maps for the various Paleozoic units (Figures 6, 7, 9, 10, 11, 12, and 13), further illustrates the effect the inliers had on their distribution and thickness.

The regional dip is well illustrated in a schematic true elevation cross–section (Figure 8) oriented approximately east–west across the study area . The line of section is oriented partly parallel to the regional strike (between holes OGS–93–01 and OGS–93–11) and partly oblique to the regional dip (between OGS–93–11 and OGS–93–13).

Figure 8 also illustrates the lateral change in thickness of 3 units: the Shadow Lake Formation; the burrow–mottled bed of the lower member of the Gull River Formation; and the shaly lithofacies of the upper member of the Gull River Formation. The Shadow Lake Formation thins over paleo–topographically higher basement between holes OGS–93–11 and OGS–93–01. The burrow–mottled bed thins from west to east, pinching out east of drill hole OGS–93–11. The shaly lithofacies only occurs in the 3 eastern holes of the section, rapidly pinching out west of drill hole OGS–93–11.

A schematic cross–section drawn using the top of the green marker bed (GMB) as a datum (Figure 15) more clearly illustrates the lateral thickness variability of the Shadow Lake Formation and the burrow–mottled bed. It also indicates a possible controlling factor for this variability: the basal clastics of the Shadow Lake Formation appear to have in–filled a paleo–topographic low in the west. While most of the lower member of the Gull River Formation was deposited in very shallow, restricted subtidal to intertidal environments, the burrow–mottled bed (BMB) represents a deposition in a subtidal lagoonal environment (Grimwood et al. 1999). The thicker section of burrow–mottled bed in the west (Figure 15) indicates that these conditions continued there for a longer period of time. This also indicates that the effect of basement topography on depositional environments persisted well into the deposition of the lower member. The green marker bed appears to have been unaffected by the paleo–relief of the basement.

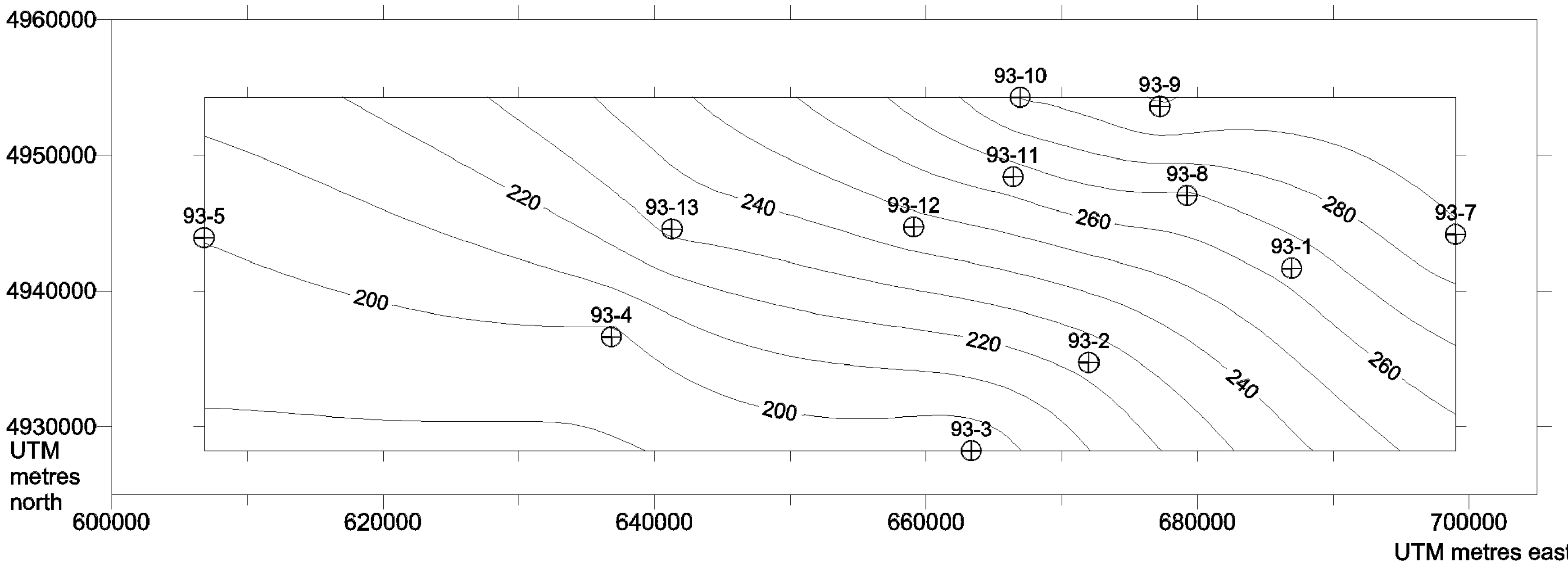

Figure 14: Structure contour of top of Gull River Formation (metres above sea level). Data points (circled crosses) include numbered OGS drill holes (e.g., 93-3). Value for OGS-93-05 calculated using estimate for upper member of Gull River Fm. See Figure 2 for location. Contour interval = 10 m.

