

## Regional Stratigraphic Framework of Surficial Sediments and Bedrock Beneath Lake Ontario

### Le cadre stratigraphique régional de la roche en place et des sédiments de surface sous le lac Ontario

### Der regionale stratigraphische Rahmen der Oberflächensedimente und des Sockels unter dem Ontariosee

D. R. Hutchinson, C.F. Michael Lewis and G. E. Hund

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Article abstract

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# REGIONAL STRATIGRAPHIC FRAMEWORK OF SURFICIAL SEDIMENTS AND BEDROCK BENEATH LAKE ONTARIO\*

D.R. HUTCHINSON, C.F.M. LEWIS and G.E. HUND\*\*: first and third authors, United States Geological Survey, Woods Hole, Massachusetts 02543, U.S.A.; second author, Geological Survey of Canada, Atlantic Geoscience Centre, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2.

**ABSTRACT** Approximately 2550 km of single-channel high-resolution seismic reflection profiles have been interpreted and calibrated with lithological and geochronological information from four representative piston cores and one grab sample to provide a regional stratigraphic framework for the subbottom deposits of Lake Ontario. Five units overlying Paleozoic bedrock were identified and mapped. These are classified as informal units and represent, from oldest to youngest: (A) subglacial till (?) deposited by the Port Huron ice at the end of the Wisconsin glaciation; (B) an ice-marginal (?) unit confined to the western part of the lake that was probably deposited during retreat of the Port Huron ice shortly after 13 ka; (C) a regionally extensive unit of laminated glaciolacustrine clay that accumulated until about 11 ka; (D) a weakly laminated to more massive lake clay deposited during a period of reduced water supply and rising water levels after the drawdown of the high-level glacial lakes (Iroquois and successors); and (E) modern lake clay less than 10 m thick that began accumulating around 6-8 ka with the subsequent return of upper Great Lakes drainage through the Ontario basin. Seismic reflections also define the configuration of the bedrock surface and pre-glacial stream valleys incised in the bedrock surface. Several anomalous bottom and subbottom features in the surficial sediments are mapped, such as discontinuous and offset reflections, furrows, gas pockets, and areas of large subbottom relief. None of these features appear to be spatially correlative with the diffuse seismicity that characterizes the lake area or with deeper structures such as Paleozoic bedrock faults or crustal-penetrating faults in the Precambrian basement.

**RÉSUMÉ** Le cadre stratigraphique régional de la roche en place et des sédiments de surface sous le lac Ontario. On a interprété et étalonné environ 2550 km de profils de sismique réflexion monocanal à haute résolution selon les données lithologiques et géochronologiques de quatre sondages représentatifs faits par carottier à piston et un échantillon prélevé avec une benne afin d'établir le cadre stratigraphique des dépôts accumulés sous le fond du lac Ontario. Cinq unités recouvrant le substratum paléozoïque ont été identifiées et cartographiées. Ces unités informelles, de la plus ancienne à la plus jeune, sont : (A) un till sous-glaciaire (?) déposé par les glaces de Port Huron à la fin de la glaciation wisconsinienne; (B) une unité de limite glaciaire (?) confinée à la partie ouest du lac et qui a probablement été déposée pendant le retrait des glaces de Port Huron, peu après 13 ka; (C) une unité d'étendue régionale d'argile glaciolacustre feuilletée qui s'est accumulée jusqu'à environ 11 ka; (D) une argile lacustre, de faible-ment feuilletée à massive, mise en place au cours d'une période où il y eut approvisionnement en eau réduit et hausse du niveau de l'eau après l'abaissement des lacs glaciaires (Iroquois et ultérieurs); et (E) une argile lacustre moderne de moins de 10 m d'épaisseur qui a commencé à s'accumuler à partir de 6-8 ka après la reprise du drainage des Grands Lacs par le bassin Ontario. La sismique réflexion a aussi permis de délimiter la configuration de la surface du socle et des vallées pré-glaciaires qui y sont entaillées. Plusieurs éléments des sédiments de surface du fond du lac et sous le fond ont été cartographiés, comme des réflexions de discontinuités et de décalages, des rainures, des poches de gaz et des zones de grandes formes enfouies. Aucun de ces éléments ne semble correspondre spatialement à la sismicité diffuse qui caractérise la région du lac ou aux structures profondes comme les failles de substratum paléozoïque ou celle du socle précambrien.

**ZUSAMMENFASSUNG** Der regionale stratigraphische Rahmen der Oberflächen-sedimente und des Sockels unter dem Ontariosee. Ungefähr 2550 km seismischer Reflexionsprofile wurden interpretiert und kalibriert mit lithologischen und geochronologischen Informationen von vier repräsentativen Kolbenbohrkernen und einer ausgeschürften Probe, um den regionalen stratigraphischen Rahmen für die unter dem Bett des Ontariosees gelegenen Ablagerungen zu erhalten. Man hat fünf Einheiten, die das anstehende Gestein aus dem Paläozoikum überlagern, identifiziert und kartographiert: (A) eine subglaziale Grundmoräne (?), die durch das Eis von Port Huron am Ende der Wisconsin-Vereisung abgelagert wurde; (B) eine auf den westlichen Teil des Sees begrenzte Eisrand (?)-Einheit, die wahrscheinlich während des Rückzugs des Port Huron-Eises kurz nach 13 ka abgelagert wurde; (C) eine regional ausgedehnte Einheit von blättrigem glaziallimnischem Lehm, die sich bis etwa 11 ka ansammelte; (D) ein schwach- bis massivblättriger Seelehm, der während einer Periode verminderter Wasserzufuhr und steigenden Wasserspiegeln sich ansammelte; und (E) moderner Seelehm von weniger als 10 m Dicke, der sich um etwa 6-8 ka anzusammeln begann, mit der Rückkehr der Drainage der oberen Großen Seen durch das Ontariobecken. Seismische Reflexionen lassen auch die Konfiguration der Sockeloberfläche und der präglazialen in die Sockeloberfläche eingeschnittenen Flußtäler erkennen. Mehrere unregelmäßige Grund- und Untergrundscheinungen der Oberflächensedimente wurden kartographiert, wie Diskontinuität und Höhenunterschiede der Reflexionen, Mulden, Gastaschen und Gebiete mit breitem Untergrundrelief. Keine dieser Erscheinungen scheint räumlich mit der für das Seen-Gebiet charakteristischen Seismik zu korrelieren oder mit tieferen Strukturen, wie die Verwerfungen des anstehenden Gesteins aus dem Paläozoikum oder durch die Kruste dringende Verwerfungen im präkambrischen Untergrund.

\* Geological Survey of Canada Contribution No. 33593

\*\* Present Address: 3850 Calvert St. NW, Washington, D.C. 20007, U.S.A.

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## INTRODUCTION

Lake Ontario, the smallest of the Great Lakes, is 290 km long by 85 km at its widest point, and covers an area of 19,477 square kilometres (Fig. 1). The lake basin is located on the West St. Lawrence Lowland, which is in turn bounded by the Canadian Shield to the north, the Allegheny Plateau to the south; the Niagara Escarpment to the southwest and west and the Adirondack Plateau to the east (Bostock, 1970; Sanford and Grant, 1975; Chapman and Putnam, 1984; Muller and Prest, 1985). The lake is generally understood to be positioned along a former (pre-Quaternary) drainage system which was deepened and broadened to its present configuration below sea level by multiple Quaternary glaciations (Spencer, 1890; Hough, 1958). Research on the geology and geophysics of Lake Ontario has resulted in the compilation of a comprehensive bibliography (Hutchinson and Wold, 1979), but no single publication has yet attempted to summarize the many and varied data on the Quaternary deposits and bedrock. A recent review of the geology of the lake has outlined the need for synthesis studies (Martini and Bowlby, 1988).

The work presented in this paper gives a regional reconnaissance of the offshore geology of Lake Ontario based principally on high-resolution seismic reflection data correlated to cores. The distribution and character of subbottom surficial sedimentary sequences, bedrock surface, and features of potential neotectonic significance are described. No attempt was made to include nearshore areas or areas that are locally complex, such as the offshore areas adjacent to the Niagara River, the Kingston Basin, or the westernmost part of the lake. The present compilation adds a regional context to earlier local studies off Toronto (Lewis and Sly, 1971) and in

Kingston Basin and off Niagara River (Sly and Prior, 1984). It adds a vertical dimension to pioneering work on the distribution of offshore surficial sediments carried out by Lewis and McNeely (1967) and Thomas *et al.* (1972 a, b).

## REGIONAL GEOLOGICAL SETTING

Lake Ontario forms an asymmetrical basin in relatively soft Upper Ordovician shales and limestones, contained within a sequence of Cambrian to Carboniferous sedimentary rocks, which thicken and dip gently southwards into the Appalachian Basin. These Paleozoic rocks are about 500 m thick beneath southern Lake Ontario and unconformably overlie undifferentiated Precambrian basement rocks of the Grenville Province which are exposed about 30-130 km north of the lake and immediately east of the lake (Rickard and Fisher, 1970; Sanford and Baer, 1981; Johnson *et al.*, 1992; Easton, 1992). Beneath the Paleozoic cover, the Grenville basement is subdivided by at least three major south- to southwest-trending crustal penetrating shear zones which reflect northwest directed Proterozoic (Grenvillian) thrusting (Forsyth *et al.*, in press a, in press b). The profound unconformities represented by the contacts between middle Proterozoic basement, early Paleozoic cover rocks, and late Cenozoic glacial and postglacial deposits of the lake are fundamental boundaries in the geologic and tectonic history of the region.

