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Multibeam sonar backscatter lineaments and anthropogenic organic components in lacustrine silty clay, evidence of shipping in western Lake Ontario [1]

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Abstract

A multibeam sonar survey (95 kHz) covering more than 500 km^2 of western Lake Ontario revealed anomalous lineaments of relatively high backscatter. The lineaments did not align with or parallel the most prominent structural zones beneath the lake as expected. Instead, the principal lineaments lay on lines between ports on opposite sides of the lake, especially between Toronto and Welland Canal, and Toronto and Niagara River mouth. As the lineaments underlie current and historical shipping routes used during the steamship era, they are interpreted as an acoustic response to shipping debris cumulated in the near-surface bottom sediment. An exploratory study of the organic components in the silty clay surface sediment, using geochemical and petrological techniques, shows that the upper 10 cm commonly contains silt-sized particles of anthropogenic origin, especially combustion residues. Combustion residues are more abundant on or near the lineaments, consistent with an origin related to shipping. Enhanced acoustic backscatter is evident where silt-sized combustion particles are hosted in dominantly clay-sized sediment. The coarser- grained anthropogenic particles increase the acoustic impedance of the lakebed relative to the bottom water as well as the roughness and volume scattering contributions to lakebed backscatter.

Keywords: multibeam sonar mapping, acoustic backscatter, sediment organic components, shipping, Lake Ontario, neotectonics, seismic hazard

1. Introduction

The onshore area around western Lake Ontario is densely populated (7 million) and supports an extensive urban and industrial infrastructure (Fig. 1). Although seismic hazard is relatively low in this part of the North American craton, it is currently under renewed investigation to test the hypothesis that basement faults may be reactivated under the current compressional stress regime (Wallach, 1990; Wallach and Mohajer, 1990; Wallach et al., 1998; Mohajer, 1993; Mohajer et al., 1992; Geomatrix, 1997; Mariolakos, 1998). Future earthquakes might not then be randomly distributed as formerly assumed, but would be located preferentially on zones of basement weakness. As a result, seismic hazard might be enhanced near these zones (Fig. 2), a significant concern in this highly developed region (Wallach et al., 1998).

The Quaternary sediments of Lake Ontario have been the target of traditional high-resolution seismic reflection and sidescan sonar surveys to test for past evidence of neotectonic activity (sediment and bedrock deformation) (Thomas et al., 1993; Lewis et al., 1995; McQuest Marine Sciences, 1995; Sanford, 1995). Another approach has been to map the lakebed with new high-density multibeam sonar methods (collecting both bathymetric and acoustic backscatter data) to search for lakebed evidence of the hypothesis of neotectonic fault reactivation. A survey of this type using the advanced Simrad EM-1000 mapping technology aboard CSS (now CCGS) *Frederick G. Creed* was completed in 1993. An area of over 500 km^2 was mapped in western Lake Ontario over the trend of basement faults or structural zones beneath the lake (Fig. 2). Lineaments of moderately high acoustic backscatter were discovered. However, they did not align with the most prominent structural zones, but appeared to lie on shipping routes between ports on the lake which were known to handle traffic by modern oil-powered cargo ships and former coal-fired steamships (Mayer et al., 1994). Nine samples of the upper 10 cm of sediment were collected in a transect across the basin, seven of which are in the survey area, to explore the possibility that the zones of enhanced backscatter might be associated with shipping routes along which combustion residues or other anthropogenic debris were discharged (Lewis et al., 1998). The organic components in these samples have been identified and characterized in separate studies using petrological (Mukhopadhyay et al., 1997) and geochemical (Kruge et al., 1998) methods. In this paper, we relate the findings to the acoustic backscatter lineaments.

2. Setting of Lake Ontario and the Niagara basin

2.1. Physical and geological setting

Lake Ontario, 306 km long in an east–west direction and 84 km wide at its maximum breadth, is situated at the downstream end of a chain of five North American Great Lakes which drain to the North Atlantic Ocean via the St. Lawrence River. The basin is thought to have resulted mostly from preglacial riverine erosion and glacial scour (Hough, 1958), possibly influenced by tectonic zones of weakness (Martini and Bowlby, 1991; Thomas et al., 1993). The western third of Lake Ontario (Niagara basin) is less than 50 km wide, is oriented ENE, and reaches depths of 150 m (Figs 1 and 3) (Canadian Hydrographic Service Chart 881). The basin is asymmetric with a steeper southern margin. The gently sloping northern margin reflects the southward dip of underlying Ordovician limestone and shale bedrock. The present lake outlet dates from about 11.7 ka BP after the retreat of the last ice cover and drainage of glacial lakes. Differential rebound has raised the northeastern basin rim (outlet) and caused relative lake level to rise (transgress) up to 100 m at its western end (Karrow et al., 1961; Anderson and Lewis, 1985; Coakley and Karrow, 1994).

Niagara River, carrying discharge of Lake Erie and the upper Great Lakes, is the major inflow and enters western Lake Ontario from the south cutting through Ordovician shales and Silurian dolostones, limestones, shales and sandstones (Hough, 1958; Sanford and Baer, 1981; Johnson et al., 1992). Direct runoff to Lake Ontario is mostly over glaciated Paleozoic sedimentary bedrock terrain of the St. Lawrence Platform, with some over Precambrian metamorphic rocks of the Canadian Shield in the northeastern sector of the basin. Although a weak anti-clockwise gyre is apparently associated with Niagara River outflow, most motion in the lake is wind-driven as waves, currents, storm surges and seiches (Canadian Hydrographic Service, 1985; Murthy, 1996).