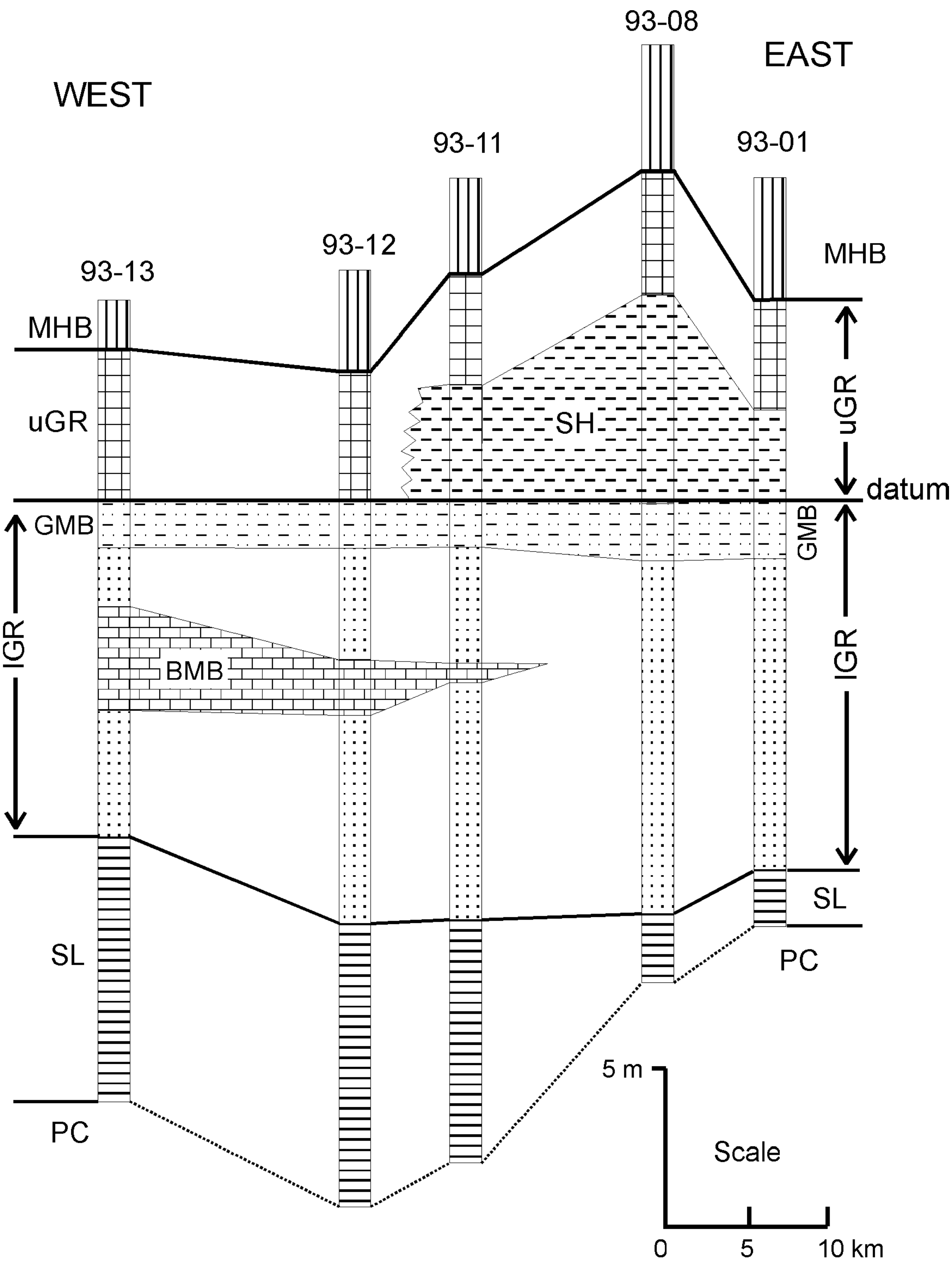

Figure 15: Schematic east-west cross-section section of Moore Hill bed and lower units across study area (drill hole locations plotted in Figures 2 and 3) with the top of the "green marker bed" as datum. See Figure 8 for Legend.

The anomalous thickness of upper member of the Gull River Formation in the eastern part of the section (Figures 11 and 15) is due almost entirely to the development of the shaly lithofacies. Controls on its development are more apparent if the cross–section is redrawn using the base of the Moore Hill beds as datum (Figure 16). This datum is reasonable given the occurrence of a K–bentonite bed (an event timeline) within this unit. In this section (Figure 16) the green marker is displaced downwards east of drill hole OGS–93–12 and the shaly lithofacies appears to have been deposited in a small sub–basin. One possible explanation for the development of this sub–basin is that it was formed by syndepositional faulting during the deposition of the upper member of the Gull River Formation. Although minor faults and fractures are not uncommon in the study area (Armstrong and Rhéaume 1993a), no major faults (i.e., throws greater than 1 m) were mapped in the vicinity of the boundaries of the shaly lithofacies (Armstrong and Rhéaume 1995).

Economic Geology

The Paleozoic limestone bedrock of the north Lake Simcoe area has been an important source of building stone and aggregate since this area was settled by Europeans. In fact the first building stone quarry in Ontario is located in the present study area, on the shore of Georgian Bay, north of Port McNicoll, about 5 km east of Midland (locality 93DKA–343, Appendix 2). Limestone blocks were extracted from this site as early as 1639 by Jesuit Missionaries for use in construction of fireplaces, the altar base and bastion walls of Sainte Marie I (J. Hunter, Huronia Museum, personal communication, 2000). Almost 200 years later, in 1832–34, limestone was extracted from nearby Quarry Island for use in the construction of the Officers' Quarters at Penetanguishene (J. Hunter, Huronia Museum, personal communication, 2000).

Miller (1904), Parks (1912) and Goudge (1938) documented limestone quarrying activity in Ontario during the early part of the 20th century. A more up–to–date list of quarries in this area is included in the comprehensive review of the limestone industry in Ontario by Derry Michener Booth and Wahl and Ontario Geological Survey (1989) and in an inventory of inactive quarries in Ontario by Wolf (1993).

A list of the active and inactive quarries in the north Lake Simcoe area in 1992–93 is presented in Appendix 1 of this report. Two of the active quarries extracted limestone from the lower Gull River Formation for landscaping applications. The remaining 11 active quarries extracted limestone from the Gull River, Bobcaygeon and Verulam formations for a variety of aggregate products.