The Lake Ontario basin has been glaciated several times during the Quaternary; it lies 200-300 km north of the maximum extent of the last (Laurentide) ice sheet about 18-21 ka (Coates, 1976; Dreimanis, 1977; Muller, 1977; Dyke and Prest, 1987; Karrow, 1989; Barnett, 1992). The last ice load downwarped the Lake Ontario area to the north-northeast. Retreating Wisconsin ice reached the southern Lake Ontario

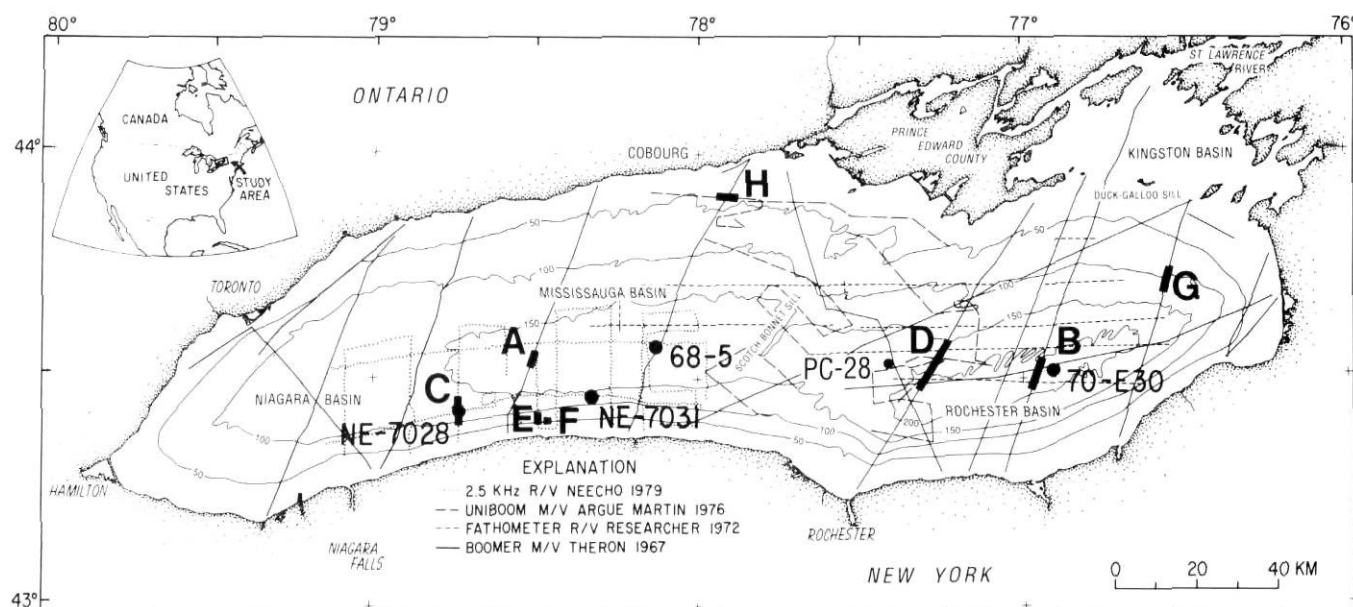


FIGURE 1. Index map of Lake Ontario showing bathymetry (in meters) and locations of seismic profile tracklines. Illustrated profile sections (Fig. 3) and core locations (Fig. 4) are shown by heavy lettering and annotation. Datum is lake level (74 m asl).

Carte repère du lac Ontario montrant la bathymétrie (en mètres) et les tracés des profils sismiques. La localisation des profils (fig. 3) et des sondages (fig. 4) est donnée par les lettres en gras et les annotations. Le niveau de référence est celui du lac (74 m au-dessus du niveau de la mer).

shoreline about 12.3 ka (Calkin and Brett, 1978). Following retreat of the ice dam in the Upper St. Lawrence Valley around 12 ka (Fullerton, 1980), lake levels fell by as much as 145 m from the glacial Lake Iroquois water plane. Subsequently, they rose again as a consequence of differential glacioisostatic uplift of the lake outlet (near Kingston), with a maximum recovery of about 100 m in the western lake area and 40 m in the eastern lake area (Coleman, 1937; Karrow *et al.*, 1961; Sutton *et al.*, 1972; Sly and Prior, 1984; Anderson and Lewis, 1985; Pair *et al.*, 1988). This glacial history suggests that the Lake Ontario sedimentary deposits should record a history of variable ice advances prior to 12 ka followed by regional tilting and changing water levels to the present.

## GEOLOGICAL AND GEOPHYSICAL DATA

The maps and diagrams contained in this paper are based on 2550 km of high-resolution seismic reflection data collected by Canadian and U.S. investigators between 1967 and 1979 and selected Canadian and U.S. core data (Fig. 1). The seismic data obtained by Canadian workers are 1168 km of E.G. & G. BOOMER<sup>1</sup> profiles collected in 1967 by the Geological Survey of Canada and Canada Centre for Inland Waters. Navigation was by radar and dead reckoning. Part of the data obtained by U.S. workers consists of two studies conducted by the U.S. Geological Survey (USGS), one in 1976, in which 440 km of E.G. & G. UNIBOOM profiles were collected, and the other in 1979, in which 540 km of 2.5 kHz profiles were collected. Navigation for both USGS cruises was Loran C. The rest of the data obtained by U.S. workers is 410 km of fathometer data collected by NOAA during the International Field Year of the Great Lakes (IFYGL) in 1972, using DECCA navigation. An additional 1000 km of fathometer data from this NOAA survey were omitted from this study because of its limited penetration and poor resolution. One sidescan sonar record obtained on the USGS cruise in 1979 is shown for illustrative purposes in the discussion of furrows. Sidescan data were not part of this study.

Of the many kilometres of Lake Ontario seismic data reported in Hutchinson and Wold (1979), only the profiles described above were selected for this study because of their availability, regional distribution, and similarity of penetration and resolution. Line crossing statistics show that the data are compatible: analysis of 72 (one-half) of the crossings indicates that about 60% have bottom and subbottom depths that agree within 3 m (4 ms two-way travel time), or well within uncertainties that can be ascribed to source-receiver depths. An additional 20% of the crossings show agreement from 3-5 m (4-7 ms), but can be corrected to within 3 m by small shifts in line locations that are within the navigational uncertainties (.2-1 km). The final 20% of the crossings, which have discrepancies of 5-15 m (7-20 ms), occur in an area of large subbottom relief and can be attributed to small navigational errors. The resolution of the seismic profiles, which varies according to the frequency and length of the seismic source

signal, is estimated to be between 0.5 and 3.0 m. Because the line spacing ranges from 5 to 25 km, the resolution of the horizontal boundaries of features is limited to the order of kilometres.

Four piston cores and one grab sample from the eastern and western basins of the lake were chosen to demonstrate lithology and chronology of the seismic units (Fig. 1). Core 68-5, a 15.12-m-long core from the Mississauga basin, has been dated by <sup>14</sup>C-calibrated pollen stratigraphy (McAndrews, 1972; 1973) and lies approximately 1100 m from the nearest seismic line. Core 70-E30, a 16.94 m long core from the deepest part of the lake in the Rochester basin, has been dated by amino acid and <sup>14</sup>C methods (Schroeder and Bada, 1978) and pollen stratigraphy (J. McAndrews, unpublished data); it lies approximately 1200 m from the nearest seismic line. Core PC-28, a 15-m long piston core collected 40 km northwest of Rochester, has three <sup>14</sup>C-calibrated pollen age estimates and a paleomagnetic profile throughout its length showing secular oscillations in the magnetic field (Anderson *et al.*, 1976); it is located 1400 m from the nearest seismic line. Core NE-7028, a 3.53-m-long core from Mississauga basin and grab sample NE-7031 have not been dated, but were collected during the simultaneous operation of a hull-mounted 7-kHz seismic profiling system, and located on an existing seismic line using LORAN C navigation. Hence, the first 3 piston cores are dated but not well tied to the seismic stratigraphy, whereas the final piston core and grab sample are not dated but are closely linked with the seismic stratigraphy.

Lithological information from an additional 12 undated piston cores from the Mississauga and Niagara basins, and 3 undated piston cores from the Rochester basin (D.R. Hutchinson and C.F.M. Lewis, unpublished data), ranging in length from 3.01 to 17.91 m, was correlated with the seismic stratigraphy on profiles which ranged from 0-1100 m away from the cores. Five of these cores also have been analyzed for paleomagnetic trends (Brennan *et al.*, 1984) but lack well constrained age-calibrations. Other piston cores in water depths less than 100 m contain evidence of former lower lake levels; some have been dated from pollen stratigraphy (Anderson and Lewis, 1985). Because the 4 cores and one grab sample discussed above are representative of the results of correlations of all cores, only these are used here. The 1976 USGS profiles (Hutchinson *et al.*, 1979), the amino acid and <sup>14</sup>C dates of core 70-E30 (Schroeder and Bada, 1978), the pollen stratigraphy of core 68-5 (McAndrews, 1972; 1973) and the paleomagnetic profile of core PC-28 (Anderson *et al.*, 1976) have all been published; other data used here have not been published before.

## BEDROCK SURFACE

The clarity and strength of reflections from the surface of bedrock greatly facilitate mapping the bedrock surface beneath the Quaternary cover. A bedrock contour map (Fig. 2) was compiled based on the depth to bedrock on the seismic profiles, assuming a velocity of sound of 1500 m/s, and limits imposed by the bathymetry (Canadian Hydrographic Service, 1970). Contours for the area near

1. Trade names are used for descriptive purposes only and do not imply endorsement by either the U.S. Geological Survey or the Geological Survey of Canada.



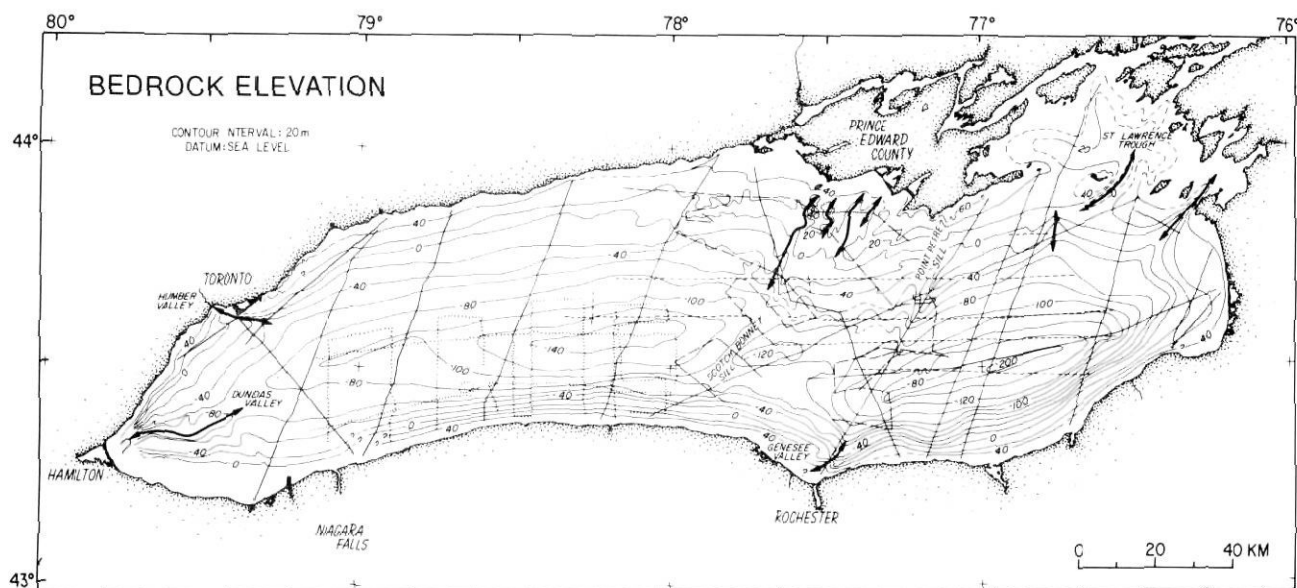


FIGURE 2. Bedrock elevation. This map is based on the depth to bedrock digitized in two-way travel time on the 2550 km of seismic profiles shown on the map plus 755 km of unpublished data for the area between Hamilton, Toronto and Niagara-on-the-Lake. Depths were computed assuming an average velocity of sound in water and sediment of 1500 m/s. Bedrock valleys are shown by arrows.