Glacial sediments at the shores are undergoing wave erosion. Wave-drifted sand has formed barrier spits and beaches in front of spacious lagoons at Toronto and Hamilton, providing natural harbours and a basis for growth of these cities (Fig. 1). A sparse thin sand–gravel lag over eroded glacial sediments or bedrock occurs on much of the northern flank of the basin. Holocene and modern deposition in the form of soft silty clay mud occurs in offshore areas of the Niagara basin, below 40–60 m water depth on the southern margin, and below 40 to 130 m on the northern margin (Fig. 3). In the offshore areas, these sediments have accumulated from less than 4 to 8 m. They onlap older glacial or glaciolacustrine sediments at their perimeter. The Niagara basin terminates eastward at a zone of non-deposition, the Whitby–Olcott sill, where a sand veneer over glaciolacustrine clay is exposed at the lakebed. The principal sediment sources stem from erosion of drainage basin, shore and shallow lakebed. Mainly composed of quartz, feldspar and clay minerals, the organic C content of the offshore silty clay mud ranges 3–4%. The grain size of the basin mud is dominantly clay (50% to 75%) (Thomas et al., 1972a,b).

The sediments of Lake Ontario carry evidence of historically increased lake eutrophication (biological production and sedimentation of organic matter (OM) and carbonate). This increase started in the early to mid-1800s with European settlement, deforestation and widespread practice of mixed farming, horticulture and animal husbandry (Chapman and Putnam, 1984). Since the 1940s, the onshore and hinterland region of western Lake Ontario was rapidly urbanized and now supports a population of about 7 million. Eutrophication accelerated since 1940 due to increased anthropogenic-related input of nutrients, especially phosphorus (Schelske et al., 1988). Contaminants in the modern sediments, such as PAHs, PCBs, DDTs, Mirex, Dieldrin, Dioxin and metals such as Hg, Pb, Cu, Zn, Cd, Be and V, are thought to arrive mainly by atmospheric deposition, but also in outflow from major harbours, Niagara River and other streams (as summarized in Coakley and Lewis, 1999).

2.2. Ship transportation

The lake has been heavily used for transportation of people and goods since settlement. The Welland Canal, constructed in 1829, connects upstream Lake Erie with Lake Ontario at the southern shore of the Niagara basin. The capacity of this canal has been progressively enlarged over time to accommodate the pressure of increasing traffic through western Lake Ontario and from Lake Erie. It has facilitated the ship transport of coal, iron ore, and other resources for steel making, winter heating, power production and other industrial activity at ports around western Lake Ontario (Menzies and Taylor, 1998). A recent study sponsored by the Canadian Coast Guard found that over 16 million tons of ship cargo are processed annually around western Lake Ontario and in the Welland Canal (Melville Shipping and LGL, 1993).

Commercial vessels, such as bulk carriers, tankers, and package freighters dominated the Great Lakes trade. Cargo sweeping, or cleaning of vessels while travelling on the lake between ports is a standard practice (Melville Shipping and LGL, 1993). Passenger steamships also plied the lake until about 1950.

Steamships were powered first by wood-fired boilers and later by coal-fired boilers. Coal-fired boilers were commonly used from the mid-19th century well into the 1960s after which date oil-fired boilers became dominant. The conversion from coal to oil coincided with the opening of the St. Lawrence Seaway in 1958 which gave ocean-going vessels access to the lake.

A byproduct of coal-fired boilers was clinker and ash. To dispose of ash and clinker, most steamships were equipped with "ash chutes". Ash was moved into the chute and the application of steam and/or a jet of water forced the ash overboard. This could not be done in harbours or within the canal systems. As a result, ash was put over the side in the open lake away from populated areas.

3. Methods and analytical procedures

3.1. Multibeam acoustic survey

Over 500 km^2 of the Niagara basin depositional zone was surveyed in 1993 with the Simrad EM-1000 multibeam sonar aboard CSS (now CCGS) *Frederick G. Creed*, a SWATH (Small Waterplane Area Twin Hull) vessel capable of surveying at speeds up to 16 knots. The EM-1000 operates at a frequency of 95 kHz from a semi-circular transducer mounted on the starboard pontoon of the *Creed*. Sixty beams are formed (upon reception) with a spacing of 2.58 (38 wide in the alongship direction. resulting in 60 independent depth measurements collected from one to four times per second in an athwartship swath of 1508 or 7.4 times the water depth (to depths up to about 200 m — the system works to depths beyond 800 m but the swath width narrows in deeper water).

In addition to providing detailed bathymetric data, the EM-1000 also provides quantitative backscatter data that can be displayed in a sidescan sonar-like image and used to gain insight into the distribution of seafloor or lakefloor properties. Because it is collected at the same time and with the same transducers as the bathymetric data, the backscatter data can easily be co-registered and ‘‘draped’’ on the bathymetry providing an unprecedented perspective on the relationships among bathymetry, sea- and lakefloor processes, and the distribution of backscatter.

The EM-1000 multibeam data was processed (bathymetric data edited to remove noise and outliers, corrected for vessel motion and water-column refraction; backscatter corrected for propagation losses, gain changes, beam-pattern and angular variations and insonified area) in near-real-time aboard the *Creed* using software developed by the Ocean Mapping Group of the University of New Brunswick (Hughes Clarke et al., 1996). The processed bathymetric data was gridded to form a digital terrain model (with 15 m cell size) and backscatter data was mosaiced to form a sidescan sonar-like image with a pixel resolution of 5 m, though the plots produced here have been decimated to 15 m pixel resolution.

3.2. Sediment sampling

Relatively undisturbed sections of surficial lakebed mud about 900 cm^2 in area and 10 cm deep were carefully raised to the deck of the research vessel (CCGS *Samuel Risley*) at nine sites in 1994 using a Van Veen grab sampler (Fig. 1) (Table 1.). The block of mud from each sampling site was generally dark grey to black, reduced, with a thin oxidized brown surface layer up to 1 cm thick. Subsample layers comprising the 0–5 and 5–10 cm intervals below the top of sediment were collected and stored at 48°C for subsequent analysis. The samples from sites 16–25 make up a west-to-east transect through most of the Niagara depositional basin. Except for sites 16 and 17, all of the sites were within the area of the sonar backscatter map.