ALKALI–CARBONATE REACTIVITY

As previously mentioned, aggregate from certain beds within the Simcoe Group react with alkali elements in cement, causing expansion and cracking of the resultant concrete. Previous studies, mainly by Ontario Ministry of Transportation researchers (e.g., Ryell et al. 1974), identified the stratigraphic position of alkali–carbonate reactive beds at specific locations (e.g., the Uhthoff Quarry, northwest of Orillia; Figure 3). Testing for alkali–carbonate reactivity traditionally involved construction of concrete prisms and measuring their expansion over a long period of time. Rogers (1985, 1986) devised a geochemical screening technique that identifies potentially alkali–carbonate reactive samples. He demonstrated that such samples plot in a specific field on a graph of CaO/MgO versus some measure of siliciclastic content, such as Al_2O_3 content. The potentially alkali–carbonate reactive field corresponds to dolomitic limestone and expands to include more dolomitic and calcareous compositions with increasing argillaceous content. An example of one of these plots, created with data from drill hole OGS–93–08, is presented in Figure 17. Using the geochemical screen, potentially alkali–carbonate reactive samples were identified from samples suites from each of the OGS drill holes. The stratigraphic distribution of these samples was determined by plotting their depth locations on graphic logs for each hole (Figures 4 through 15, *in* Armstrong 1999a).

In general, potentially alkali–carbonate reactive beds are restricted to the lower member of the Gull River Formation. Samples of the shaly lithofacies developed locally in the upper member of the Gull River Formation, also commonly plot in the potentially alkali–carbonate reactive field. A few samples from

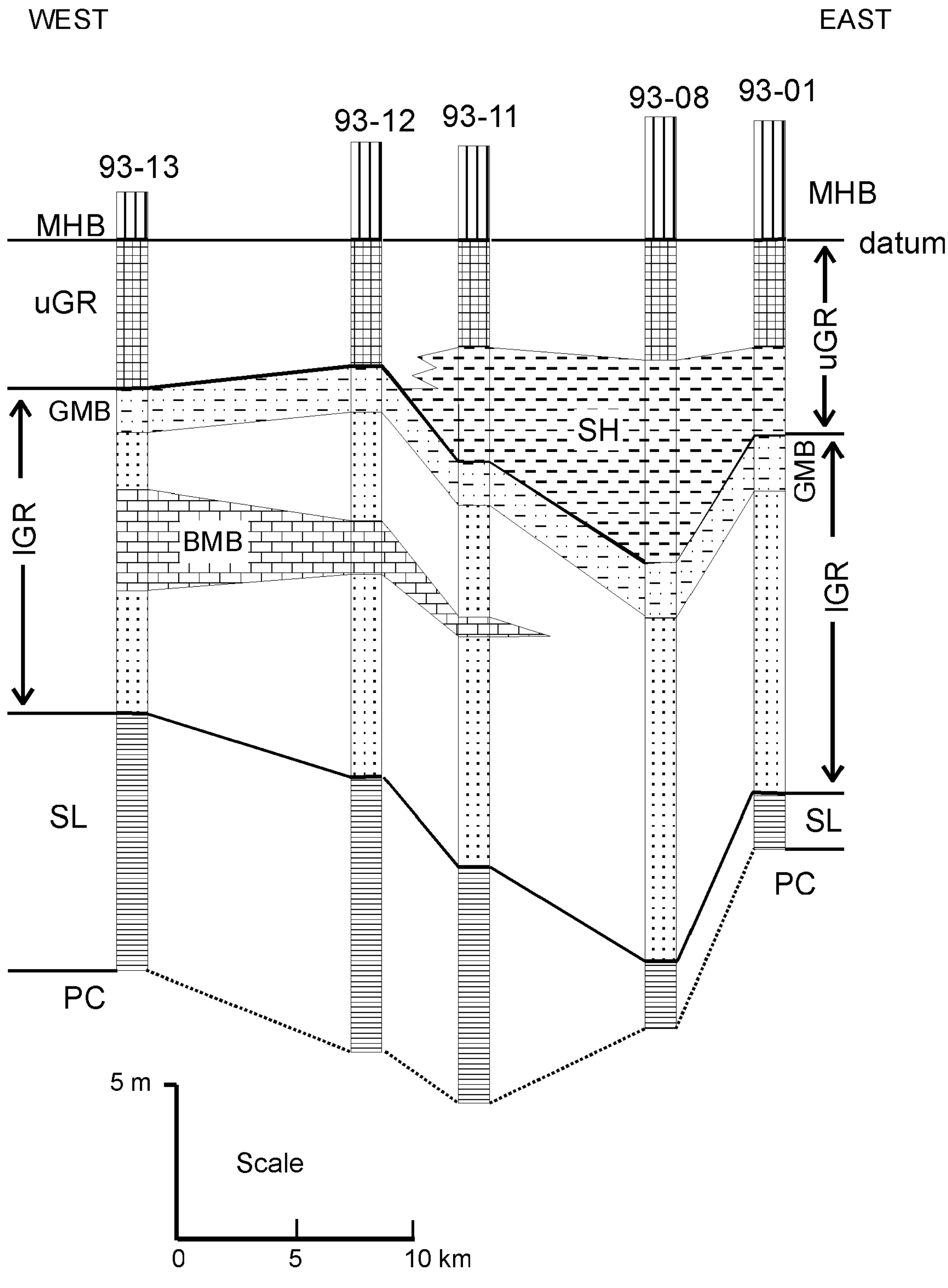

Figure 16: Schematic east-west cross-section section of Moore Hill bed and lower units across study area (drill hole locations plotted in Figures 2 and 3) with the base of the Moore Hill beds as datum. See Figure 8 for Legend.