*Topographie de la surface rocheuse fondée sur le temps de propagation aller-retour des ondes jusqu'au socle converti en numérique sur les 2550 km de profils sismiques illustrés et les 755 km de données non publiées pour les régions entre Hamilton, Toronto et Niagara-on-the-Lake. Les profondeurs ont été reconstituées en présumant une vitesse moyenne du son dans l'eau et le sédiment de 1500 m/s. Les flèches identifient les vallées dans la roche en place.*

Hamilton, where the data used in this study show no control, were taken from a bedrock contour map compiled from 755 km of seismic data (C.F.M. Lewis, unpublished data).

The bedrock surface is steeper along the southern shore than along the northern shore, and is deeper in the eastern half. A bedrock sill, with a crestal elevation of 80-100 m below sea level (bsl), the Scotch Bonnet sill, separates a western depression (> 140 m bsl) from an eastern depression (> 200 m bsl). This configuration has been the primary control on sedimentation within the lake. The western depression trends E-W and underlies the two sedimentary basins, the Niagara and Mississauga basins, distinguished by their Quaternary deposits (Thomas *et al.*, 1972a, b). The axis of the eastern depression is offset to the south by 30 km, trends WSW and underlies the Rochester basin (Fig. 1). A second bedrock feature, the Point Petre sill, has little bathymetric expression and has been mostly buried by Quaternary deposits. These sills and the generally rougher topography of the mid-lake region may be related to monoclinical folding and faulting of the Paleozoic rocks of Prince Edward County (Kay, 1937). Several large valleys (Fig. 2, arrows) can be inferred from the map. The complete infilling of these valleys by Quaternary sediments, with prograding and crosscutting reflector geometries, indicates rapid channelized water flow, and suggests that the valleys mark buried river channels or sub-ice tunnels. The largest of these valleys, the Dundas valley, is near Hamilton and contains 90 m of sediment.

### QUATERNARY STRATIGRAPHY

Five units, recognized by seismic facies or stratigraphic position, overlie the bedrock surface and are designated by

letters A to E, from oldest to youngest. Representative seismic profiles showing the 5 units are shown in Figure 3. The correlation of the piston cores and grab sample with the seismic stratigraphy is shown in Figure 4. The areal distributions of the 5 units are shown in Figures 5-9. Because of the sparse track line coverage, isopach contouring has not been attempted. Figure 10 presents age information from the cores plotted versus subbottom depth. The seismic character, contact relationships, interpreted lithology and inferred environment of deposition of each of the units is summarized in Figure 11.

#### UNIT A

The oldest unit, A, is characterized by large diffractions and no internal order (Fig. 3A-3D). Its lower boundary is a strong and coherent reflector interpreted as the bedrock surface. Its upper boundary is commonly sharp and strong (in areas where unit B is absent) or discontinuous and unresolved (in areas where unit B occurs). Unit A may be smooth and massive (e.g., Fig. 3A) or hummocky and mound-like (e.g., Fig. 3B). More than one component may comprise unit A, but seismic resolution and coverage were insufficient to separately map these subunits. Thicknesses of unit A may reach 25 m. Grab sample NE-7031, collected from sediments thought to be reworked from an outcrop of the hummocky type of unit A in the western part of the study area (Fig. 4E) is comprised of coarse and fine gravel in a sandy matrix. A 3-m section of unit A was sampled north of Rochester by Anderson and Lewis (1975) in core PC-29 (not illustrated) and consisted of gray, pebbly, silty, sandy till. A second 3-m section which sampled unit A at PC-28 (Fig. 4C) consisted of pebbly, sandy, gray till (Anderson *et al.*, 1976). Unit A, therefore, is interpreted as a glacial diamict, probably subglacial till, that underlies most of the lake.

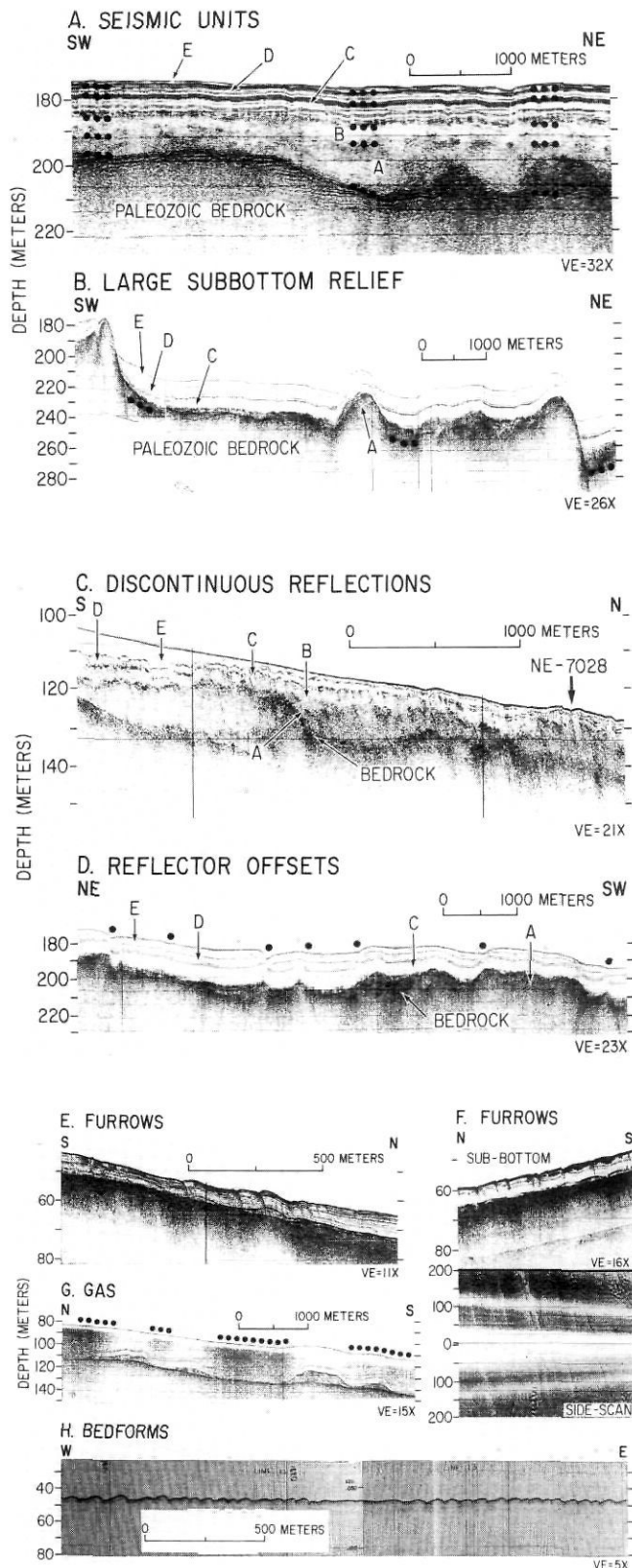


FIGURE 3. Profiles showing seismic stratigraphy and morphologic features in Lake Ontario. Locations are given in Figure 1. Depths are relative to the surface of Lake Ontario (74 m asl). (A) Seismic units A, B, C, D, E, and Paleozoic bedrock. Dots show the base of each lettered unit. (B) Seismic units in the region of large subbottom relief.

Unit A occurs throughout Lake Ontario (Fig. 5). The massive, uniformly thick part of this unit occurs in western Lake Ontario beneath unit B where water depths are less than 120 m. The hummocky character occurs primarily in eastern portions of the lake where water depths exceed 200 m and accounts for a zone of large subbottom relief described later in this paper. This unit may occur in water depths as shallow as 30 m near Rochester. Isolated pockets rather than uniformly thin deposits characterize the area labeled thin and/or absent (Fig. 5).

#### UNIT B

Like unit A, unit B is acoustically incoherent, but is distinguished by its more opaque (lower amplitude) character and lack of strong diffractions. It is generally less than 10 m thick (Figs. 3A, 3C, 4D). Its lower boundary is either strong and distinct (where it immediately overlies bedrock) or weak and uncertain (where it overlies unit A). Its upper boundary is a continuous, coherent but rough and irregular reflector with local relief < 5 m. The bottom of core NE-7028 (Fig. 4D), which sampled 1.8 m of unit B, consists of stiff dark gray clay or silty clay containing lighter gray silt and sand blebs and occasional pebbles. Given its general lack of coherent reflections or diffractions, unit B is probably more uniform than unit A and lacks significant pebble or gravel components. It is tentatively interpreted as a glacial diamict, possibly a subglacial till composed of deformed glaciolacustrine sediment or a flowtill.

This unit has been identified only in the western part of the lake (Fig. 6). On the south shore, its limit closely follows the 100 m isobath whereas on the north shore, it follows the 70 m isobath. Immediately east of longitude 78° W, its edge extends below the 170-m isobath. The sand and gravel deposits along the northern offshore area (Rukavina and St. Jacques, 1970; St. Jacques and Rukavina, 1972; Thomas *et al.*, 1972a, b) may be reworked outcrops of both units A and B. Most of unit B is buried by younger deposits.

Dots indicate the top of Paleozoic basement. (C) Seismic units in the region of discontinuous reflections. (D) Seismic units in the region of reflector offsets. Dots near the lake floor indicate positions of reflector offsets. (E) Examples of furrows at the lake floor. (F) Example of furrows on a vertical incidence profile and simultaneous coincident side-scan sonar image. Scale bar on the side scan sonar profile gives uncorrected horizontal range from the profiler. (G) Example of sub-bottom gas from eastern Lake Ontario. Dots indicate lateral extent of gas on the profile. (H) Example of bedforms from northern Lake Ontario.

