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Regional geology and tectonic setting of Lake Ontario region

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M. Hinton, M. Lewis, D. Sharpe, B. Todd**

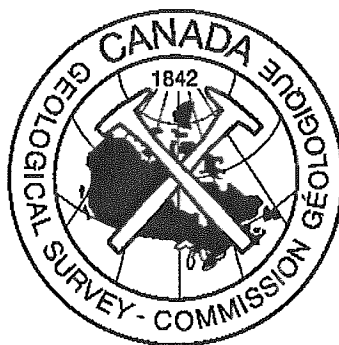
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REGIONAL GEOLOGY AND TECTONIC SETTING OF LAKE ONTARIO REGION

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REGIONAL GEOLOGY AND TECTONIC SETTING OF LAKE ONTARIO REGION

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Preface

The Geological Survey of Canada (GSC) recognizes that a number of studies have been underway concerning the tectonic stability of southern Ontario and adjoining Lake Ontario. The GSC has been invited by the Siting Task Force Secretariat of Natural Resources Canada (responsible for cleaning up low-level radioactive waste in and near Port Hope) to participate in and/or comment on some of these studies and will no doubt be asked to provide geoscience information to all interest groups in the future.

The geological, geophysical and tectonic history of southern Ontario and Lake Ontario is complex, and in part, is poorly known, particularly in the offshore area. Because of this complexity and the public interest in the geologic stability of the area, the GSC is releasing this short regional summary. The report attempts to lay out the basic regional geologic information from existing published data or work in progress, in an objective manner. Hopefully it will aid the discussions on the regions geologic and tectonic history.

The report presents the scientific views of the individual authors and is not necessarily the collective view of the GSC. There are clear differences of opinion on some of the evidence and its interpretation. This is to be expected in an area with a complex geological structural history and limited data in large areas such as Lake Ontario and areas of thick Quaternary cover.

1. REGIONAL CRYSTALLINE BASEMENT STRUCTURE IN SOUTHERN ONTARIO

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In the regional magnetic map of Southern Ontario, two visually prominent linear anomaly trends extend southwards from the exposed crystalline basement rocks to meet each other close to Lake Ontario. Prominent anomalies within these magnetic trends do not appear to correspond to any major faults within the ca. 450 million year old limestones which sit on top of the crystalline rocks, thereby raising the possibility that the anomaly sources lie within the crystalline rocks which formed before the limestones were deposited. The eastern anomaly trend appears to represent the southward extension of the Central Metasedimentary Belt boundary thrust zone, while the western anomaly trend runs along the length of the northwest coast of Georgian Bay.

The Central Metasedimentary Belt boundary thrust zone

General Features:

Southern Ontario contains part of the exposed eroded roots of an ancient mountain chain, referred to as the **Grenville orogen**, which stretched from Texas to Labrador, and beyond. In its prime, the mountains of the Grenville orogen would have looked very much like the Himalaya today. Indeed, for some scientists, the two mountain chains were created by similar geological processes. However, it is important to realise that the Grenville orogen and its associated mountains formed 1200 to 1000 million years ago.

In Southern Ontario, the Grenville orogen is divided into three major southeast-dipping, structurally overlapping blocks of continental crust. These are, from northwest to southeast, (i) the Grenville Front Tectonic Zone, (ii) the Central Gneiss Belt and (iii) the **Central Metasedimentary Belt**, all flanked to the southeast by the Adirondack Highlands in New York state.

The Central Gneiss Belt is composed of a collage of individual sheets of crystalline gneiss, up to 5 km thick by ca. 20+ km long, which were thrust over each other toward the NW during the **Grenville orogeny** (*mountain building period*). They are bounded along their bases by thick plastic or ductile movement zones (shear zones), up to several hundreds of metres thick. These zones are "faults". However, it is important to realise that they are not discrete, brittle fractures. Because they formed at temperatures of ca. 800+°C, at crustal depths of ca. 35km, they resembled hot taffey when they were active and are better described as ductile deformation zones. At the end of their active lives, they were annealed (tempered) by recrystallisation at high temperatures, similar to metals in industrial processes.

The Central Metasedimentary Belt is the size of Switzerland and sits directly above the Central Gneiss Belt. It is a very large version of the small crystalline sheets which make up the Central Gneiss Belt. It too was thrust towards the northwest along a shear zone, referred to as the **boundary thrust zone**. From detailed regional geological mapping and reconnaissance seismic studies in Ontario, the exposed boundary thrust zone dips shallowly to the southeast, varies in width from about 5-40 km, and runs from the Pembroke area to south of Minden. It is a 10 km thick by 200+ km long, and probably accommodated ancient displacements of the order of 10's of kilometres. Internally, it is a stack of crystalline sheets, enclosed by an anastomosing network of plastic shear zones, formed at mid- to deep-crustal levels. The shear zones have a very striking banded, or slabby appearance which is due to the large movements they have accommodated. The

first thrusting occurred at ca. 1200 million years ago, and was renewed at ca. 1080 to 1050 million years ago. Clearly, the boundary thrust zone is a very large fault. However, its last recorded movement occurred over one billion years ago.

Immediately on top of the boundary thrust zone is a much smaller plastic shear zone, referred to as the Bancroft shear zone. It is made of short segments, perhaps several kilometres in length, but no more than a maximum of 10m thick. These represent relatively late movements along the top of the boundary thrust zone. However, because the segments do not link to form a continuous network, it is highly improbable that they accommodated displacements greater than a few 100's of metres at most. Again, it is emphasised that these movements occurred at ca. 950 million years ago.

Seismic Features

At depth, seismic methods (**Lithoprobe** and related studies), also indicate the boundary thrust zone dips shallowly (10 to 40 degrees) to the southeast, and probably extends at least as far as (Lakes Ontario and Erie. The seismic images consist of reflections from geological structures that form a cross section through the crust beneath the survey lines. Rock properties for compositions nearly identical to rocks exposed in the Central Metasedimentary Belt and the boundary thrust zone have been studied. The results indicate that ductile Grenville structures such as exposed in southern Ontario are very suitable sources (have appropriate reflective coefficients) for the seismic reflections. Figure 2 is a seismic image of the Precambrian basement structure beneath relatively horizontal Paleozoic strata beneath western Lake Ontario. Figure 3 shows the structure of the top 5 km of the crust beneath eastern Lake Erie. Note that the faulted offset of the lower part of the Paleozoic section diminishes toward the surface beneath Lake Erie indicating that the faulting activity had essentially stopped by the time near-surface sediments were being deposited some 400 million years ago.

Georgian Bay lineament

The Grenville Front Tectonic Zone (Fig. 1) dips to the southeast and has been identified as an ancient one billion year old plastic shear zone, somewhat comparable to the Central Metasedimentary Belt boundary thrust zone. Seismic study in Georgian Bay indicates that the buried section of the Grenville Front Tectonic Zone is similar in size and internal architecture to the boundary thrust zone. However, the segment of the Grenville Front Tectonic Zone exposed on land appears significantly narrower than the seismic image suggests, and structurally rather simple. This difference *could* lend credence to the suggestion that the magnetic anomaly along the Georgian Bay shoreline (Georgian Bay lineament) may indicate an unmapped fault or shear zone. However, it should be noted that there is no indication in the magnetic pattern marking the Front itself that it has been off-set, as would be expected in a fault model. In addition, the anomaly trends along the northeast shore of Georgian Bay are part of a series of northwest trending anomalies that also occur both northeast and southwest of the Georgian Bay shoreline. Accordingly, we can only conclude that, while the possibility that the Georgian Bay lineament may mark a fault or shear zone cannot be excluded, it is unlikely that it represents important displacements which are significantly different from the deformation that characterises the rest of the surrounding Central Gneiss Belt. Since we cannot observe the rocks associated with the magnetic anomaly, we can say little about the age of such a putative fault or shear zone. Rather, such constraints would come from the study of the overlying limestone cover.

Summary

The more easterly of the two magnetic anomaly trends appear to represent the extension of the Central Metasedimentary Belt boundary thrust zone beneath the limestone cover. This was a very important fault or shear zone more than one billion years ago. It has since healed, and in the crystalline basement there is no evidence for recent reactivation of the structure.

Will the boundary thrust zone move again as a large-scale fault zone? Could the sheet-like or

slabby structure of the boundary thrust zone represent a weakness which modern faulting could locally exploit and re-activate? Is the boundary thrust zone a significant regional-scale variable which could affect the safety of people and energy infrastructure? It is difficult provide a definitive not no as a response to these issues and the questions will have to addressed with respect to the level of seismic activity measured and expected for the area. However, the level of known seismic activity in southern Ontario, the relatively undisturbed billion-year old Grenvillian crustal structures, the relatively undeformed and only locally fractured Paleozoic strata, and the minor subsequent adjustments to the crustal structure beneath southern Ontario, suggest that potential seismic hazard is low.

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FIGURES

Figure 1.1 Geology of the Central Metasedimentary Belt boundary thrust zone (CMBbtz), after Hanmer and McEachern (1992). Foliations (not shown) are concordant to lithological contacts and dip shallowly to the southeast. The dotted lines are structural traces. Discussed in text. Schematic illustration of the principal tectonic elements of the southwest Grenville orogen in Ontario. CGB, Central Gneiss Belt; CMBbtz, Central Metasedimentary Belt boundary thrust zone; GFTZ, Grenville Front Tectonic Zone.

Figure 1.2 Seismic Section

Figure 1.3 Detail of seismic section

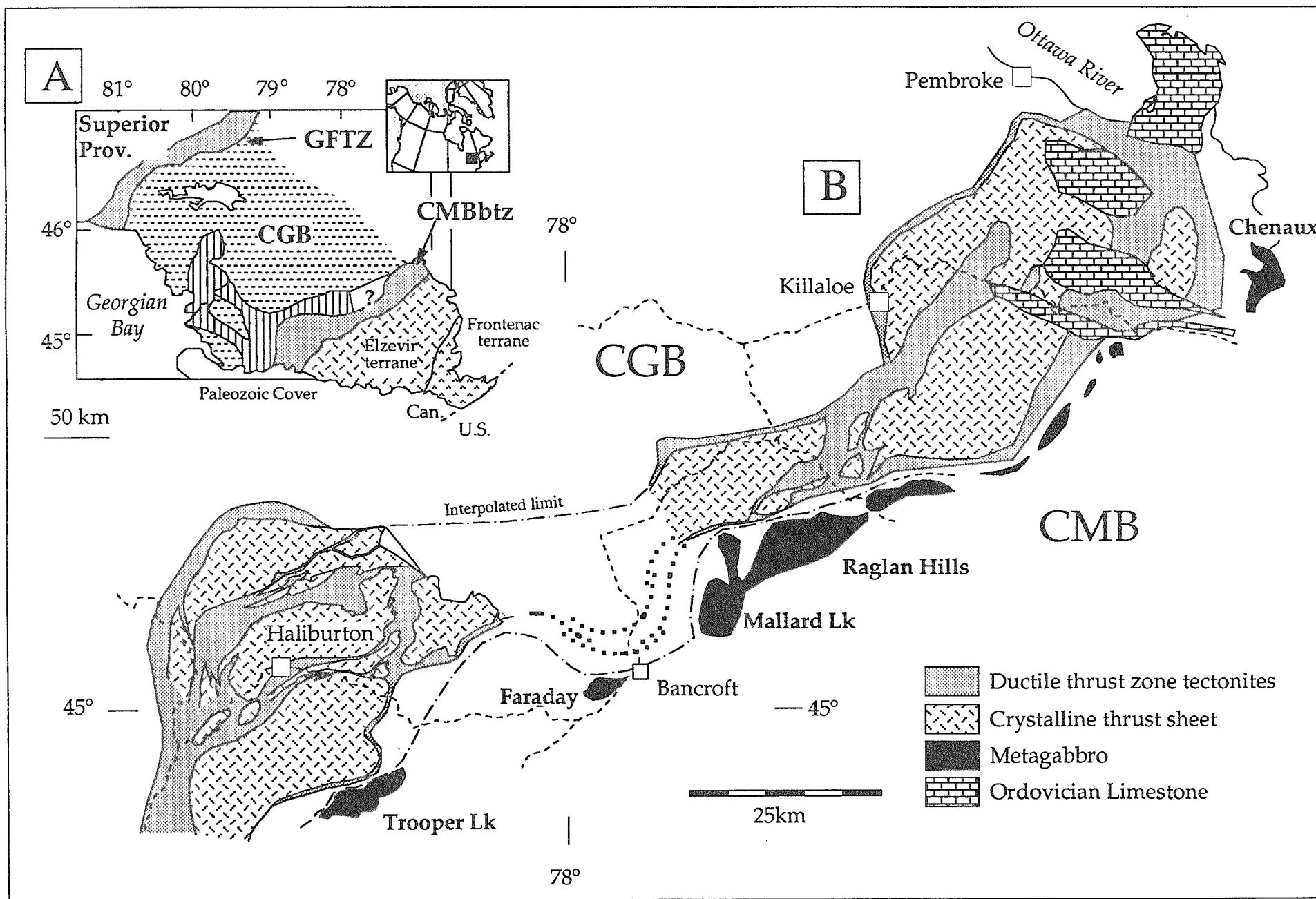
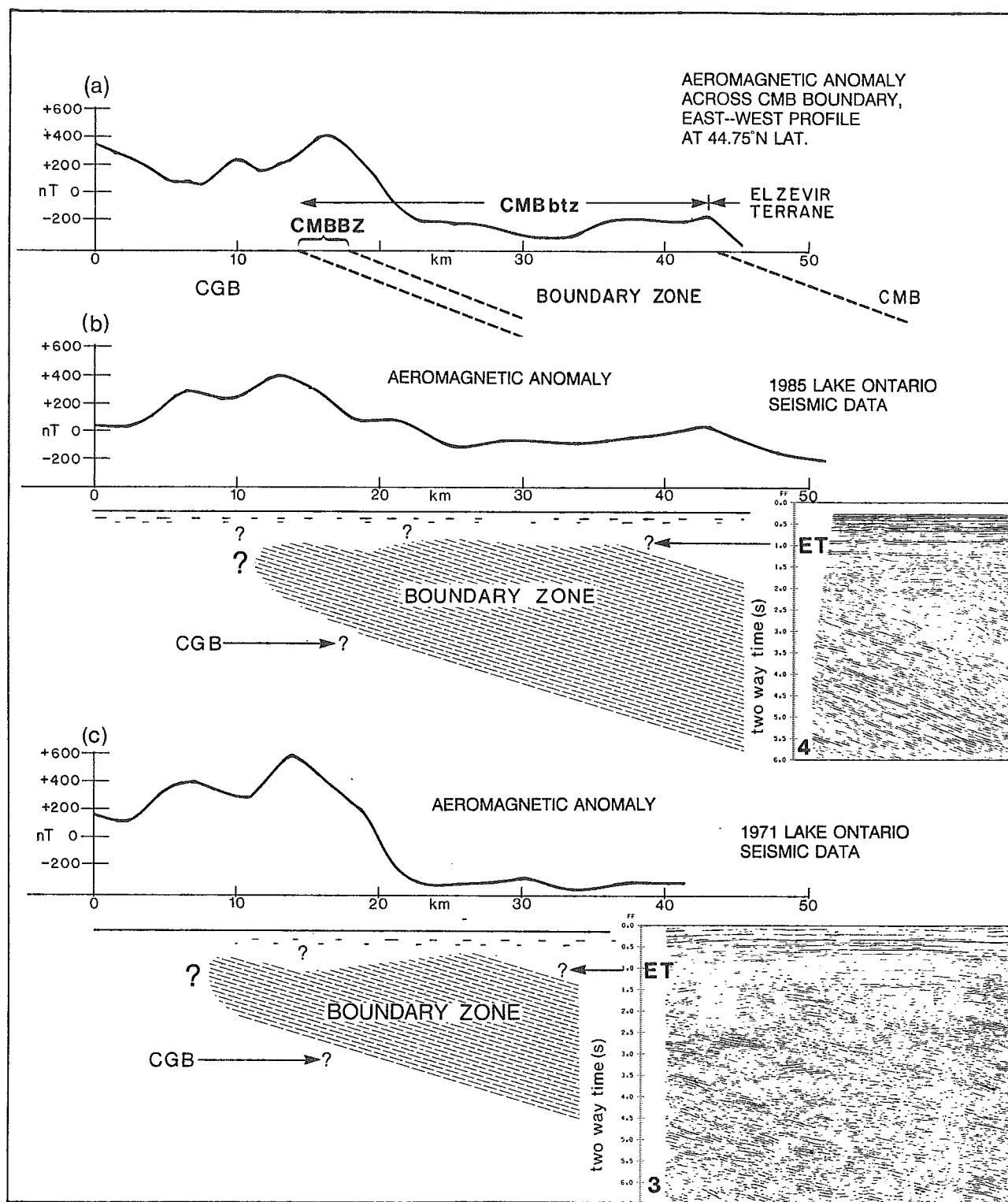