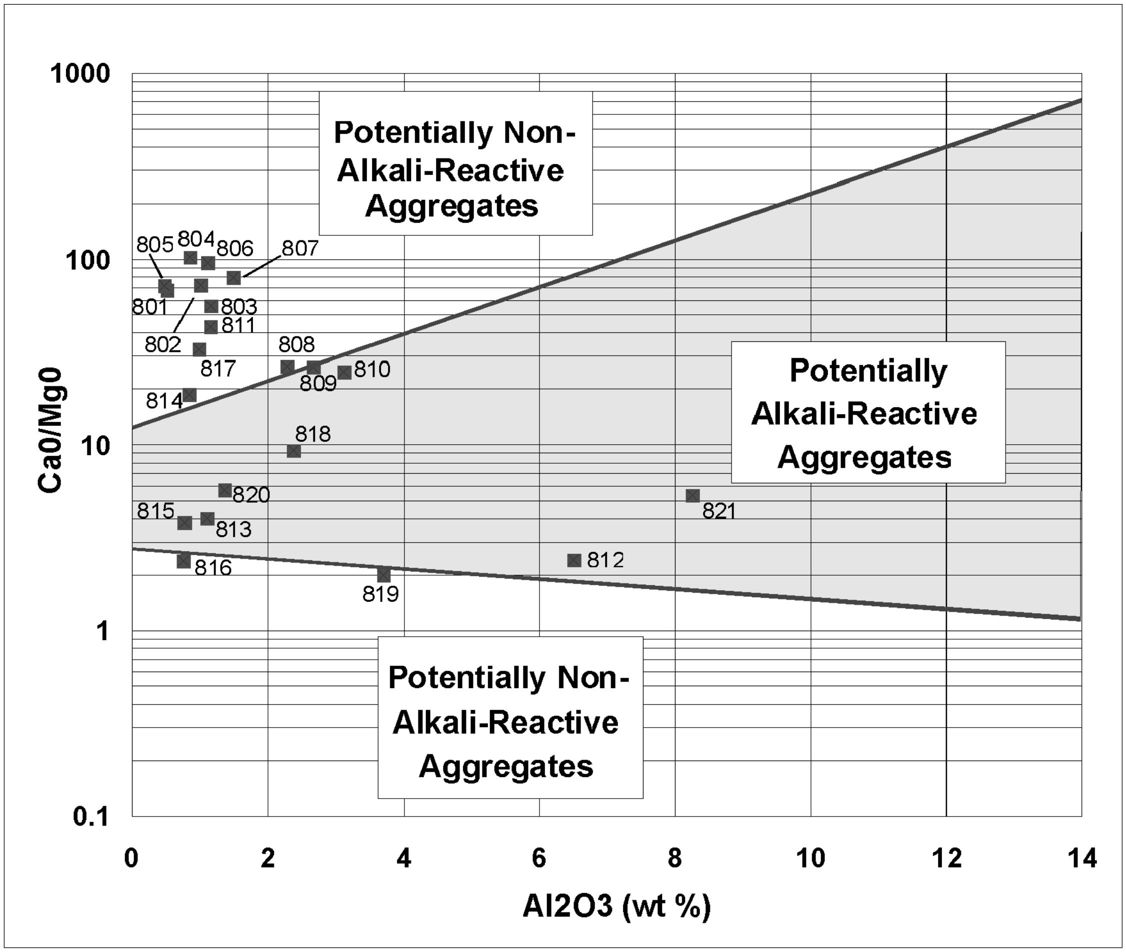

Figure 17: Cross–plot of CaO/MgO values versus Al_2O_3 content for samples from drill hole OGS-93–08. Sample numbers are indicated for each point. Fields of potentially alkali-reactive (shaded) and non-alkali reactive aggregates are indicated (after Rogers 1985).

stratigraphically higher units also plot in this field, but these are from thin, discontinuous, argillaceous beds and do not represent economically deleterious units.

The occurrence of potentially alkali–carbonate reactive beds is controlled by argillaceous content and degree of dolomitization. Dolomite in the alkali–reactive beds in the north Lake Simcoe area occurs throughout the rock matrix as an early diagenetic phase, likely related to the proximity of shallow intertidal and supratidal environments (Grimwood 1998; Grimwood et al. 1999). Two occurrences of later stage (possibly hydrothermal), likely fracture–controlled dolomitization, are know in the study area (Armstrong and Rhéaume 1993a, Armstrong 1997). The occurrence of potentially alkali–carbonate reactive beds does not appear to be related to this style of dolomitization. However, faulting may have had an indirect effect on the occurrence of alkali–reactive beds, in that the distribution of the shaly lithofacies (an alkali–carbonate reactive unit) in the upper Gull River Formation may be due in part to the activation of syndepositional faults (see Figures 15 and 16 and discussion above).

Results of further aggregate testing being conducted by the Ontario Ministry of Transportation on samples from the north Lake Simcoe drill cores will be presented in a future report (Armstrong and Williams, in prep.).

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Appendix 1: List of quarries in north Lake Simcoe area (as of 1993).

