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Recent Deformation in the Bottom Sediments of Western and Southeastern Lake Ontario and its Association with Major Structures and Seismicity

Déformations récentes dans les sédiments de fond de l'ouest et du sud-est du lac Ontario et leurs liens avec les principales structures et la sismicité

Neuere Verformungen in den Grundsedimenten des westlichen und südwestlichen Ontariosees und ihre Zusammenhänge mit den Haup-strukturen und der Seismik

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La néotectonique de la région des Grands Lacs
Neotectonics of the Great Lakes area

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Résumé de l'article

Des levés géophysiques effectués dans le corridor Toronto-Burlington, dans l'ouest du lac Ontario, a révélé la présence d'éléments qui altèrent les jeunes sédiments lacustres du fond. Dans la partie ouest du lac, dans la roche en place, il s'agit de structures de soulèvement (pop-ups) et, dans les boues récentes, de structures plumeuses, de réseaux de traits sombres et de zones linéaires de tracés circulaires à elliptiques. Dans la partie sud-est du lac Ontario, il y a dans les sédiments glaciaires et postglaciaires des rejets verticaux de l'ordre de 10 à 15 m. Les structures de soulèvement sont d'origine tectonique. Les formes dans les boues récentes, généralement parallèles à l'orientation des contraintes de compression mesurées dans les roches paléozoïques voisines, sont spatialement reliés, comme les structures de soulèvement, à un linéament aéromagnétique. De plus, toutes ces formes se trouvent dans une zone sismique active. Les rejets verticaux dans les sédiments glaciaires et postglaciaires stratifiés, à l'intérieur du basssin de Rochester, sont localisés le long de la bordure sud du prolongement présumé WSW du système actif du rift du Saint-Laurent et sont probablement attribuables à la formation de failles. La jeunesse des sédiments altérés par les déformations et les caractéristiques des déformations mêmes laissent croire que ces sédiments ont probablement enregistré les effets de processus néotectoniques.

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RECENT DEFORMATION IN THE BOTTOM SEDIMENTS OF WESTERN AND SOUTHEASTERN LAKE ONTARIO AND ITS ASSOCIATION WITH MAJOR STRUCTURES AND SEISMICITY

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ABSTRACT Geophysical surveys, undertaken in the Toronto-Burlington corridor of western Lake Ontario and in the Rochester Basin of southeastern Lake Ontario, revealed the presence of features affecting the young lake-bottom sediments. In the western part of the lake, they include inferred pop-ups in bedrock, and plumose structures, dark linear patterns, and linear belts of circular to elliptical signatures in the modern mud. In southeastern Lake Ontario the glacial and post-glacial sediments display vertical separations of on the order of 10-15 m. Pop-ups are tectonically-induced structures. The features in the modern mud commonly parallel the orientation of P-stresses measured in Paleozoic rocks nearby and, along with the pop-ups, are spatially related to an aeromagnetic lineament. Furthermore, all of these features occur within a seismically active belt. The vertical displacements of the layered glacial and post-glacial sediments, within the Rochester Basin, are located along the southern margin of the postulated WSW extension of the seismically active St. Lawrence rift system and are interpreted to be due to faulting. The geologically young age of the sediments affected by the various deformational features, along with the characteristics of the features themselves, suggest that the lake-bottom sediments surveyed in this study may have recorded the effects of neotectonic processes.

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RÉSUMÉ *Déformations récentes dans les sédiments de fond de l'ouest et du sud-est du lac Ontario et leurs liens avec les principales structures et la sismicité.* Des levés géophysiques effectués dans le corridor Toronto-Burlington, dans l'ouest du lac Ontario, a révélé la présence d'éléments qui altèrent les jeunes sédiments lacustres du fond. Dans la partie ouest du lac, dans la roche en place, il s'agit de structures de soulèvement (*pop-ups*) et, dans les boues récentes, de structures plumeuses, de réseaux de traits sombres et de zones linéaires de tracés circulaires à elliptiques. Dans la partie sud-est du lac Ontario, il y a dans les sédiments glaciaires et postglaciaires des rejets verticaux de l'ordre de 10 à 15 m. Les structures de soulèvement sont d'origine tectonique. Les formes dans les boues récentes, généralement parallèles à l'orientation des contraintes de compression mesurées dans les roches paléozoïques voisines, sont spatialement reliés, comme les structures de soulèvement, à un linéament aéromagnétique. De plus, toutes ces formes se trouvent dans une zone sismique active. Les rejets verticaux dans les sédiments glaciaires et postglaciaires stratifiés, à l'intérieur du basssin de Rochester, sont localisés le long de la bordure sud du prolongement présumé WSW du système actif du rift du Saint-Laurent et sont probablement attribuables à la formation de failles. La jeunesse des sédiments altérés par les déformations et les caractéristiques des déformations mêmes laissent croire que ces sédiments ont probablement enregistré les effets de processus néotectoniques.

ZUSAMMENFASSUNG *Neuere Verformungen in den Grundsedimenten des westlichen und südwestlichen Ontariosees und ihre Zusammenhänge mit den Haupstrukturen und der Seismik.* Geophysikalische Vermessungen, die im Toronto Burlington-Korridor des westlichen Ontariosees und im Rochester-Becken des südöstlichen Ontariosees durchgeführt wurden, deckten die Anwesenheit von Elementen auf, welche auf die jungen Seegrundsedimente einwirken. Im westlichen Teil des Sees bestehen sie aus Hebungen im anstehenden Gestein und im modernen Schlamm aus federartigen Strukturen, dunklen linearen Mustern und linearen Gürteln mit kreisförmigen bis ellipsenförmigen Umrissen. Im südöstlichen Ontariosee gibt es in den glazialen und postglazialen Sedimenten vertikale Verwürfe der Größenordnung von 10-15 m. Die Hebungen sind tektonischen Ursprungs. Die Formen im modernen Schlamm liegen im allgemeinen paralell zu der Orientierung der in den benachbarten paläozoischen Felsen gemessenen P-Stresse und sind zusammen mit den Hebungen räumlich mit einem aeromagnetischen Lineament verbunden. Außerdem treten alle diese Formen innerhalb eines seismisch aktiven Gürtels auf. Die vertikalen Verstellungen der geschichteten glazialen und postglazialen Sedimente innerhalb des Rochester-Beckens werden entlang des südlichen Rands der angenommenen WSW-Verlängerung des seismisch aktiven Sankt-Lorenz-Spaltensystems lokalisiert. Das geologisch relativ junge Alter der durch die verschiedenen Verformungen läßt vermuten, daß die in dieser Studie gemessenen Seegrundsedimente möglicherweise die Wirkungen neotektonischer Prozesse aufgezeichnet haben.

INTRODUCTION

Southern Ontario generally has been considered to be a tectonically stable region, possibly due to the lack of documented moderate to large earthquakes (M ≥ 5) and the earlier perception that there were very few, if any, major faults located there. For example, a map of the Paleozoic bedrock in the area of Niagara Falls-St. Catharines-Welland, bounded by latitudes 43°00′ and 43°15′, and longitudes 79°00 and 79°30′, shows no faults at all (Ontario Division of Mines, 1976). Similarly, no faults are displayed in the area along the north shore of Lake Ontario, referred to as the Trenton-Consecon area and bounded by latitudes 43°49′ and 44°15′, and longitudes 77°30′ and 78°00′ (Carson, 1980). According to Freeman (1978), there are only three faults in the Paleozoic rocks underlying the vast area bounded by Lakes Erie and Ontario, Georgian Bay, and the exposed Canadian Shield. All three occur to the north and east of Prince Edward County (Fig. 1) and are continuations of faults from the Canadian Shield, but none was shown to reach Lake Ontario.