Approximate age estimates for the 10-cm sample intervals are based on published cores with ^{210}Pb activity or pollen profiles. A core near site 19 in the west suggests that each 10-cm interval represents about 80–100 years or less (Kemp et al., 1974; Robbins et al., 1978). Farther east, about 16 km east of site 25, a similar sediment accumulation rate was found, indicating that a 10-cm interval would represent approximately 70 years (Farmer, 1978). However, pollen profiles in cores (Kemp and Harper, 1976) and our seismic profiles (not shown) between these sites indicate thinner Holocene sediment, such that a longer time span, perhaps in the range of 150 to >200 years, is expected for each 10-cm interval at sites 21–25. Although it is assumed the sample intervals represent continuous deposition, it is possible that some contain hiatuses and redistributed sediment due to occasional storm surge activity (Robbins et al., 1978).

3.3. Particle size analysis

At each site, equal weights of sediment from the 0–5 and 5–10-cm samples were combined for analysis of particle size distribution in the 0–10-cm depth interval. The weight distribution of particles in the < 2 mm fraction was determined by sieving through a 63 μm screen and analysing the fine fraction using the Sedigraph method (Coakley and Syvitski, 1991) (Table 1).

3.4. Organic petrology

The methods for separating the OM, identifying its components, and the resulting data are given in Mukhopadhyay et al. (1997). The OM was isolated from its inorganic matrix by using standard methods for kerogen isolation in petroleum source rock analysis (Tissot and Welte, 1984). The samples were then prepared in polished block and smear slide forms. The data consist of volume percentages of each component obtained by point counting under a microscope with incident and transmitted light using white and blue light illumination.

3.5. Geochemistry

Bulk geochemical values for total organic carbon, Rock-Eval S1, S2, S3 and Production, Hydrogen and Oxygen Indices were obtained for each sample using Rock-Eval pyrolysis (Mukhopadhyay et al., 1997). A subset of selected samples was analysed by pyrolysis–gas chromatography/mass spectrometry (Py–GC/MS) for organic compounds, and a more limited subset was further analysed by injection gas chromatography/mass spectrometry after extraction with *n*-hexane for PAH compounds (Kruge et al., 1998).

4. Results and discussion

4.1. Multibeam sonar mapping

The multibeam survey area was chosen to test for lakebed bathymetric or acoustic backscatter anomalies possibly associated with the NNE trend of major magnetic and gravity field anomalies and a structural zone (the Niagara-Pickering Linear Zone, NPLZ, and the Central Metasedimentary Belt Boundary Zone, CMBBZ, Fig. 2). The linear structural zone is in Proterozoic basement rocks beneath the Paleozoic sedimentary cover under the lake. The area mapped by multibeam sonar was situated over the linear structural zone and extended approximately 10 km or more both east and west of it, such that any recent sediment disruption due to neotectonic activity, such as gas release along the zone, should be recorded. No features could be found in the bathymetry or acoustic backscatter that could be attributed to this tectonic lineament. However, acoustic backscatter lineaments were recorded, as described below.

The acoustic backscatter map (Fig. 4a) presents the average backscattered acoustic energy at 45° grazing angle returned from the lakebed. Given the operating frequency of the sonar (95 kHz), the very low attenuation of sound in fresh water (about 3 dB/km) and the very fine-grained nature of the lakefloor sediments, there will also be a contribution from volume scattering within the upper 5 to 10 cm of the sediment. While the EM-1000 has the potential to present calibrated backscatter values (assuming all corrections have been done properly), we are not confident enough in the correction process to present these results in terms of absolute backscatter and thus treat the backscatter images as plots of relative backscatter.

The eastern side of the map shows concentrations of pixels with relatively high backscatter, as expected, from a part of the sand-veneered Whitby–Olcott sill (Fig. 4a,b). The highest backscatter in the survey area is recorded in the northeastern corner of the map and on individual tracks between the main survey area and Toronto Harbour. Again, this is an expected response as these tracks cross a lakefloor comprising sandy lag over bedrock or eroded glacial deposits (Fig. 3). Very low backscatter was expected from the soft silty clay mud elsewhere in the map area. Yet, distinct linear zones of relatively high backscatter are evident. The zones are clearly not consistent with the most prominent tectonic lineament, the NPLZ (Fig. 2). Although some linear backscatter zones are broadly consistent with structural trends in the Georgian Bay Linear Zone (GBLZ), and others with the Hamilton–Presqu'ile Fault (HPF) (Fig. 2), multibeam acoustic backscatter features have no subsurface expression of sediment disruption in high-resolution seismic profiles (Lewis et al., 1995), suggesting an origin unrelated to neotectonic processes. Thus, the backscatter lineaments likely originate with physical property changes in the surface sediments.

When viewed in detail, isolated pixels of high backscatter occur throughout the survey area. Pixels within the linear zones of moderately high backscatter are of variable value, ranging irregularly from low to high, suggesting the source of backscatter is not uniformly distributed. Though irregular in detail, the backscatter sources comprise distinct cross-lake linear zones with diffuse edges when the survey area is viewed as a whole (Fig. 4a,b). When plotted on a map of the lake, the backscatter lineaments and their projections join ports on the southern and northern shores, suggesting the lineaments are a cumulative response to ship traffic along commonly travelled routes (Fig. 5). Most likely, the backscatter lineaments are related to steamship ash or other ship debris in the fine-grained bottom sediment as discussed later. Scattering from sedimentary roughness induced by the wakes of ships is considered less likely owing to the substantial water depth (100 m and deeper).

Three linear principal backscatter zones are identified (Figs. 4a,b and 5). A relatively weak lineament, WC-M, trends northwest between the Welland Canal on the south and the lakeshore at Mississauga west of Toronto. The strongest zone, WC-T, is a Y-shaped lineament between the Welland Canal and the two entrances to Toronto Harbour, western and eastern gaps. A third linear zone, T-N, comprises two weak subparallel sets of traces between the eastern gap of Toronto Harbour and Niagara-on-the-Lake at the mouth of the Niagara River.