Fig. 1.1



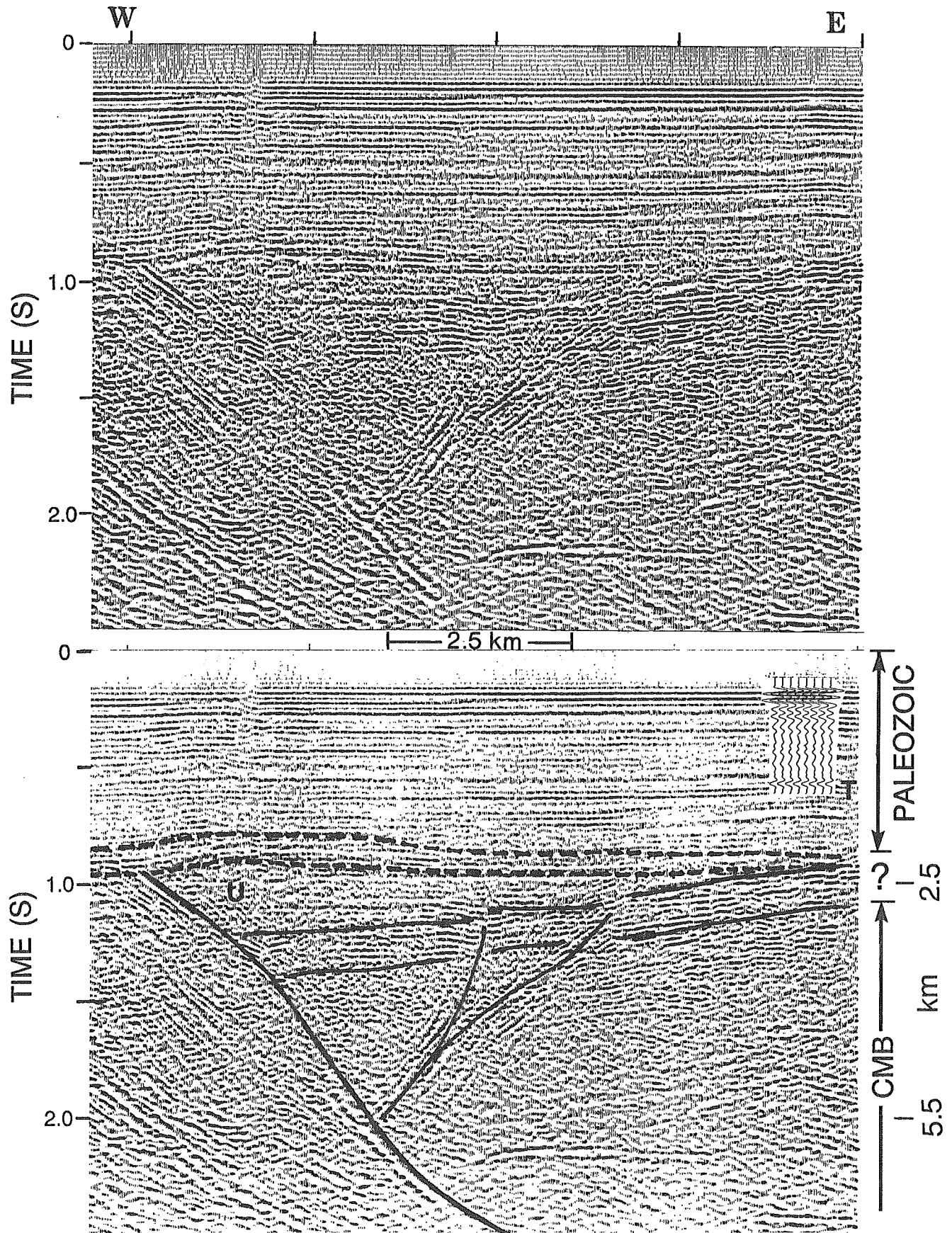


Fig. 1.3

2. PALEOZOIC GEOLOGY OF CENTRAL ONTARIO AND ADJACENT LAKE ONTARIO

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Regional geological setting

The Paleozoic rocks of central Ontario and adjacent Lake Ontario (*see* Hachured area of Figure 1) form a small part of the St. Lawrence Lowlands, a major physiographic province underlain by relatively flat lying Paleozoic strata that extend northeastward from the Great Lakes region of Canada and United States, through the Ottawa-Quebec Lowlands and northern Gulf of St. Lawrence, to the west coast of Newfoundland. Throughout this region, the strata are underlain and bounded on the north by crystalline Precambrian rocks of the Canadian Shield, and on the south by highly deformed and metamorphic Paleozoic terranes collectively referred to the Appalachian Orogen (Figure 1). Along the southern perimeter of the St. Lawrence Lowlands the Paleozoic strata have undergone major deformation (fracturing and folding) where they were compressed by over-riding slices of Appalachian terranes that were thrust into the lowland region coincident with the more intensive phases of Appalachian mountain building processes. These processes controlled by plate movements of global proportions in turn led to widespread marine inundation of the Canadian Shield, and to corresponding vertical crustal movements along the St. Lawrence Lowlands, including that small segment of central Ontario to be discussed herein.

Some of the more profound crustal movements in the western segment of the St. Lawrence Lowlands associated with Appalachian compressional forces were uplift of the positive structural elements, including the Frontenac, Algonquin, Findlay and Fraserdale arch systems (*see* Figure 1), and corresponding inception and progressive development of the Michigan and Appalachian sedimentary basins, processes that continued from Cambrian, through Ordovician, Silurian, Devonian to Carboniferous time.

Appalachian Mountain building processes appear to have stabilized at the close of the Paleozoic, but plate movements of an extensional nature continued to affect the Canadian craton including the St. Lawrence Lowlands throughout much of the ensuing Mesozoic Era, principally during the Jurassic and Cretaceous periods. Evidence of major rifting here and there along the St. Lawrence Lowlands in the form of dyke and pluton emplacement (intrusive magmas), in addition to the deposition of Jurassic sediments in the Michigan Basin (Sanford *et al.*, 1979), and Jurassic to Cretaceous sediments in the Moose River and Hudson Bay basins, and adjacent deep channels of Hudson Strait and Foxe Channel (Sanford and Grant, 1990) point to widespread vertical movements of the Canadian craton throughout much of the Mesozoic.

The basement arches (Figure 1), most of which have risen intermittently throughout geological time, are still active as evidenced by the concentration of earthquake epicentres that appear to parallel their axes (Sanford *et al.*, 1985). This is especially so of the Frontenac Arch and the structurally related Adirondack Uplift, that have had a long and complex history of vertical rejuvenation (uplift). Adding to the complexity of the regional structure of the arch and the adjacent Paleozoic lowland regions which it intersects, is the Central Metasedimentary Belt of the Grenville Province (crystalline basement). These rocks cross the Frontenac Arch northwest of the Adirondack Uplift, and from there, their structural trend is NE-SW beneath the Paleozoic cover rocks of the Ottawa Lowland and Appalachian Basin respectively. The succession of vertical movements that have affected the Frontenac Arch have thus, in turn locally fractured the Paleozoic cover rocks in orientations that have a tendency to reflect the southwest trending structural grain of the underlying crystalline basement rocks of the Central Metasedimentary Belt. Some of these fractures extend for considerable distances into Paleozoic terrain to the southwestward across

central Ontario (notably Prince Edward County), and beneath the waters of Lake Ontario (Liberty, 1960; Carson, 1981a). Contemporary movement of one or another of these fractures could have been responsible for the earthquake recorded in western New York State, the Niagara Peninsula and adjacent locations beneath lakes Ontario and Erie, and in southwestern Ontario.

Stratigraphic framework

The Paleozoic strata of central Ontario are comprised of limestones and shales that range from Middle to Late Ordovician age (*see* figures 2, 3 and 4). From their northern erosional edges, the beds dip at a low angle (less than 1°) into the Appalachian Basin. The onshore distribution of the principal rock units, shown in Figure 2, was compiled from published maps of the Geological Survey of Canada (Liberty, 1969; Winder, 1954; Sanford and Baer, 1981), and Ontario Geological Survey (Carson, 1980a, 1980b; Carson, 1981a, 1981b). The offshore extension of these beds beneath Lake Ontario was compiled from maps recently constructed by the writer from marine seismic data (Sanford, in press).

The older Ordovician strata that are preserved throughout most of central Ontario are largely carbonate rocks (limestones) that are identified by the terms Shadow Lake, Gull River, Bobcaygeon, Verulam and Lindsay formations in that respective ascending order of succession. Completing the Ordovician succession, mainly in the offshore beneath Lake Ontario, are shales of the Blue Mountain, Georgian Bay and Queenston formation in that ascending order (*see* figures 2 and 3).

Structural framework

The Precambrian basement complex beneath the Ordovician succession in central Ontario decreases in elevation in a southward direction beneath the Appalachian Basin at the rate of about 7 metres/kilometre (*see* Figure 1). Throughout the years a fair number of boreholes have been drilled within the region in exploration for hydrocarbons and for other purposes, and many of these have passed completely through the Paleozoic succession to terminate in the underlying Precambrian basement (Sanford and Quillian, 1959; Sanford (1961); Petroleum Resources Section, (1984a, 1984b). With certain exceptions, the locations of the boreholes are too widely separated to map the major structural lineaments on the Precambrian surface, or to establish an accurate framework of the major fractures that may propagate upward from the basement to intersect the Ordovician strata. In a few areas of central Ontario however, where closely spaced borehole data are available, major structural lineaments on the basement surface, oriented to the northeast and to the northwest, are observable.

Recent detailed stratigraphic investigations by the writer (Sanford, 1993), along the Paleozoic/Precambrian contact between Orillia and Burleigh Falls in central Ontario have determined the location of a number of major fractures that intersect the Ordovician strata of that region. Their dominant orientation is southwest with subordinate southeast and east-west orientations.

Similar fracture systems have been mapped beneath Lake Ontario based on the interpretation of airgun seismic data (Sanford, in press; McQuest Marine Sciences Ltd., 1995). Figures 5 and 6 are two examples where Ordovician strata (Lindsay and Queenston formations respectively) appear to have been intersected by major fractures. In addition to the fractures that are interpreted to intersect Lindsay strata in Figure 5, there are strong indications from the seismic data that some of the vertical movements may have also taken place during the deposition of the overlying Quaternary and Recent sediments beneath the floor of the lake. The fractures shown in Figures 5 and 6 have orientations in a northeast direction as do many of the other possible fractures identified by the writer in other widely separated segments of the lake bottom. Most of the fractures in this region have a similar orientation to those identified along the Paleozoic/Precambrian boundary (Sanford, 1993), as well as to the structural grain of the underlying Precambrian Central Metasedimentary Belt (*see* Figure 1), as interpreted from aeromagnetic maps published by the Geological Survey of

Canada, and the Ontario Geological Survey. Much of the Ordovician bedrock surface between Lake Ontario and the Paleozoic boundary is obscured by Quaternary deposits, and there is thus some element of uncertainty as to where, and to what extent, these major fracture systems do in fact interconnect across the intervening area of central Ontario.

In southwestern Ontario (west of Niagara Escarpment), where information is available for several thousand boreholes drilled in exploration for oil and gas, the major fracture framework has been pieced together with a fair degree of accuracy (Sanford *et al.*, 1985). The same borehole data have also provided the stratigraphic and sedimentological framework to reconstruct the timing of the fracturing at periodic intervals of geological time, from Ordovician to Carboniferous. Some of the fractures have been rejuvenated during and/or subsequent to Quaternary time, as evidenced by sharp linear features at surface locally observable on LANDSAT imagery.

One other important finding concerning fracture rejuvenation in southwestern Ontario, is that the timing of the movements appear to closely coincide with the more intensive plate tectonic events and related Appalachian mountain building processes active at those times (grossly 470-350 million years ago) along the eastern continental margin of North America. If one can thus conclude that external forces (regional compressional and extensional stresses) were in some way responsible for the fracturing of the Paleozoic strata in southwestern Ontario, it is only reasonable to expect that the Paleozoic strata lying beneath Lake Ontario and in central Ontario should be similarly affected.

The location and frequency of the earthquake epicentres recorded in southwestern Ontario and beneath Lake Erie are compatible with the complex fracture framework that has been mapped in these regions by Sanford *et al.* (1985). The preponderance of earthquake epicentres reported beneath Lake Ontario and in adjacent onshore areas of central Ontario would strongly suggest a bedrock fracture framework of similar complexity.

FIGURES

- Figure 1 Regional tectonic elements-Great Lakes Region.
- Figure 2 Paleozoic geology of Central Ontario and adjacent Lake Ontario.
- Figure 3 Section A-A'
- Figure 4 Generalized stratigraphic succession.
- Figure 5 Seismic profile- 40 km southwest of Cobourg. Vertical exaggeration is 1:45.
- Figure 6 Seismic profile- 75 km southwest of Picton. Vertical exaggeration is 1:40.

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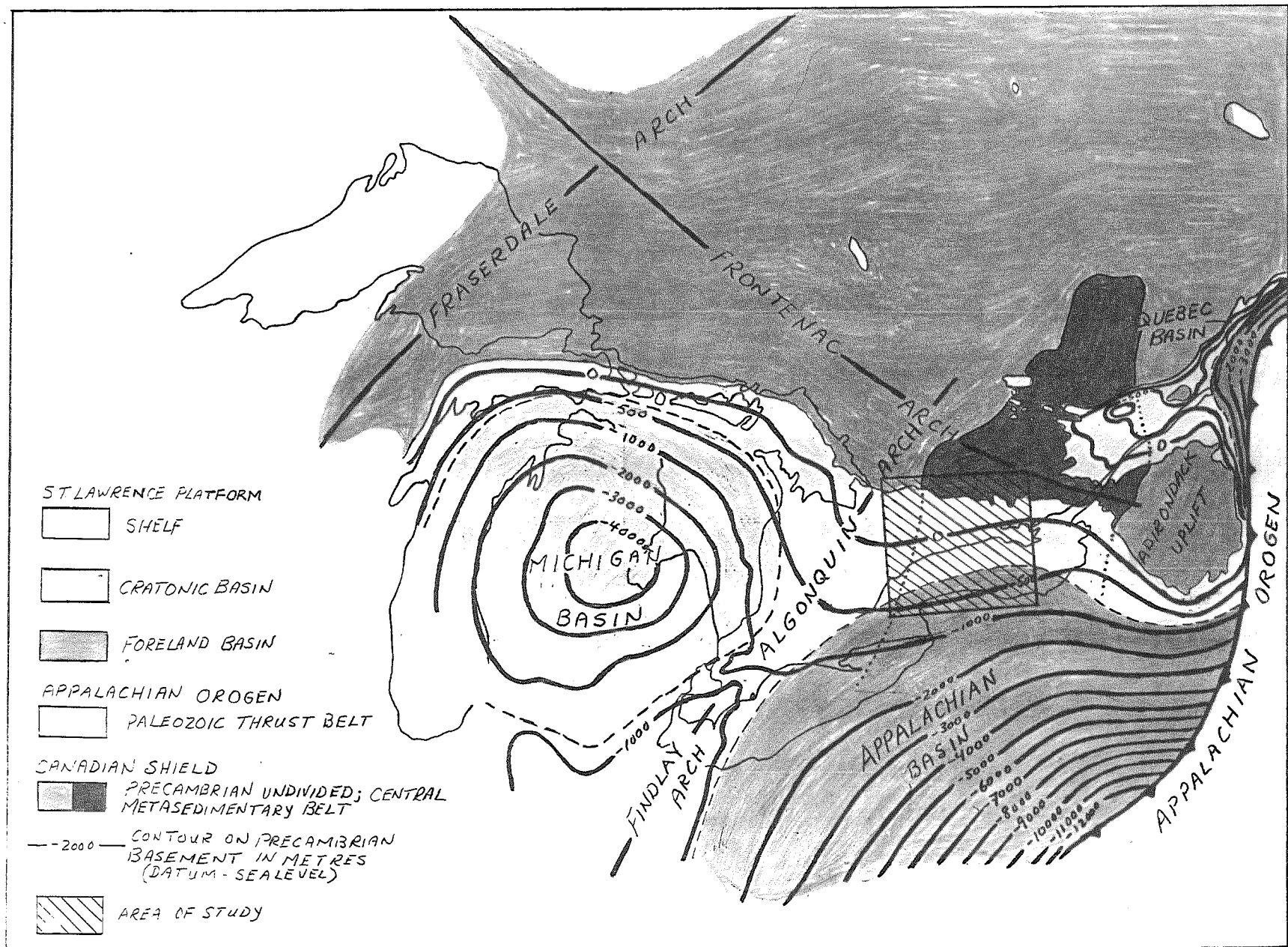
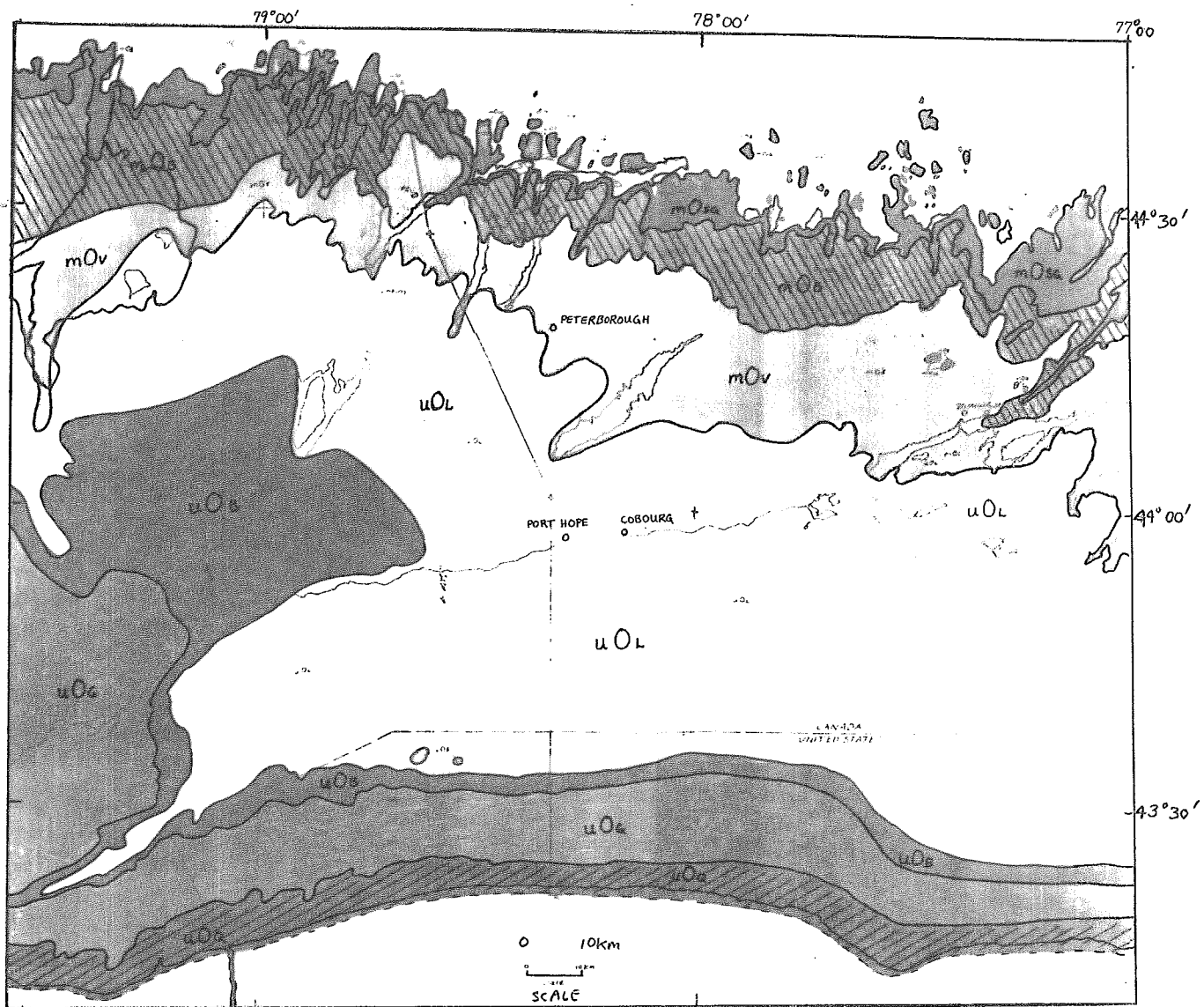


FIGURE 1: REGIONAL TECTONIC ELEMENTS-GREAT LAKES REGION



ORDOVICIAN UPPER ORDOVICIAN

- Queenston Formation: red shale, siltstone and sandstone
 - Georgian Bay Formation: grey shale, siltstone and sandstone
 - Blue Mountain Formation: black shale
 - Lindsay Formation: argillaceous limestone with shale interbeds