Although deformation in southern Ontario was not generally well known, some examples were, nonetheless, reported in, and around, Prince Edward County. For example, Kay (1942) referred to a series of northeast-trending monoclines that deform the Ordovician rocks of what he called the Lake Ontario homocline. Liberty (1960) described one fault in Prince Edward County, which is about 35 km long, and another (Liberty, 1963) along the Salmon River, just north of Prince Edward County, which is at least 14 km long. Both are normal faults in which the west side has been downthrown about 30 m relative to the east side and, from the locations, they may be the same structures interpreted as monoclines by Kay. Hutchinson *et al.* (1979) described the Scotch Bonnet sill, which crosses central Lake Ontario from New York State to Ontario (Thomas *et al.*, 1972), as a topographic extension of the Clarendon-Linden fault, a major, seismically active structure in western New York State (Fakundiny et *al.*, 1978).

There are now, however, several indications that southern Ontario has been, and currently is, subjected to instability of one form or another. First of all faults, cutting upper Middle Ordovician rocks, have been recognized from subsurface data collected west of Lake Ontario, as well as north and east of Toronto and north of Prince Edward County (Ontario Geological Survey, 1984 a, b and c). Other faults, in excess of 100 km in length, are traceable in the subsurface adjacent to, and beneath, Lake Ontario (Ontario Geological Survey, 1991). McFall (1990) reported on outcrop-scale, strike-slip faulting which affects, and therefore postdates the emplacement of, a Jurassic-age dike near Picton, Ontario. Mohajer *et al.* (1992) described east-west to west-northwest trending normal faults, which displace the contact between the bedrock and the overlying Quaternary sediments, in eastern Metropolitan Toronto. The origin and exact age of this faulting are not known but, from the stratigraphy of the unconsolidated sediments, the age is bracketed between 70,000 and 13,000 years BP. Besides faults, broad, open, 045°-oriented anticlines were observed by two of us (JLW and AAM) in Silurian-age rocks on the Niagara escarpment, west of Lake

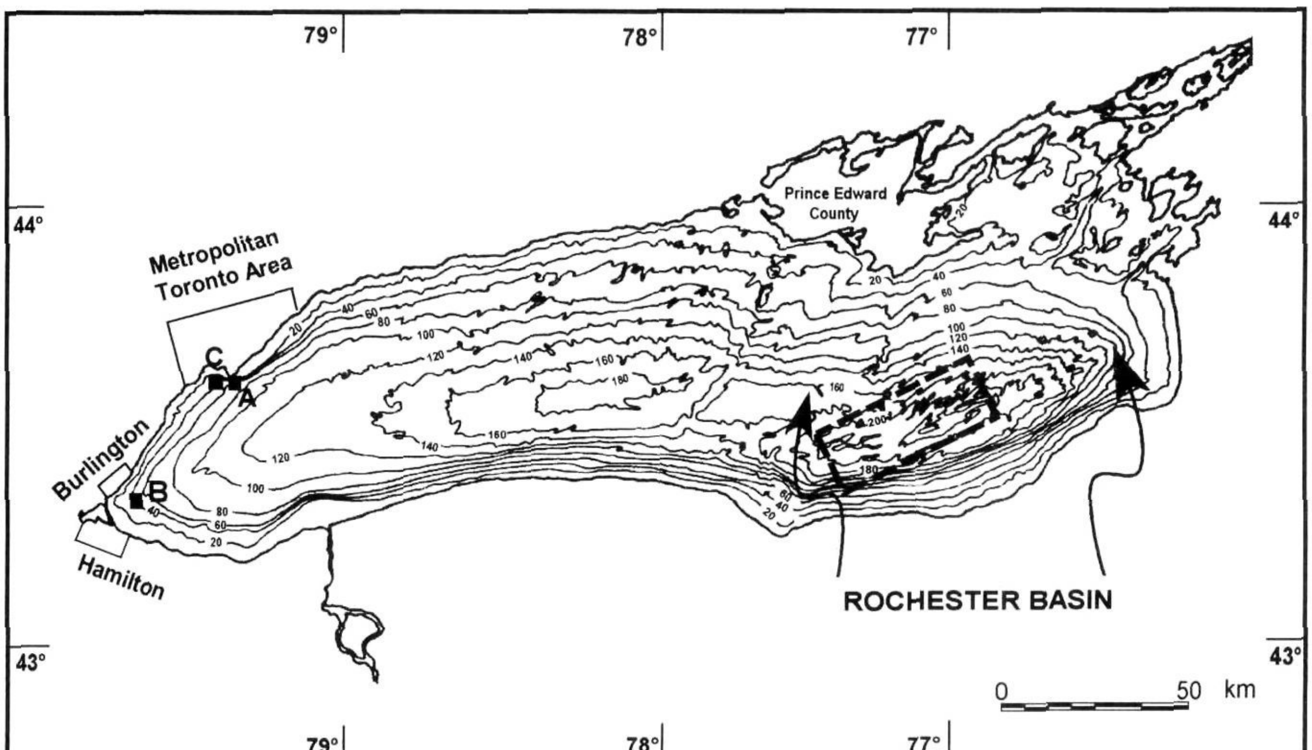

FIGURE 1. Lake Ontario showing study areas. A, B, and C denote, respectively, the areas south of Toronto Island, Bronte, and the Humber River in the western part of the lake. The dashed-line, rectangular box outlines the study area in the southeastern part.

Le lac Ontario et les sites à l'étude. A, B et C désignent respectivement les régions au sud de l'île de Toronto et des rivières Bronte et Humber, à l'ouest du lac. Le rectangle en tireté identifie la région à l'étude dans la partie sud-est.

Ontario. There the folds exhibit a parallel geometry which, in combination with their orientation, suggests that they resulted from crustal compression, presumably during the Lower to Middle Paleozoic. Detailed stratigraphic studies, supplemented by remote-sensing, led Sanford *et al.* (1985) to interpret that all of southwestern Ontario, and adjacent areas, have been affected by recurrent tectonic activity throughout the entire Phanerozoic. Martini and Bowlby (1991), in assessing multi-faceted, pre-existing information, concluded that there has been periodic tectonism from the Precambrian to the present in the Lake Ontario Basin.

The most recent manifestations of tectonism are expressed as small to moderate earthquakes (Drysdale *et al.*, 1987; 1989) and minor surficial bedrock structures, such as pop-ups (White *et al.*, 1973; White and Russell, 1982) and offset boreholes (Wallach, 1990). There is no documented evidence of any earthquakes of $M \geqslant 5$ in southern Ontario, although there were two such events in adjacent western New York State, the 1857, $M \approx 5$ Lockport and the 1929, $m_b = 5.2$ Attica earthquakes. Adams and Basham (1989; 1991), and Basham and Adams (1989), in following up on an idea initially proposed by Kumarapeli and Saull (1966), postulated that the seismically active St. Lawrence rift system extends upstream along the St. Lawrence River, through the lower Great Lakes (Ontario and Erie), towards New Madrid, Missouri. Because of the occurrence of seismic events of $M \approx 7$ along this structure, the implication of their suggestion is that southern Ontario could conceivably be the site of a future, similar-sized earthquake. This paper presents evidence of deformation in the glacial and post-glacial sediments that underlie portions of both western and southeastern Lake Ontario. In the western portion of the lake, structures were found between Toronto and Burlington, whereas the southeastern structures were recognized in the Rochester Basin, the deepest part of the lake (Fig. 1).