Quarry Name	Alternate Name	Operator	LSI #	Town–ship	Lot	Conc–ession	UTM easting	UTM northing	Mapping locality	Status
Port McNicoll		Canada Iron Furnace Company	H–019	Tay	V	19–20	593150	4957300	93DKA–344	I
Waubaushene	Coldwater; Cook	Allan G. Cook Ltd. (Lafarge Canada)	H–003	Tay	XIV	8–11	606300	4958200	93DKA–443	A
Medonte	Coldwater; MTO	Ministry of Transportation and Communications	H–004	Medonte	XIII	19–20	609600	4950700	93DKA–440	I
Medonte		unknown	H–020	Medonte	XIV	20	610850	4951850	–	I
Uhthoff		Nelson Aggregate Co.	H–005	Orillia	III–V N Div.	7–10	619200	4949500	92DKA–203	A
Hampshire Mills		unknown	H–022	Orillia	VII	11	621600	4952000	92DKA–214	I
Grass Lake	Sparrow Lake	Beamish Construction	–	Orillia	XI	13	626500	4956200	92DKA–200	A
Lake St. George	Lake St. George South	unknown	H–025	Orillia	XI	8	628900	4953900	92DKA–205	I
Woods–Longford	Longford; Woods	Fowler Construction Co. Ltd.	H–006	Rama	BF	26–29	631800	4950400	92DKA–103	A
Longford	Longford Mills	Longford Quarries Ltd.	H–026	Rama	B.F.	24–26	631750	4949500	92DKA–104	I
Rama Township		Rama Township	H–007	Rama	E	3	637400	4950300	92DKA–102	I
Speiran		Carson S. Speiran	H–010	Rama	B	3–4	638800	4948050	92DKA–117	I
Millington		unknown	H–030	Mara	VIII	14	640800	4939300	92DKA–120	I
Harrington	Udney	unknown	H–032	Mara	IX	6	645250	4941750	92DKA–126	I
Sebright		M. Campbell	H–028	Rama	A	16	643800	4949100	92DKA–218	I
Brechin		Standard Aggregates (Lafarge Canada)	H–009	Mara	I–II	7–10	646500	4932000	92DKA–232	A
East Brechin		unknown	H–033	Mara	IV	4	648550	4935500	92DKA–243	I
Gamebridge	Mara Limestone	James Dick Construction Ltd.	H–008	Mara	A	11–12	646175	4928900	92DKA–128	A

N.B.: LSI# = Quarry number assigned in "Limestone Industries of Ontario" (Derry Michener Booth and Wahl and Ontario Geological Survey 1989); Mapping localities are listed in Appendix 2; Status "A" = active, "I" = inactive.

Appendix 1: List of quarries in north Lake Simcoe area (as of 1993). cont'd.

Quarry Name	Alternate Name	Operator	LSI #	Town–ship	Lot	Conc–ession	UTM easting	UTM northing	Mapping locality	Status
Carden	Gormely	Gormley Sand & Gravel Ltd. (Dufferin Aggregates)	L–003	Carden	I	1–4	651000	4936600	92DKA–229	A
Dalrymple	Miller	Miller Paving Ltd.	L–002	Carden	II–III	8–12	650600	4940850	92DKA–230	A
New Kirkfield	Kirkfield	FPL Aggregates	–	Carden	VIII	4	659850	4940850	92DKA–247 93DKA–404	A
Old Kirkfield	Kirkfield	Kirkfield Crushed Stone Ltd.	L–013	Eldon	IX	31–32	661200	4938800	92DKA–248	I
Shadow Lake	Norland	unknown	L–016	Laxton	XI	1	673900	4952000	92DKA–150	I
west of Shadow Lake		Central Ontario Stone	–	Laxton	X	1	673400	4951950	–	A
west of Talbot Lake		Central Ontario Stone	–	Laxton	VII	3–4	668875	4951825	93DKA–416	A
Corsons		unknown	L–015	Bexley	IV	4	666950	4943450	92DKA–255	I
Old Coboconk	Coboconk West	Toronto Lime Company	L–017	Somer–ville	Front	36	674650	4946800	93DKA–420	I
Coboconk	Coboconk East	Cedarhurst Crushing & Quarries Ltd.; Beamish Const.	L–004	Somer–ville	Front	37	675000	4947100	93DKA–415	A
Britnell	Burnt River	unknown	L–005	Somer–ville	VI	13	682100	4948200	93DKA–433	I
Dudman	Burnt River	Dudman Construction Ltd.	–	Somer–ville	VI	9	684600	4949800	93DKA–326	A
Burnt River	south Burnt River	unknown	L–019	Somer–ville	IV	13	683150	4946900	93DKA–327	I
Fell		unknown	L–018	Somer–ville	III	17	681200	4943850	93DKA–332	I
Rocky Point		unknown	L–024	Harvey	XVIII	17	697000	4936300	93DKA–320	I
Little Bob		unknown	L–022	Verulam	XIX	12	695950	4933550	93DKA–310	I
Volturno Lake		unknown	L–026	Harvey	XIII	30	700100	4946000	93DKA–302	I

N.B.: LSI# = Quarry number assigned in "Limestone Industries of Ontario" (Derry Michener Booth and Wahl and Ontario Geological Survey 1989); Mapping localities are listed in Appendix 2; Status "A" = active, "I" = inactive.

Appendix 2: Locations and stratigraphy of mapping station localities cited in the report.