MIDDLE ORDOVICIAN

- Verulam Formation: interbedded limestone and shale
 - Bobcaygeon Formation: argillaceous limestone and shale
- Gull River Formation: lithographic limestone
 - Shadow Lake Formation: red and grey-green shale with limestone and dolostone

PRECAMBRIAN

- Igneous and metamorphic rocks

FIGURE 2. PALEOZOIC GEOLOGY OF CENTRAL ONTARIO AND ADJACENT LAKE ONTARIO

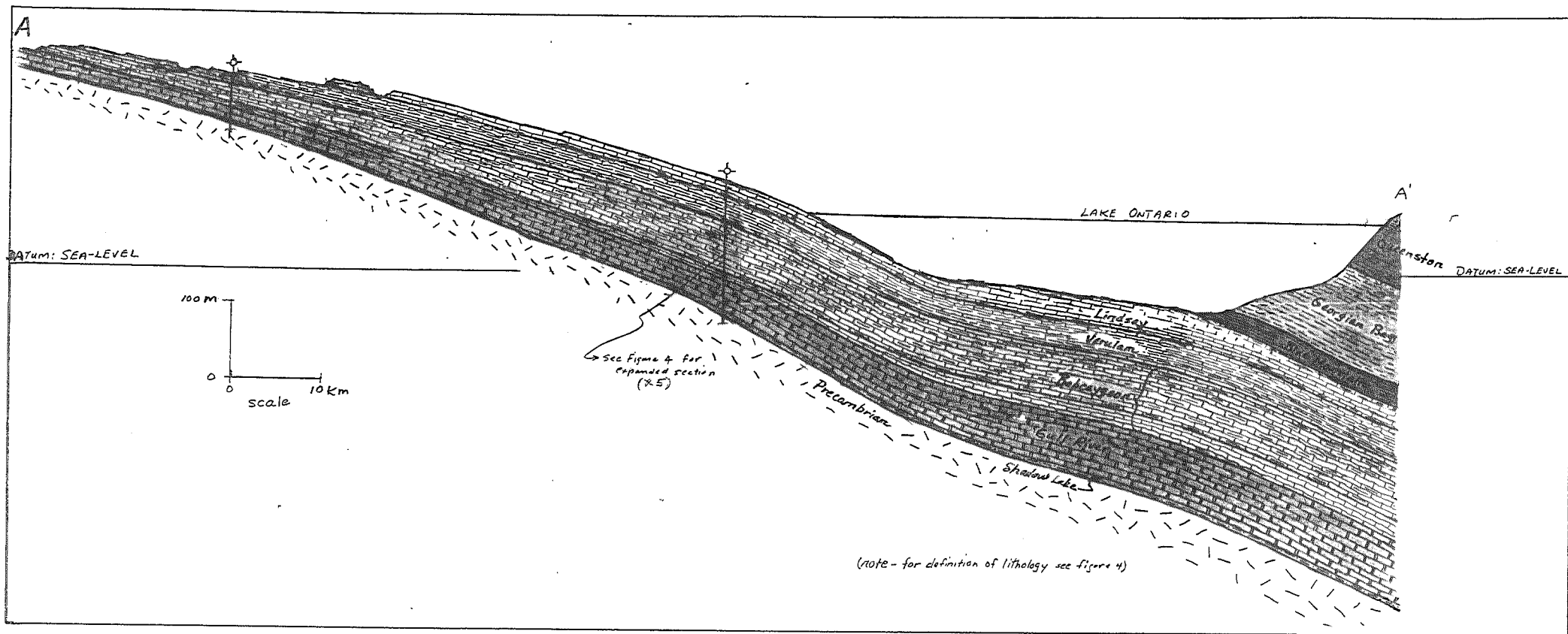


FIGURE 3: STRUCTURE-STRATIGRAPHIC SECTION A-A' (SEE FIGURE 2 FOR LOCATION)

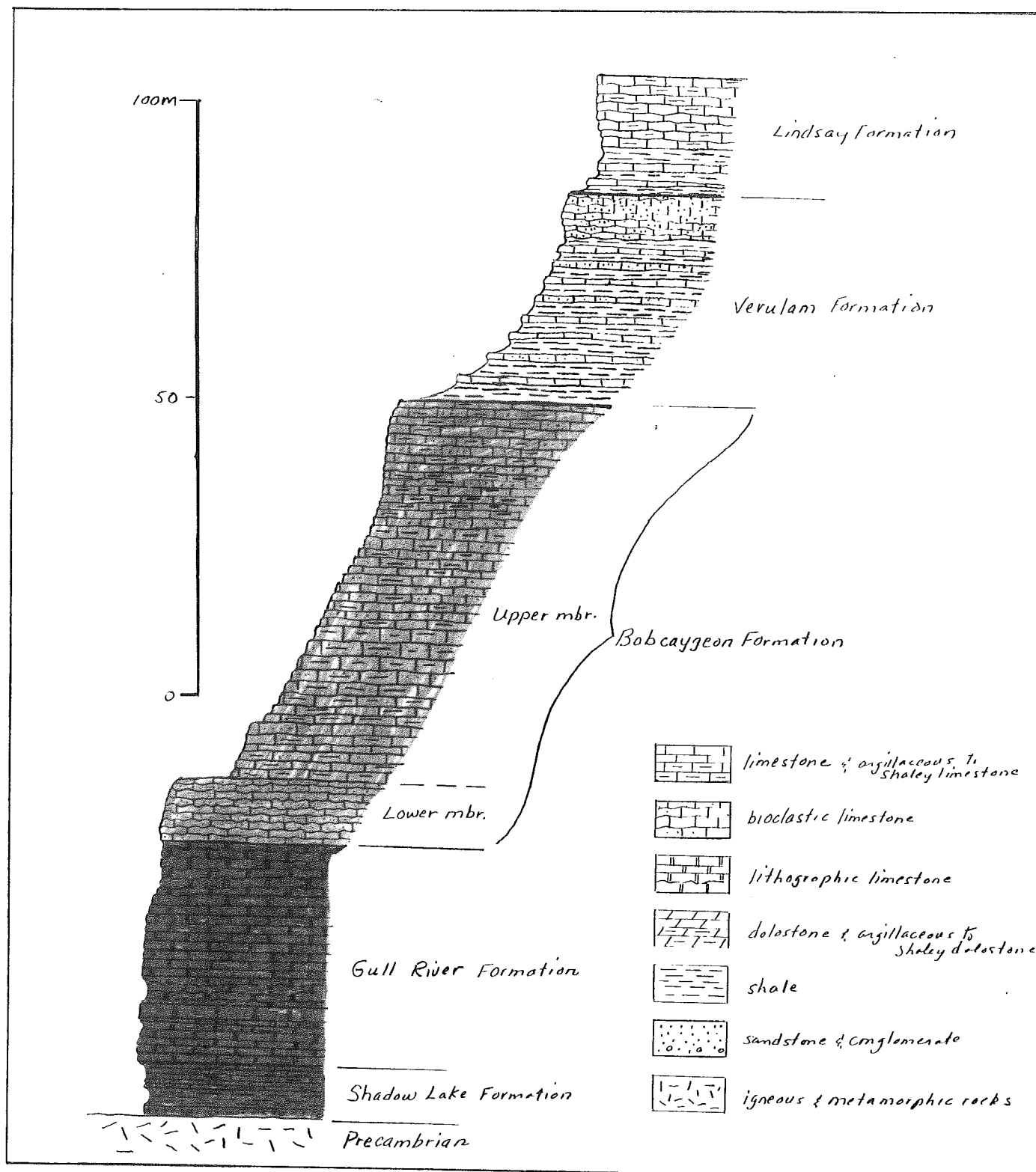


FIGURE 4: GENERALIZED STRATIGRAPHIC SUCCESSION

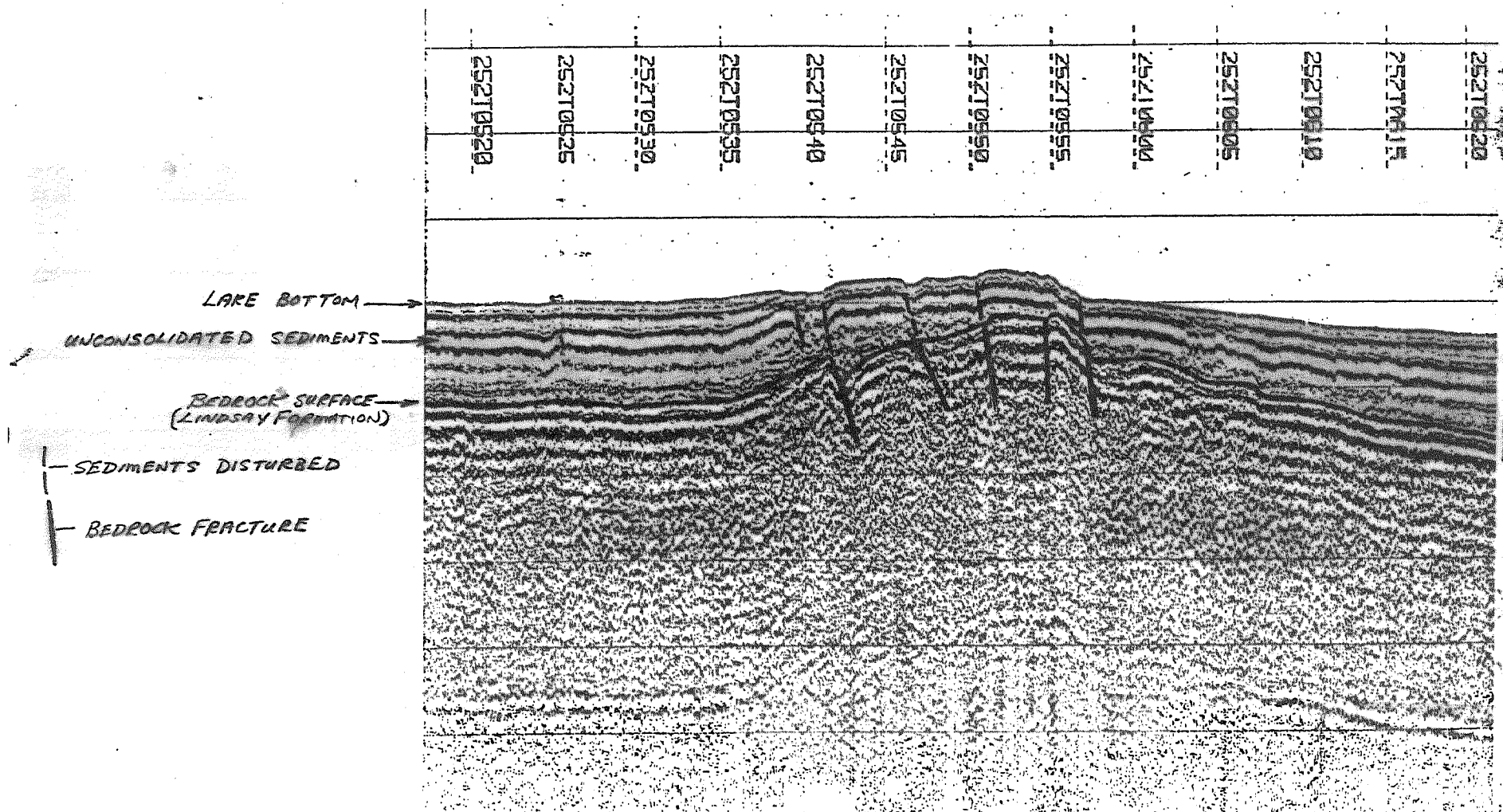


FIGURE 5: SEISMIC PROFILE - 40 KM. SOUTHWEST OF COBourg

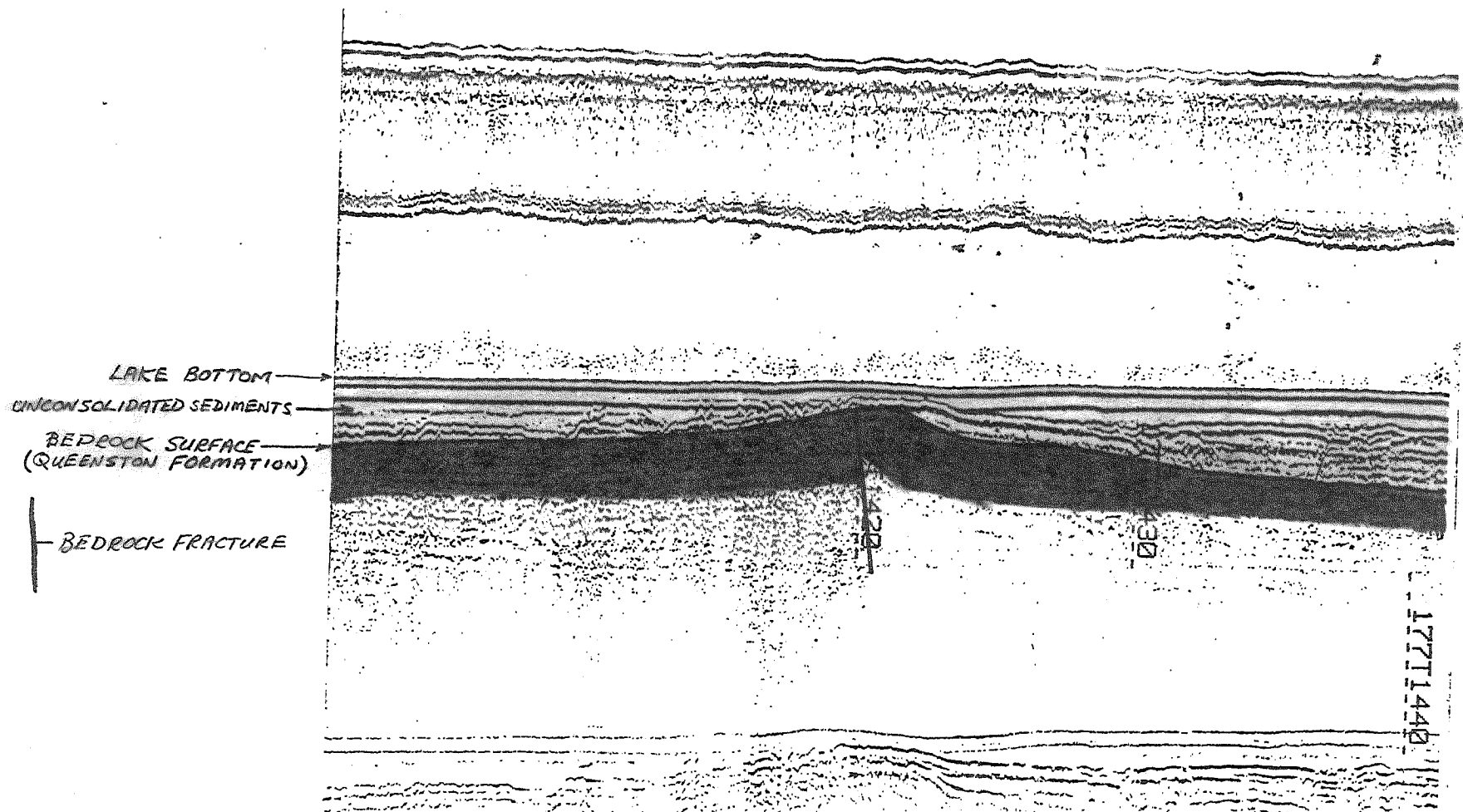


FIGURE 6: SEISMIC PROFILE-75 KM. SOUTHWEST OF PICTON

3. SEDIMENTS AND LATE QUATERNARY HISTORY OF LAKE ONTARIO

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Basin bathymetry and morphology

Lake Ontario stands 74.6 m above sea level and trends 290 km east-west; its maximum width is 85 km (Canadian Hydrographic Service, 1970). The deepest water, 246 m, occurs in the eastern basin; the maximum water depth in the western half of the lake is 190 m (Fig. 1a). Four sedimentological basins, from west to east, the Niagara, Mississauga, Rochester and Kingston Basins, are separated by zones of non-deposition called the Whitby-Olcott, Scotch Bonnet and Duck-Galloo Sills (Fig. 1b)(Thomas et al., 1972a).

The Lake Ontario basin is generally understood to be positioned on a former (pre-Quaternary) drainage system on Paleozoic sedimentary rock strata which was deepened to its present configuration below sea level by Quaternary glacial erosion (Spencer, 1890; Hough, 1958). The depression is differentially excavated into relatively soft Late Ordovician shales which dip gently into the Appalachian Basin to the south (Sanford and Baer, 1981). As a result, the basin is asymmetric in cross-section with its southern margin being steeper than the northern flank. Martini and Bowlby (1991) further suggest that tectonic adjustments have also contributed to the morphology of the lake basin.

Surface sediment distribution

Bedrock, deposits of glacial till and glaciolacustrine clay outcrop on the lakebed in near-shore regions (Fig. 2)(Rukavina, 1969,1976). Silty clay mud covers most of the deeper lakefloor, with local deposits of sand and sandy mud off major rivers (Fig. 3)(Thomas et al., 1972). The fine-grained sediments in deeper water accumulate at about 0.7-0.8 mm/year on average (Kemp and Harper, 1976).

Basin sedimentary fill

Bedrock elevation is shown in Figure 4. The configuration of the bedrock surface resembles the lakebed bathymetry (Fig. 1a). This small scale representation suggests the bedrock is smooth, but locally, for example off Port Hope, relief up to 12 m has been profiled and bedrock scarps 2-8 m high are common.

Subsurface knowledge of the lakebed is based on regional reconnaissance by seismic profiling, acoustic mapping and local sampling (Lewis and Sly, 1971; Anderson and Lewis, 1975; Sly, 1983a,b; Sly and Prior, 1984; Hutchinson et al., 1993). Five sedimentary units, recognized by seismic facies and stratigraphic position, overlie the bedrock surface and are designated by letters A to E, from oldest to youngest, as shown in a representative seismic section (Fig. 5). These units are the record of sedimentation in the Lake Ontario basin dating from the last glacial ice cover and its dissipation about 12-15 ka (Units A,B). They also record subsequent periods dominated by glacial lakes and glacial meltwater to about 10.5 ka (Unit C), followed by the Holocene record of Lake Ontario sedimentation (Units D,E). The seismic character, contact relationships, interpreted lithology and inferred environment of deposition of each of the units is summarized by Hutchinson et al. (1993) and shown in Figure 6. A cross-section of Lake Ontario shows the configuration of bedrock surface, sediment thickness, and the lakebed south of Port Hope (Fig. 7).

