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# Storm-induced Redistribution of Deepwater Sediments in Lake Ontario

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***ABSTRACT.*** *High-resolution seismic reflection profiles, side-scan sonar profiles, and surface sediment analyses for grain size (% sand, silt & clay), total organic carbon content, and carbonate content along shore-perpendicular transects offshore of Olcott and Rochester in Lake Ontario were utilized to investigate cm-thick sands or absence of deepwater postglacial sediments in water depths of 130 to 165 m. These deepwater sands were observed as each transect approached and occupied the "sills," identified by earlier researchers, between the three deepest basins of the lake. The results reveal thin (0 to 5-cm) postglacial sediments, lake floor lineations, and sand-rich, organic, and carbonate poor sediments at the deepwater sites (> 130 m) along both transects at depths significantly below wave base, epilimnetic currents, and internal wave activity. These sediments are anomalous compared to shallower sediments observed in this study and deeper sediments reported by earlier research, and are interpreted to indicate winnowing and resuspension of the postglacial muds. We hypothesize that the mid-lake confluence of the two-gyre surface current system set up by strong storm events extends down to the lake floor when the lake is isothermal, and resuspends and winnows lake floor sediment at these locations. Furthermore, we believe that sedimentation is more likely to be influenced by bottom currents at these at these sites than in the deeper basins because these sites are located on bathymetric highs between deeper depositional basins of the lake, and the bathymetric constriction may intensify any bottom current activity at these sites.*

***INDEX WORDS:*** *High-resolution seismic profiles, side scan sonar records, bottom sediment mobilization, Lake Ontario.*

## INTRODUCTION

A better understanding of the sedimentary processes influencing the lake floor is critical for forecasting the fate of pollutants associated with them, defining the habitat for benthic organisms within the lake ecosystem and other concerns. Research in the 1970s revealed that postglacial sediment thickness typically increased from nearshore to offshore locations with over 12 m of sediment in the deepest subbasins of the lake (Thomas *et al.*1972, Kemp and Harper 1976). Notable exceptions to this trend are at the Whitby-Olcott and Scotch-Bonnet Sills (Fig. 1), the bathymetric highs (130 and 150 m depths, respectively) between the Niagara, Mississanga, and Rochester basins (max depths of 140, 190, and 240 m, respectively), where postglacial sediment accumulation is minimal even though the water depths are significantly below wave base (Thomas *et al.* 1972). These sills are ele-