OBSERVATIONS

WESTERN LAKE ONTARIO

In 1987, through the use of side-scan sonar, features were discovered in sediments covering a 2.5 × 1.5 km area on the bottom of Lake Ontario, south of Toronto Island (Fig. 1, site A). The lake bottom in the area is fairly smooth and consists principally of a thin sequence of glaciolacustrine clay which overlies the bedrock and is, itself, covered by a thin lag sand deposit (*e.g.* Lewis and Sly, 1971). The bottom generally gives little acoustic return on the side-scan system, except for rather narrow, linear areas where strong acoustic shadowing indicates material raised above the lake bed (Fig. 2). Of the lithostratigraphic units present, only bedrock would normally be expected to produce such a response. The strong returns commonly appear as elongate, scar-like features, up to about 7 m wide and 1.5 km long, which project as much as 1.5 to 2 m above the lake bottom surface. They are marked by various intersections and apparent displacements, and there are suggestions of an en-echelon arrangement, as seen on the left side of Figure 2. Their overall distribution suggests that they are randomly oriented, however when both length and orientation are plotted on a rose diagram, these features display a predominant west-northwest trend (Fig. 3). Their configuration connotes beds dipping away from sharply defined hinges characterized by what appear to be extension fractures. The pattern that they portray resembles that of pop-ups which are common in the Paleozoic rocks that crop out in a belt of varying width that extends along the St. Lawrence River and the lower Great Lakes (*e.g.* Saull and Williams, 1974; Williams *et al.*, 1985; Wallach *et al.*, 1993). Though the features responsible for the strong linear acoustic returns have not been "ground-truthed", all of the foregoing suggest that they signify upheavals of bedrock, or pop-ups, that have pierced through the overlying glaciolacustrine clay.

In 1988 and 1989 side-scan sonar was used in the areas south of Bronte and beneath Humber Bay (Fig. 1, sites B and C respectively) where two types of features were detected in the recent deposits of silty clay. The first type, named plumose structures by Thomas *et al.* (1989), displays a feather-like character (Figs. 4-6) which arises from a series of delicate ridges and depressions in the sediments, with relief presumably not exceeding 10-15 cm. The second is expressed principally as a continuous straight line of dark tone caused by a change in the reflectivity of the bed material (Fig. 5a). However, it may also be manifested as darkly-toned, circular to elliptical signatures which occur either as isolated markings, or in a suite that defines a discontinuous, linear array (Figs. 5a and 6).

Plumose structures, one of which is about 2 km long (Fig. 6a), are the result of some natural phenomenon, to be discussed further on in this paper. Fader (1991), however, pointed out that plumose structures are similar in appearance to marks caused by anchor chains moving on the seafloor, in response to tidal shifts and wind-induced wave action. Fader's point is valid because, as the water swells, a stationary ship will oscillate causing the anchor chain to be lifted and returned to the lake floor repeatedly, thereby producing the

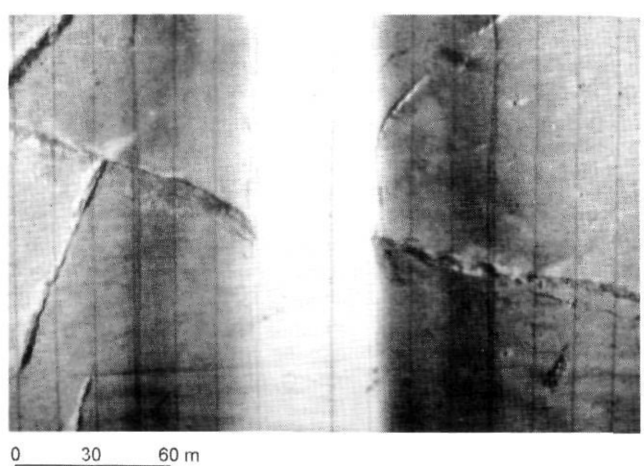

FIGURE 2. Side scan record illustrating high-intensity, linear acoustic returns at site A (see Fig. 1). These features are interpreted as pop-ups. The horizontal and vertical scales are equal.

Balayage latéral montrant les levés acoustiques linéaires de haute intensité au site A (fig. 1). Ces formes sont considérées comme étant des structures de soulèvement. Les échelles verticales et horizontales sont les mêmes.

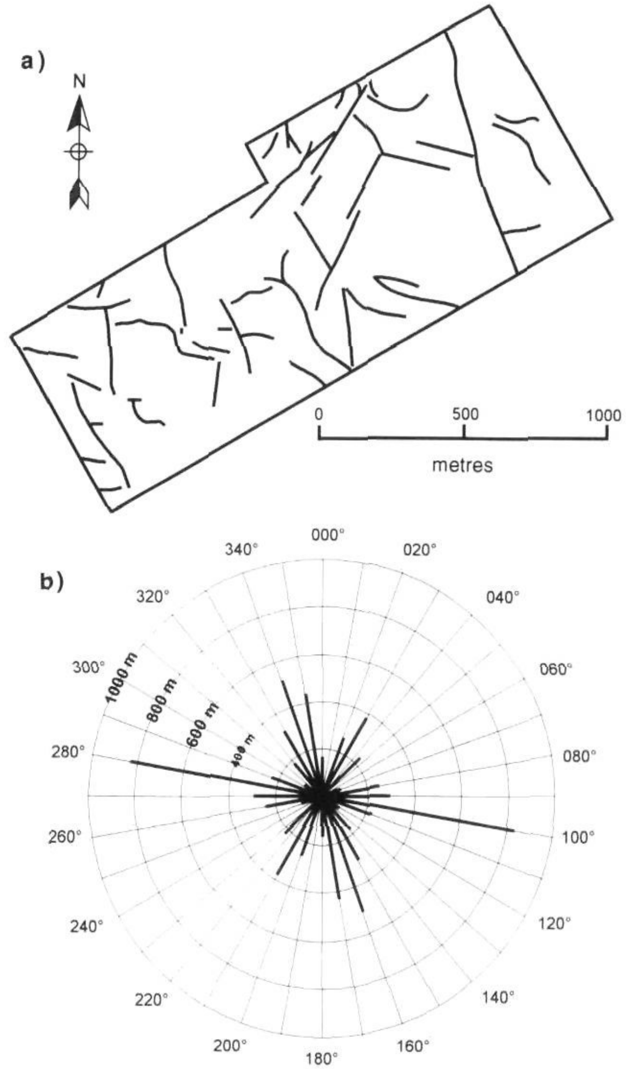

FIGURE 3. (a) Map of pop-ups at Site A (see Fig. 1), traced from side-scan sonar records, and (b) a rose diagram showing the distribution of the pop-ups by length and orientation. The length interval represented by each concentric circle is 200 m.

a) Cartographie des structures de soulèvement au site A (fig. 1), faite à partir des données de balayage latéral. b) Diagramme circulaire montrant la répartition des structures de soulèvement selon leur longueur et leur orientation. L'intervalle entre chacun des cercles concentriques est de 200 m.