*Profils sismiques illustrant la stratigraphie et les entités morphologiques du lac Ontario (localisations à la fig. 1). Les profondeurs sont relatives à la surface du lac Ontario (74 m asl). A) unités sismiques A, B, C, D, E et roche paléozoïque. Les points montrent la base de chaque unité identifiée par une lettre. B) Unités sismiques dans la zone de grandes formes enfouies. Les points montrent la limite supérieure de la roche paléozoïque. C) Unités sismiques dans la zone de réflexions discontinues. d) Unités sismiques dans la zone de réflecteurs décalés. E) Exemples de rainures sur le fond du lac. F) Exemples de rainures sur un profil à incidence verticale et sur image sonar latéral coïncident dans le temps et l'espace. L'échelle verticale sur l'image sonar provient de l'enregistreur et n'est pas corrigée. G) Exemple de la présence de gaz, dans l'est du lac Ontario. Les points donnent l'étendue latérale du gaz. H) Exemple de formes du fond dans l'ouest du lac Ontario.*

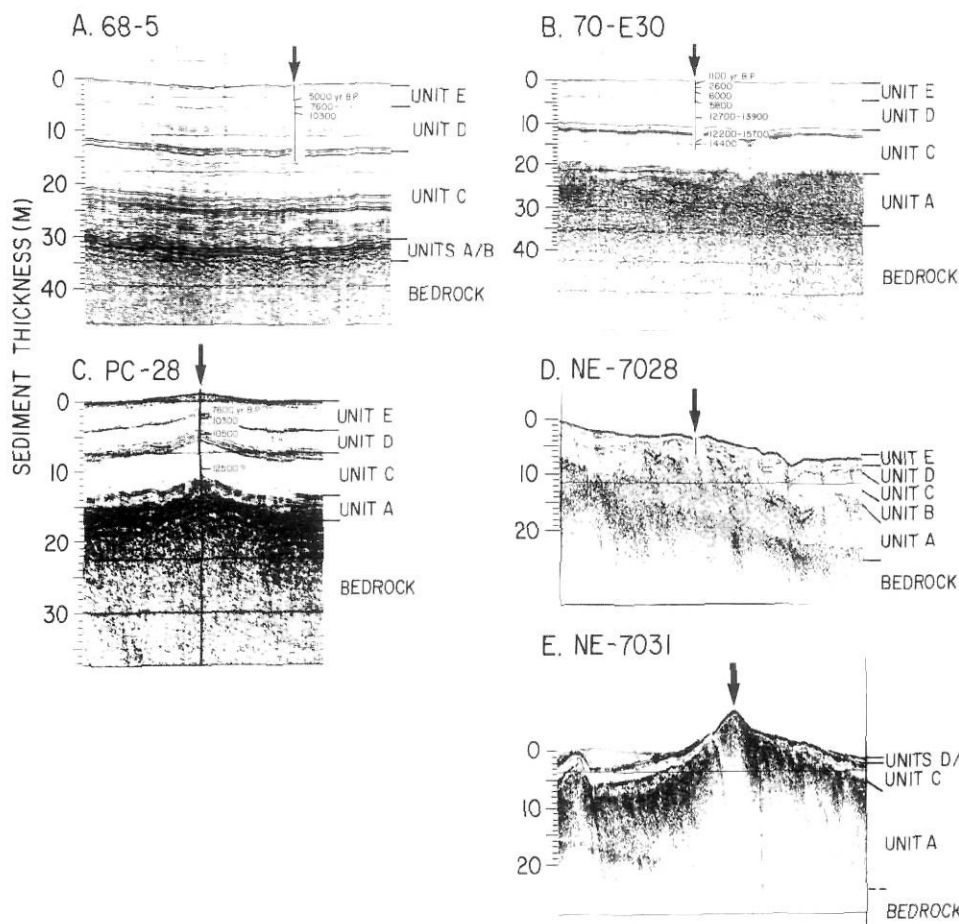


FIGURE 4. Seismic reflection profiles showing core and grab sample correlations. Locations are given in Figure 1. (A) Core 68-5 (GSC). Labeled ages are based on  $^{14}\text{C}$ -calibrated pollen zones (McAndrews, 1972; 1973). (B) Core 70-E30 (GSC). Labeled ages are based on amino-acid age estimates (Schroeder and Bada, 1978) which have large scatter. Ages from  $^{14}\text{C}$ -calibrated pollen zones for core 70-E30 (J.H. McAndrews, personal communication) are shown in Figure 10. (C) Core PC-28 (GSC). Labeled ages are from  $^{14}\text{C}$ -calibrated pollen zones (three younger ages) and paleomagnetic analysis (oldest age). (D) Core NE-7028 (USGS). (E) Grab sample NE-7031 (USGS).

*Profils de sismique réflexion montrant la correspondance entre les carottes et l'échantillon prélevé à l'aide d'une benne. A) Carotte 68-5 (CGC). Les datations accolées sont fondées sur les zones polliniques calibrées au  $^{14}\text{C}$  de McAndrews (1972, 1973). B) Carotte 70-E30 (CGC). Les datations accolées sont fondées sur des estimations de Schroeder et Bada (1978) sur les acides aminés. Les datations de la carotte 70-E30 fondées sur les zones polliniques calibrées au  $^{14}\text{C}$  (J.H. McAndrews, comm. pers.) sont données à la figure 10. C) Pour la*

*carotte PC-28 (CGC), les datations fondées sur les zones polliniques calibrées au  $^{14}\text{C}$  (les trois âges plus jeunes) et une analyse paléomagnétique (l'âge le plus vieux). D) Carotte NE-7028 (USGS). E) Échantillon NE-7031 (USGS).*

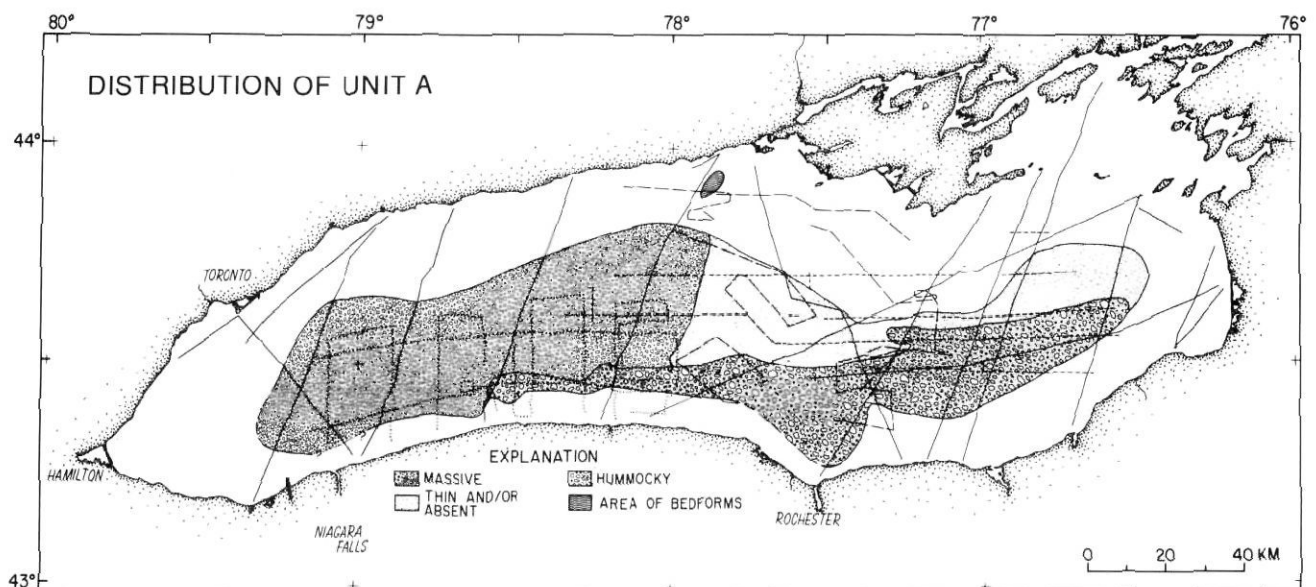


FIGURE 5. Distribution of seismic unit A. Tracklines are the same as those shown on Figure 1. Unit A has a more massive character in the western half of the lake and a more hummocky character in the eastern part.

*Répartition de l'unité sismique A. Les tracés sont les mêmes que ceux qui apparaissent à la figure 1. L'unité A a un caractère plus massif dans la partie ouest du lac et plus bosselé dans la partie est.*



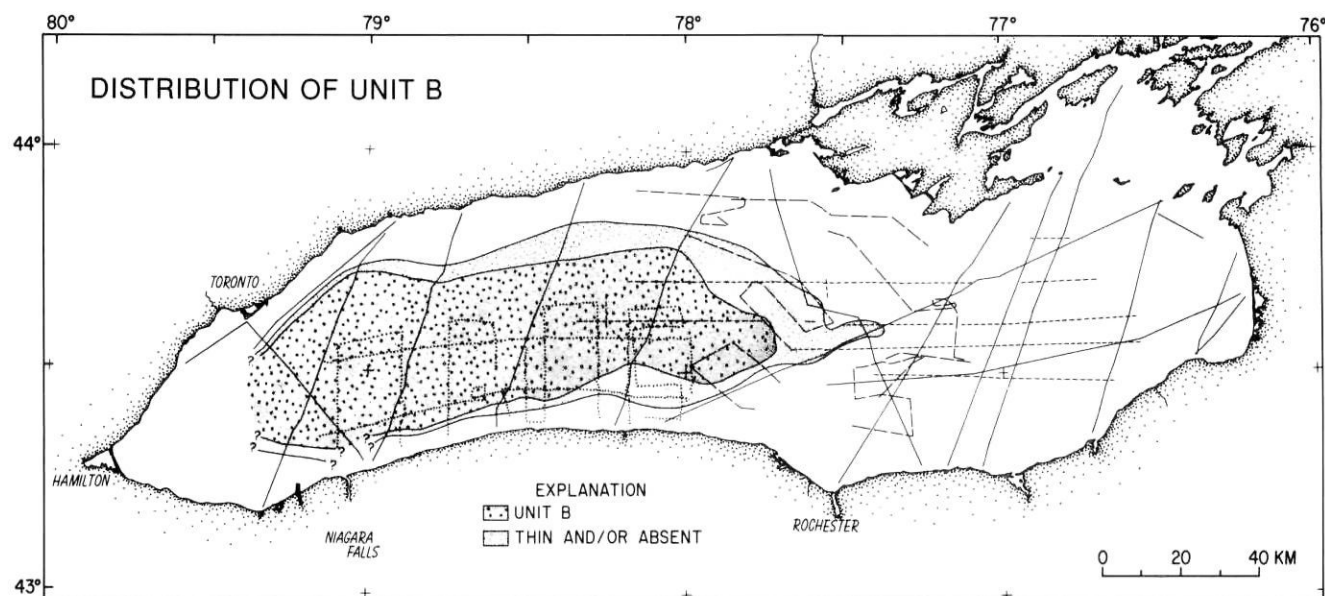


FIGURE 6. Distribution of seismic unit B. Tracklines are the same as those shown on Figure 1.

Répartition de l'unité sismique B. Les tracés sont les mêmes que ceux qui apparaissent à la figure 1.

#### UNIT C

Unlike units A and B, the next younger unit, C, (Figs. 3A-3D) contains strong parallel reflections indicative of a well ordered, probably layered or laminated sequence. Its contact with underlying units B or A is generally sharp though it may be gradational with parts of unit B (Fig. 3C). Its upper contact generally consists of two relatively high-amplitude closely spaced reflections (Figs. 3A, 3B) forming a regionally traceable horizon, which shifts cycles upward and therefore represents gradually younger reflectors towards the eastern part of the lake. All reflections within the unit are parallel to subparallel and almost perfectly reproduce the topography of the underlying surface of deposition. Thicknesses are uniformly about 10 m. The cores indicate that this unit is a dark grayish brown clay with faint horizontal banding consisting of dark gray-brown, silty clay grading upwards into a dark gray clay. The couplets average 1-1.5 cm thick where measurable. The depth of the upper boundary of unit C coincides with the position of more sandy couplets in core 68-5 (Fig. 4A). These sandier couplets may be the cause of the distinctive uppermost reflections. Unit C is interpreted to be composed of proglacial and periglacial lake sediments, deposited in a quiet-water environment that allowed undisturbed draping over the deeper units.