Geological history (late and post-glacial)

Following an advance to the eastern Erie basin at 13 ka, the margin of the Laurentide Ice Sheet

retreated to the Ontario basin (Barnett, 1992; Muller and Prest, 1985; Chapman and Putnam, 1984). By 12 ka the ice margin had retreated north of the basin but remained in the St. Lawrence Valley, impounding high-level glacial Lake Iroquois in the Ontario basin (Fig. 8). Continued retreat in the St. Lawrence Valley opened lower routes for drainage. As the glacial waters stabilized for short periods during this lowering trend they formed glacial lakes Frontenac, Belleville and Trenton (Pair et al., 1988). In the Port Hope area, the former water planes of glacial lakes Iroquois and Frontenac are now found about 87 m and 65 m above the present Lake Ontario. Those of lakes Belleville and Trenton are thought to now lie at about the present lake level and 19 m below it, respectively, near Port Hope (Fig. 9).

At about 11.6 ka, the ice dam decayed and seawater flooded the St. Lawrence Valley forming the Champlain Sea. Although the lake surface in Ontario basin fell to sea level (then about 60 m below present lake level at Port Hope) for about 300 years, the outflow of runoff and glacial meltwater from upstream basins prevented the intrusion of saltwater (Pair et al., 1988). This unusual proximity to the ocean was possible because the load of the former ice sheet had depressed the earth's crust. The crustal downwarp was greater in a north-northeasterly direction toward the area of greater ice loading. This action had tilted the Ontario basin downward toward the north and northeast, tipping its northeastern basin sills below the then current sea level. By the time of the glacial lakes, the crust beneath the basin was already recovering, more rapidly in the northeast than in the southwest. This differential recovery, or uplift, progressed at a steadily decreasing rate, and is still continuing today as indicated by changes in water level gauges around Lake Ontario (Clark and Persoage, 1970; Tushingham, 1992). The Duck-Galloo sill (Fig. 1b), once raised above sea level, controlled the surface elevation of low-level Early Lake Ontario. Because this sill, followed by the more rapidly uplifting Cape Vincent and then Thousand Island sills (Fig. 1b), were rising faster than any other part of the basin, lake water was continually backfilling the basin and raising its surface level throughout the history of Lake Ontario (Fig. 9).

A significant reduction of inflow to the basin occurred at 10.5 ka when ice retreated from the then depressed lowland at North Bay, Ontario, diverting glacial meltwater and runoff in the upper Great Lake basins away from the Erie and Ontario basins to Ottawa River (Chapman and Putnam, 1984; Barnett, 1992; Lewis et al., 1994). This reduction is shown by an inflection or short reversal in the rising trend of relative lake level in the Ontario basin at Port Hope (Fig. 9). By 5 ka, crustal rebound of the North Bay area had returned the discharge of the upper Great Lakes to the Erie and Ontario basins. This increased the discharge through Lake Ontario and resulted in a concurrent increase in the rate of lake level rise as shown in Figure 9.

The wave and surf base of Lake Ontario has risen continuously with lake level from its lowest Early Lake Ontario phase. The erosive action of waves and nearshore currents has progressively swept across the northern slope of the basin, leaving an erosional lag of sand and gravel over older glacial and glacial lake deposits or bedrock as mapped in Figures 2 and 3. Erosion of the shore continues, as evidenced by the modern presence of wave-cut shore bluffs of glacial and glaciolacustrine sediment at the shoreline (Brookfield et al., 1982; Martini et al., 1984). This erosional coastal environment is likely to continue in future, driven, in part, by ongoing crustal rebound and basin tilting which are raising the lake level against the shore at Port Hope at about 10 cm/century (Tushingham, 1992; Clark and Persoage, 1970).

Stability, bedrock and sedimentary structural features

Lineaments of aeromagnetic and other geophysical attributes, which cross beneath the lake basin have been recognized (Wallach and Mohajer, 1990; Mohajer, 1993). Features on lakebed acoustic records, such as zones of backscatter, feather-like markings, and surficial bedrock ridges are enigmatic at this time. They have been interpreted by some authors to indicate neotectonic (post-glacial) activity (Thomas et al., 1989a, b, 1991, 1992, 1993; Wallach, 1990). Also, porewater chemistry in sediment mud cores from the lake have suggested infiltration of groundwater,

possibly via fractures (Frape et al., 1991; Bowins et al., 1992; Drimmie, 1994). The sediments of Lake Ontario are currently undergoing study by several agencies to determine the extent to which these and other enigmatic features result from post-glacial fault and earthquake activity, or are the result of other processes, such as glaciation, meltwater flow, sediment deposition and consolidation, or shipping activity.

Acknowledgement

We appreciate helpful comments from S.M. Blasco and D.E. Buckley.

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FIGURES

Figure 1. a) Bathymetry of Lake Ontario with 20 m contour intervals; b) Nomenclature of major zones and depositional regions in Lake Ontario. From Thomas et al. (1972a).

Figure 2 . Surficial sediment distribution in the nearshore zone of northern Lake Ontario. After Rukavina (1969).

Figure 3. Surficial sediment distribution in Lake Ontario. From Thomas et al. (1972a)

Figure 4. Bedrock elevation in Lake Ontario. From Hutchinson et al. (1993).

Figure 5. Profile showing seismic stratigraphy in Lake Ontario. Depths are relative to surface of Lake Ontario (74 m asl). Seismic units designated as A, B, C, D, E and Paleozoic bedrock. Dots show base of each lettered unit. From Hutchinson et al. (1993).

Figure 6. Interpretations of seismic units giving seismic stratigraphy and lithostratigraphy together with inferred environment of deposition, regional correlation and inferred age. From Hutchinson et al. (1993).

Figure 7. South-north cross-section of Paleozoic bedrock surface and thickness of overlying Quaternary sediments in Lake Ontario at the longitude of Port Hope (78° 17.5' W). Overlying the bedrock surface are up to 20 m of sediments (Units A-C) deposited by glaciers, proglacial lakes and glacial meltwater. This material is overlain by up to 10 m of lacustrine sediment (Units D, E) deposited in Lake Ontario since 10.5-11 ka.

Figure 8. Maps showing former shorelines of glacial Lake Iroquois, Early Lake Ontario and subsequent phases of Lake Ontario relative to the present shoreline. From Anderson and Lewis (1985).

Figure 9. Changes in lake levels inferred for the Port Hope area since ice retreat. I, F, B, T = glacial lakes Iroquois, Frontenac, Belleville and Trenton. ELO = Early Lake Ontario. The lowest water level at about 60 m below present Lake Ontario between about 11,600 and 11,300 years ago was confluent with sea level (Champlain Sea) in the St. Lawrence Valley.

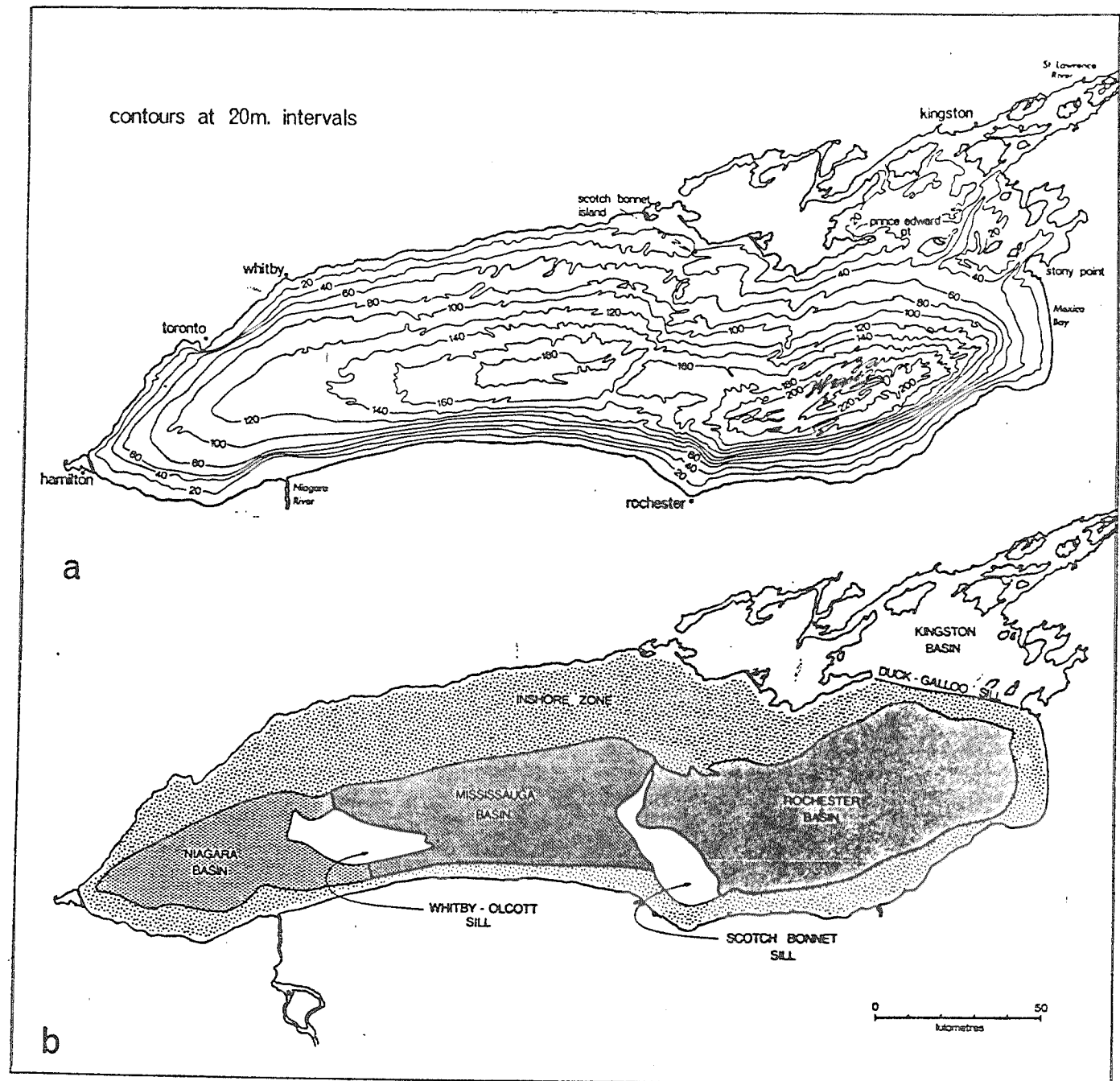


Fig. 1

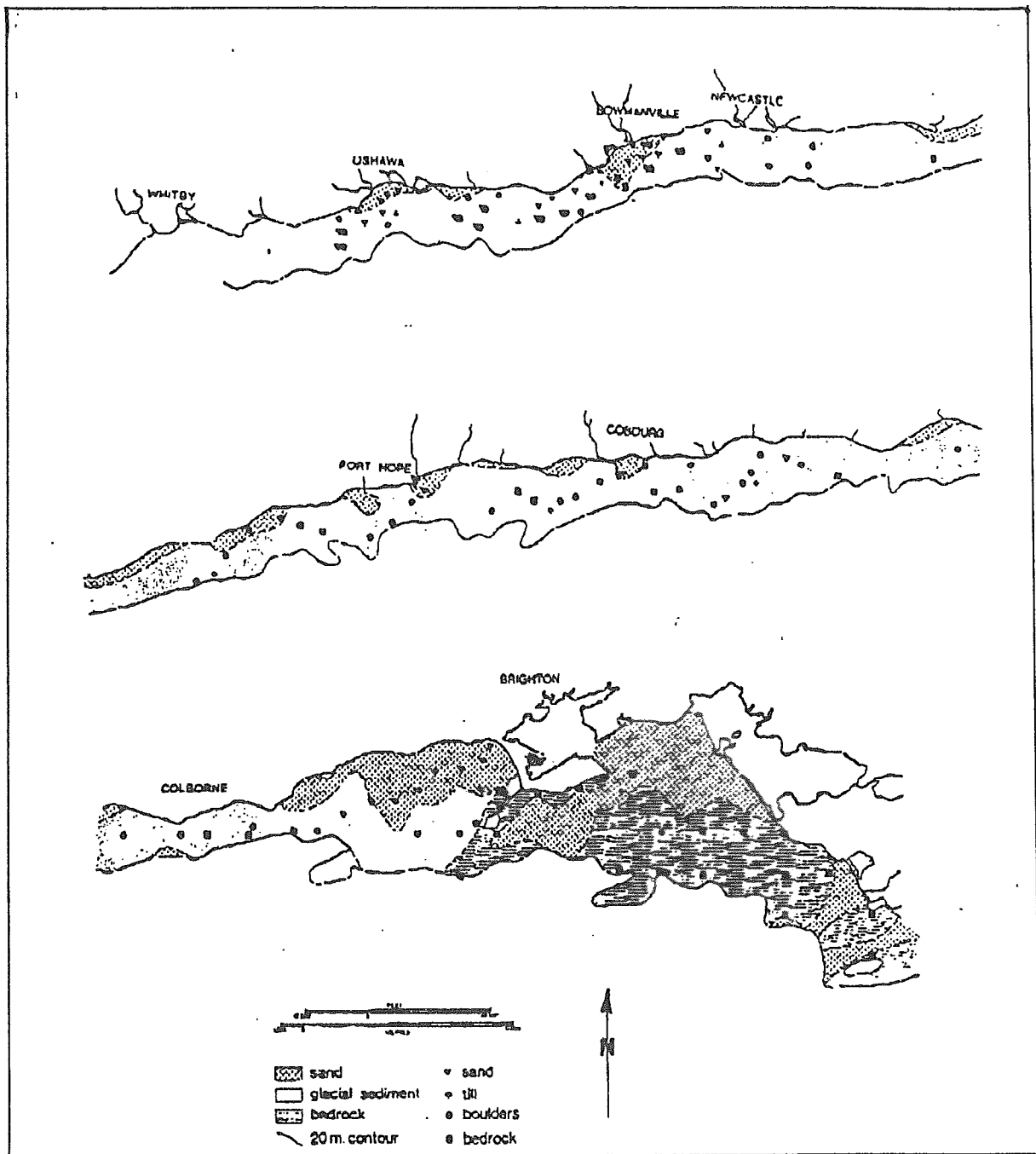


Fig. 2. Distribution of bottom types in the nearshore zone of northern Lake Ontario