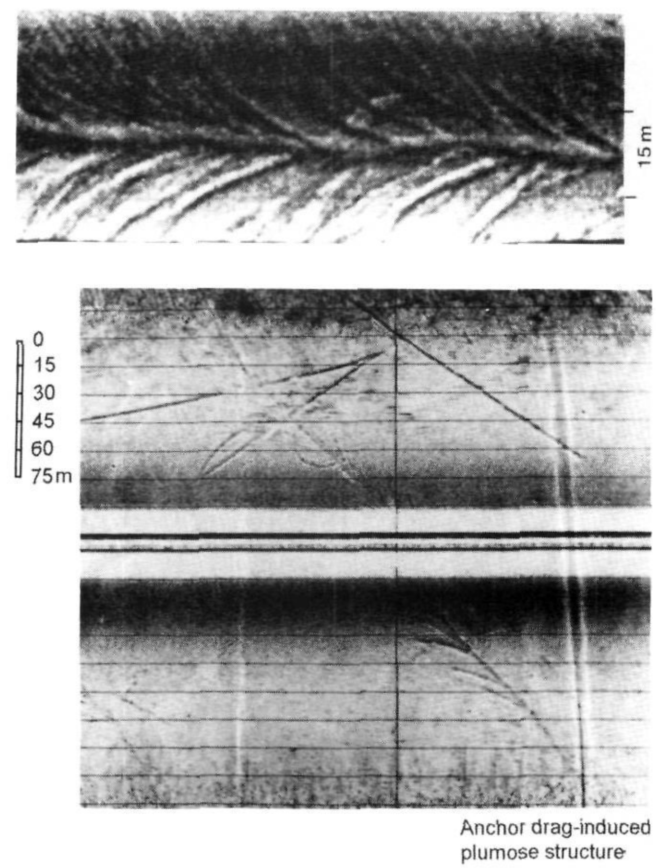

FIGURE 4. Side scan records showing: (a) a naturally-produced plumose structure at site B (see Fig. 1) and (b) an anchor-induced plumose structure in the area of Humber Bay at site C (see Fig. 1). Note in (a) that the radial arms extend along the length of the central linear "trunk". In (b) the feature resembling a plumose structure is uni-lateral. The horizontal and vertical scales are equal.

Enregistrement de balayage latéral montrant: (a) une structure plumeuse naturelle au site B (fig. 1) et (b) une structure plumeuse produite par une ancre dans la région de Humber Bay, au site C (fig. 1). Noter en (a) que les barbes latérales s'étirent le long d'un axe central. En (b) la forme qui rappelle une structure plumeuse n'a qu'un côté. Les échelles verticales et horizontales sont les mêmes.

plumose-like markings. Nonetheless, despite the apparent similarities, there are distinguishing characteristics. The naturally formed plumose structures, recognized to date in Lake Ontario, show bi-lateral symmetry and a relatively uniform distribution of arms radiating outwards along the entire length of the central trunk (Fig. 4a). The anchor marks which resemble plumose structures, on the other hand, may display either uni-lateral (Fig. 4b) or bi-lateral symmetry. In the latter case, however, the radiating arms are not distributed along the entire length of the trunk, but tend to focus toward one end where the chain has lifted off, and been returned to, the bottom. As with the plumose structures, the darkly-toned features are interpreted as having formed in response to some natural process, though Fader (personal communication) cautioned that they may be similar to dredge spoils seen in Halifax Harbor. However, the difference between the naturally-occurring darkly-toned features and the dredge spoils observed thus far in Lake Ontario is readily apparent (Compare Figs. 5a and 5b). The naturally formed features south of Bronte show a wider range of orientations than their counterparts beneath Humber Bay, however at both locations ENE trends prevail. For example, 21 of the 39 structures identified near Bronte are oriented between 064° and 094°, whereas in Humber Bay 11 of the 14 range from 061° to 097° (Table I, Fig. 6).

Prior to the discovery and naming of the plumose structures by Thomas *et al.* (1989), there had been no similar sightings reported in the literature. However, Pecore and Fader (1990) described feather-like structures, which they also referred to as plumose structures, in the sediments from beneath Passamaquoddy Bay. They noted that the plumose structures are proximal to pockmarks, ascribed to the venting of gas from beneath the sea, and are located near the

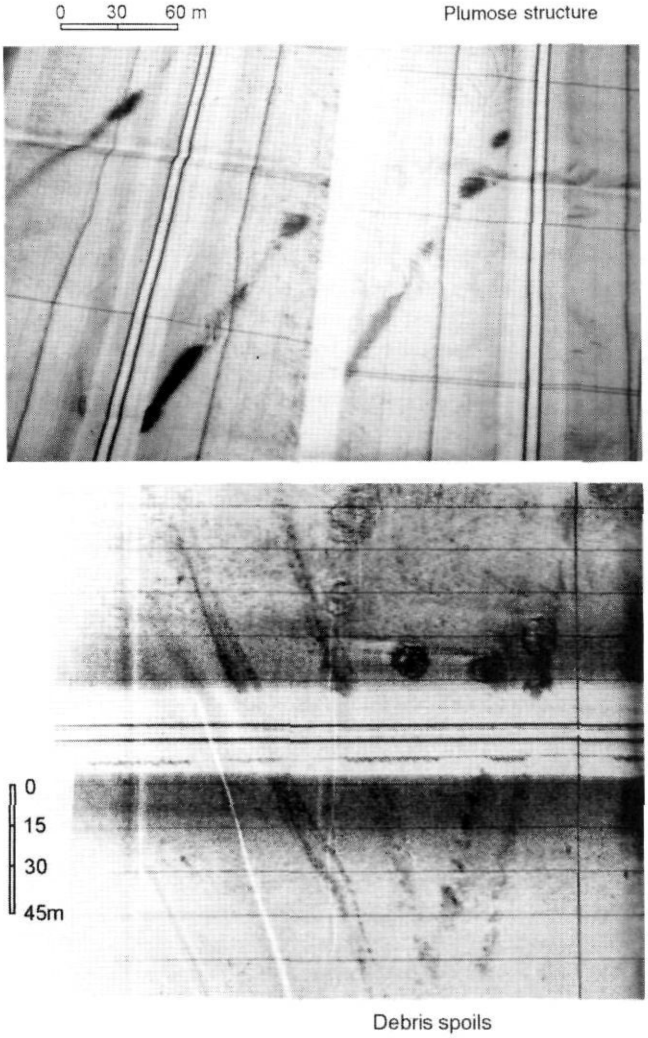

FIGURE 5. Side scan records showing: (a) an area of dark return, linearly aligned elliptical features and plumose structures at site B (see Fig. 1), and (b) dredge spoils. The horizontal and vertical scales are equal.

Enregistrement de balayage latéral montrant: (a) une zone sombre, des formes elliptiques linéaires et des structures plumeuses au site B (fig. 1) ainsi que des déblais de dragage. Les échelles verticales et horizontales sont les mêmes.

seaward extension of faults mapped on land. Moreover, Pecore and Fader (1990) stated that plumose structures are interpreted to be the result of recent activity on faults, and Fader (1991) added that plumose structures overlie the Oak Bay fault, which he described as active.

SOUTHEASTERN LAKE ONTARIO

Echosounding traverses were carried out in the Rochester Basin of southeastern Lake Ontario (Thomas *et al.*, 1972) in both 1988 and 1989 using an Atlas navigational sounder operating at 32 kHz (Fig. 7). The resulting echograms (Fig. 8) display a number of places where the horizontal to subhorizontal reflectors, which occur in glaciolacustrine clays and modern muds, are displaced along steeply-dipping gradients in an area about 45 km long and 15 km wide (Fig. 7). The dashed lines (Fig. 8, lines a-g), which pass from one echo-