Secondary backscatter lineaments are also recognized (Fig. 4a,b). These are much weaker and less extensive than the principal lineaments. Lineament "a", near the south central border of the backscatter map, consists of a few strong elements; their trend suggests the lineament might reflect shipping to and from the Welland Canal prior to 1932 when the Canal entrance was at Port Dalhousie (Fig. 5). Lineament "b", farther east, is a narrow well-defined track lying on a projected course between the western gap of Toronto Harbour and the Niagara River mouth, a frequently travelled route for passenger steamship traffic prior to 1950. Lineaments "c" to "e", in the northeastern part of the backscatter map, appear to trend east–northeast. These possibly reflect low-stand shorelines of early Lake Ontario (Anderson and Lewis, 1985), or ship traffic between Hamilton and ports on the northern shore east of Toronto (Fig. 1). Lineament "f" is one of several small segments of backscatter of unknown connection which trend northeast in the northeastern sector of the multibeam area. Lineaments "x,y,z", in the eastern part of the survey area, are artifacts related to cross tracks of the Creed and do not represent any real change in physical properties of lakebed sediment.

4.2. Particle size

The results of the grain size analysis show that samples 19–25 in the multibeam survey area are all clay-rich silty clay (Table 1) (Figs. 1 and 4b). Clay contents range from 74.4% to 81.2%, and silt contents range from 18.2% to 25.0%.

4.3. Organic petrology and geochemistry

The total organic carbon (TOC) contents of the samples collected for the present study (Fig. 1) varied from 1.5% to 3.5%, consistent with the values (2–4%) found by Thomas et al. (1972a; b) for the upper 3 cm of silty clay mud. In addition, the upper layer (0–5 cm) samples of the present study had higher TOC (also higher S1, S2 and Hydrogen Rock-Eval index values) than those from the lower layer (5–10 cm) at each site (Mukhopadhyay et al., 1997), consistent with previous work in Lake Ontario documenting decreasing organic carbon with increasing sediment depth (Schelske and Hodell, 1991; Schelske et al., 1988; Silliman et al., 1996).

The molecular geochemistry of the samples was assessed by Py–GC/MS (Kruge et al., 1998). Pyrolyzates of samples richer in OM were relatively enriched in aliphatic hydrocarbons and pyrrolic nitrogen compounds, while samples leaner in OM were more aromatic and pyridinic. Alkylbenzene and alkylphenol distributions in the pyrolyzates were most compatible with derivation from aquatic (algal, bacterial) OM. Organonitrogen compounds indicated the presence of degraded proteinaceous material from aquatic sources and/or sewage. Normal and polycyclic aromatic hydrocarbon (PAH) distributions indicate, at least in part, contributions of fossil fuels and combustion residues. These observations were confirmed by the organic petrologic examination. The PAHs were readily detected in "raw sediment" at sub-ppm concentrations using selected ion monitoring, a more sensitive mass spectrometric technique. An ubiquitous input of aquatic OM to the sediments (enhanced by anthropogenic nutrient oversupply) was supplemented by fossil fuel-derived contamination, in proportions varying with proximity to industrial sites and shipping lanes (Kruge et al., 1998).

The particles of OM, as determined by petrology, were silt-sized and fell into three compositional groups according to the origin of the components, natural, mixed and anthropogenic (Fig. 6) (Mukhopadhyay et al., 1997). The natural organic components consist of an autochthonous subgroup of phytoplankton, bacterial clusters, and fungal residues, as well as an allochthonous subgroup of humic particles, spores, pollen, resin and suberin, and charcoal (from forest fires). The mixed origin group comprises amorphous OM from natural degradation of algae from the photic zone by bacteria and fungi, or from sewage and agricultural runoff containing bacteria and fecal pellets. It also includes vitrinite and inertinite which could be natural clasts from sedimentary sequences within the drainage basin or components from anthropogenic coal debris as no coal measures are known in the basin. The anthropogenic group has numerous components including coal, oil, bitumen, fly ash, coke or char, semi-coke or char, and plastics and chemicals (Fig. 7). The char and coke structures are silt-sized, up to 50 μm (Mukhopadhyay et al., 1997).

Fossil fuel combustion products have long been recognized in Lake Michigan (Griffin and Goldberg, 1981; Bostick, 1994) and in Lake Erie (Dell and Booth, 1977). Combustion products are also known in European lakes (Renberg and Wik, 1984, 1985a,b; Wik and Renberg, 1991). Recently, Ghorbani et al. (1997) have used slag particles from steamship debris to build a chronology for recent sediments in the Austrian lakes, Attersee and Mondsee.

4.4. Relation of organic particles to acoustic lineaments

The acoustic backscatter recorded with the multibeam sonar is the result of the complex interaction of the emitted soundwaves with the lakebed. In general, the amount of sound scattered back to the sounder (i.e., the amplitude of the backscatter value) for a given angle of incidence will be a function of the acoustic impedance contrast between the bottom waters and the lakebed sediment, as well as the ''roughness'' of sediment surface and near-surface. The acoustic impedance is an inherent property of the material that is, in turn, a function of the speed of sound in the material and the saturated bulk density of the material. In general, very fine-grained sediments tend to be low density, and have low sound speeds, and thus have low acoustic impedances. The ''roughness'' of the seafloor is defined within the context of the frequencies involved (i.e., the higher the frequency the smaller the scale of feature that will scatter the sound) with rougher surfaces scattering more sound than smoother surfaces. Roughness can be a function of the nature of the material (e.g., fractured rock surfaces), the presence or absence of bedforms, and the size distribution of the particles making up the lakebed sediment. Volume scattering may also contribute to the backscattered signal with thin interbedded layers or small point scatterers resulting in increased backscatter.

In the western Lake Ontario survey area, the high degree of variability in backscatter amplitude between pixels imposes uncertainty on the correlation of sediment sample properties with backscatter lineaments. The uncertainty is exacerbated by the observation that anthropogenic particles and compounds are widely distributed in samples from western Lake Ontario (Mukhopadhyay et al., 1997; Kruge et al., 1998) (Fig. 6). Nonetheless, the exploratory sampling suggests a relationship between acoustic lineaments and anthropogenic components that is consistent with an interpretation of their origin as a response to ship debris contamination in the surface sediments.

Anthropogenic components dominate samples at three sites, 19, 23, and 25. Sample 23 is on the WC-T principal backscatter lineament. Sample 25 is near the ''b'' secondary lineament, but no lineament is evident near sample 19. It is possible that sample 19 is from one of the isolated high-amplitude pixels within a region of low backscatter.