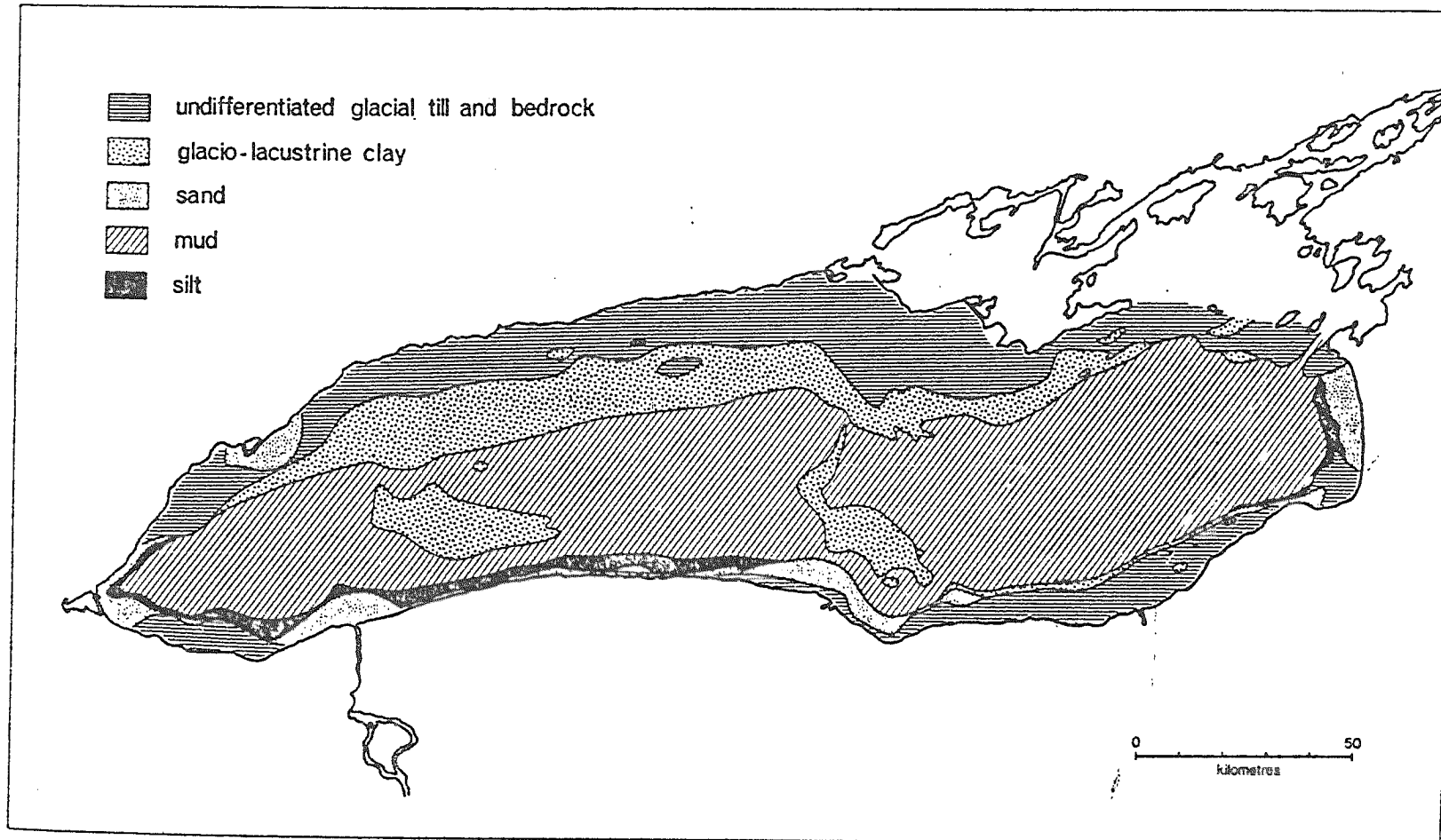


Fig. 3

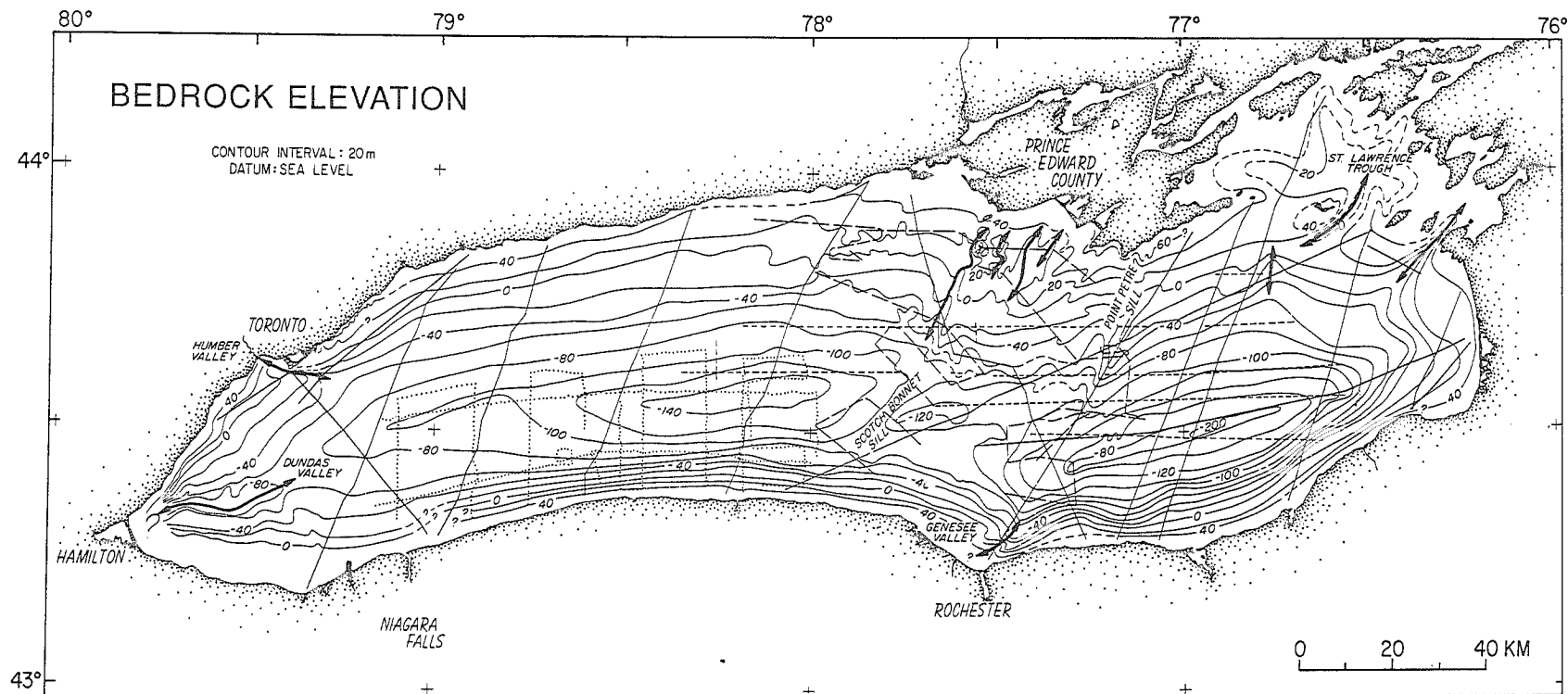


Fig. 4

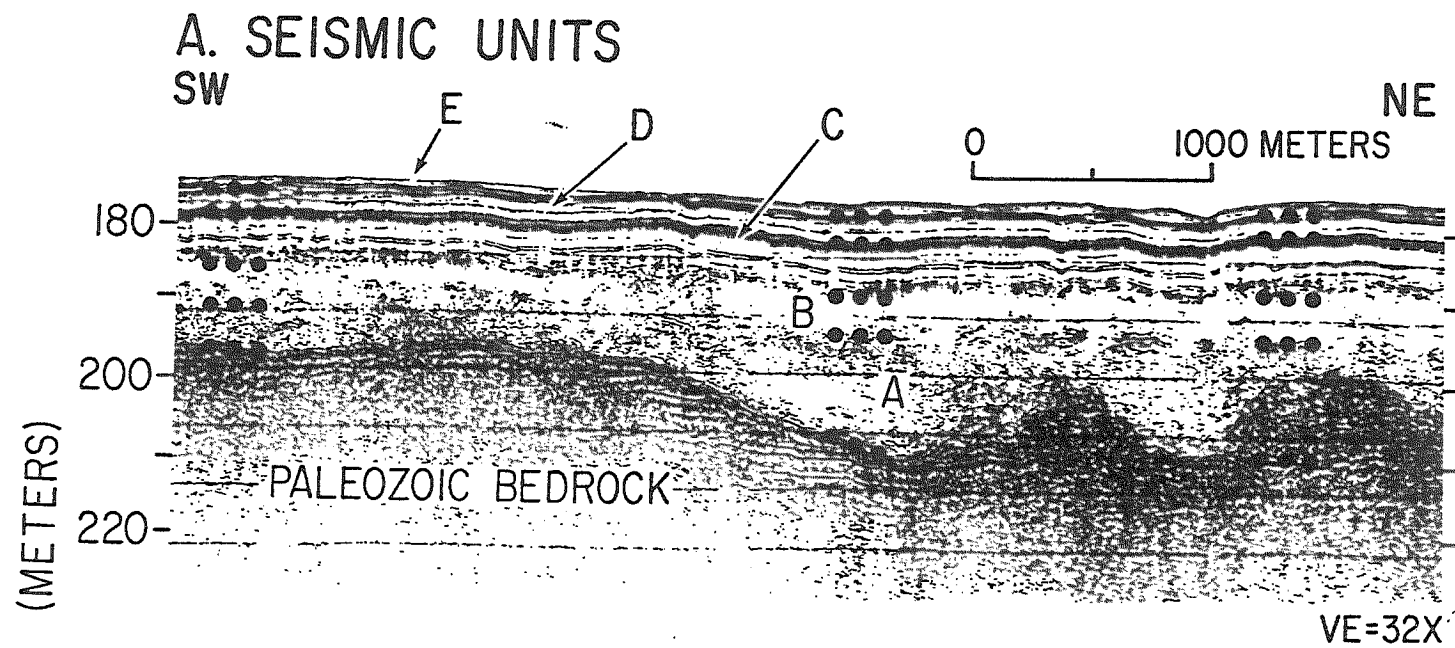


Fig. 5.

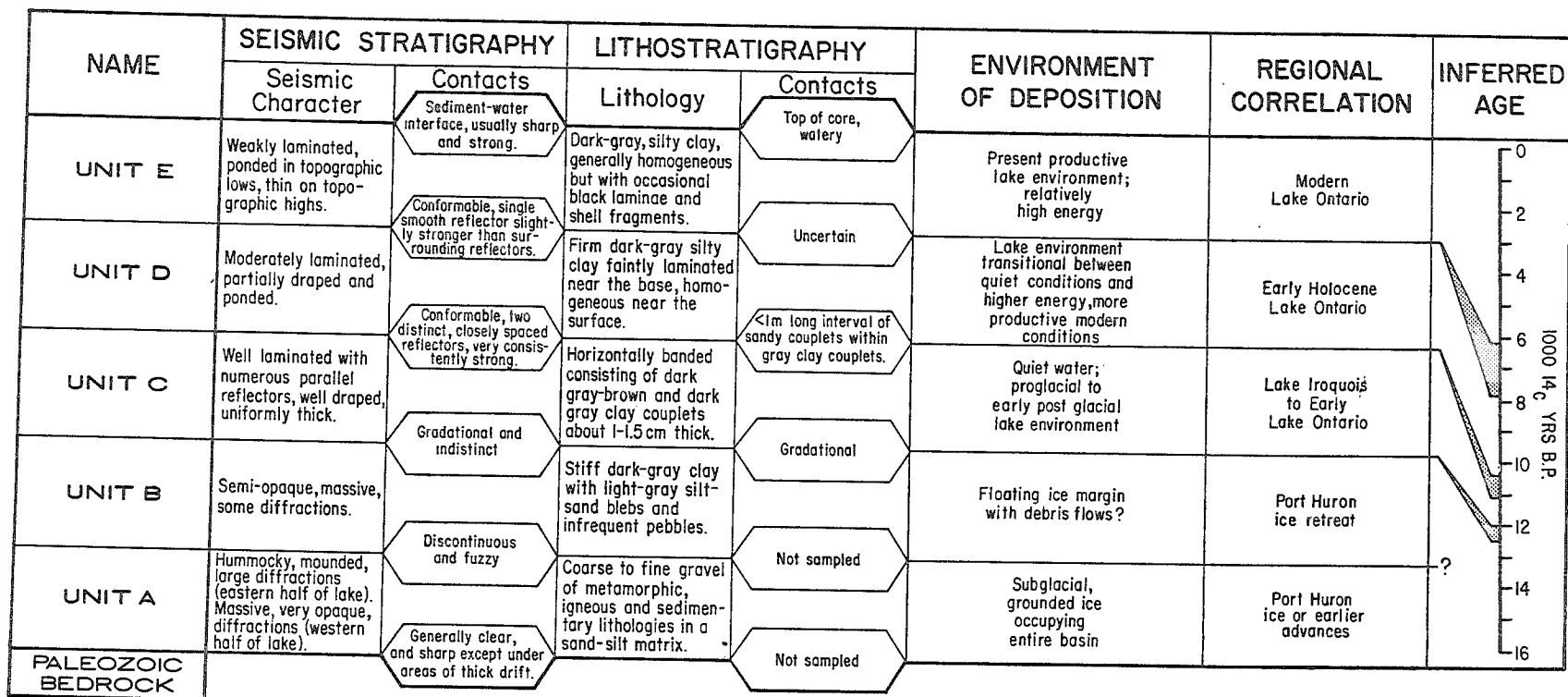


Fig. 6

LAKE ONTARIO CROSS SECTION AT PORT HOPE (78° 17.5' W)

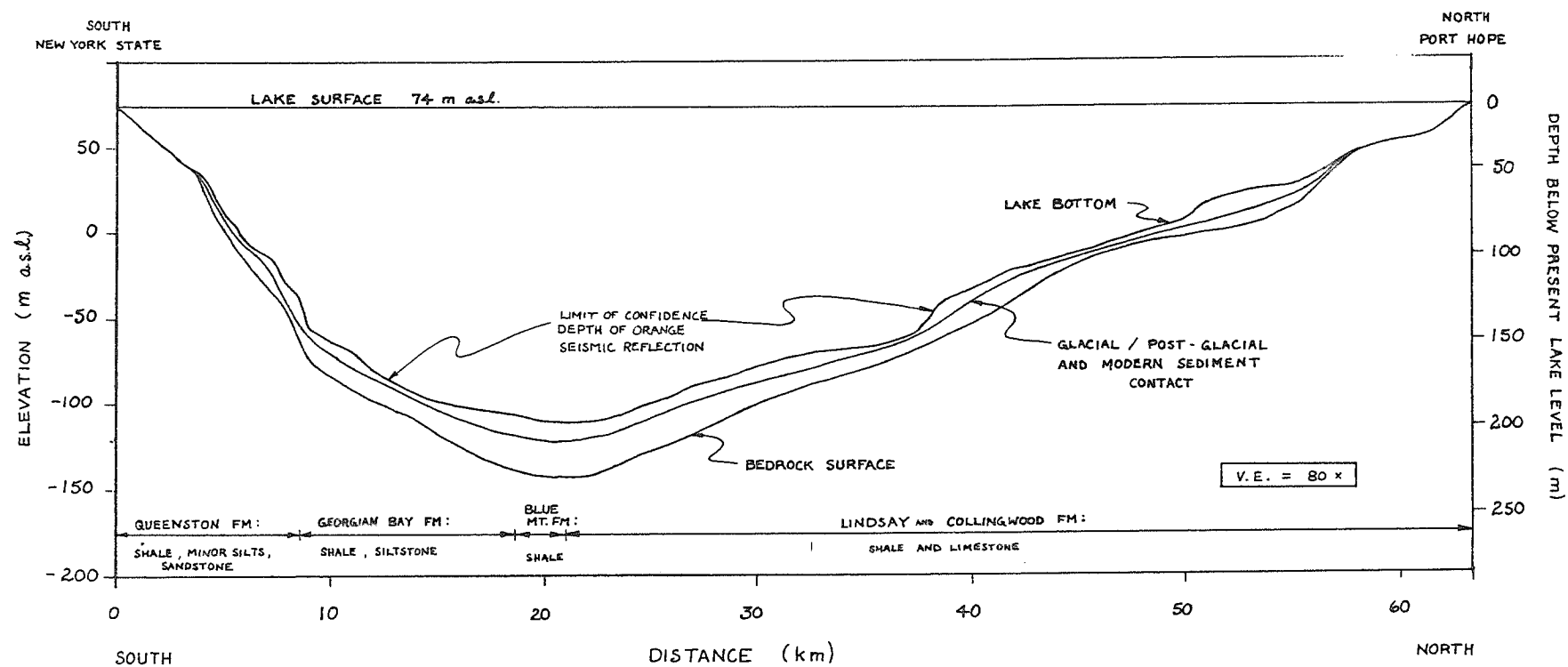


Fig. 7

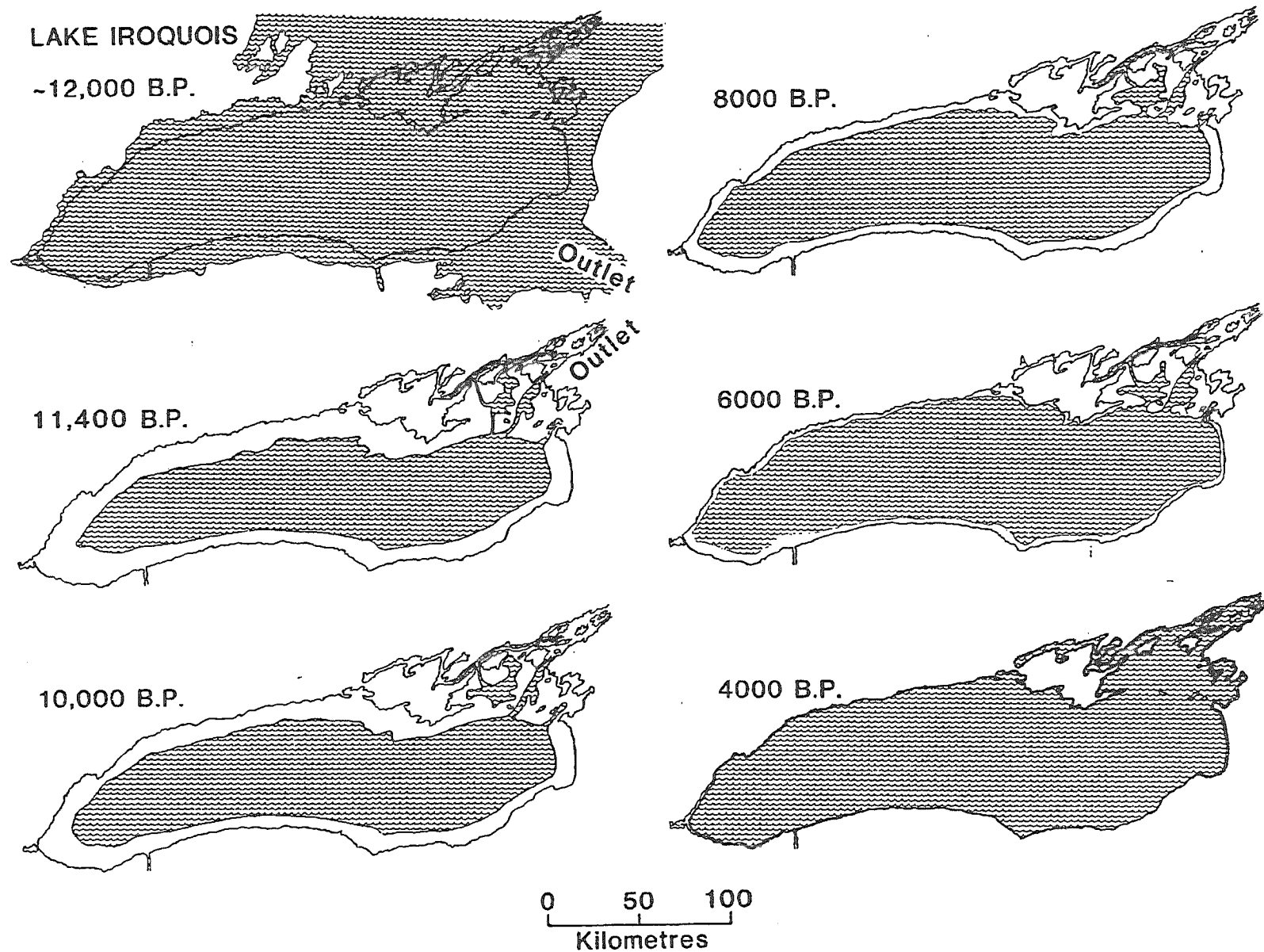


Fig. 8

Areal extent of Lake Ontario basin at time of Lake Iroquois (ca. 12 000 B.P.) and at 11 400, 10 000, 8000, 6000, and 4000 B.P.

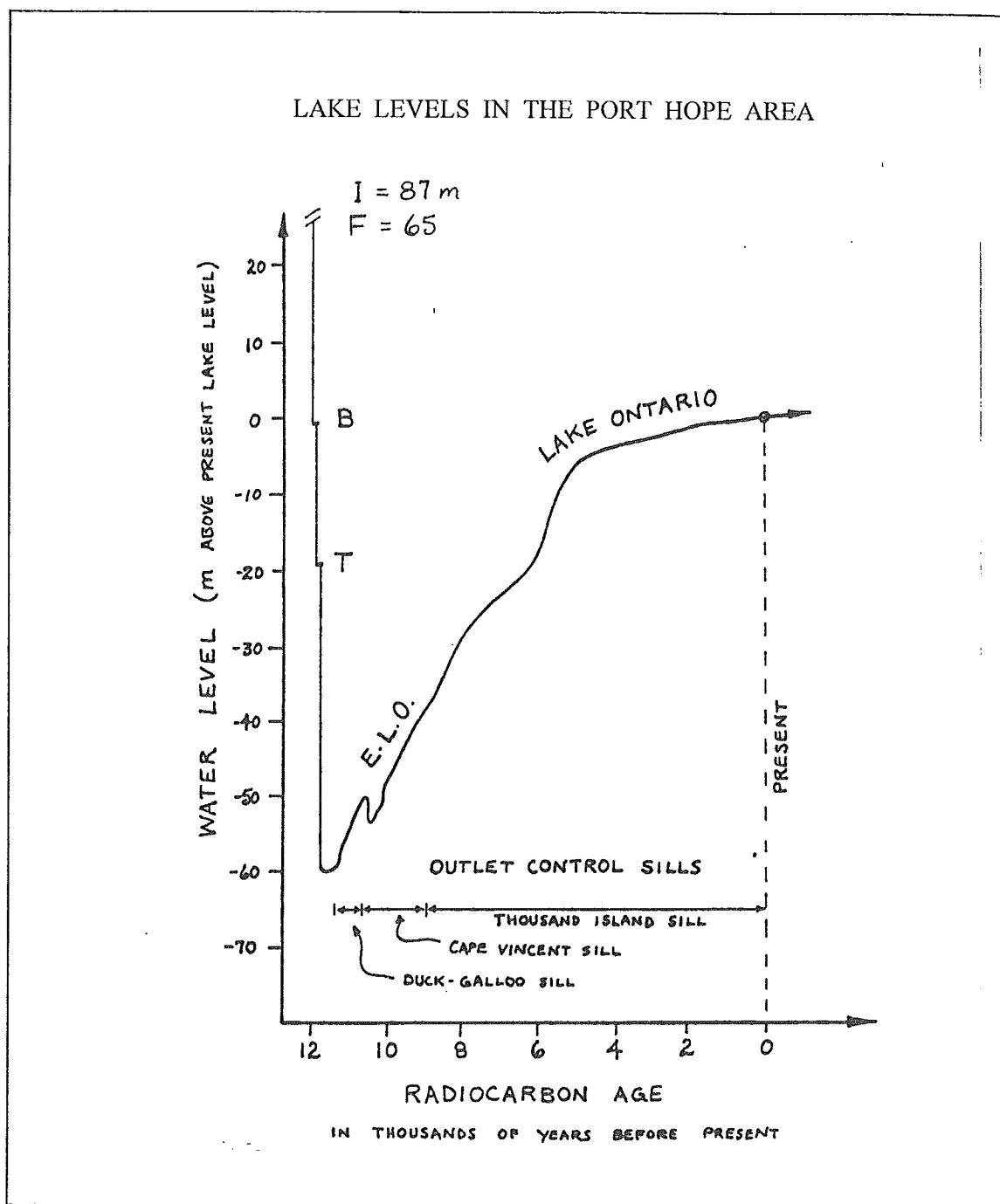


Figure 9. Changes in lake levels inferred for the Port Hope area since ice retreat. I, F, B, T = glacial lakes Iroquois, Frontenac, Belleville and Trenton. ELO = Early Lake Ontario. The lowest water level at about 60 m below present Lake Ontario between about 11,600 and 11,300 years ago was confluent with sea level (Champlain Sea) in the St. Lawrence Valley.