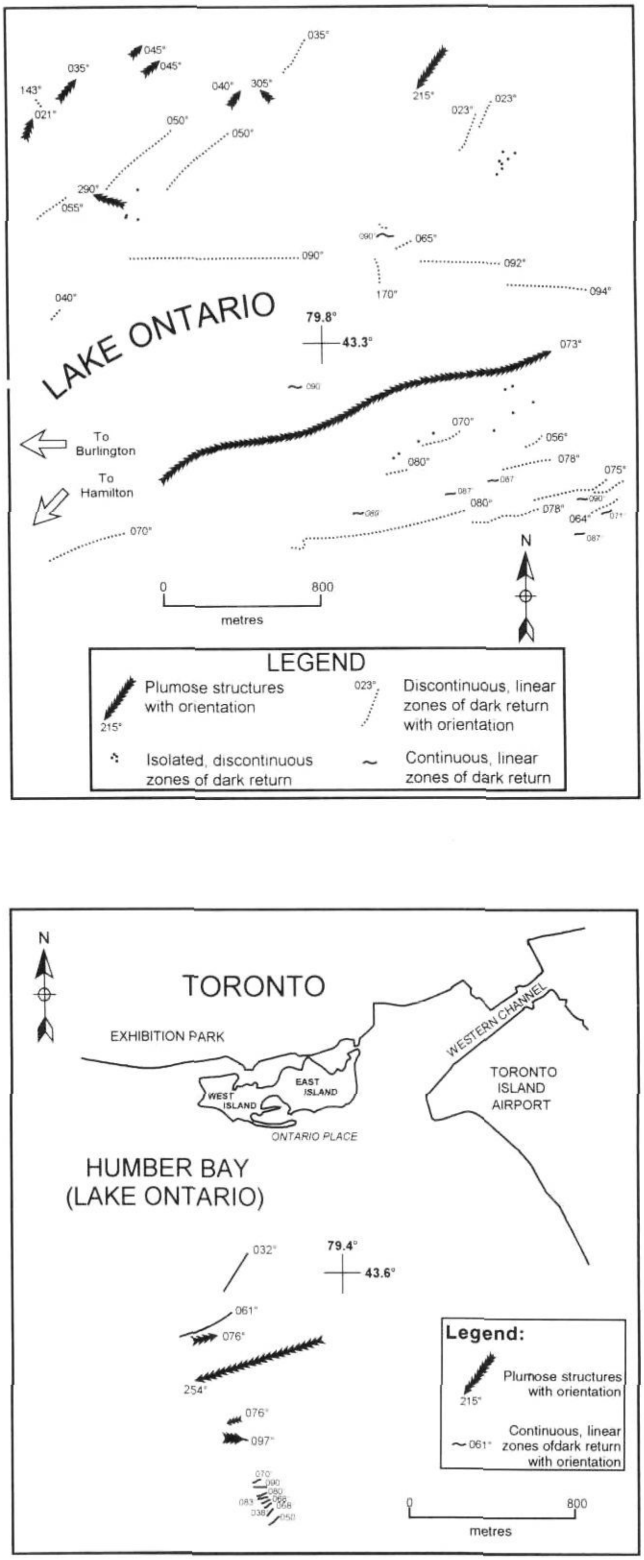

FIGURE 6. (a) Map of the Bronte area (Fig. 1, site B) and (b) map of the Humber Bay area (Fig. 1, site C) showing the distribution of plumose structures and dark linear features.

(a) Carte de la région de Bronte (fig. 1, site B) et (b) carte de la région de Humber Bay (fig. 1, site C) montrant la répartition des structures plumeuses et des tracés linéaires sombres.

TABLE I

Orientations of plumose structures and linear features beneath Bronte and Humber Bay

	Bronte				
	000°-019°	020°-039°	040°-059°	060°-079°	080°-099°
Plumose structures	0	3	3	1	0
Linear signatures (C)	0	0	0	1	7
Linear signatures (D)	0	3	5	7	5
Total	**0**	**6**	**8**	**9**	**12**
	100°-119°	120°-139°	140°-159°	160°-179°	
Plumose structures	1	1	0	0	
Linear signatures (C)	0	0	0	0	
Linear signatures (D)	0	0	1	1	
Total	**1**	**1**	**1**	**1**	
	Humber Bay				
	000°-019°	020°-039°	040°-059°	060°-079°	080°-099°
Plumose structures	0	0	0	3	1
Linear signatures (C)	0	2	1	4	3
Total	**0**	**2**	**1**	**7**	**4**

(C)-continuous; (D)-discontinuous

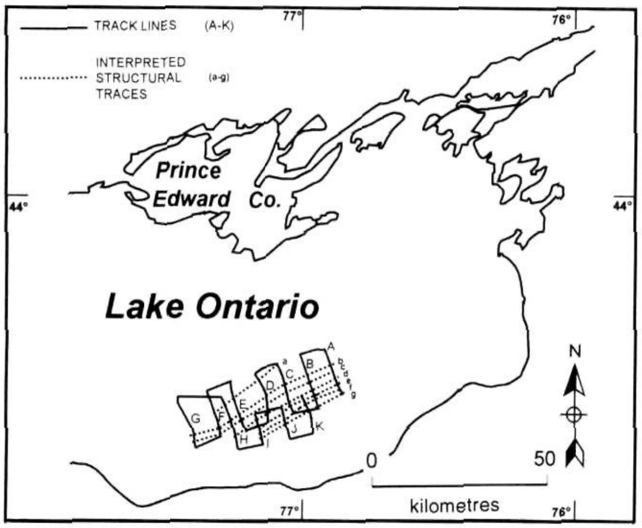

FIGURE 7. Echosounding survey lines (A-K) and the interpreted traces of the normal faults (a-g) defining the SOSZ.

Les lignes de levés d'échosondage (A-K) et les tracés présumés des failles normales (a-g) définissant la zone structurale du sud de l'Ontario (SOSZ).

gram to another (Fig. 8, A-K), are assumed to represent the trends of the gradients which displace the reflectors, though it is recognized that not all of the connected signatures along any particular line (*e.g.* Fig. 8, lines e and f) are obvious equivalents. However, the patterns along most of line "b" appear to be similar, as do several along line "c" (*e.g.* A, B, C, E & H). Furthermore, the dashed lines parallel the approximately 070° trend of the bathymetric contours within the Rochester Basin (Fig. 1), suggesting that the inferred orientation of the gradients is not unreasonable.

Another survey was undertaken in 1990 using a high resolution boomer seismic reflection system in addition to the echosounder. The boomer seismic reflection system did not penetrate to bedrock, but it did provide confirmation of major structures detected during the earlier echosounding surveys and, in particular, a clearer picture of the displaced reflectors in the unconsolidated sediments which signify stratigraphic displacements (Fig. 9). The displacements, commonly on the order of 10-15 m, are interpreted as post-depositional normal faults, rather than bathymetrically-controlled sediments deposited across a bedrock scarp. This is principally because neither slumping, nor any obvious thinning or thickening of strata adjacent to the scarps is evident. However, it is not yet possible to determine the origin of these structures. Because the displacements occur in unconsolidated sediments, and the bedrock underlying Lake Ontario is predominantly carbonate, it is conceivable, as suggested by P.S. Kumarapeli (personal communication), that the structures formed by collapse due either to melting ice or to dissolution of the carbonate bedrock. Whether the faults are related to tectonics or to collapse, their suggested parallelism to the bathymetric contours of that part of Lake Ontario does imply some degree of structural control. Consequently, the area in which they are present is designated in this paper as the South Ontario structural zone (SOSZ) (Figs. 7 and 8), although further work is required to try to ascertain the true nature of the faulting.