As shown in Fig. 7, the principal anthropogenic components present at the most heavily contaminated sites, 19, 23, and 25, are coke and semi-coke, combustion products of coal. These particles are silt-sized in a fine-grained host sediment of mostly clay size (Table 1). The coarser-grained particles associated with these anthropogenic materials will increase the acoustic impedance of the lakebed relative to the bottom water as well as the roughness and volume scattering contributions. Additional sampling, more densely spaced than could be obtained in this initial study, is needed to better constrain the sedimentary controls on the multibeam backscatter lineaments.

4.5. Relation of multibeam lineaments to sidescan sonar backscatter features

Conventional sidescan sonar also maps the acoustic backscatter of seabed or lakebed, but in swaths from a few 10s to 100s of metres in width and at angles of incidence much lower than those typically found with multibeam sonars. This survey method produces a qualitative graphic image of backscatter with a pixel size that varies with the frequency of the system used but is often on the order of one metre or less. Compared with the multibeam survey system, the conventional sidescan sonar method produces images of higher resolution (the lower angle of incidence more effectively casts shadows), but is often non-quantitative due to poor location of pixels and use of uncalibrated sound sources. Also, sidescan sonar is much less effective for continuously mapping the backscatter of large areas because it must be towed at slow speed.

The broad multibeam backscatter lineaments were not recognized on sidescan sonar records (100 kHz. from western Lake Ontario (Lewis et al., 1995). A re-examination, after the multibeam mapping was completed, showed only a featureless background of low-amplitude backscatter in the vicinity of the lineaments. Sidescan sonar did not detect the broad multibeam lineaments because significant variations in backscatter amplitude could not be detected within the range of the relatively narrow sidescan swath (200–300 m). However, the sidescan did reveal small-scale, high-amplitude, linear backscatter features on the order of 10-m wide and several 10s to 100s metres long on the bed of Lake Ontario throughout the survey area. These features, variously referred to as areas of dark return, linear acoustic backscatter anomalies (LABAs), and acoustic backscatter anomalies (ABAs., were first interpreted as features related to neotectonic faulting and gas release (Thomas et al., 1989a,b, 1991). Later sampling and mapping of some of the features suggested they were cargo-sweeping debris (Cameron and Lewis, 1994; Lewis et al., 1995; Ferrini, 1998). The LABAs or ABAs differ from the multibeam sonar lineaments; they are of smaller scale and higher amplitude than the kilometre-broad by 10s of kilometres long multibeam backscatter lineaments. It is possible the LABAs were detected in the multibeam sonar map, but show only as isolated pixels of high-amplitude backscatter. It is also possible that some LABAs are too small to register clearly on the multibeam sonar backscatter map.

5. Conclusions

(1) A multibeam sonar survey of more than 500 km^2 of the silty clay depositional (Niagara) basin in western Lake Ontario shows broad kilometre-scale lineaments in the acoustic backscatter map.

(2) Three principal acoustic backscatter lineaments and six secondary lineaments were identified on the basis of their size and intensity. The lineaments arise from physical property changes in the surface sediments and are not related to basement faults and structural zones beneath the lake basin, as originally expected.

(3) The principal acoustic lineaments, when projected beyond the bounds of the survey area, join ports on opposite sides of the lake, and are interpreted as evidence of debris associated with ship traffic. Lake Ontario has been heavily used for shipping since European settlement in the early 1800s.

(4) Exploratory sampling of the bottom sediment suggests that anthropogenic components are common. Sediment in or near two of the acoustic backscatter lineaments contain elevated quantities of anthropogenic OM, especially coke and semi-coke combustion products, consistent with an origin related to shipping (steamship) debris.

(5) Enhanced acoustic backscatter is evident where silt-sized combustion particles are hosted in dominantly clay-sized sediment. The coarser-grained anthropogenic particles increase the acoustic impedance of the lakebed relative to the bottom water as well as the roughness and volume scattering contributions to lakebed backscatter.

(6) The relationship between acoustic backscatter and steamship debris is complicated by a high degree of variability in the lakebed backscatter, and by the possibility that scatterers also come from other sources such as atmospheric deposition and cargo vessel cleaning.

Additional sampling, more detailed than could be obtained in this initial study, would be beneficial in further defining the sedimentary controls for the multibeam backscatter lineaments.

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Table 1. Particle size distribution in surface sediment samples (0–10 cm) from western Lake Ontario

Sample site no.	Latitude/ longitude	Water depth (m)	Percentage sand (63 μm–2 mm)	Percentage silt (8–63 μm)	Percentage clay (< 8 μm)
16	43°20.39′N/79°39.61′W	64	0.82	37.34	61.84
17	43°20.37′N/79°39.61′W	64	0.81	37.59	61.60
19	43°24.40′N/79°26.99′W	107	0.27	21.05	78.67
20	43°24.40′N/79°25′W	108	0.66	18.18	81.16
21	43°24.40′N/79°20.99′W	113	0.063	20.67	78.70
22	43°24.40′N/79°18.90′W	117	0.57	20.21	79.22
23	43°24.40′N/79°17.99′W	121	0.76	18.59	80.64
24	43°24.39′N/79°14.69′W	121	0.49	22.12	77.39
25	43°24.40′N/79°12.50′W	120	0.58	25.03	74.39

Fig. 1. Map of western Lake Ontario showing bathymetry, area of multibeam survey (dashed line), sample sites, and infrastructure within the coastal zone. From Canadian Hydrographic Service (1985; 1985–1994).