4. TERRESTRIAL QUATERNARY GEOLOGIC AND HYDROGEOLOGIC FRAMEWORK - PORT HOPE REGION (OSHAWA-COBOURG)

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Background

Low level radioactive waste is stored on the north shore of Lake Ontario in sediments which bury bedrock. The characteristics, distribution and thickness of these sediments vary as a result of their genesis and history. These stacked sequences of Quaternary-age glacial sediments have hydraulic characteristics which cause some to behave as permeable groundwater aquifers, whereas others behave as low-permeability aquitards. Precipitation that infiltrates the soil recharges the water table and discharges into streams and lakes along local and regional flowpaths. Both local and regional geology govern groundwater flow and migration patterns. Long term lake bluff erosion may have consequences for waste management.

Regional setting

The physiographic region known as the Iroquois Plain (Chapman and Putnam, 1966), lies on the north shore of Lake Ontario, and is bordered to the north by the Peterborough drumlin field, the South Slope, and the Oak Ridges Moraine (ORM) (Fig.1). The Oak Ridges Moraine is an east-west trending, mainly sandy ridge which forms a surface and groundwater divide, as well as a recharge zone. The Peterborough drumlin field and South Slope exhibit NNE-SSW oriented hills (drumlins) cut into glacial sediments. An anastomosing network of broad tunnel channels (generally oriented NW-SE) truncates the drumlins north of the ORM. The wave-washed Iroquois Plain and raised shorelines record the presence of Glacial Lake Iroquois, a larger, ice-dammed version of Lake Ontario, which existed at the end of the last glaciation (~12,500 years ago).

Quaternary sediments

The thickness of Quaternary sediments over bedrock is variable: it thins northward towards the Canadian Shield, southward toward the Lake Ontario bluffs, and over the Niagara escarpment, but it thickens under the ORM and over channels cut in bedrock (>180 m in places) (Fig. 2). In the Port Hope region, drift cover is generally <60 m. The present-day Ganaraska River is cut to bedrock, as is the Lake Ontario shoreline at Cobourg.

Unlithified Quaternary sediments in southern Ontario record a series of glacial and non-glacial events. Between glaciations the land surface was either drowned by lakes or exposed to soil formation and fluvial dissection. Glacial episodes are recorded by unsorted sediments (tills). Locally, tills may be associated with sorted sand and gravel. Non-glacial sediments record lake (muds), river (sandy organic beds), and wetland sediments (organic beds).

The regional Quaternary stratigraphy is poorly known except at the Lake Ontario bluffs (e.g. Singer 1973, 1974; Brookfield et al., 1982; Martini et al., 1984), along river valleys, and in gravel pits. Drill cores and geophysical surveys extend our stratigraphic knowledge in regions lacking exposure. A growing geology and hydrogeology database for the Oak Ridges Moraine and environs covers the north shore of Lake Ontario (Brennand et al., 1995). This database includes Ontario Ministry of Environment and Energy (MOEE) water well records, geotechnical and hydrogeological drilling reports, and new Geological Survey of Canada and Ontario Geological Survey field data.

Exposures along the Bowmanville-Newcastle bluffs have been reported to record four tills, three glaciolacustrine packages and one subaerial glaciofluvial package overlying bedrock (Brookfield et al., 1982) (Table 1). The precise geometry and extent of the proposed subaerial sand bodies (unit 4, Table 1) is unknown, but they may record discrete fan-like wedges. These fans are overlain by

an extensive sandy silt till, in places separated by sand packages. This regional till may extend as far west as Newmarket (Sharpe et al., 1993) where the till sheet has been locally dissected by channels, providing a window through this regional aquitard (Sharpe et al., 1994). The extent and correlation of sediment packages below the regional till sheet is unknown. Glacial Lake Iroquois eroded a plain and deposited discontinuous sand, silt and clay at the land surface (Fig. 1). Where observed, stratified sediments throughout the stratigraphic sequence are undisturbed or exhibit deformation produced during sediment accumulation or during ice loading or unloading.

Quaternary geologic cross-sections, such as the north-south section shown in Figure 3, based on water well data west of Port Hope suggest: (1) confirmation of a regional, southerly bedrock slope with local relief; (2) likely presence of a regional sandy till beneath the ORM; (3) sandy sediment packages that cannot be traced far inland. However, these observations are preliminary, and correlation is made difficult by: (i) need for further database verification; (ii) relatively thin drift in the Port Hope region (Figs. 2, 3).

Groundwater flow in Quaternary sediments and bedrock

Aquifers are not well delineated in the area north of Lake Ontario (Table 1). Much of the regional groundwater flow in the deeper aquifers is believed to originate from groundwater recharge on the ORM. However, streams originating on the ORM flanks, suggest that some of this recharge flows within local groundwater flow systems and is discharged to local streams (Fig. 4).

The contact between the Paleozoic bedrock and the unlithified Quaternary sediments (Fig. 2) slopes regionally to the southwest (Fig. 5). Bedrock is dissected by old river valleys which create local relief generally on the order of 30 m, but may exceed 80 m. Bedrock channels may focus groundwater flow.

In bedrock, permeability is due to fractures, joints, bedding planes or dissolution cavities. Rock permeability generally decreases with depth. Pump tests in bedrock indicate a slight increase in hydraulic conductivity, from the bedrock surface to depths of 4-11 m below that surface (10^{-6} ms^{-1} to $2 \times 10^{-5} \text{ ms}^{-1}$), with decreasing hydraulic conductivity ($< 10^{-7} \text{ ms}^{-1}$) below these depths (Haefeli, 1970; Golder Associates, 1984).

Where the hydraulic conductivities of the upper bedrock are similar to those measured in the overburden, there is likely to be a hydraulic connection between the overburden and the bedrock and a small but possibly significant proportion of the groundwater could flow within the upper 10 m to 20 m of the bedrock. Where bedrock is overlain by low permeability sediments such as glaciolacustrine clays, the groundwater flow through the upper bedrock could be greatly reduced. At depths of 50 m or more below the bedrock surface, existing data suggest that groundwater flow at depth within the bedrock is insignificant compared to flow in the upper bedrock and Quaternary sediments. Although groundwater flow in the bedrock is likely to be part of a regional flow system beneath and along the south slope of the ORM, closer to the lakeshore local groundwater flow systems could extend to bedrock where the overburden is much thinner.

FIGURES

- Figure 1. Regional surficial geology of the north shore of Lake Ontario (ORM NATMAP area) (Barnett 1990).
- Figure 2. First approximation of Quaternary sediment (drift) thickness above bedrock in the ORM NATMAP area. Thicknesses were queried from a geologically coded MOEE water well database, and are therefore depths to potential bedrock surfaces.
- Figure 3. Schematic north-south cross section showing the Quaternary sediment package and bedrock topography in the Port Hope region. On land Quaternary stratigraphy and potential bedrock topography derived from queries on a geologically coded, MOEE water well database. Bedrock geology from Sanford (this report); lake bed geology from Lewis and Todd (this report).
- Figure 4. Schematic north-south geologic cross-section (cf. Fig. 3) with conceptual groundwater flow pattern.
- Figure 5. First approximation potential bedrock topography generated from a query on the MOEE water well database.

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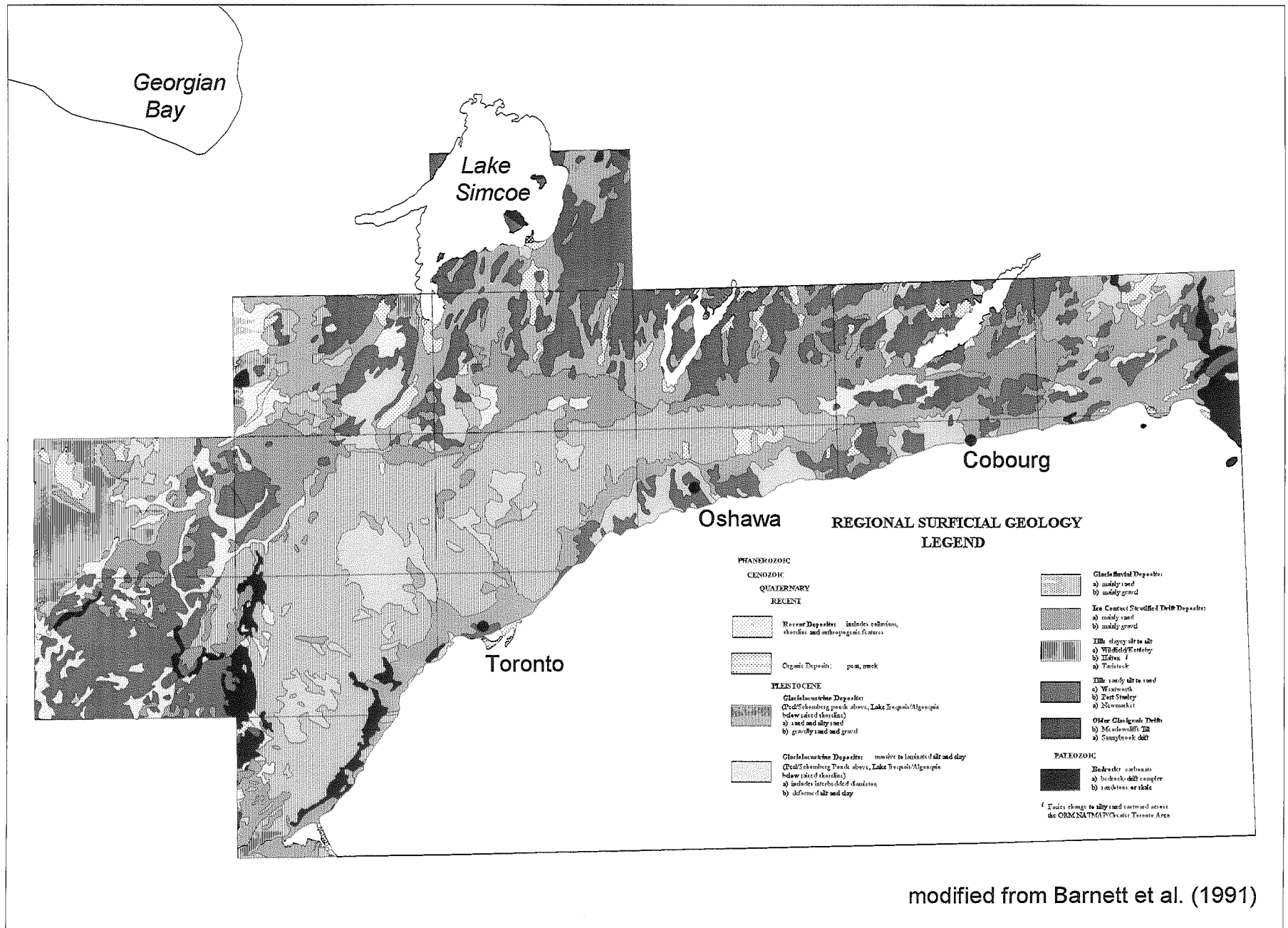
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Table 1. Port Hope region (Oshawa-Cobourg) stratigraphy, proposed regional correlations, and hydrostratigraphy

Stage	Port Hope region stratigraphy (Brookfield et al., 1982; Martini et al., 1984)	Scarborough and West Durham Correlations (Karrow, 1967, Dillon, 1994a)	Material		Hydrostratigraphic Unit	Hydraulic Conductivity cm/s ¹	Average Hydraulic Conductivity cm/s ¹
Recent 12.5 ka - present	8: Lake Ontario, fluvial and organic deposits	Lake Ontario, fluvial and organic deposits	Gravel, sand, silt, clay, organics		Local aquifer	NA	NA
Late Wisconsinan	7: Lake Iroquois ~ 12.5 ka	Lake Iroquois and Peel Ponds	Gravel, sand, silt, clay, shells		Local aquifer	10 ⁻⁶ - 10 ⁻¹	10 ⁻³
	6: Bouchette Till < 13.5 ka	Upper Leaside or Halton Till	Silty diamicton, locally varying to a sandy silt to clayey silt diamicton with < 2 % gravel, with sand lenses		Local aquifer or aquitard	10 ⁻⁹ - 10 ⁻³	10 ⁻⁶
	5c: Bowmanville Till (Upper)	Lower Leaside or Upper Northern Till	Sandy silt to silty diamicton, dense, massive, boulder horizons, drumlinized		Regional aquitard	10 ⁻⁹ - 10 ⁻⁴	10 ⁻⁶
	5b: Glaciofluvial sand	Not reported	Sand locally present		Local aquifer	10 ⁻⁷ - 10 ⁻²	10 ⁻⁴
	5a: Bowmanville Till (Lower) < 23 ka	Lower Northern Till	Sandy silt to silty diamicton with interbedded sand		Regional aquifer		
Plum Point IS?	4: Glaciofluvial sand	Not reported	Sand, gravel filling large channels		Aquifer, local?		
Middle Wisconsinan	3: Clarke Beds > 30 ka	Thornccliffe Formation with Meadowcliffe and Seminary Tills (Glaciolacustrine deltaic to fluvial succession)	Complex glaciolacustrine sequence	3c: Silty varves, coarsening and thickening up	Regional aquifer	10 ⁻⁷ - 10 ⁻⁴	NA
				3b: Bond Head Till: very compact silty diamicton; discontinuous	Aquitard		
				3a: Coarsening upward sequence of sand-silt-clay varves with interbedded diamictons and sandy gravel	Regional aquifer		
Early Wisconsinan	2: Port Hope Till > 40 ka	Sunnybrook Till	Silty or clayey diamicton with disturbed silt-clay rhythmites		Aquitard	10 ⁻⁷ - 10 ⁻⁶	NA
Ordovician	1b: Limestone Bedrock	Shale Bedrock	Weathered limestone or shale		Regional aquifer	10 ⁻⁶ - 10 ⁻³	10 ⁻⁴
	1a: Limestone Bedrock	Shale Bedrock	Sound limestone and shale		Regional aquitard	< 10 ⁻⁷ - 10 ⁻⁸	10 ⁻⁷

¹ Estimates from recent IWA investigations for Durham (Dillon, 1994a, b) and Port Granby and Welcome low level radioactive waste site investigations

Regional Surficial Geology



modified from Barnett et al. (1991)