DISCUSSION

WESTERN LAKE ONTARIO

The plumose structures, linear features and inferred pop-ups are proximal to both the linear western shoreline of Lake Ontario and a conspicuous aeromagnetic lineament which

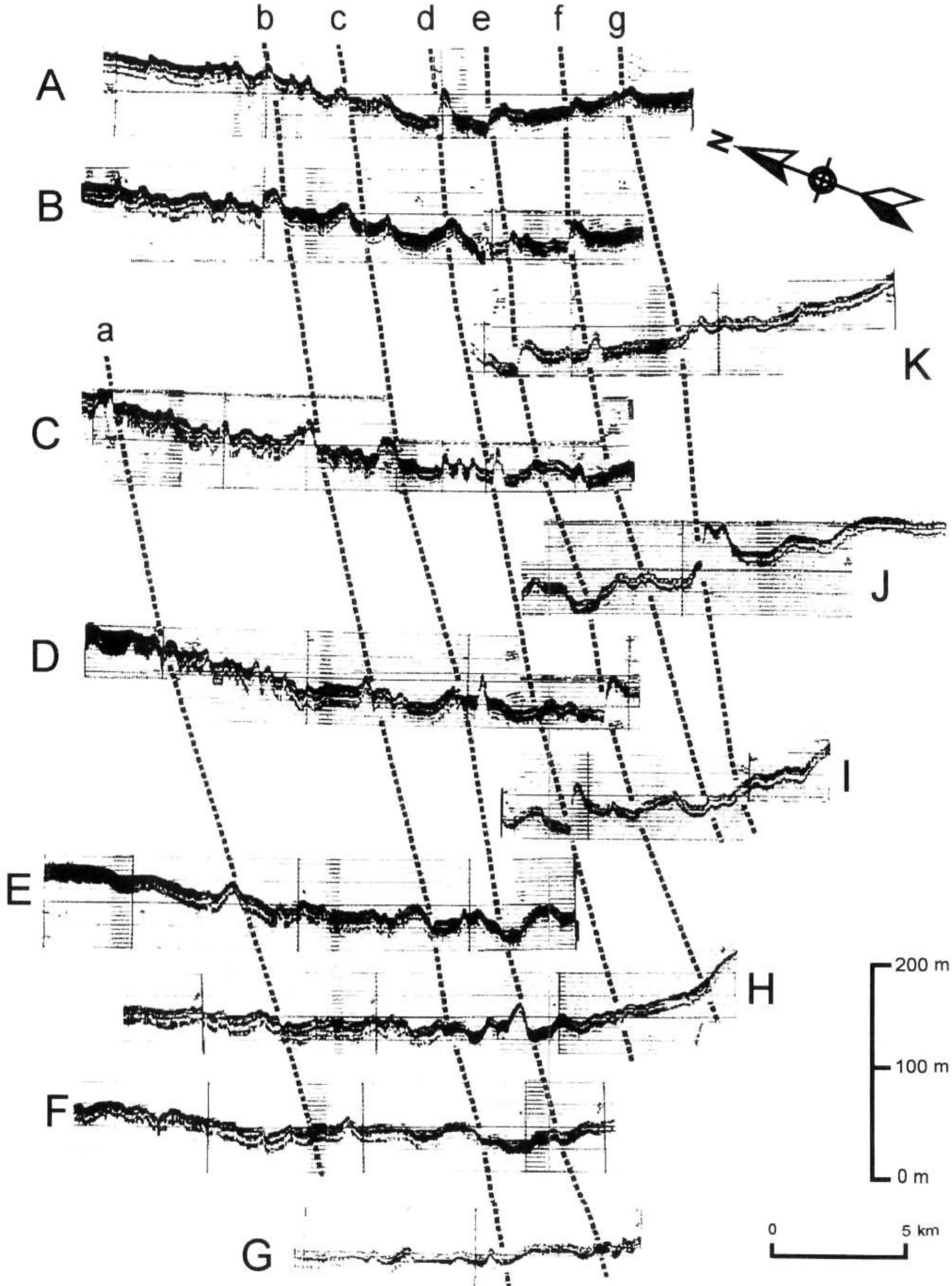

FIGURE 8. Echograms of survey lines (see Fig. 7, A-K) and the interpreted traces of the suspected normal faults (a-g).

Échogrammes des lignes de sondage (fig. 7, A-K) et tracés présumés des failles normales (a-g).

parallels, and lies just to the east of, the shoreline (Fig. 10). The magnetic lineament, referred to in this paper as the Burlington-Toronto magnetic lineament (BTML), extends in the direction 035° from east of Burlington to Toronto, a distance of about 40 to 45 km. In Toronto it abruptly changes orientation to 045° and continues in that direction for at least another 20 km. The general area in which the aforementioned features occur has also been the site of recurrent earthquakes (Fig. 10). Several of the epicenters, two of which are spatially associated with the BTML, occur in an area extending along the western Lake Ontario shoreline from Toronto towards Lake Erie. This area of seismicity, named the Toronto-Hamilton seismic zone (THSZ) by Mohajer (1993), is also parallel to the pronounced NNE-oriented magnetic grain, which is particularly evident west and southwest of Lake Ontario. The earthquakes in the THSZ have been predominantly small to moderate in size, and include a $M=3.4$ event in July, 1987 (Drysdale *et al.*, 1987), and $M=3.2$ and 2.2 tremors in August, 1989 (Drysdale *et al.*, 1989). However, as reported in the unpublished files of the Geological Survey of Canada, there were also two earthquakes of $4 \leq M < 5$ (Fig. 10).

Pop-ups are stress-induced structures in bedrock which, in eastern North America, have always been interpreted as being post-glacial in age (*e.g.* Gilbert, 1892; Hofmann, 1966; White *et al.*, 1973; White and Russell, 1982). Those which occur in quarries are known to have formed subsequent to excavation, hence they are obviously very young. Pop-ups which are exposed in open fields, and disrupt glacially striated bedrock surfaces, are post-glacial in age, however the age of other open-field pop-ups cannot be ascertained with certainty. The age of the pop-ups south of Toronto Island is unknown, but they pierce through the late- and post-glacial sedimentary cover making a geologically young age a distinct possibility.

The plumose structures, along with the dark lines and aligned elliptical features in the sediment south of Bronte and in Humber Bay (Fig. 10, sites B and C, respectively), may record very recent movements of materials. Their predominant ENE orientation (Table I, Figs. 6a and b) is approximately parallel to the prevailing trend of σ_1 (the greatest principal horizontal compressive stress) which has been directly

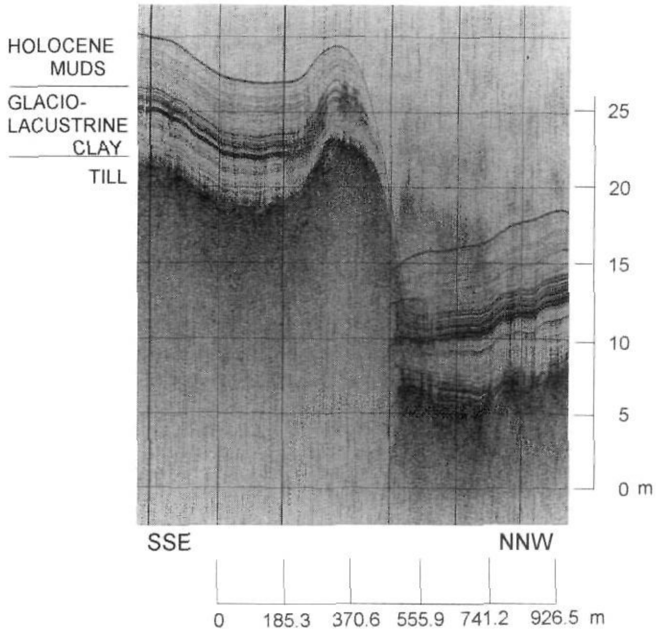

FIGURE 9. Boomer seismic profile of interpreted normal fault cutting till, glaciolacustrine clay and Holocene basin muds in the SOSZ.