Locality #	UTM easting	UT northing	Location Name	Stratigraphy Exposed "lowermost unit – uppermost unit"
92DKA–102	637400	4950200	Rama Township Quarry	lower Gull River
92DKA–103	631500	4950300	Woods–Longford Quarry	lower Gull River – lower Bobcaygeon
92DKA–104	631500	4949500	old Longford Quarry	lower Gull River – Moore Hill Beds
92DKA–109	640200	4951000	north of Snodon's pit	Shadow Lake
92DKA–110	635900	4946200	southeast of Mud Lake	upper Gull River – lower Bobcaygeon
92DKA–111	631700	4950900	north end of Lake St. John	lower Gull River
92DKA–113	629700	4948600	north of Geneva Park	upper Gull River – lower Bobcaygeon
92DKA115	637000	4950150	Highway 169 roadcut	lower Gull River
92DKA–117	638900	4948400	Speiran Quarry	upper Gull River – upper Gull River
92DKA–121	647050	4940800	southwest side of Dalrymple Lake	upper Gull River – lower Bobcaygeon
92DKA–125	646400	4935500	northeast of Brechin	upper Bobcaygeon
92DKA–126	645100	4941700	Harrington Quarry	upper Gull River – Moore Hill Beds
92DKA–128	646000	4928900	Gamebridge Quarry	lower Verulam
92DKA–144	674750	4946900	Coboconk east roadcut	upper Gull River – lower Bobcaygeon
92DKA–148	663550	4957350	northwest of Head Lake	Shadow Lake – lower Gull River
92DKA–149	666150	4953650	Hwy 503 roadcut, southeast of Head Lake	lower Gull River – lower Bobcaygeon
92DKA–150	673950	4951950	old Shadow Lake Quarry	lower Gull River
92DKA–152	677200	4956700	Dongola west	lower Gull River
92DKA–155	689900	4950100	Highway 649 roadcut	upper Gull River – lower Bobcaygeon
92DKA–200	626550	4956200	Grass Lake Quarry	Shadow Lake – lower Gull River
92DKA–203	619000	4949000	Uhthoff Quarry	lower Gull River – lower Bobcaygeon
92DKA–212	624050	4953100	northeast of Hampshire Mills	upper Gull River – lower Bobcaygeon
92DKA–214	621550	4951900	Hampshire Mills Quarry	upper Gull River – lower Bobcaygeon
92DKA–218	643900	4949100	Sebright Quarry	upper Gull River – lower Bobcaygeon
92DKA–226	646800	4947500	south of Sebright on Hwy 503	upper Gull River – lower Bobcaygeon
92DKA–228	650200	4945100	south of Dalrymple	upper Gull River – lower Bobcaygeon
92DKA–229	651000	4936500	Carden Quarry	lower Bobcaygeon – lower Verulam
92DKA–230	650600	4941000	Dalrymple Quarry	Moore Hill Beds – middle Bobcaygeon
92DKA–232	646500	4932000	Brechin Quarry	upper Gull River – lower Verulam
92DKA–238	655200	4934600	south of Canal Lake	lower Verulam
92DKA–242	662800	4929800	south of Kirkfield	upper Verulam
92DKA243	648500	4935500	East Brechin Quarry	middle Bobcaygeon
92DKA–247	659850	4940850	New Kirkfield Quarry	middle Bobcaygeon – upper Bobcaygeon
92DKA–248	661200	4939000	Old Kirkfield Quarry	upper Bobcaygeon – lower Verulam

Appendix 2: Locations and stratigraphy of mapping station localities cited in the report. cont'd.

Locality #	UTM easting	UT northing	Location Name	Stratigraphy Exposed "lowermost unit – uppermost unit"
92DKA–250	659500	4939050	Kirkfield Liftlock	middle Bobcaygeon – lower Verulam
92DKA–255	667000	4943250	Corson's Quarry	middle Bobcaygeon
92DKA–260	672650	4935500	south shore of Balsam Lake	upper Bobcaygeon – lower Verulam
93DKA–302	700100	4946100	Volturno Lake Quarry	lower Gull River – Moore Hill Beds
93DKA–310	695975	4933550	Little Bob Quarry	lower Bobcaygeon – middle Bobcaygeon
93DKA–318	689850	4930150	south of Ancona Point	lower Verulam
93DKA–320	697000	4936300	Rock Point Quarry	upper Gull River – lower Bobcaygeon
93DKA–326	684600	4949800	Dudman Quarry	lower Gull River – Moore Hill Beds
93DKA–327	683025	4946825	Burnt River Quarry	upper Gull River – lower Bobcaygeon
93DKA–339	602750	4959950	Highway 69/400 roadcut	Shadow Lake – lower Gull River
93DKA–341	601900	4956750	shore at Waubaushene	Shadow Lake – lower Gull River
93DKA343	693750	4957650	"oldest quarry" – north of Port McNicoll	lower Gull River
93DKA–344	693250	4957275	Port McNicoll Quarry	lower Gull River – upper Gull River
93DKA–346	593050	4965300	Quarry Island	Shadow Lake – lower Gull River
93DKA–404	659850	4940800	New Kirkfield Quarry	lower Bobcaygeon – upper Bobcaygeon
93DKA–412	669925	4955600	southwest of Beech Lake	Shadow Lake – lower Gull River
93DKA–415	675025	4947175	Coboconk Quarry	Moore Hill Beds – lower Bobcaygeon
93DKA–416	668875	4951825	small quarry west of Talbot Lake	lower Bobcaygeon
93DKA–418	674050	4951850	Highway 35 roadcut north of Coboconk	Shadow Lake – lower Gull River
93DKA–420	674675	4946725	Old Coboconk Quarry	upper Gull River – lower Bobcaygeon
93DKA–421	673950	4948625	Highway 35 roadcut beside Moore Hill	upper Gull River – lower Bobcaygeon
93DKA–431	680175	4950275	east shore of Four Mile Lake	upper Gull River – lower Bobcaygeon
93DKA–433	682050	4948200	Britnall Quarry – Burnt River	lower Gull River
93DKA–434	677900	4945225	south of Four Mile Lake	lower Bobcaygeon – middle Bobcaygeon
93DKA–436	677950	4933050	south of Balsam Lake	Precambrian – upper Bobcaygeon
93DKA–437	679850	4933450	Fenelon Falls	upper Bobcaygeon
93DKA–440	609750	4950700	Medonte Quarry	lower Gull River – lower Bobcaygeon
93DKA–441	619500	4948200	Uhthoff Quarry – upper south wall	upper Gull River – lower Bobcaygeon
93DKA–443	606300	4958250	Waubaushene Quarry	Shadow Lake – lower Gull River

Appendix 3: Unit thicknesses and elevations in OGS drill holes.

Table 1: Thickness of units (m) in each drill hole.