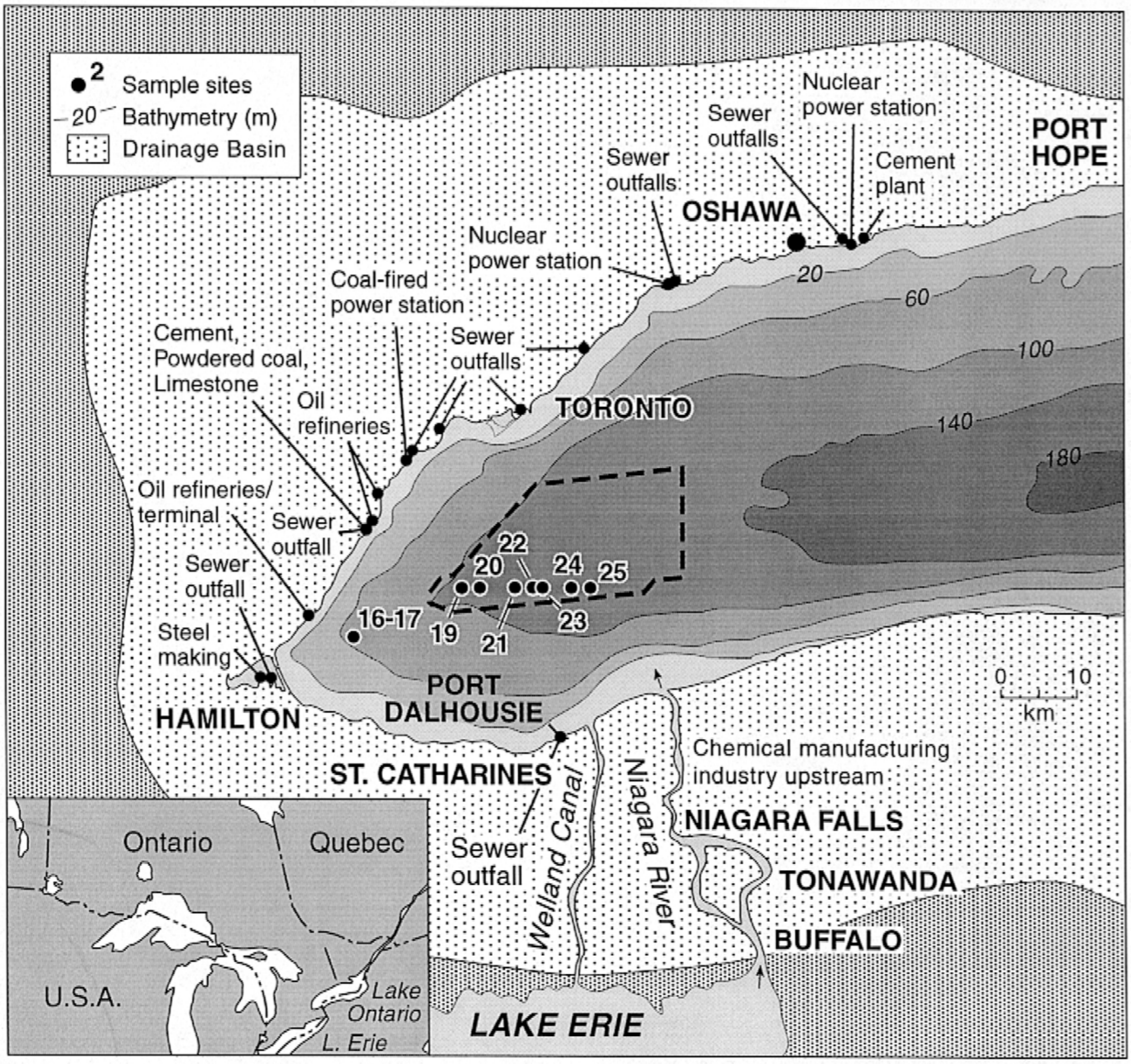

Fig. 2. Zones of basement weakness and possible neotectonic reactivation in the western Lake Ontario region. Adapted from Wallach et al. (1998). CMBBZ = Central Metasedimentary Belt Boundary Zone, GBLZ = Georgian Bay Linear Zone, HLEL = Hamilton-Lake Erie Lineament, HPF = Hamilton-Presqu'ile Fault, NPLZ = Niagara-Pickering Linear Zone, WPHL = Wilson-Port Hope Lineament.

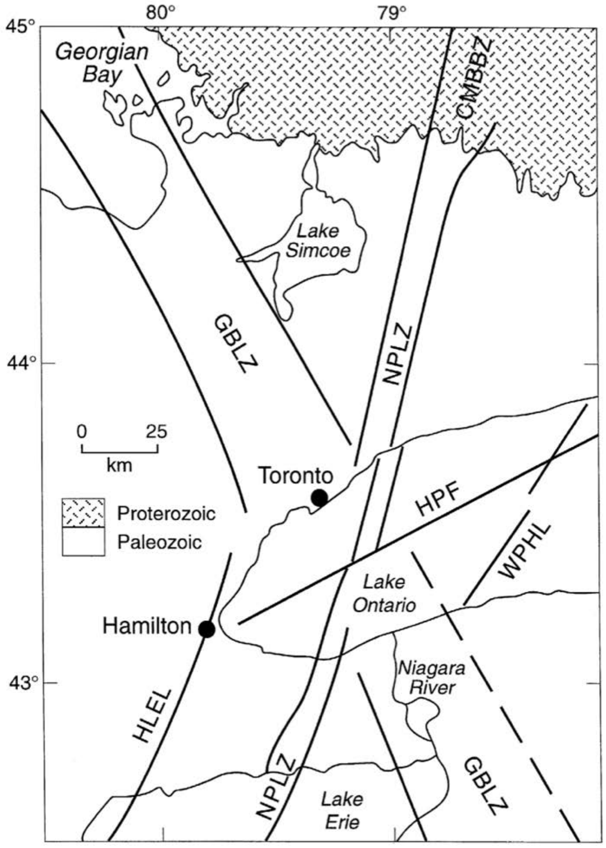

Fig. 3. Bottom sediment distribution and basin designation in western Lake Ontario. From Thomas et al. (1972a; b).