Profil sismique de générateur sonique d'une faille normale entaillant du till, de l'argile glaciolacustre et des boues holocènes dans la zone structurale du sud de l'Ontario. (SOSZ)

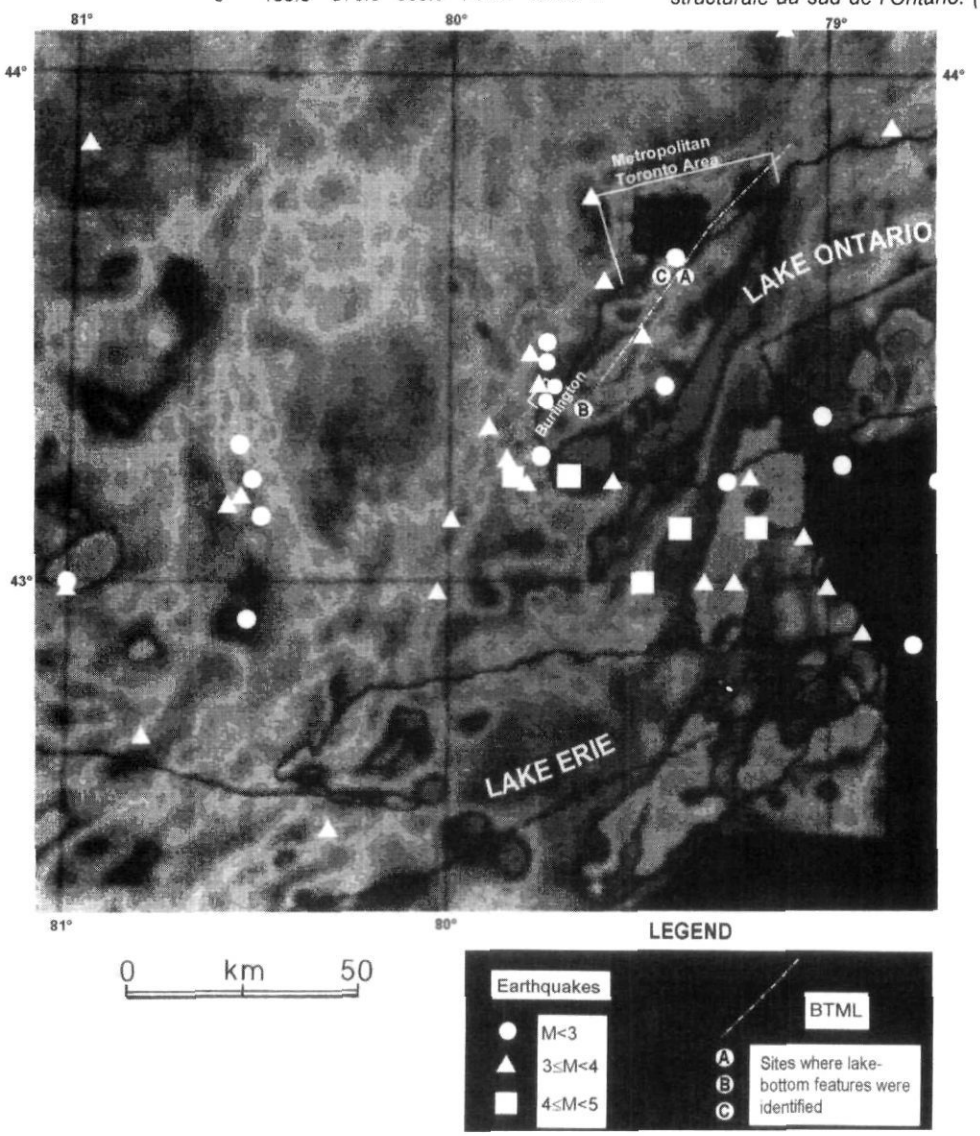

FIGURE 10. Total-field aeromagnetic map of the western Lake Ontario-eastern Lake Erie area showing the survey sites, the Burlington-Toronto magnetic lineament (BTML) and superimposed seismicity. The aeromagnetic map was provided by the Geological Survey of Canada (GSC) and the seismological data are from the unpublished files of the GSC.

Carte aéromagnétique de l'ouest du lac Ontario et de l'est du lac Érié montrant les sites à l'étude, le linéament magnétique Burlington-Toronto (BTML) et la sismicité en surimposition. La carte aéromagnétique a été fournie par la Commission géologique du Canada et les données sismologiques proviennent de dossiers non publiés de la Commission géologique du Canada.

measured or determined from earthquake focal mechanisms throughout eastern North America (*e.g.* Zoback, 1987; Talwani, 1982; North *et al.*, 1989). The nearest stress measurements to the western Lake Ontario survey areas were made in Paleozoic bedrock east of Toronto and show P-stress orientations of 055°-077° (Haimson and Lee, 1980). The mechanism of formation of the plumose structures is unknown. Plumose structures have been produced on fracture surfaces formed under tension in the laboratory (Nádai, 1950) and are interpreted as indicating direction of fracture propagation. Those on the surface of the recent clays may have resulted from upward and longitudinal growth of fractures from the underlying bedrock in response to either tension or extension, the latter being a lengthening phenomenon actually induced by compression. Their parallelism to σ_1 favors extension. If the proposed mechanism of formation is correct, their pointed form, which resembles the wake created by a ship moving through water, may also indicate direction of propagation. Given the presence of seismicity within and adjacent to western Lake Ontario, along with the generally preferred ENE trend of the plumose structures and the dark linear features, it is suggested that both are possibly crustally-related neotectonic structures.

Areas of dark return on side-scan sonar records are commonly due to a change in the physical character of the sediment surface. Their linearity and parallelism to σ_1 suggest that they may be structurally-controlled. Three possible mechanisms were considered to explain their origin: 1) sand ejection consequent upon seismic activity (*e.g.* Tuttle *et al.*, 1990), 2) dewatering leading to a change in the consistency of the sediment, also possibly caused by seismic activity or 3) upwelling of natural gas. Upwelling of gas is the suspected cause because, in a subsequent survey (Thomas *et al.*, in preparation), samples were taken of both the sediments marked by the areas of dark return, and the overlying water column. The sediments devoid of the dark signatures were also sampled. The results show that where the dark signatures appear there are elevated levels of methane gas, but where there are no dark signatures, there is no gas. The areas of degassing are spatially related to the BTML (Fig. 10, sites A and C) and an ENE-oriented magnetic lineament immediately east of site B (Fig. 10). Thus, these two lineaments may represent open fractures, or faults, which were partially or completely open, thereby allowing the gas to escape. An on-land example, which tends to support this interpretation of the lineaments representing open fractures or faults, comes from the seismically active Clarendon-Linden fault in western New York State. There degassing occurred, in response to the 1988, $m_{bLg} = 6.5$ Saguenay earthquake (Jacobi and Fountain, 1991, 1993).

SOUTHEASTERN LAKE ONTARIO

Extension of the St. Lawrence rift system (Kumarapeli and Saull, 1966) southwesterly into Lake Ontario and beyond was postulated by Adams and Basham (1989, 1991), and Basham and Adams (1989). The St. Lawrence rift system comprises a set of faults which lie within, and most likely are responsible for, the St. Lawrence, Saguenay and Ottawa River Valleys. Several moderate to large seismic events ($5.0 \leq M \leq 7.0$) have been associated with this intracontinental rift system, including the 1663, 1860 and 1925 Charlevoix ($M \approx 7.0$), the 1935 Timiskaming ($M = 6.25$) and the 1944 Cornwall ($M = 5.9$) earthquakes. The SOSZ, characterized by what appears to be a series of young, ENE-oriented normal faults, lies parallel to, and just north of, the southern margin of the postulated extension of the St. Lawrence rift system (Fig. 11). Its presence further supports the hypothesis of Adams and Basham (1989, 1991) and Basham and Adams (1989) that this rift system extends into Lake Ontario.