Drill Hole #	Lindsay Fm.	upper Verulam	lower Verulam	upper Bobcay–geon	middle Bobcay–geon	lower Bobcaygeon (w/o MHB)	Moore Hill beds	upper Gull River	shaly litofacies (upper Gull River)	lower Gull River	Shadow Lake
OGS–93–1	–––	–––	–––	12.90	2.53	9.46	3.87	3.29	2.84	11.41	1.63
OGS–93–2	–––	–––	9.97	13.00	6.20	5.82	5.38	3.51	3.45	12.41	3.83
OGS–93–3	9.38	4.14	47.27	13.08	6.33	6.25	4.15	4.16	2.41	9.20	3.60
OGS–93–4	–––	–––	–––	–––	10.57	5.20	1.05	5.29	0.00	14.09	7.82
OGS–93–5	–––	–––	–––	–––	–––	–––	–––	–––	–––	12.01	5.21
OGS–93–7	–––	–––	–––	–––	–––	4.04	7.75	0.00	1.64	9.19	6.25
OGS–93–8	–––	–––	–––	–––	–––	7.50	3.97	3.08	6.35	12.94	2.16
OGS–93–9	–––	–––	–––	–––	–––	3.41	1.74	5.30	3.29	13.99	6.23
OGS–93–10	–––	–––	–––	–––	–––	2.85	3.58	3.59	0.00	13.19	9.15
OGS–93–11	–––	–––	–––	–––	6.23	6.95	3.02	3.45	3.68	13.09	7.62
OGS–93–12	–––	–––	–––	–––	18.91	6.28	3.15	4.09	0.00	13.22	8.84
OGS–93–13	–––	–––	–––	–––	–––	3.33	1.54	4.76	0.00	13.08	8.30

Table 2: Elevations of tops of units (masl) in each drill hole.

Drill Hole #	Lindsay Fm.	upper Verulam	lower Verulam	upper Bobcay–geon	middle Bobcay–geon	lower Bobcay–geon	Moore Hill beds	upper Gull River	shaly litofacies (upper Gull River)	lower Gull River	Shadow Lake	Precam–brian
OGS–93–1	–––	–––	–––	283.30	279.16	276.63	267.17	263.30	260.01	257.17	245.76	244.13
OGS–93–2	–––	–––	263.64	253.67	240.67	234.47	228.65	223.27	219.76	216.31	203.90	200.07
OGS–93–3	282.94	273.56	269.42	222.15	209.07	202.74	196.49	192.34	188.18	185.77	176.57	172.97
OGS–93–4	–––	–––	–––	–––	214.57	204.00	198.80	197.75	219.90	192.46	178.37	170.55
OGS–93–5	–––	–––	–––	–––	–––	–––	–––	–––	–––	178.55	166.54	161.33
OGS–93–7	–––	–––	–––	–––	–––	300.60	296.56	288.81	288.81	287.17	277.98	271.73
OGS–93–8	–––	–––	–––	–––	–––	279.90	272.40	268.43	265.35	259.00	246.06	243.90
OGS–93–9	–––	–––	–––	–––	–––	305.33	301.92	300.18	294.88	291.59	277.60	271.37
OGS–93–10	–––	–––	–––	–––	–––	297.18	294.33	290.75	298.25	287.16	273.97	264.82
OGS–93–11	–––	–––	–––	–––	281.38	275.15	268.20	265.18	261.73	258.05	244.96	237.34
OGS–93–12	–––	–––	–––	–––	274.72	255.81	249.53	246.38	275.63	242.29	229.07	220.23
OGS–93–13	–––	–––	–––	–––	–––	237.18	233.85	232.31	244.29	227.55	214.47	206.17

N.B. Drill hole locations reported in Table 1 of Armstrong (1999a).

Appendix 4: Geochemistry of K–bentonite samples.

Major and Minor Elements: (analyzed by XRF) all values in weight %

Sample #	**SiO2**	**Al2O3**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**	**TiO2**	**P2O5**	**Fe2O3**	**LOl**	**TOTAL**	**S**	**CO2**
92DKA–232B1	50.55	22.09	0.03	2.86	1.00	0.14	5.75	0.17	<0.05	2.97	13.53	99.09	1.49	1.09
92DKA–232B2	49.28	21.68	0.01	3.95	1.02	0.22	5.66	0.17	<0.05	3.11	12.00	97.10	1.42	0.43
92DKA–103D	35.89	14.40	0.04	2.44	17.25	0.14	4.09	0.25	<0.05	2.79	20.45	97.74	0.50	14.90
93DKA–441H	44.85	18.78	0.02	3.55	10.13	0.12	4.87	0.18	<0.05	2.94	13.52	98.96	1.16	7.37
detection limits	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.05*		*0.01*	*0.03*

Trace Elements: (analyzed by XRF) – all values in ppm

Sample #	**Th**	**Nb**	**Zr**	**Y**	**Sr**	**Rb**	**Ba**	**Cr**	**As**	**Pb**	**Sn**	**Ga**
92DKA–232B1	21	18	159	9	466	120	327	9	8	44	<6	22
92DKA–232B2	25	18	149	8	425	133	349	13	8	44	<6	22
92DKA–103D	11	15	128	13	187	95	194	24	<6	16	<6	14
93DKA–441H	10	16	116	6	211	105	110	21	<6	51	6	19
detection limits	*10*	*3*	*5*	*5*	*5*	*5*	*8*	*2*	*6*	*7*	*6*	*5*

Rare earth elements: (analyzed by ICP–MS) – “d” indicates duplicate analysis – all values in ppm

Sample #	**La**	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Tb**	**Gd**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**
92DKA–232B1	2.73	5.72	0.74	3.00	0.90	0.18	0.23	0.96	1.67	0.40	1.43	0.25	1.75	0.27
92DKA–232B2	2.42	4.77	0.63	2.57	0.82	0.18	0.23	0.95	1.69	0.42	1.40	0.25	1.81	0.29
92DKA–103D	7.35	15.19	1.83	7.08	1.65	0.29	0.29	1.58	1.87	0.41	1.25	0.21	1.48	0.22
93DKA–441H	7.34	15.05	1.83	6.51	1.41	0.19	0.19	1.18	1.06	0.20	0.61	0.09	0.62	0.09
92DKA–232B1d	2.52	5.22	0.69	2.81	0.87	0.18	0.23	0.95	1.73	0.39	1.39	0.26	1.81	0.28
92DKA–232B2d	2.60	5.15	0.67	2.74	0.83	0.19	0.22	0.95	1.72	0.40	1.43	0.25	1.75	0.28
92DKA–103Dd	7.35	15.36	1.85	6.97	1.67	0.31	0.29	1.59	1.88	0.40	1.26	0.21	1.48	0.23
93DKA–441Hd	7.26	14.78	1.80	6.37	1.38	0.20	0.20	1.18	1.04	0.20	0.62	0.10	0.61	0.10
detection limits	*0.05*	*0.05*	*0.05*	*0.18*	*0.15*	*0.07*	*0.03*	*0.14*	*0.13*	*0.03*	*0.10*	*0.03*	*0.11*	*0.04*