Unit C is the most widely distributed of the 5 units (Fig. 7). It is eroded in shallow water, causing only its lower parts to remain preserved on the basin flanks. Along the north shore, it generally occurs in water depths greater than 70-100 m, with more shallow occurrences (up to 40 m) near the St. Lawrence River and deeper occurrences (> 80 m) in the western part of the lake. This regional shallowing to the east agrees with that expected from known glacioisostatic rebound directions to the northeast (Coleman, 1937; Walcott, 1970; Sly and Prior, 1984; Anderson and Lewis, 1985). The north-south oriented lobe of unit C in the north central part of

the lake is a wedge filling a buried bedrock valley along the western side of the Scotch Bonnet sill (Hutchinson, 1977; Hutchinson et al., 1979).

#### UNIT D

Although it also contains well developed, parallel to subparallel reflections, unit D differs from unit C in that: (1) reflections within it are weaker and more widely spaced, (2) relief inherited from the underlying surface of deposition tends to be smoothed up section (i.e., the unit tends to be ponded instead of draped), and (3) it is generally less than 10 m thick. The upper contact is recognized as a single or double reflection, less intense than the strong reflections at the base of the unit but stronger than reflections from within the unit. Cores NE-7028 (Fig. 4D) and 68-5 (Fig. 4A) indicate that unit D is a firm, dark gray, silty clay which changes from a massive, uniform character at the top to weakly laminated with silt lenses near the middle to a well laminated rhythmically bedded clay near the base of the unit. The couplets that compose the rhythmic bedding consist of alternating gray-brown and reddish brown very firm layers with occasional sandy lenses or homogenous gray intervals. The top of the unit in core 68-5 may correlate with a 0.8-m thick interval of sandy blebs within homogenous gray clay. The change from laminations to homogenous clay and the smoothing of underlying relief inherited from unit D suggests the start of lake-wide circulation and/or a more energetic environment of deposition within the lake.

Unit D occurs throughout the lake (Fig. 8) and is found at varying depths in different parts of the lake. From Niagara River to Rochester, it occurs in water depths greater than 50 m; east of Rochester it is generally in water depths greater than 100 m; from the Duck-Galloo sill to Cobourg it occurs in water depths greater than 70-100 m; and from Cobourg to Toronto it occurs in water depths greater than 110-150 m. It



is thinner in the western area, where it is less than 5 m, than in the eastern area, where it averages 5-10 m thick. One gas pocket in the easternmost part of the lake (Fig. 3G) appears to originate from buried unit D sediments.

#### UNIT E

The youngest unit, E, contains weak reflections and is acoustically transparent. Generally less than 6 m thick, it tends to thin over topographic ridges and thicken over

depressions, resulting in a much subdued and essentially smoothed bottom relief. This smoothing is more extreme than that observed in underlying unit D. This smoothing and the generally thin nature of the unit suggests it was deposited in a higher energy environment than was the case for either units D or C. The cores (Figs. 4A-4C) show that unit E is a dark-gray, silty clay with occasional black FeS laminae several millimetres thick. Shell fragments occur in places in the uppermost few centimetres. Unit E includes modern offshore

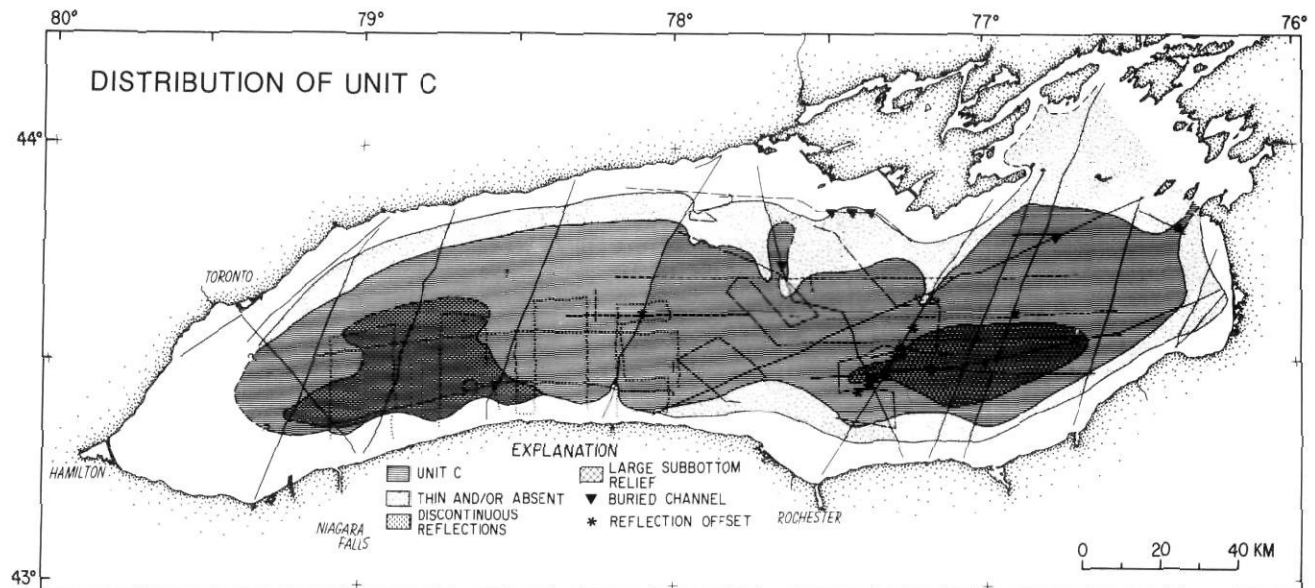


FIGURE 7. Distribution of seismic unit C. Tracklines are the same as those shown on Figure 1. Subbottom features associated with unit C (areas of discontinuous reflections, large subbottom relief, offset reflections, and channels) are also shown.

Répartition de l'unité sismique C. Les tracés sont les mêmes que ceux qui apparaissent à la figure 1. Les éléments sous le fond du lac associés à l'unité C (zones de réflexions discontinues, de grandes formes enfouies, de réflexions décalées et chenaux) sont également montrés.

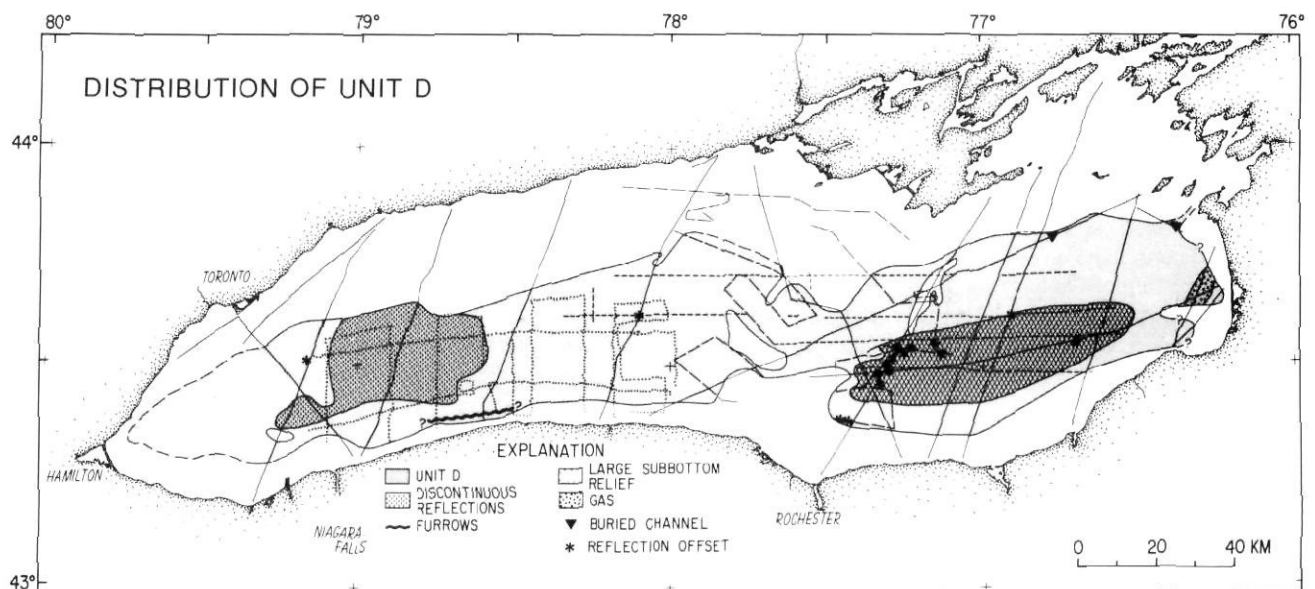


FIGURE 8. Distribution of seismic unit D. Tracklines are the same as those shown on Figure 1. Subbottom features within unit D (areas of discontinuous reflections, large subbottom relief, offset reflections, channels, gas, and furrows) are also shown.

Répartition de l'unité sismique D. Les tracés sont les mêmes que ceux qui apparaissent à la figure 1. Les éléments de la base associés à l'unité D (zones de réflexions discontinues, de grandes formes enfouies, de réflexions décalées, chenaux, gaz et rainures) sont également montrés.

lake sediment. The differences between units D and E (number of reflections, amount of infilling) suggest that modern lake conditions are somewhat more energetic than those of the preceding phase and may reflect a shift in climate and/or lake circulation.

Modern lake sediment of unit E blankets much of the lake floor and is still accumulating (Fig. 9). Unit E extends into more shallow water depths (10-20 m) along the southern shore than along the northern shore (80-100 m). Maximum thickness is around 10 m in the eastern (Rochester) basin. Only thin unit E occurs in much of western Lake Ontario. Unit E is absent from the sills between the Niagara and Mississauga basins and the Mississauga and Rochester basins, as mapped by Thomas *et al.* (1972a, b).

The stratigraphy represented by units A to E is a refinement of the stratigraphy reported by Thomas *et al.* (1972a, b), Anderson and Lewis (1975), Hutchinson *et al.* (1979), and Sly and Prior (1984). Much of this earlier work recognized three basic units: modern lake sediment, glaciolacustrine sediment, and undifferentiated glacial drift. Units A, B, D and E, reported here, separate that glacial drift and modern sediment into upper and lower subunits respectively. Holocene or modern lake sediment reported by these other authors is equivalent to unit E reported here.

### AGE OF SEISMIC UNITS

Correct age assignments depend on the accuracy of the correlation between the seismic profiles and cores. Core sites 68-5, 70-E30, and PC-28 are located over one kilometre from the nearest seismic lines. Of these, core 68-5 has the most certain correlation because the sediment thicknesses appear

to be uniform within several kilometres of the core. Even though the ages and lithologies of all cores are consistent, the correlation of cores and seismic stratigraphy must still be considered tentative.