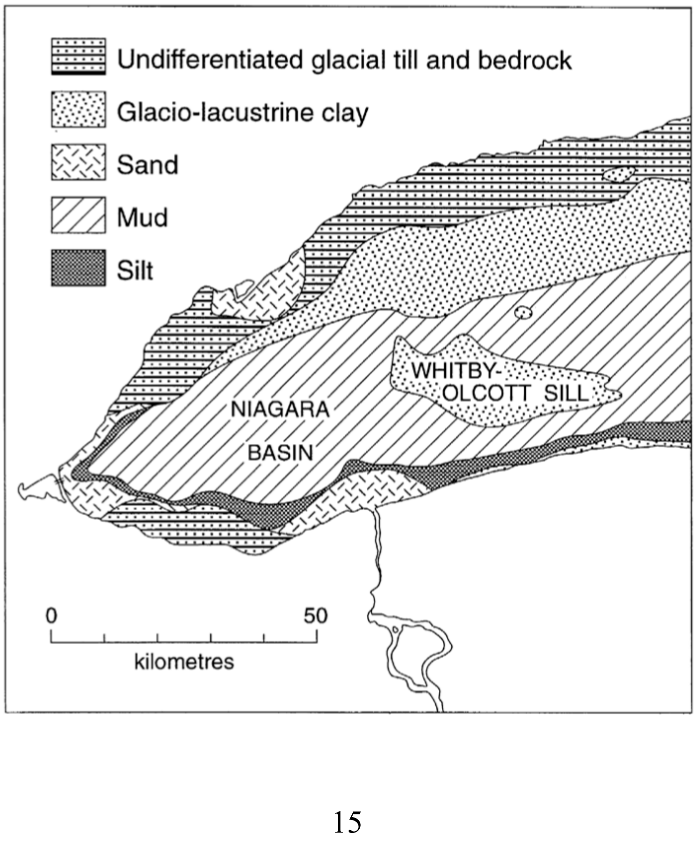

Fig. 4. (a) Multibeam sonar (95 kHz) backscatter map of the Niagara basin (part) of western Lake Ontario. Map illustrates relative amplitude of backscattered acoustic signals. Dark blue represents lowest backscatter, with green, yellow and red representing progressively higher backscatter. Most survey lines parallel the northern and southern borders of the survey area. Variations in tone paralleling these lines are artifacts of the sonar correction process and should be ignored. (b) Line drawing of the backscatter map in (a) showing sample sites and interpretation of the backscatter trends; dotted line outlines areas of high natural backscatter, solid lines principal lineaments, dashed lines a–f = secondary lineaments, and dashed lines x–z = artifacts.

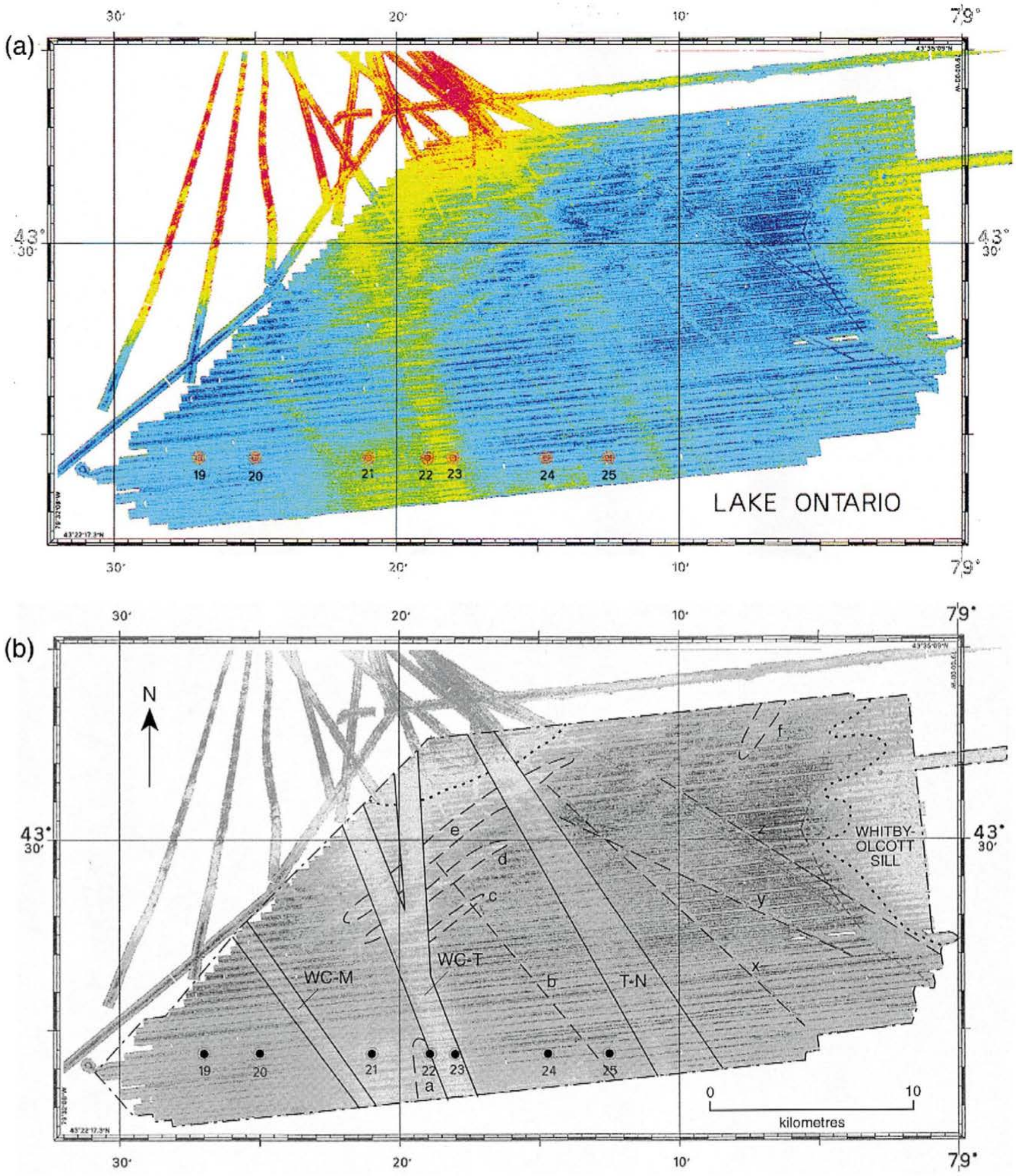

Fig. 5. Map of western Lake Ontario showing how ports on the northern and southern shores of the lake lie on the projections of the principal acoustic backscatter lineaments. Base map from Canadian Hydrographic Chart 881.