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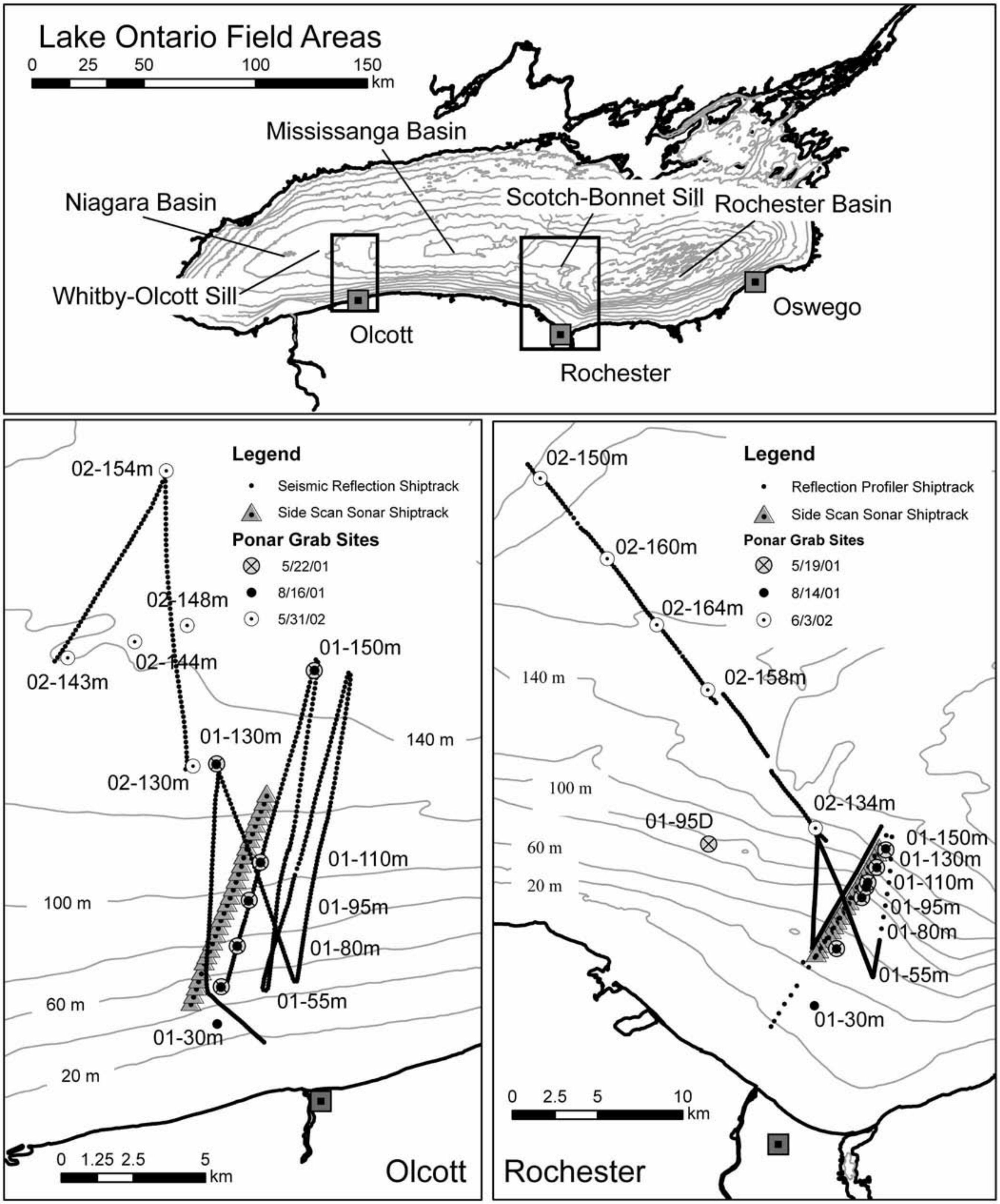


*FIG. 1. Bathymetric maps (20 m contour interval) of Lake Ontario with the location of the basins and sills discussed in the text, and the Olcott and Rochester survey areas revealing the high-resolution seismic reflection and side scan sonar shiptrack, and Ponar grab sites.*

vated due to the topographic relief in the underlying glacial tills and/or bedrock (Hutchinson *et al.* 1993). The previous authors speculated without elaboratation that these thin sediment accumulations resulted from sediment focusing around the two sills due to the local bathymetric relief (Thomas *et al.* 1972, Hutchinson *et al.* 1993).

Growing evidence suggests that a variety of additional processes including density currents, turbidity currents, contour currents and other sedimentological events can influence sediment winnowing and redistribution below wave base (e.g., Flood and Johnson 1984, Johnson *et al.* 1984, Johnson and Ng'ang'a 1990, Vickman *et al.* 1992, Hawley *et al.* 1996, Scholz *et al.* 1993, Soreghan *et al.* 1999). This paper examines the sedimentological evidence for the controls on deepwater sedimentation offshore of Olcott and Rochester in Lake Ontario using high resolution seismic reflection profiles, side scan sonar profiles, and sediment analyses.