A pollen diagram of core 68-5 in Mississauga Basin (McAndrews, 1972; 1973) correlates to the  $^{14}\text{C}$  dated pollen zones recognized in organic-rich sediments from small lakes in southern Ontario (T.W. Anderson, personal communication). This correlation provides ages for the base (3.5 ka) of the latest hemlock peak, top (4.8 ka) and base (7.6 ka) of an earlier hemlock peak, and for the pine increase/spruce decline at 10-10.5 ka. The age-vs-depth plot for core 68-5 (Fig. 10A) shows that the base of the youngest unit, E, is about 7.9 ka and that of the next older unit, D, is older than 10.5 ka.

Core 70-E30 also has  $^{14}\text{C}$ -calibrated pollen-zone ages (J. McAndrews, personal communication), as well as radiocarbon and amino-acid age estimates (Schroeder and Bada, 1978), some of which are plotted in Figure 10B. Radiocarbon dates on inorganic carbon in core 70-E30 were considered unreliable due to contamination by old carbonate (*i.e.* Paleozoic bedrock) material (Schroeder and Bada, 1978). The Schroeder and Bada radiocarbon ages on the organic carbon fraction may be more reliable but could still be affected by older recycled organic matter, particularly in sediments with a low organic carbon content, as has been observed in other Great Lakes (Mothersill, 1988; Colman *et al.*, 1990). The amino acid ages show an age reversal from 250-500 cm, indicating one of those ages is suspect. The amino acid ages from 105 to 1600 cm show considerable scatter, whereas the organic  $^{14}\text{C}$  dates are in correct stratigraphic order. The apparent age of the unit E/unit D contact

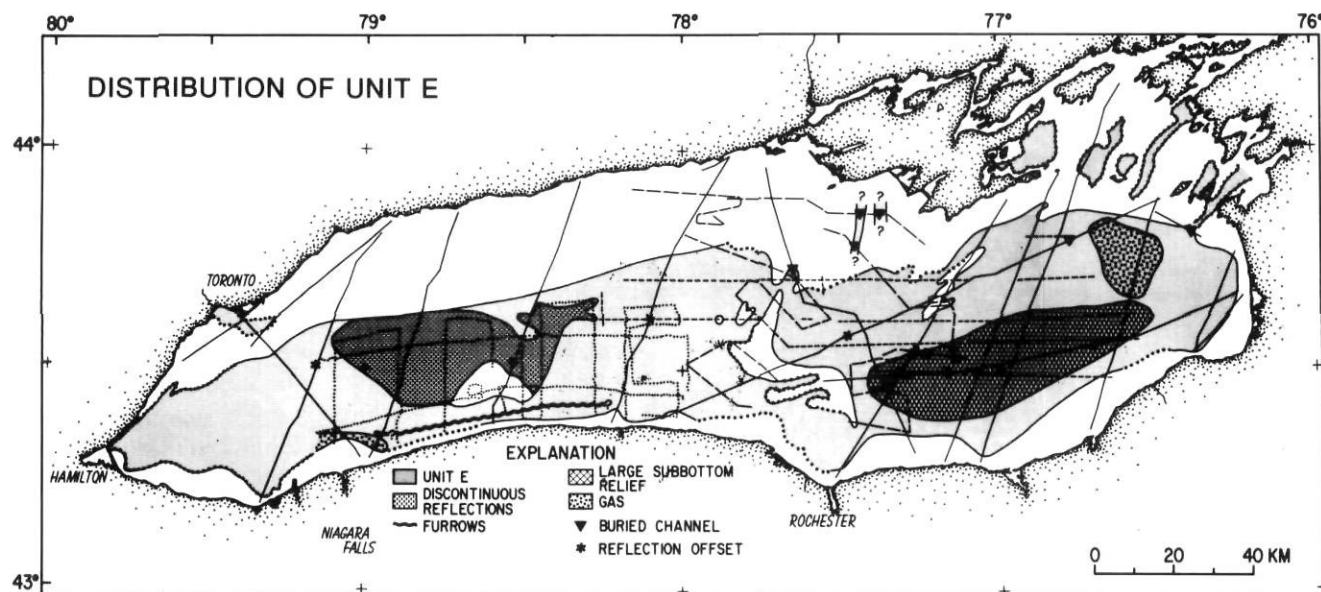


FIGURE 9. Distribution of seismic unit E. Tracklines are the same as those shown in Figure 1. Subbottom features associated with unit E (areas of discontinuous reflections, large subbottom relief, offset reflections, channel, gas, and furrows) are also shown. Dotted contacts are from J.R. Bowlby and C.F.M. Lewis, unpublished map of the surficial geology of Lake Ontario (1976), 1: 400,000.

Répartition de l'unité sismique E. Les tracés sont les mêmes que ceux qui apparaissent à la figure 1. Les éléments sous le fond du lac associés à l'unité E (zones de réflexions discontinues, de grandes formes enfouies, de réflexions décalées, chenaux, gaz et rainures) sont également montrés. Les limites en pointillé sont de J. R. Bowlby et C.F.M. Lewis dans une carte non publiée de la géologie des formations superficielles (1976) à 1/400 000.

is between 6 ka (Pollen-zone ages) and 8 ka (amino acid and organic-fraction  $^{14}\text{C}$  ages), which is consistent with the age of 7.9 ka from core 68-5. Below 5 m depth, the pollen concentration decreases by 35-fold (McAndrews, 1972; 1973) and the amino-acid and organic  $^{14}\text{C}$  ages show large scatter.

Hence, the ages of the boundaries between the older units are not reliable in this core.

The ages of the older contacts can be estimated by paleomagnetic evidence from core PC-28. The age-depth plot for this core (Fig. 10C) is extended beyond a pollen date of 10.5 ka on the basis of the duration of a paleomagnetic declination cycle, estimated to be 1200 years (Anderson *et al.*, 1976) or possibly 2400 years, the fundamental period for secular variation (Lund and Banerjee, 1985). The correlation of seismic units to PC-28 suggests that the ages of the unit contacts are bracketed between 7.2 and 8 ka (D/E), 10.5 and 11 ka (C/D), 12 and 13.2 ka (A/C). Unit B is not present in this core.

The age data from core PC-28 suggest that the onset of stratified, lacustrine sediment which gives rise to strong coherent parallel seismic reflections within unit C may have occurred about 12-13 ka. This age is consistent with the retreat of Port Huron ice across the basin at about 12.3 ka (Calkin and Brett, 1978) and with the generally recognized deglaciation history of the Ontario basin (Dreimanis and Karrow, 1972; Karrow, 1989; Barnett, 1992). Thus units A and B probably represent subglacial and ice marginal deposits, respectively, associated with Port Huron or older ice.

The retreat of Port Huron ice initiated glacial Lake Iroquois, which existed until about 11.7 ka when the ice dam across the upper St. Lawrence Valley failed and the water surface fell to much lower altitudes. Water levels fell first to sea level (*i.e.*, about 100 m below present lake level in the western part of Lake Ontario), and then began to rise about 11.4 ka, being controlled by the rebounding threshold of the upper St. Lawrence River (Sly and Prior, 1984; Anderson and Lewis, 1985; Muller and Prest, 1985; Pair *et al.*, 1988). The top of unit C, tentatively inferred to be about 10.5-11 ka in age from core PC-28, indicates unit C contains both glaciolacustrine sediment and deposits of early Lake Ontario when water levels were at a minimum. The end of deposition of unit C may be linked to several regional events affecting the Ontario basin: (1) initial rapid rise in water levels of early Lake Ontario (Anderson and Lewis, 1985), (2) a shift in drainage of the upper Great Lakes through the Ottawa River at about 10.5 ka, thereby bypassing Lake Ontario (Anderson and Lewis, 1985), and (3) a shift in sedimentation conditions, possibly associated with the Younger Dryas period of climatic cooling that affected the Great Lakes basin at 11-10.5 ka (Lewis and Anderson, 1992).

The reflector separating the youngest lacustrine units D and E appears to be about 6-8 ka in age and marks the final change to the modern energetic environment in which sediment is ponded or focussed in deep basins. The cause for this change is not known. It may correlate with a shift in mid-continental climate when cold meltwater-capped glacial lakes finally disappeared due to drainage to Hudson Bay about 8 ka (Anderson and Lewis, 1992); with a return of upper Great Lakes discharge through Lake Ontario that was completed by 5 ka (Lewis, 1969; Lewis and Anderson, 1989); or with a period at 8-5 ka when lake levels were not rising as fast as in earlier times (Anderson and Lewis, 1985). In this interpretation, unit D contains deposits of early Lake Ontario that

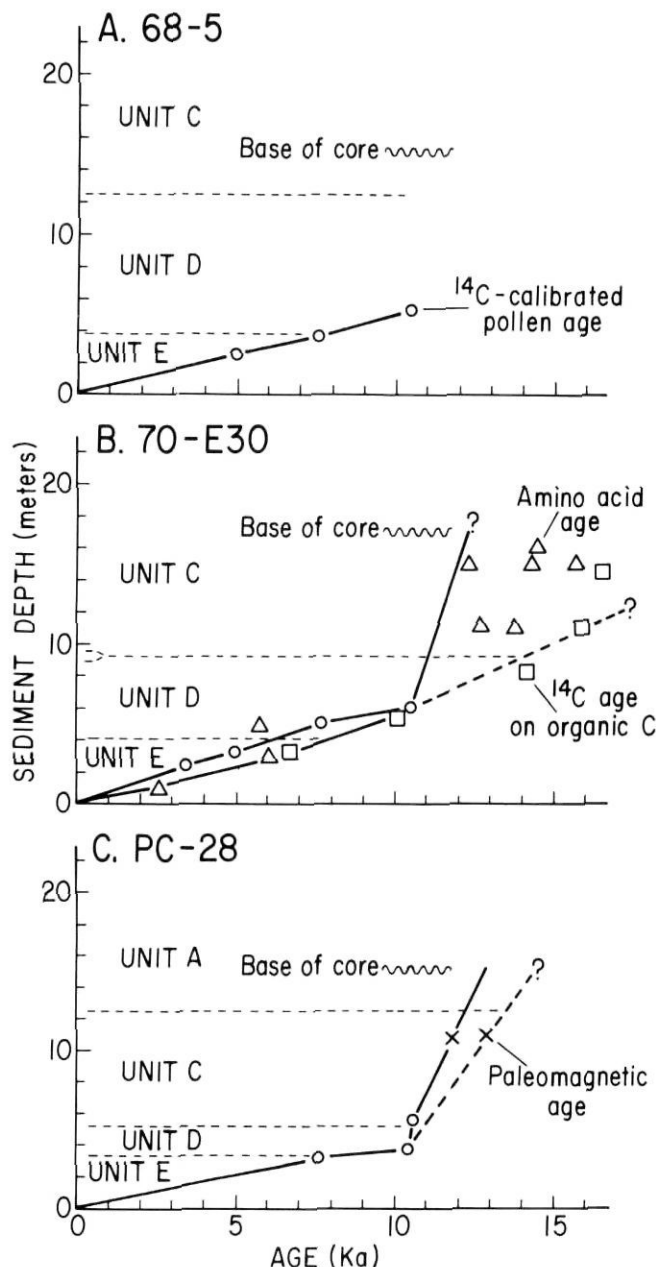


FIGURE 10. Age versus sediment depth plots for cores (A) 68-5, (B) 70-E30 and (C) PC-28. The age of nearby seismic unit boundaries can be inferred from their sediment depths and are also plotted for each core. Dashed lines give alternative permissible interpretations of the data but are not the preferred solution. The slope of the age-depth curve gives sedimentation rate.