Fig. 1

Drift Thickness - MOEE Water Wells

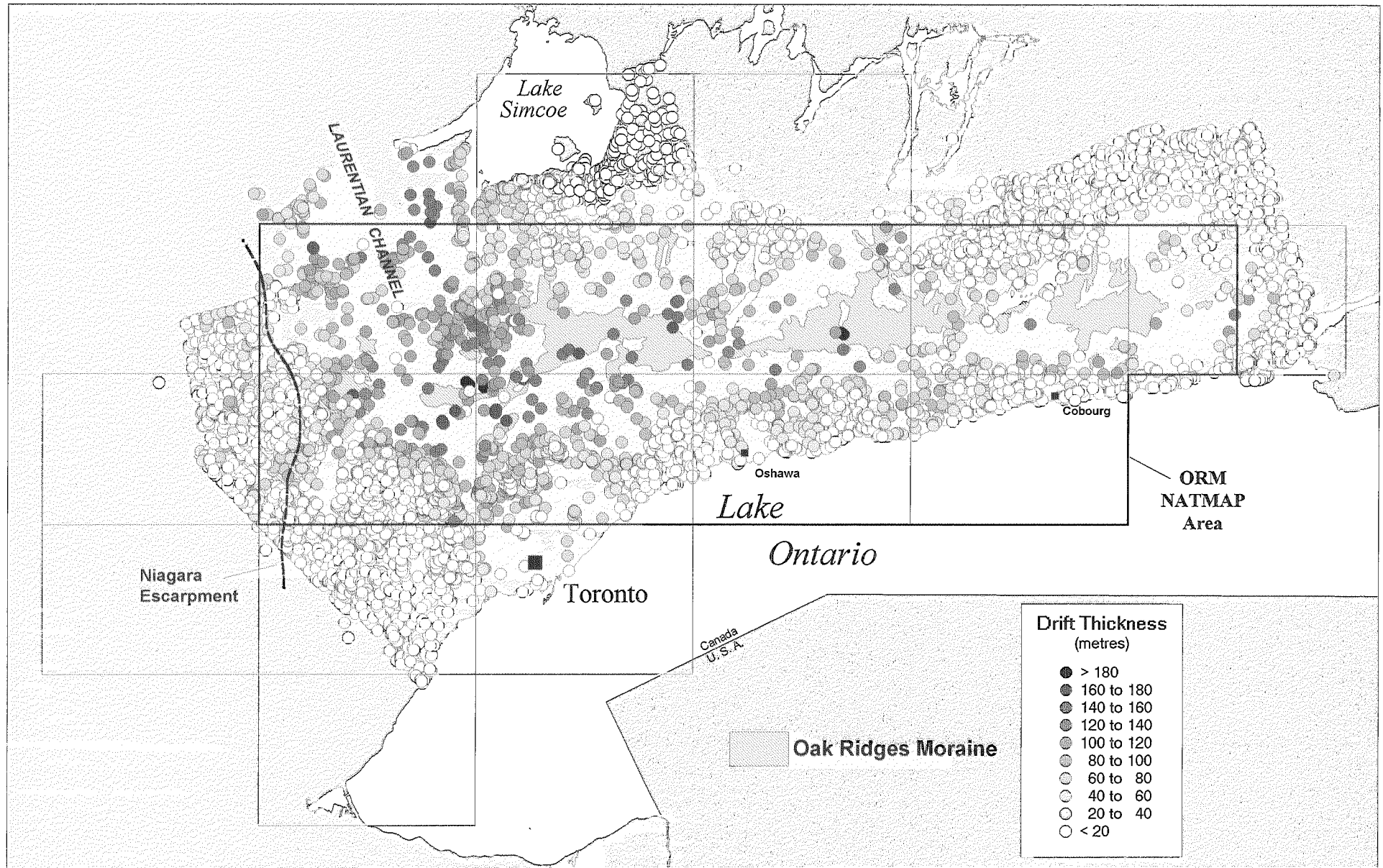


Fig. 2

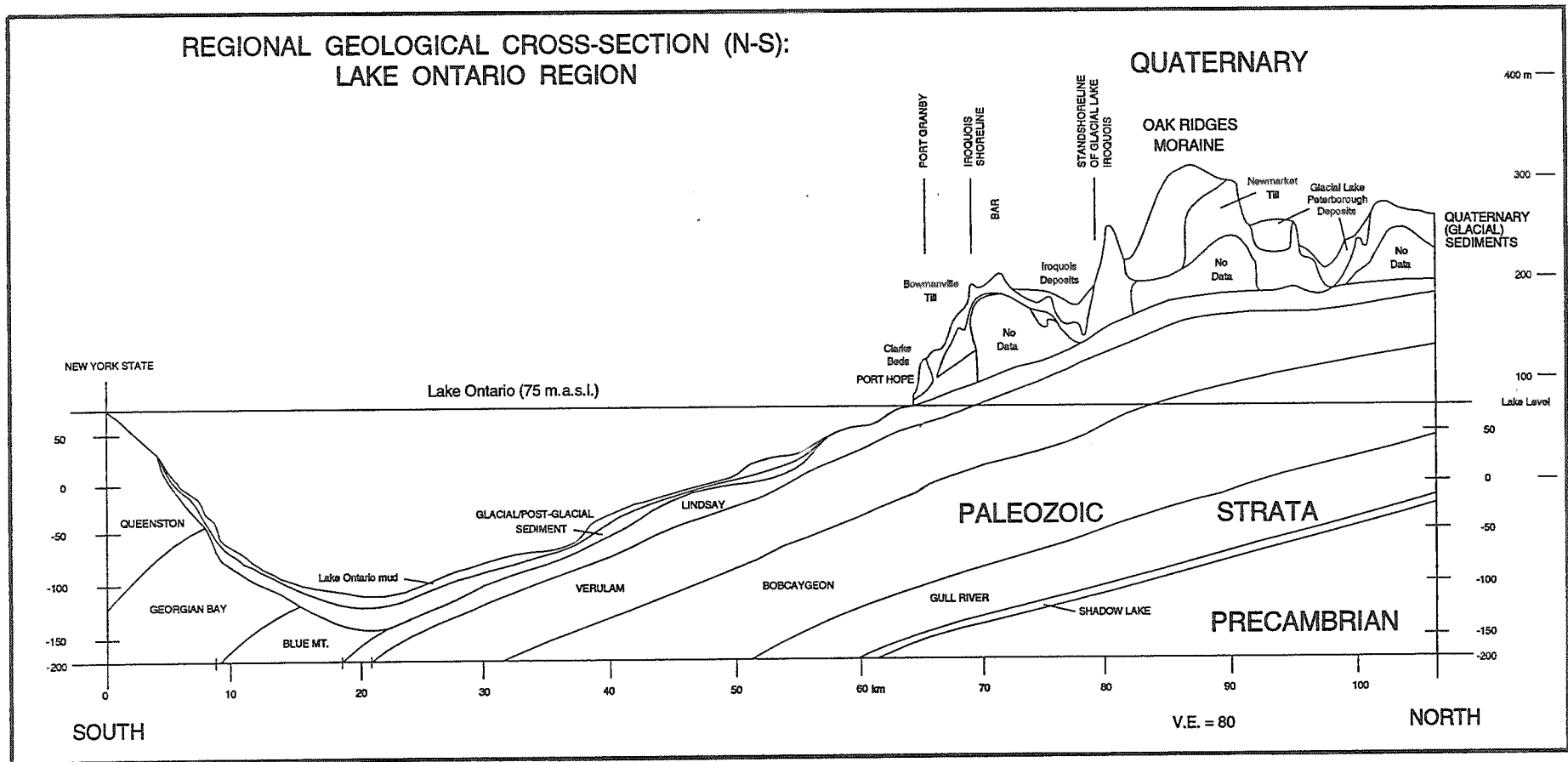


Fig. 3 OAK RIDGES MORaine = sand, silt and gravel
Clarke Beds, Lake Iroquois and Lake Peterborough deposits = sand, silt and clay

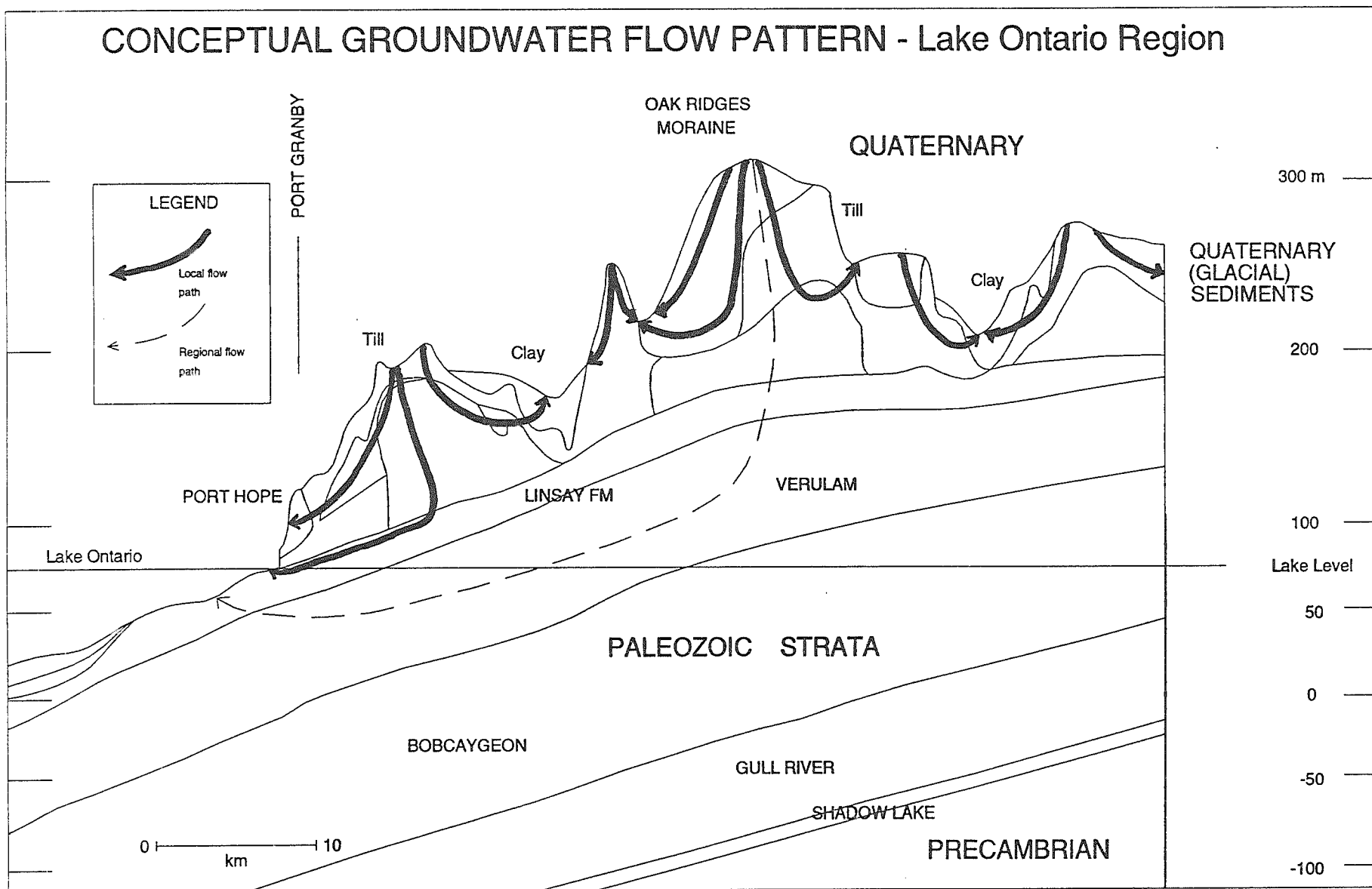


Fig. 4

Bedrock Elevation - MOEE Water Wells

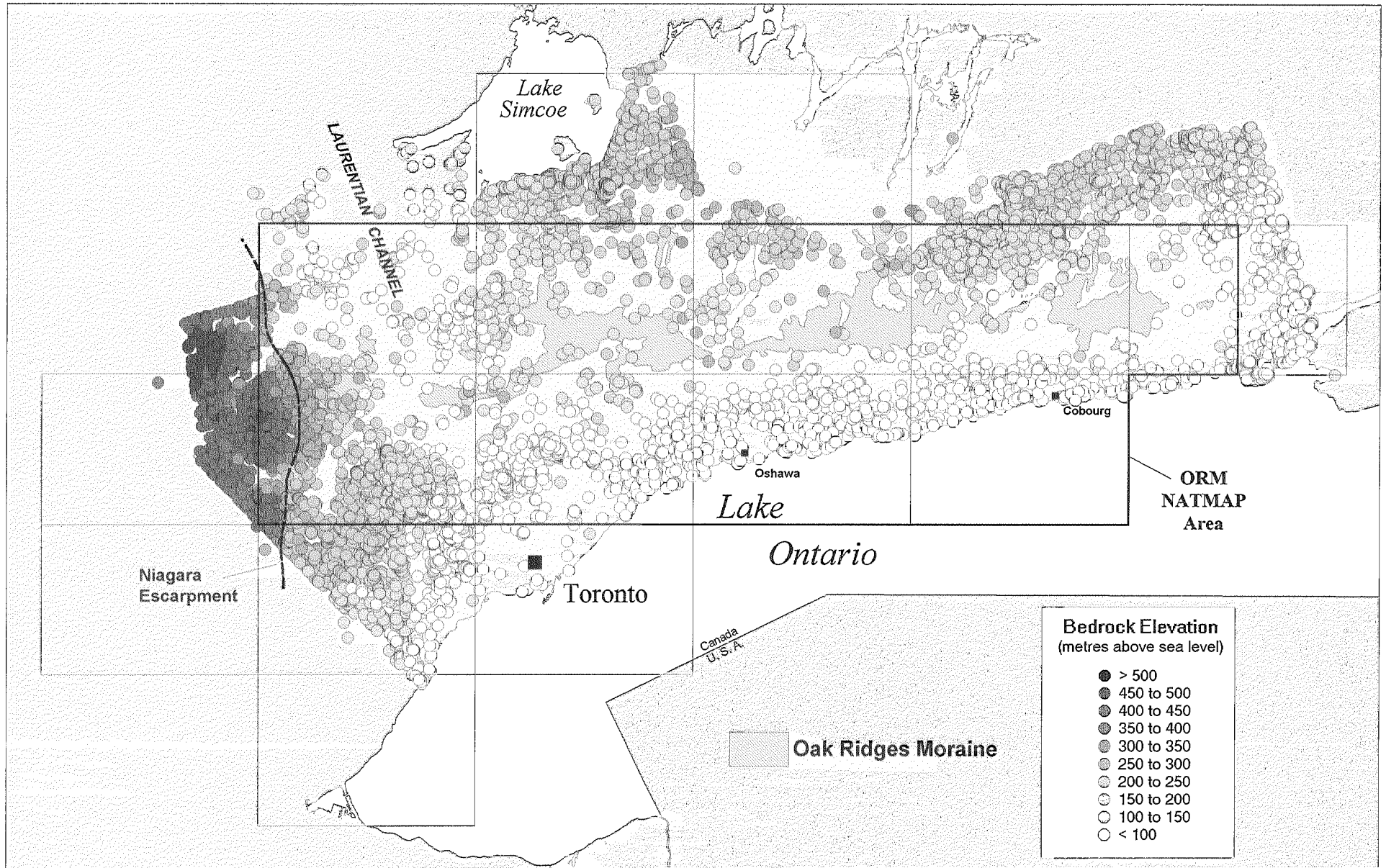


Fig. 5

5. EARTHQUAKES

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History of Earthquakes in the Lake Ontario region

Earthquakes have been reported felt in the Lake Ontario region from time to time since at least the 1850s. Because of the sparse early population and scant written record, little is known about the earliest earthquakes, even the larger ones. It is also likely that many smaller earthquakes were not reported, so the early historical record is very incomplete. In the present century, both Canadian and American seismograph stations have monitored earthquake activity in the Lake Ontario region, with the number and sensitivity of these stations increasing with time.

Figure A shows the earthquakes of the Lake Ontario region to the end of 1994, where the epicentre symbols denote the magnitude of the earthquake (see legend). The same epicentres are replotted on Figures B, C, and D to illustrate the relative accuracy of the epicentres in four different time periods. The plotted error bars represent typical uncertainties in each time period. On average, we would expect an earthquake to have been located somewhere within the circle defined by its error bars.

It is important to contrast the representation of Figure A, where every earthquake is plotted at a particular point, with the other three maps that convey the understanding that, though an earthquake happened in the vicinity of its plotted symbol, its exact location is not known. In Figures B and C the earthquake locations may be in error by up to 60 - 100 km, the diameter of the implied error circles. This means that we cannot propose any alignments or simple patterns in the earthquake locations before 1970, the time range of Figures B and C. Consequently, before interpreting any of the possible alignments in the earthquakes plotted in the composite map of Figure A, we need to identify and ignore all the earthquakes whose location is open to question.

This leads us to Figure D, where the earthquake locations are on the average much more accurate than those in previous decades, thanks to improved instrumental monitoring. A number of small magnitude earthquakes have occurred under Lake Ontario. Very few have occurred anywhere along the north shore. As construction and quarry blasts are frequently recorded and located in many parts of the Lake Ontario region, we know that our seismographs would have recorded any earthquake activity in the same region. Figure D shows no apparent pattern in the earthquake locations. This is not really surprising as earthquakes in many other parts of eastern Canada scatter over relatively large areas and do not either concentrate into a small area nor form linear patterns. For other information on Lake Ontario seismicity, see Stevens (1993; 1995). For a recent review of eastern Canada seismicity, see Adams and Basham (1991).

Effects of Earthquakes

Small earthquakes (magnitude 3 and below) are often not even felt; moderate earthquakes (magnitudes 3 to $4^{3/4}$) are usually felt, and may cause minor damage; large earthquakes (for eastern Canada magnitude $4^{3/4}$ and up) may cause significant to great damage, depending on size and distance from the epicentre, and on the characteristics of the ground and building construction. The effects of damaging earthquakes fall into several classes:

ground rupture. Some earthquakes break and displace the surface of the earth, tearing apart buildings built across them, rupturing underground utilities, and changing the underground hydrogeology. Fortunately such surface faulting is extremely rare in the middle of continents.

shaking. Earthquakes represent the sudden release of energy on an underground fault in the earth's crust. The vibrations are felt on the surface as shaking. In general, the strength of shaking

decreases with distance, so the farther away from a given earthquake, the weaker the shaking. Earthquake shaking is the primary cause of building failure.

ground amplification. When earthquake vibrations pass from rock to the overlying sediment and soil they slow down and their severity increases. Thus a house on deep soil in a river valley may be shaken much more strongly than a nearby house on a rock foundation. The extra degree of shaking depends on the type and thickness of the soil.

liquefaction. During earthquake shaking certain types of soil lose their strength and liquefy. The sediment/water mixture may be ejected from the ground. Building foundations may subside and cause damage.

consequent fires. Earthquakes cause damage not only from their shaking but also from fires that started accidentally through upset appliances and broken gas mains. Because of a loss of communications, broken water lines and limited access through rubble-choked streets, such fires often spread before they can be controlled.

Numbers and sizes of earthquakes

Worldwide, there is an observed relation between the number of small earthquakes and the number of large ones. In general there are about ten times as many magnitude 2 earthquakes as there are magnitude 3 earthquakes in a given region. This empirical relation can be used to estimate the rate of tiny earthquakes from the historical earthquake catalogue. Earthquakes of magnitude zero are detectable by modern seismograph instruments, even though too small to be felt. One thousand of these might occur for each felt magnitude 3 earthquake. Because of the low historical seismicity rates, the same relation predicts a low rate of moderate earthquakes in the vicinity of Port Hope; sufficiently low that it is not surprising that a moderate earthquake has not happened near Port Hope during the short recorded history.

Large earthquakes felt on the north shore of Lake Ontario

Several large earthquakes have been felt in the Port Hope area, the closest of these was the magnitude $5^{3/4}$ Attica, N.Y., earthquake of 1929, located about 100 km south of Port Hope. Other large earthquakes felt mildly in Port Hope in this century were located in Québec at distances of 300 km to 800 km from Port Hope (March 1925, Charlevoix–Kamouraska; November 1935, Temiscaming; November 1988, Saguenay). Two earthquakes in October 1983 in the Adirondacks of upper New York State and near Ottawa were felt mildly in the Port Hope area. No earthquake in at least the past 150 years has caused strong ground vibrations in the Port Hope area.

Earthquakes and Faults

Earthquakes occur on faults, usually deep underground. Geologists in California, New Zealand and many other places have mapped the surface trace of some of the larger faults, and seismologists talk about this or that earthquake happening "on the San Andreas Fault". Hence, there is a general misconception that every earthquake can be associated with a previously-known fault. Unfortunately the picture in eastern Canada is more complicated. Our few earthquakes happen far from plate boundaries, unlike California where faults like the San Andreas have moved many tens of kilometres over the years and are clearly displayed to anyone flying over the ground.

In eastern Canada there is a knowledge gap between the earthquakes, which probably happen 5-20 km underground, and the geologically observable surface. As shown by Hanmer and Forsyth (this Open File), the Precambrian rocks of the Canadian shield are found to be disrupted by many faults formed 1 to 2 billion years ago. Under Lake Ontario similar faults must exist, but are concealed by the Paleozoic limestones and shales, Quaternary sediments, and the waters of the lake. We expect that some fault or other in the Precambrian basement will be the origin of the next small earthquake near Port Hope, but we can't possibly map all of them. Detailed mapping of the surface faults is possible where the Precambrian rocks are exposed, as near Bancroft, and the position and orientation of the largest features can be projected down into the earth with some confidence. This doesn't help much because i) it doesn't take a very large fault (a few km is

enough) to cause a sizeable earthquake; ii) even where mapped at the surface, not one Precambrian fault has been identified as "active"; and iii) even if the "active" faults were identified, there is no guarantee that a hitherto inactive fault will not move in the future. In fact, some of the larger earthquakes in California in the past 20 years have occurred on faults that were not recognized until after the earthquake.