Lake Ontario is the smallest (19,477 km$^2$) and hydrologically farthest downstream of the Laurentian Great Lakes. It occupies a trough cut by fluvial and glacial processes into the northern margin of the Appalachian basin and much of the present day bathymetry reflects the topography of the underlying bedrock and glacial drift (Martini and Bowlby 1991). The offshore sediment sequence, from oldest to youngest, is glacial till, glaciolacustrine clays and postglacial muds (Lewis and Sly 1971, Thomas *et al.* 1972, Kemp *et al.* 1974, Kemp and Harper 1976, Hutchinson *et al.* 1993). The postglacial sediment is dominated by silicate minerals with up to 5% carbonate and 5% organic matter (Thomas *et al.* 1972). The primary sediment sources include fluvial inputs and shoreline erosion of exposed glacial materials for the allochthonous fraction and in-lake precipitation for the autochthonous calcite and organic matter. Sediment resuspension, shoreline erosion and sediment transport from west to east dominates the nearshore region along the southern margin of the lake (e.g., Lewis and Sly 1971, Sutton *et al.* 1970, Rukavina 1976).

## METHODS

High resolution seismic reflection profiles, side scan sonar profiles, and Ponar grab sediment samples were collected in 2001 and 2002 during multiple daylong cruises on the USGS research vessel, R/V *Kaho* (Fig. 1). Navigation was by Differential Global Positioning System (DGPS, 10 meter accuracy). The 2001 fieldwork centered on two shore perpendicular transects from 30 to 165 m of water offshore of Olcott and Rochester. The transects and Ponar sites were predetermined by an ongoing investigation of the benthic *Diporeia* (arthropod) and *Driessena* (zebra and quagga mussels) community in Lake Ontario (Owens and Dittman 2003, Dittman *et al.* 2005). The 2002 field season extended the 2001 survey lakeward in a north to northwesterly direction to further investigate the thin, cm-thick, postglacial sands or missing postglacial sediments recovered at the deepest-water sites in 2001 (Etherington *et al.* 2002, Walker *et al.* 2002).

Approximately 150 km of high-resolution seismic reflection data were collected from the lake, divided between each field area, at a ship's speed of ~ 5 km/hr (Fig. 1). Profiles were collected with EG&G's (EdgeTech) X-Star subbottom profiling system, that utilizes chirp technologies, sweep frequencies of 2–12 kHz, and a SB-216B tow vehicle. Seismic and navigation data were recorded on magnetic tape and plotted in real time on an EPC graphic recorder (GSP-1086) with a time-varying gain that increased linearly (0.4 dB/m) below the lake floor. In general, subbottom penetration with this system varies from nil over bedrock, muds with gas, or sand-rich and coarser sediments to 50 m or more in mud-rich, gas-free sediments with decimeter resolution. Seismic reflectors correspond to acoustic impedance boundaries (changes in sediment bulk density and sound velocity), and are more reflective (darker in the profiles) with larger contrasts. Higher amplitude (darker) reflectors typically correspond to coarser-grained sediments at the lake floor or larger changes in grain-size or water content at the internal reflector boundary, whereas lower amplitude reflectors correspond to finer-grained or smaller water content contrasts. The EG&G software assumed the conventional sound velocity of 1,500 m/s in the water column and upper sediments for the distance to two-way travel time conversions even though the actual velocity of sound is ~1,430 m/s or 3 to 5% slower.

Approximately 10 km of side scan sonar records, recording a 200 m swath on either side of the fish, were collected and printed in real time from each field area. The shiptrack was parallel to and within 1 km of the 2001 sediment Ponar sites (Fig. 1). The side scan sonar profiles were collected from nearshore (30–40 m depth) to maximum water depth of ~130 m due to the length of the tow cable. The data were collected using EG&G's AS-600 side scan sonar system with an analog towfish set at a frequency of 100 kHz and a ship's speed of ~ 2 km/h. Higher-amplitude (darker) reflectors correspond to coarser-grained and/or rippled sediments, larger sediment bulk densities, and/or lake floor topographic surfaces that tilt toward the tow vehicle, whereas relatively lighter reflectors corresponding to finer-grained and/or smooth sediments, smaller sediment bulk densities, and/or topographic surfaces that tilt away from the tow vehicle.