Diagrammes profondeur/âge des carottes (A) 68-5, (B) 70-E30 et (C) PC-28. L'âge des limites des unités sismiques voisines peut être déduit de la profondeur des sédiments calculée pour chaque carotte. Les tiretés présentent des interprétations différentes des données, mais qui ne sont pas retenues. La pente de la courbe âge/profondeur donne le taux de sédimentation.



accumulated in a regime of reduced water supply and rising lake levels. The bulk of unit E contains deposits associated with the present drainage configuration of the Great Lakes.

The plots presented in Figure 10 indicate that sedimentation rates (slope of the age-depth curves) for the youngest postglacial units, D and E, have been fairly constant at 0.4-0.6 mm/yr whereas they were significantly higher (by as much as 10 times?) for proglacial unit C. The relatively low sedimentation rates for units D and E are comparable to rates measured within Holocene sediments in Lake Michigan (Colman *et al.*, 1990). The probable large increase in sedimentation rate during the existence of the proglacial lake is difficult to quantify in any of the Great Lakes because of limited age control, but is indirectly supported by a large decrease in pollen concentrations before about 10 ka, which is interpreted to result from a combination of cooler climates and higher sedimentation rates in proglacial times (Anderson and Lewis, 1989).

### BOTTOM AND SUBBOTTOM FEATURES

The seismic records portray a variety of morphologic and topographic features. These include zones of large subbottom relief (Fig. 3B), discontinuous reflections (Fig. 3C), reflection offsets (Fig. 3D), furrows (Figs. 3E, 3F), gas (Fig. 3G) and bedforms (Fig. 3H). Most of these features have not been described previously in the literature of Lake Ontario. Average thicknesses and measurements are computed assuming a constant velocity of sound in water and sediment of 1500 m/s.

### ZONE OF LARGE SUBBOTTOM RELIEF

This zone is characterized by rapid changes in bottom relief of up to 20 m (Canadian Hydrographic Service, 1970), and greater changes in subbottom relief of up to 30-40 m.

This zone is restricted to the eastern and deepest part of Lake Ontario in the Rochester basin (Fig. 12). The source of relief is the hummocky surface of unit A. This relief has been moderated by the ponding style of deposition of overlying units D and E. The bathymetric map (Canadian Hydrographic Service, 1970) shows the relief to consist of individual ridges that trend northeast-southwest with lengths, widths, and heights on the order of 500-1000 m, 100-200 m and 20-40 m respectively. These dimensions are typical of drumlins (Flint, 1971) and allows for a possible interpretation that these are buried drumlins. Some reflector offsets and discontinuities occur on some of the steeper slopes of this region (Fig. 3B). However, apparent discontinuities are typical artifacts of the seismic-reflection system when it is used over steep slopes and are not considered to be significant in this region.

### ZONE OF DISCONTINUOUS REFLECTIONS

Discontinuous reflections, commonly with V-shaped dips or depressions, occur in water depths greater than 100 m in the western basin (Fig. 12). These disruptions are closely spaced and are characterized by erratic signal strength and a rough surface in contrast to more uniform signal strength and smooth surfaces outside the zone of discontinuous reflections. Where units D and E are thick enough to be well resolved, only the basal reflections of unit E and older reflections appear discontinuous. Due to the acoustically opaque and chaotic nature of units A and B, it is impossible to determine if the discontinuities and depressions extend through the section. The region of discontinuous reflections that affects the three youngest units (C, D, and E) occupies an area  $30 \pm 25$  km, or about  $750 \text{ km}^2$ , in western Lake Ontario (Fig. 12).

Discontinuous reflections associated with v-shaped depressions have been identified elsewhere in Lake Ontario on echo sounder records from the Kingston Basin (Bowlby,

NAME	SEISMIC STRATIGRAPHY		LITHOSTRATIGRAPHY		ENVIRONMENT OF DEPOSITION	REGIONAL CORRELATION	INFERRED AGE
	Seismic Character	Contacts	Lithology	Contacts			
UNIT E	Weakly laminated, ponded in topographic lows, thin on topographic highs	Sediment-water interface, usually sharp and strong	Dark gray, silty clay, generally homogeneous but with occasional black laminae and shell fragments	Top of core, watery	Present productive lake environment; relatively high energy	Modern Lake Ontario	0
UNIT D	Moderately laminated, partially draped and ponded	Conformable, single smooth reflector slightly stronger than surrounding reflectors	Firm dark gray silty clay faintly laminated near the base, homogeneous near the surface	Uncertain	Lake environment transitional between quiet conditions and higher energy, more productive modern conditions	Early Holocene Lake Ontario	2
UNIT C	Well laminated with numerous parallel reflectors, well draped, uniformly thick	Conformable, two distinct, closely spaced reflectors, very consistently strong	Horizontally banded consisting of dark gray-brown and dark gray clay couplets about 1-1.5 cm thick	<1m long interval of sandy couplets within gray clay couplets	Quiet water, proglacial to early post glacial lake environment	Lake Iroquois to Early Lake Ontario	4
UNIT B	Semi-opaque, massive, some diffractions	Gradational and indistinct	Stiff dark gray clay with light gray silt-sand blebs and infrequent pebbles	Gradational	Floating ice margin with debris flows?	Port Huron ice retreat	6
UNIT A	Hummocky, mounded, large diffractions (eastern half of lake) Massive, very opaque, diffractions (western half of lake)	Discontinuous and fuzzy	Coarse to fine gravel of metamorphic, igneous and sedimentary lithologies in a sand-silt matrix.	Not sampled	Subglacial, grounded ice occupying entire basin	Port Huron ice or earlier advances	8
PALEOZOIC BEDROCK		Generally clear, and sharp except under areas of thick drift		Not sampled			10

FIGURE 11. Summary interpretations of seismic units giving seismic stratigraphy and lithostratigraphy together with inferred environment of deposition, regional correlation, and inferred age.

Résumé des interprétations des unités sismiques: stratigraphie sismique et lithostratigraphie, milieu de mise en place probable, correspondance régionale et âge présumé.



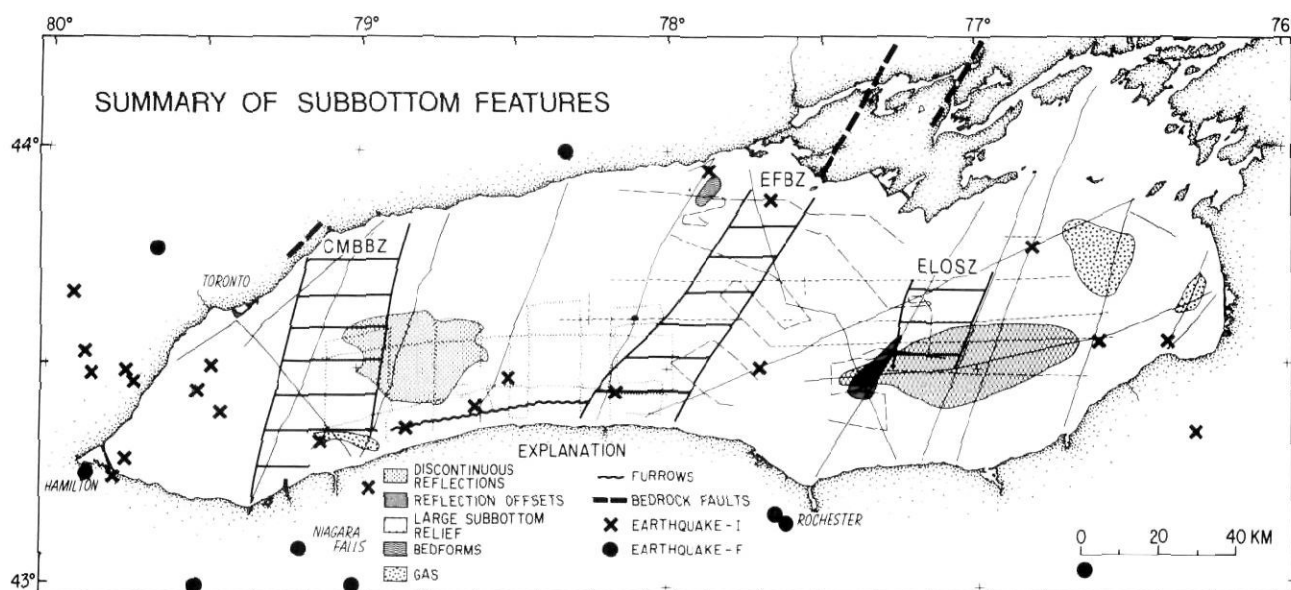


FIGURE 12. Summary map of subbottom features in Lake Ontario sediments plotted with earthquake epicenters, faults in Paleozoic bedrock, and shear zones mapped in Grenville basement rocks. Earthquakes are plotted according to locations by instruments (I) or felt reports (F). The location of the zones of discontinuous reflections and reflection offsets includes only those regions where units C, D, and E are together affected. Grenvillian shear zones are labeled: CMBBZ — Central Metasedimentary boundary zone, EFBZ — Elzevir-Frontenac boundary zone, and ELOSZ — Eastern Lake Ontario Shear Zone.

*Carte résumée des formes dans les sédiments sous le fond du lac Ontario données avec les épicentres, les failles dans la roche paléozoïque et les zones cisailées cartographiées dans le socle grenvillien. Les sites des séismes ont été déterminés par sismographe (I) ou fondées sur des rapports de perception (F). La localisation des zones de réflexions discontinues ou décalées ne comprennent que celles qui impliquent à la fois les unités C, D, et E. Les zones grenvilliennes cisailées sont CMBBZ (aire limite de la zone métasédimentaire centrale), EFBZ (aire limite Elzevir-Frontenac) et ELOSZ (zone cisailée de l'est du lac Ontario).*

1975) and offshore from the Niagara River (Sly and Prior, 1984). Bowlby (1975) suggested that these were ice wedge casts but Flood (1980) shows how small scale morphology can cause apparent incoherencies, discontinuities, and reflection offsets by an acoustic interference effect. Sly and Prior (1984) suggested that the minor discontinuities were caused by subaerial exposure during the low-water stand that followed glacial Lake Iroquois, but this does not explain discontinuities near the unit D/E contact, when water levels had risen substantially. Recently, similar features in Lake Michigan, that are associated with semicircular depressions on the lake floor, are attributed to dewatering effects, although the compaction mechanism remains unknown (Colman *et al.*, 1992). The core samples have not clarified the origin of these anomalous reflection patterns.