Trace and rare elements: (analyzed by ICP–MS) – “d” indicates duplicate – all values in ppm

Sample #	**Rb**	**Sr**	**Nb**	**Cs**	**Hf**	**Ta**
92DKA–232B1	108.85	534.51	18.53	14.00	6.43	1.68
92DKA–232B2	130.25	492.48	19.62	16.73	6.58	1.72
92DKA–103D	96.81	204.08	14.89	8.10	4.35	1.15
93DKA–441H	107.73	240.44	17.14	16.10	4.98	2.05
92DKA–232B1d	114.13	535.75	19.04	14.26	6.56	1.70
92DKA–232B2d	121.10	476.77	19.06	16.45	6.56	1.70
92DKA–103Dd	100.53	206.90	14.75	8.12	4.37	1.14
93DKA–441Hd	102.94	238.24	16.96	16.11	5.00	2.03
detection limits	*1*	*2*	*0.5*	*0.1*	*0.05*	*0.5*

Trace Elements: (analyzed by ICP–OES) – all values in ppm

Sample #	**Co**	**Sc**	**Zn**
92DKA–232B1	<5	7.89	35.43
92DKA–232B2	<5	8.12	34.59
92DKA–103D	<5	6.33	34.23
93DKA–441H	<5	7.06	40.96
detection limits	*5*	*2*	*5*

Sample locations: 92DKA–232B1 and –232B2 from Brechin Quarry; 92DKA–103D from Longford Quarry; 93DKA–441 from Uhthoff Quarry.

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 90**	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 which are 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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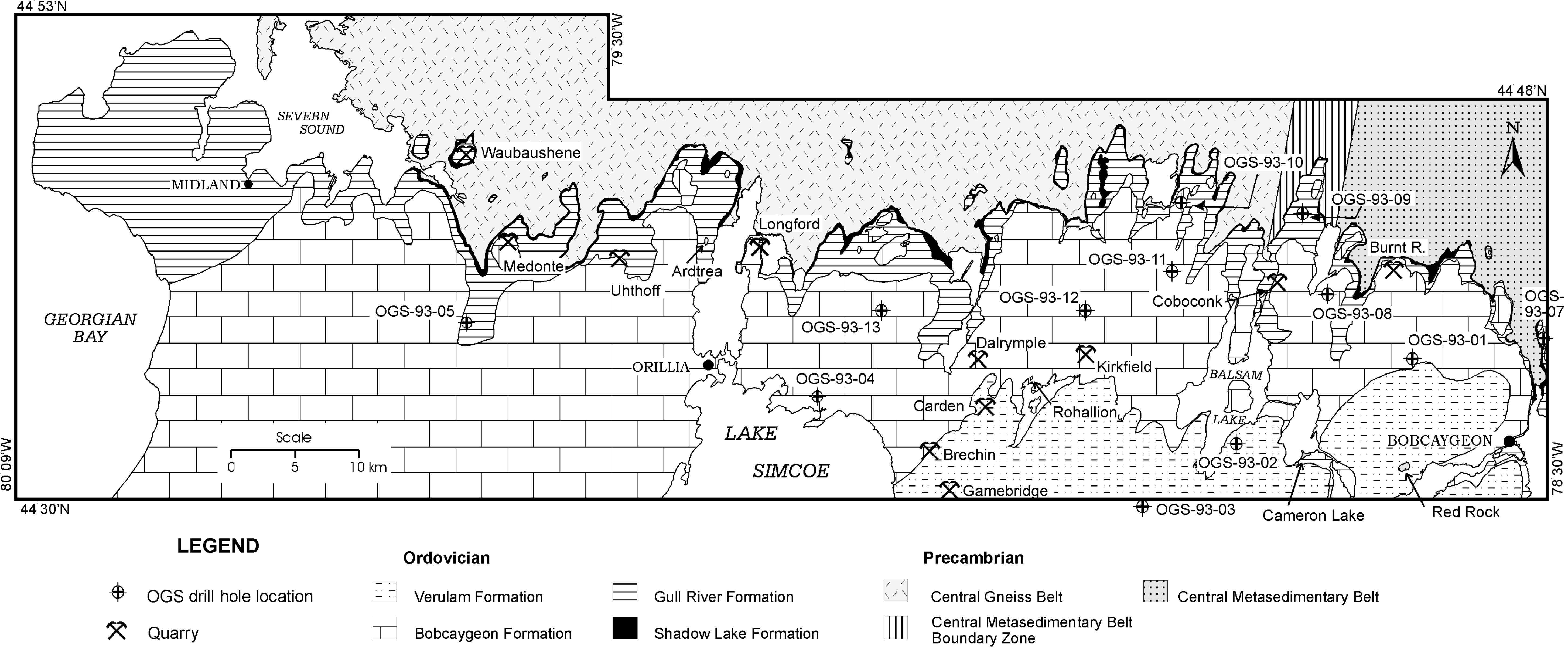

Figure 3: Bedrock geology of the north Lake Simcoe study area, showing locations of main quarries, OGS drill holes and Precambrian inliers (Ardtrea, Rohallion, Cameron Lake and Red Rock). Geology after Armstrong and Rhéaume (1993b), 1995), Armstrong and Anastas (1993) and Ontario Geological Survey (1991). See Figures 1 and 2 for location of study area.