A linear magnetic signature within the Precambrian basement beneath Lake Ontario was recognized by McFall and Allam (1991), who named it the Hamilton-Presqu'ile lineament. The Hamilton-Presqu'ile, which was subsequently classified by the Ontario Geological Survey (1991) as a fault traceable in the subsurface, parallels the SOSZ and extends from Prince Edward County into the western part of the lake, a distance of about 200 km (Fig. 11). This fault is parallel to, and just north of, the northern limit of the proposed extension of the St. Lawrence rift (Fig. 11), as illustrated by Adams and Basham (1989; 1991) and Basham and Adams (1989). The Hamilton-Presqu-ile may, therefore, either represent the geophysical expression of the northern boundary of the rift extension, or it may be one of a series of faults within a much wider rift zone than previously envisaged.

SUMMARY AND CONCLUSIONS

Several features have been discovered in the lake-bottom sediments of two widely separated portions of Lake Ontario. In the western part of the lake, which is an area of low- to moderate-level seismicity, they include inferred pop-ups in the bedrock, and plumose structures and dark, linear patterns within modern mud. Pop-ups are tectonically-induced compressional structures and the plumose structures may reflect fracture or fault propagation. The dark linear features may be the result of structurally-controlled, gas injections into the recent sediments. If the foregoing interpretations are correct, the plumose structures and dark linear features may well be indicators of crustally-related neotectonic activity beneath the lake. The fact that they occur in a seismically active area adds to the likelihood that they are products of neotectonic activity. However, all "observations" of the lake-bottom structures have been made through the use of ship-borne, remote-sensing equipment; there have been neither direct visual observations of the structures nor samples of the materials in which the structures occur. Consequently, further work is planned.

In the southeastern part of Lake Ontario a series of oppositely-dipping stratigraphic breaks, which cut glaciolacustrine clays and modern muds, show vertical separations of 10-15 m. These features are interpreted as normal faults which, thus far, have only been identified in the young, unconsolidated sediments because no attempt has yet been made to penetrate the underlying bedrock. The faults define an area, referred to as the SOSZ, that is parallel and proximal to the southern margin of the extension of the St. Lawrence rift system into the lower Great Lakes as postulated in a series of papers by Adams and Basham (1989, 1991), and Basham and Adams (1989). The origin of these interpreted

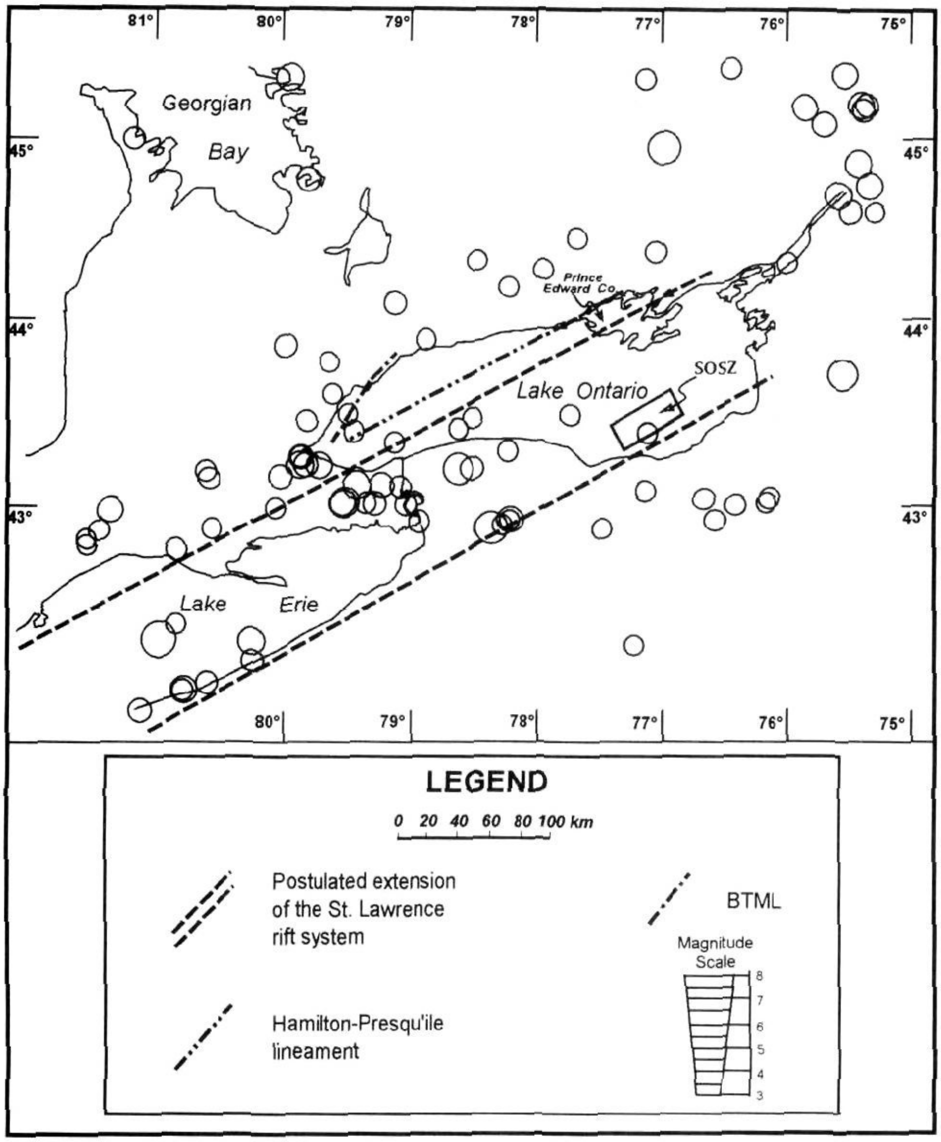

FIGURE 11. Locations of the BTML, SOSZ, the Hamilton-Presqu'ile lineament (now classified as a subsurface fault by the Ontario Geological Survey, 1991), and the postulated extension of the St. Lawrence rift system (*e.g.* Adams and Basham, 1989). Open circles show the distribution of seismicity (M ≥ 3). (Seismicity data compiled by Bowlby, unpublished.)

Localisations du linéament magnétique Burlington-Toronto (BTML), de la zone structurale du sud de l'Ontario (SOSZ) et du linéament Hamilton-Presqu'île (maintenant considéré comme une faille de subsurface par la Commission géologique de l'Ontario, 1991) et le prolongement présumé du système de rift du Saint-Laurent (voir Adams et Basham, 1989). Les cercles montrent la répartition de la sismicité (M ≥ 3) (données sismiques de Bowlby, non publ.).

normal faults, oriented generally parallel to the prevailing regional trend of σ_1, is unknown. However, they may be the result of simple uplift caused by, for example, glacio-isostatic rebound. Alternatively, as suggested for the normal faults in eastern Metropolitan Toronto by Mohajer *et al.* (1992), they may be the expression of isostatic rebound aided by extension consequent upon the application of σ_1. The northern boundary of the extended St. Lawrence rift system parallels, and is rather close to, the Hamilton-Presqu-ile fault. The latter extends from Prince Edward County, in northeastern Lake Ontario, to the western part of the lake, a distance of about 200 km.

In summary the lake-bottom features described in this paper are suspected of being different expressions of crustally-related neotectonic processes, although the precise causes are not yet known. Because the entire lake has not been surveyed with a view to looking for features similar to those described above, it is not possible to draw unequivocal boundaries around the two areas discussed in this paper. Similarly, the existence of other areas with similar features beneath the lake cannot be ruled out. If the features described in this paper are ultimately proven to be expressions of neotectonic activity, as the authors suspect, there will certainly be a need to evaluate the possible risks to lakeside communities, particularly the larger metropolitan centres.

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