One measure of likely activity is if a fault has shown significant displacement in geologically recent times. Some southwest-striking faults offset the Paleozoic bedrock in the region between Orillia and Burleigh Falls (Sanford, this Open File). Perhaps these faults will be seismically active in the future, but there has been no proof, pro or con. Still younger faults might be found by searching the Quaternary strata for neotectonically faulted strata, but as noted by Brennand et al., (this Open File), the current evidence is equivocal. Similarly, while research in Lake Ontario (Lewis and Todd, this Open File) has identified some interesting bottom features, it has not yet been able to associate any of them with past earthquakes. In the case of Paleozoic or Quaternary fault offset, even if established, there remains the troubling question: even if a few active faults are found, what about the unknown active ones and the potentially-active "inactive" ones? Unless geologists can identify the majority of future active earthquake faults, placing the hazard emphasis on the few known sources misdirects attention, and is the wrong approach. Earthquake-resistant design must take into account earthquakes that might occur anywhere in the region, at varying distances from the site of interest.

It may seem that the problem is hopeless, but it isn't. Robust estimates of earthquake occurrence can be made on seismological and seismological/geological grounds as follows.

Firstly the current earthquake history of the region (ca. 150 years) can be assumed to represent what is to be expected over the next hundred years. To do this we don't just count up the earthquakes and say "you've had three - expect three more". To begin, we have to define a region large enough to give a statistically meaningful sample while staying within a region geologically similar to Port Hope. To be large enough, such a region might extend from Niagara Falls to Kingston. Then we use the relationship between large and small earthquakes to estimate the rates of future large earthquakes. Finally we can represent the results as probabilities, for example, for an earthquake larger than magnitude x occurring within y kilometres of Port Hope.

Secondly, certain types of geological information can be used to constrain the rates of large earthquakes. For example there have been no earthquakes larger than 6 in the Lake Ontario region during recorded history. However, if one takes all the parts of the earth's continents that are geologically similar to the Lake Ontario region and uses **their** combined earthquake history, it is possible to make robust estimates for the rate of magnitude 6 earthquakes in the Lake Ontario region.

A sensible approach is to make several estimates under different hypotheses, then weight them using professional judgement and report the uncertainty in the estimated rate. This rate and its uncertainty then feed into the seismic hazard assessment.

Earthquake hazard assessment

Performing a state-of-the-art earthquake hazard assessment is necessary where a facility - such as a dam, nuclear power plant, LNG tank, or chemical plant - may pose unusual risks to a community if a damaging earthquake were to occur. Such an assessment would consider the rate and magnitude of earthquakes within a few hundred kilometres of the facility, the way the seismic waves spread out with distance, the likelihood of earthquake shaking for different probability levels, the types of earthquake effects, and in a general way how they would affect the proposed project. The results of the earthquake hazard assessment would be used by engineers to design the facilities safely and to mitigate the effects of earthquakes, should they occur.

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FIGURE CAPTIONS (Figures A to D are modified from similar figures in Stevens, 1995)

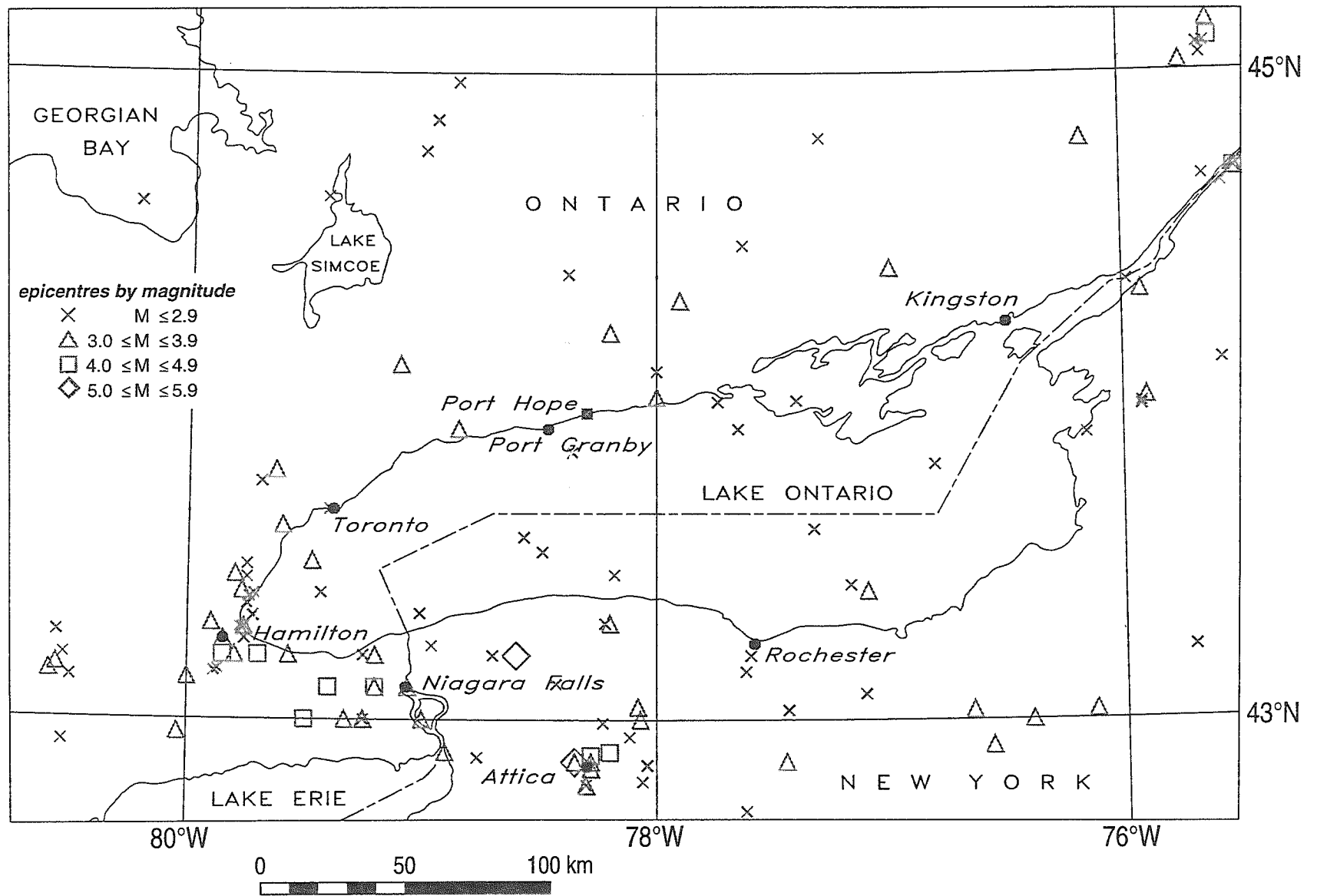
Figure A Earthquakes, Lake Ontario region, 1840 to 1994 (from the GSC database).

Figure B Earthquakes before 1930, Lake Ontario region.

Figure C Earthquakes 1930 to 1969, Lake Ontario region.

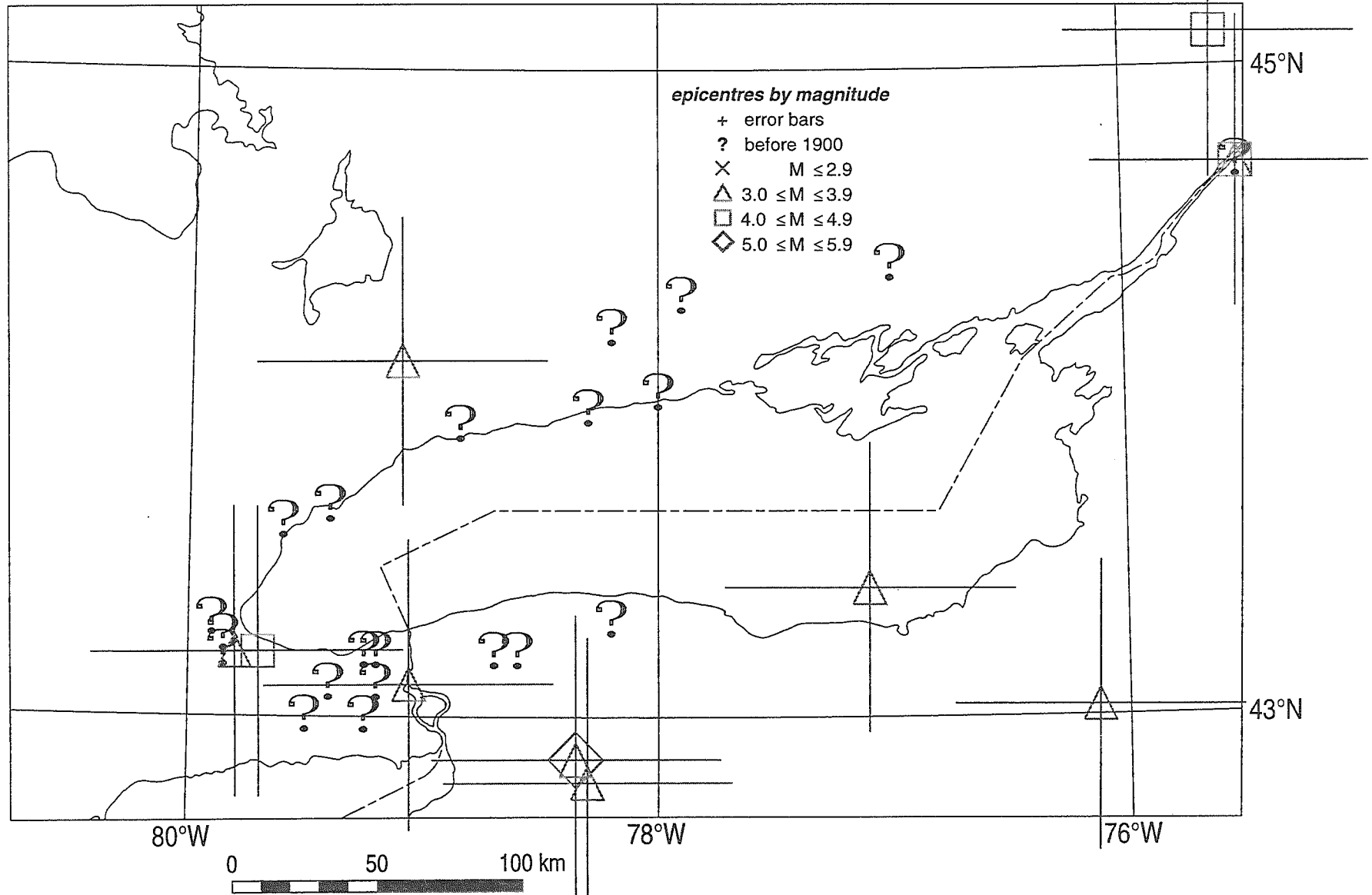
Figure D Earthquakes 1970 to 1994, Lake Ontario region.

Earthquakes, Lake Ontario region, 1840 to 1994 (GSC database)



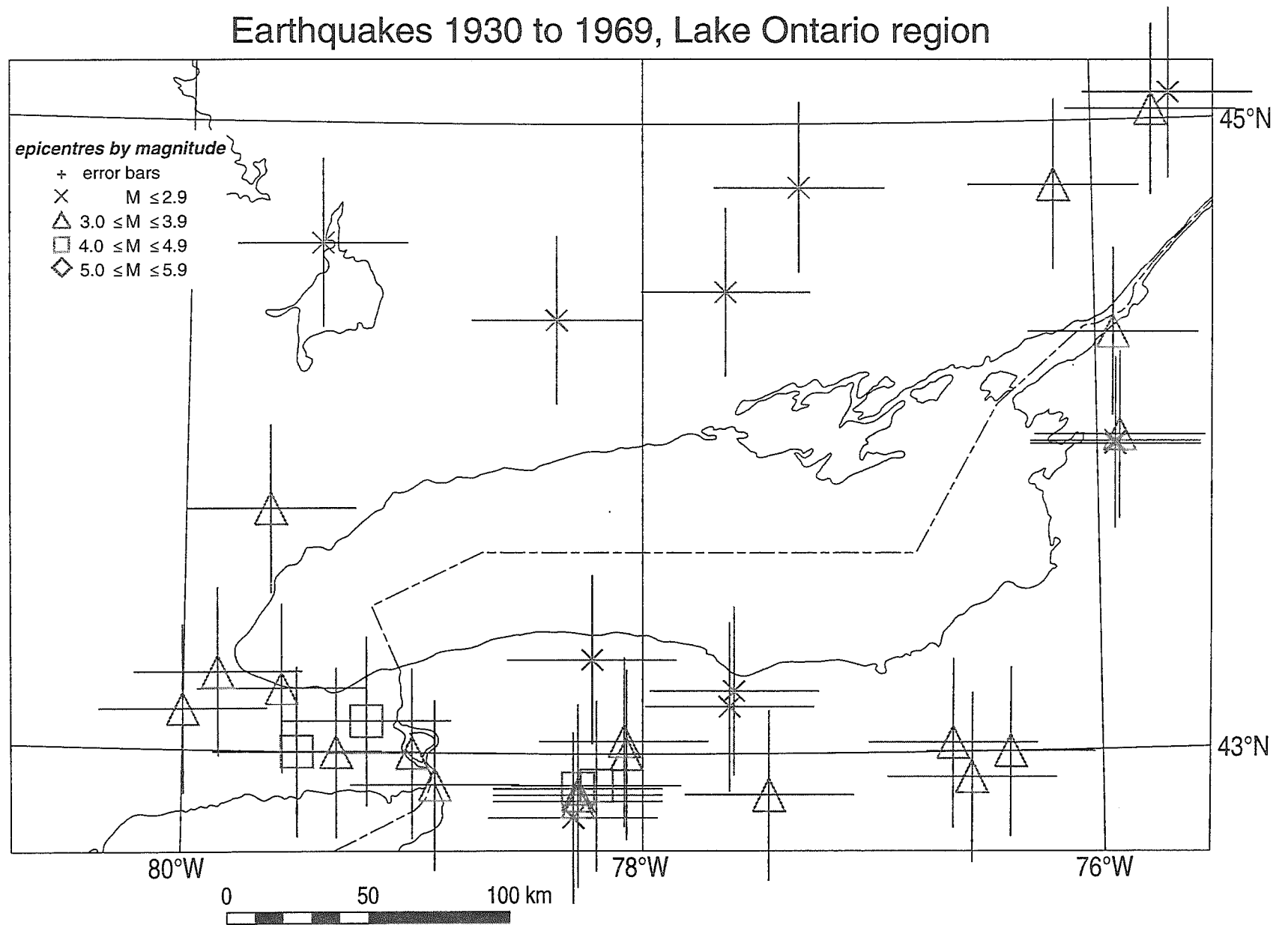
A

Earthquakes before 1930, Lake Ontario region



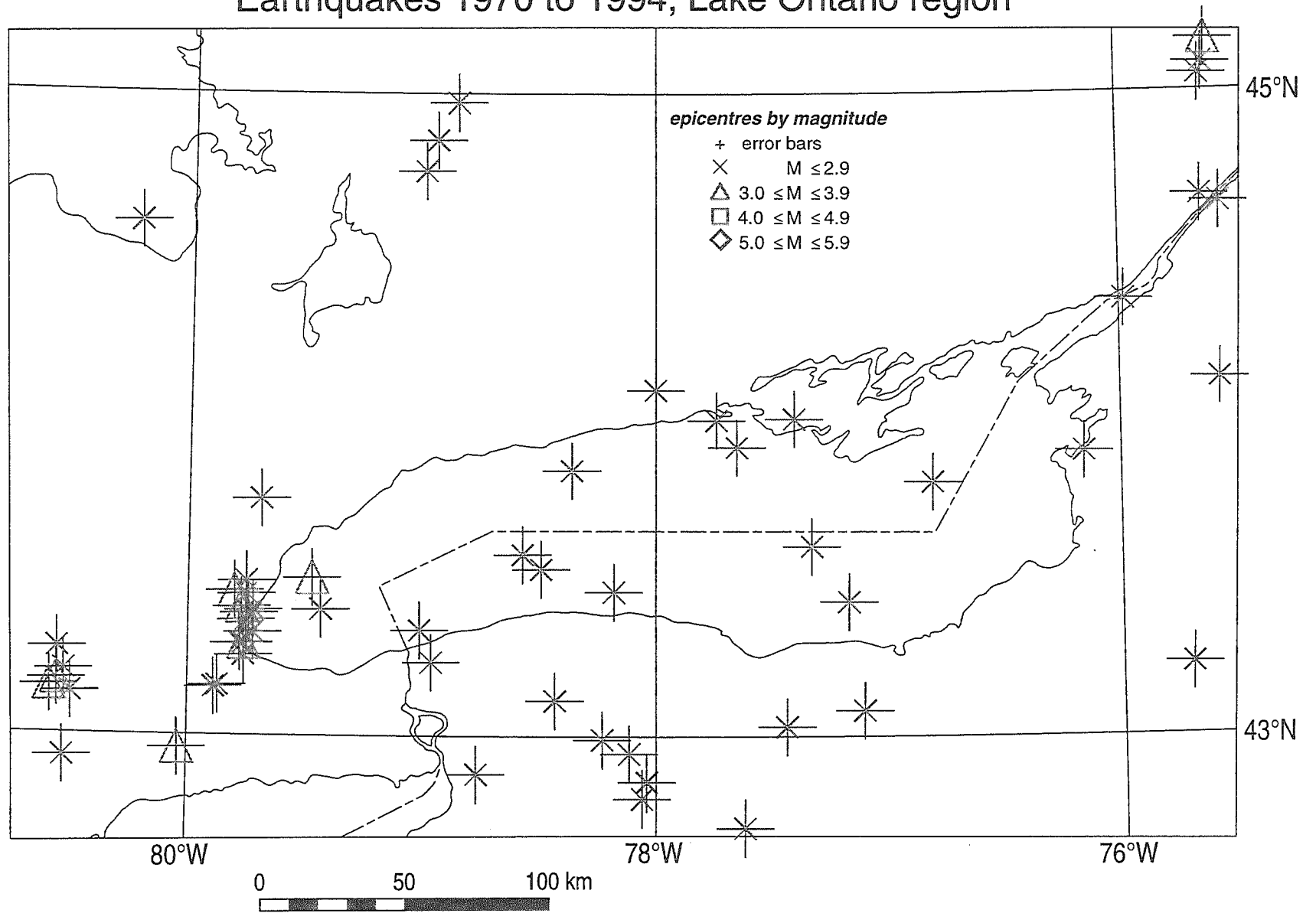
B

Earthquakes 1930 to 1969, Lake Ontario region



C

Earthquakes 1970 to 1994, Lake Ontario region



D