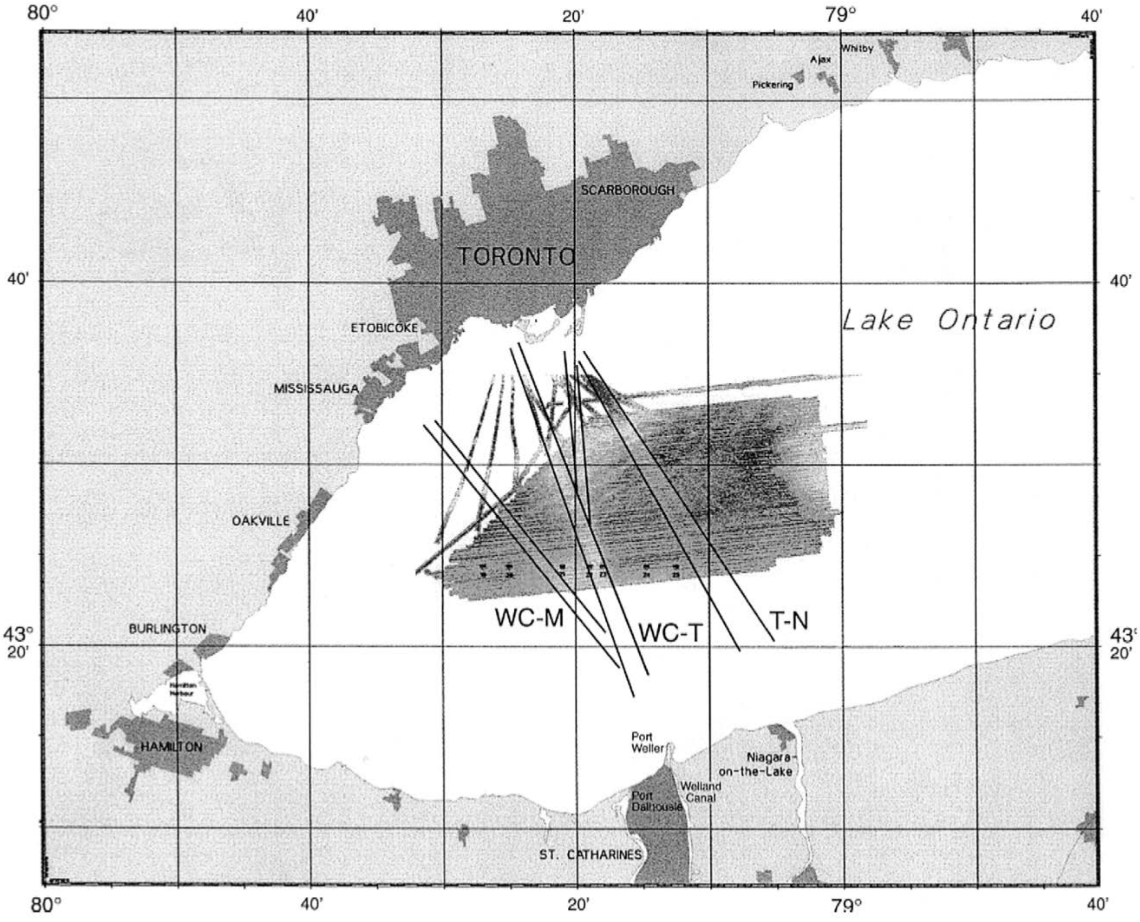

Fig. 6. Bar graphs showing the relative proportion of components in the sediment OM of western Lake Ontario by origin — anthropogenic, mixed and natural. From data in Mukhopadhyay et al. (1997).

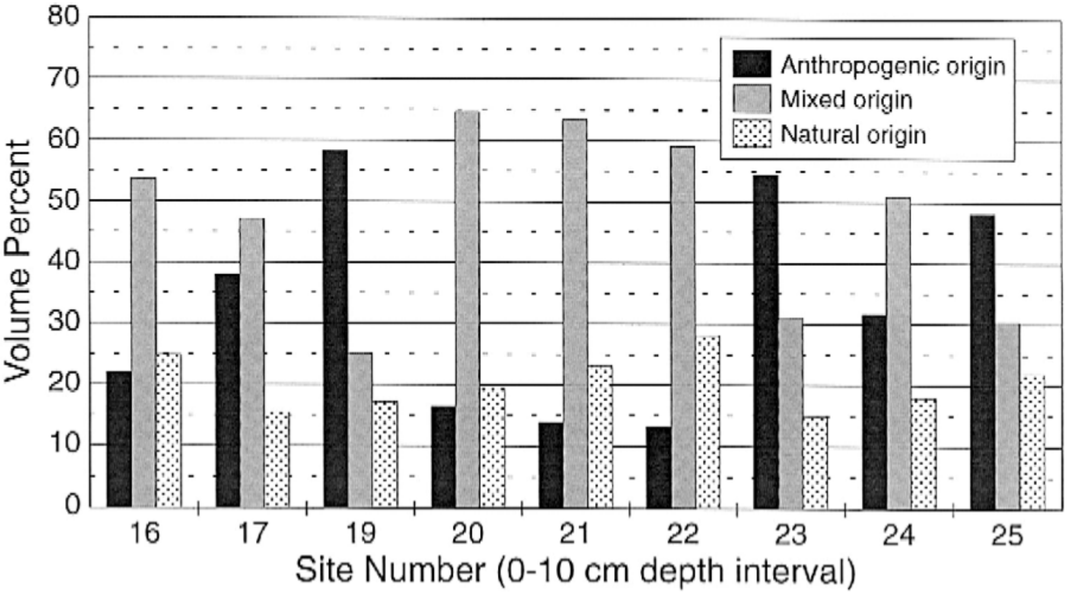

Fig. 7. Bar graphs showing the relative proportion of anthropogenic components in the sediment OM of western Lake Ontario. From data in Mukhopadhyay et al. (1997).