#### REFLECTION OFFSETS

In water depths greater than 100 m, terminations and offsets of reflections occur in any single unit or combination of units. Abrupt thinning and/or thickening of units are common on either side of the offsets (Fig. 3D). In the eastern basin of the lake, many large offsets can be associated with the imaging artifacts across steep slopes and are not considered anomalous or unusual. However, a morphological cause for the offsets is not always obvious (Fig. 3D) and locations of examples of these offsets are shown by asterisks in Figures 7 to 9. A large uncertainty exists in measuring offset across boundaries that represent unconformities (bedrock/unit A, units A/B, and possibly units B/C). The seismic profiles are

inadequate to determine whether offset on these unconformities represents a continuous penetrating structure, or whether the offset is caused by depositional or erosional relief along an unconformable surface. Two regions of reflection offset have been identified (Fig. 12): a 60-square kilometre region north northeast of Rochester (N.Y.) and a small region near the center of the lake. The clustering of offsets near Rochester suggests a localized source, but the 4-6 km profile spacing from this area is too wide to allow correlation between profiles. Possible explanations for the offsets are (1) lateral velocity variations, which could cause apparent offsets between buried reflections, but cannot explain offsets of up to 3 m at the sediment-water interface; (2) lake-bottom currents, which may reach several cm/s in water depths near 75 m (Csanady and Scott, 1974; Pickett, 1977), but which are more likely to create bedforms than discrete offsets; and (3) differential compaction and dewatering of the underlying deposits (e.g., Colman *et al.*, 1992). Areas of reflection offset at the lakefloor would be ideal targets for sidescan sonar imaging to more clearly determine their geometry and lateral extent.

#### FURROWS

Furrows are defined by acoustic diffractions which occur in the uppermost 2-3 m of reflections but do not affect the deeper section (Figs. 3E, 3F). They occur in water depths of 30-90 m along the south shore between Rochester and the Niagara River, where bottom slopes are 0.5-1°. Based on a 14-km long sidescan sonar profile (Fig. 3F), these features

are linear and roughly subparallel to the shoreline with lengths of at least 100-200 m and an average spacing of 50-100 m. The relief within furrows is on the order of 0.5 m. Possible explanations for these linear parallel features could be: 1) relict ice scour, 2) contour current deposits (Flood and Hollister, 1980; Flood, 1989), or 3) mass wasting. More data outlining the distribution and internal structure of these features would help to explain their origin.

#### GAS

Areas of acoustic scattering and limited penetration are located near the Niagara River outlet and in the northeast portion of the lake (Fig. 9). Most of the gas appears to originate from within unit E (Fig. 9), although a small region in eastern Lake Ontario originates from within unit D (Fig. 8). Gas is interpreted on the basis of the acoustic similarity of the Lake Ontario profiles to other records of documented interstitial gas occurrence in unconsolidated sediments (Schubel and Scheimer, 1973; Josenhans *et al.* 1978; Hovland and Judd, 1988). The gas is probably biogenic and indicates high concentrations of organic material in the lake sediments.

#### BEDFORMS

One area of rhythmic bedforms (Hutchinson, 1977) occurs in a 25-square kilometre region along the north shore (Fig. 12). These bedforms occur in water depths of 30-50 m. Profiles suggest that they trend northwesterly, and are asymmetric in section with the steeper side facing northeast. Amplitudes range from 2 to 3 m and apparent wavelengths are 30 to 105 m. Their occurrence in a region mapped as sand by Thomas *et al.* (1972a, b) suggests these features are sand waves or megaripples, but it is unclear whether present processes, or relict processes during an episode of former lower lake level, have formed these bedforms. Data coverage in shallow water is too sparse to identify bedforms in other parts of the lake.

### RELATIONSHIP TO SEISMICITY AND BASEMENT STRUCTURE

The distributions of subbottom features of Lake Ontario is compared with regional seismicity and basement structural trends in Figure 12. The distribution of instrumentally recorded and historic (*i.e.*, felt) earthquakes for a 60-year period within or bordering Lake Ontario shows that epicentres occur throughout the lake, although they are somewhat more abundant in the westernmost portion (Fig. 12). Within a region including the present lake and about 30 km beyond its shoreline, 23 instrumentally determined epicentres from 1974-1989 are known (Lamont-Doherty Geological Observatory, 1979; Northeast U.S. Seismic Network, 1992) and 9 historic earthquakes for the period 1928-1959 have been felt (Smith, 1966). These events are generally weak (less than magnitude 3), poorly located, and mostly unconstrained for depth of rupture.

None of the mapped zones of bottom and subbottom features can be spatially correlated with the earthquake locations. This result is not unexpected, because many of the subbottom features are probably caused by sedimentologic rather than tectonic processes (for example, bedforms or

gas). This lack of correlation suggests that the zones of discontinuous reflections and reflection offsets are not related to seismicity. However, the period of earthquake surveillance is relatively short, and the possibility remains that the zones of discontinuous or offset reflections could be caused by earthquakes predating the monitoring. Clearly, additional information is required to better understand whether some of these features are of neotectonic significance.

The distribution of pre-Quaternary structural trends also shows little correlation with the mapped subbottom features. The trends of faulted Paleozoic rocks are shown in the vicinity of Prince Edward County (Kay, 1937; Liberty, 1961, 1963; McFall and Allam, 1991) and east of Toronto (Mohajer *et al.*, 1992). Not shown due to space limitations is the north-northeast-trending Clarendon-Linden fault in New York State near 78°W (Rickard, 1973), which may extend across Lake Ontario along the Scotch Bonnet sill (Hutchinson *et al.*, 1979). These faults have probably controlled the locations of buried valleys in the bedrock surface (Fig. 2). Despite the lack of correlation between these bedrock structures and subbottom features, the Scotch Bonnet sill is an inherited Paleozoic structure that controls the distribution of Quaternary deposits into the Rochester and Mississauga basins.

Two additional basement lineaments within Paleozoic bedrock have been postulated within the lake: the southern extension of the Georgian Bay linear zone and the Hamilton-Presqu'île lineament (Wallach and Mohajer, 1990; McFall and Allam, 1991; Ontario Geological Survey, 1992). These postulates are not illustrated because they are not supported by recent deep seismic reflection data or the first-order trends of magnetic or gravity anomalies (Forsyth *et al.*, in press a, in press b).

Within Grenville basement, three crustal-penetrating east-dipping basement shear zones have been identified beneath Lake Ontario from deep seismic reflection, gravity and magnetic data (Fig. 12): the Central Metasedimentary Belt boundary zone (CMBBZ on Fig. 12), which trends northeast-southwest beneath western Lake Ontario (Forsyth *et al.*, in press b), the Elzevir-Frontenac boundary zone (EFBZ in Fig. 12), which trends northeast across central Lake Ontario (Forsyth *et al.*, in press a), and the eastern Lake Ontario shear zone (ELOSZ in Fig. 12), which is of limited north-south extent beneath eastern Lake Ontario (Forsyth *et al.*, in press a). Each of these basement structures has a north to northeast trend, which is not repeated in the orientations of the subbottom features in Figure 12. A possible exception is the zone of reflection offsets near Rochester which trends north northeast, is near the eastern Lake Ontario shear zone, and is on strike between the Point Petre sill (Fig. 1) and the Genesee valley (Fig. 2). This is a region where additional studies are warranted. An interesting and outstanding question, which is beyond the scope of this paper, is what association exists between earthquakes and pre-Quaternary structures preserved in either Paleozoic bedrock or Grenvillian basement rocks.

### SUMMARY AND CONCLUSIONS

(1) The configuration of the bedrock surface beneath Lake Ontario (74 m asl) is presented for the first time. The Scotch

Bonnet sill, trending SW from Prince Edward County, Ontario, with a crestal elevation of 80-100 m bsl, separates a deeper eastern depression (> 200 m bsl), elongated in a west-southwest direction, from a shallower western depression (> 140 m bsl), oriented in an east-west direction. Bedrock valleys are evident off Hamilton, Toronto, Rochester, Prince Edward County, and the entrance to Kingston Basin and St. Lawrence River.

(2) The offshore seismic stratigraphy of Late Quaternary sediments in Lake Ontario has been correlated with lithology and limited age information. Five units above Paleozoic sedimentary bedrock have been identified: (A) a basal unit with internal high-amplitude diffractions (< 25 m thick) that is probably a subglacial till deposited by ice during or before the Port Huron advance (> 13 ka); (B) a massive unit with fewer diffractions and more uniform thickness (< 10 m), limited to the western half of the basin, that is probably a deformation or flow till deposited during the retreat of Port Huron ice at 13-12 ka; (C) a unit of coherent, continuous, subparallel reflections, uniformly about 10 m thick that is deposited in glacial to glaciolacustrine and then periglacial environments between 12-13 ka and 10.5-11 ka; (D) a unit of moderately strong, coherent, subparallel reflections (generally < 10 m thick) which partly drapes over and partly ponds in the underlying topography and which is inferred to be deposited in a regime of reduced water supply and rising water levels between 10.5-11 ka and 6-8 ka; and (E) an uppermost unit of weak subparallel reflections (generally < 6 m thick) which thins on highs and ponds in topographic lows and which has been accumulating since 6-8 ka. The few age estimates were obtained by radiocarbon-calibrated pollen zonation and paleomagnetic secular variation.

(3) Many bottom and subbottom features exist, including zones of large subbottom relief, discontinuous reflections, reflection offsets, furrows, bedforms, and gas. Many of these features are probably caused by sedimentologic processes but some, such as the zone of discontinuous reflections and reflection offsets, have no well constrained, unequivocal explanation.

(4) The locations of earthquake epicentres within and surrounding the lake are not spatially correlated with the bottom and subbottom features, making identification of neotectonic hazards uncertain. The earthquake record is relatively short, and the possibility exists that the zones of discontinuous reflections and reflection offsets could be related to earthquakes that predate the monitoring, but this possibility is difficult to prove or disprove.

(5) The Scotch Bonnet sill is an inherited Paleozoic structure that has controlled the gross distribution of Quaternary deposits into the Rochester and Mississauga basins. Several buried channels or valleys are probably offshore extensions of Paleozoic faults or folds. Neither the trend of the Scotch Bonnet sill nor that of other Paleozoic faults or Precambrian Grenvillian basement structures appears to be significant in the formation of the mapped subbottom features within the lake. However, the data presented here are limited in horizontal spatial resolution because of wide track-line spacing.

(6) Additional studies in the lake are needed to resolve the geometry, age, and dynamic nature of the anomalous bottom and subbottom features, to refine the seismic/lithologic stratigraphy and its chronology, to better understand and distinguish sedimentary dynamic effects from neotectonic effects, and to define the relationship between lineaments and anomalies in the Precambrian basement rocks and features in the overlying Paleozoic and Quaternary sedimentary cover.

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