Lake floor sediments were collected by Ponar grabs from a total of 25 sites, recovering at least three grabs at each site (Table 1, Fig. 1). The Ponar recovers a 30 × 20 × 15 cm thick block of mud at ideal sites. Stiff clays and sand-rich or coarser sediments hamper sediment recovery. The 2001 sites were visited twice, once in May and again in August, collecting a total of six separate sediments samples from each site. The only exception was the 30 m site, which was only visited in August and thus only had subsamples from three separate sediment grabs. The sediments recovered by each grab were photographed, described, and the upper 2 to 5 cm of mud was subsampled onboard. Sediment subsamples were stored in Ziplock plastic bags and kept refrigerated at 4°C until analysis in the laboratory for grain size, total organic carbon and carbonate analyses. During the 2001 cruise, the upper 5 to 10 cm of sediment was subsampled and homogenized in the baggie. During the 2002 cruise, if a lake floor sand layer was present and at least 1 cm thick, then the sands (top) and the underlying glaciolacutrine muds (bottom) were subsampled and analyzed for the same parameters separately. Once the recovered sediments were described and subsampled, the remaining mud was carefully sieved (500 µm) onboard for enumeration of *Diporeia*, *Dreissena*, and other macroinvertebrates (see Dittman *et al.* 2005 for details).

Grain size, total organic carbon, and carbonate percentages were determined in the laboratory. Percent sand (> 63 µm), silt (63 – 4 µm), and clay (< 4 µm) relative to the dry sediment weight were determined by wet sieving and pipette analysis (Folk 1974). Total organic carbon and carbonate percentages were determined by weight loss on ignition at 550° to burn the organics and then at 1000°C to oxidize the carbonates relative to the dry sediment weight (Dean 1974, Heiri *et al.* 2001). Each sediment subsample was analyzed twice to quantify the precision of the technique. The average and standard deviation of all the analyses from each site are reported (Table 1).

## RESULTS

### High-resolution Seismic Reflection Profiles

The high-resolution seismic reflection profiles differentiate two acoustic sequences in the lake (Fig. 2). The uppermost sequence is characterized by a low-amplitude surface reflector and a number of low-amplitude, parallel to subparallel, internal reflectors. This sequence is 0 to 10 m thick, transitioning from highly-reflective nearshore sands at water depth of ~20 m with no subbottom penetration to poorly-reflective deepwater muds and deepest penetration at water depths shallower than ~100 m. The acoustic character of and sediment samples from this sequence are consistent with postglacial muds recovered in this and many other lakes within glaciated terrains (e.g., Hutchinson *et al.* 1993, Halfman and Herrick 1998, Mullins and Halfman 2001). The underlying sequence typically defines acoustic basement. Where this lower unit is imaged, decimeter-scale, high-amplitude internal reflectors are either parallel to subparallel or chaotic. If both parallel and chaotic reflectors are observed, the parallel reflectors overlie the chaotic reflectors. These acoustic characteristics are typical of glaciolacustrine muds overlying glacial outwash or till in lakes from glaciated terrains with the chaotic package filling underlying kettle holes or other depressions (e.g., Halfman and Herrick 1998, Mullins and Halfman 2001). Glaciolacustrine muds were recovered by Ponar grabs where this lower sequence was exposed at or near the lake floor.

The thickness of the postglacial sequence spans from 0 to just over 10 m offshore of Olcott and from 0 to just over 5 m offshore of Rochester (Fig. 3). A single, high-amplitude, lake-floor reflector was traced from nearshore to water depths of about 25 m. The postglacial sequence then thickens lakeward to their maximum thickness at water depths between 80 and 120 m, thinning over bathymetric highs and thinning over bathymetric lows in the underlying glacial sediments. The postglacial sediments are absent at the Rochester 90 m scarp; presumably the lake floor is too steep for modern sediment accumulation. Farther offshore, the postglacial sediments pinch out to a single, high-amplitude reflector. The single, high-amplitude reflector is detected between water depths of ~110 m and 150 m offshore of Olcott and between ~110 and 160 m offshore of Rochester, except for a few isolated, decimeter-long pods that fill depressions on the underlying floor. The low-amplitude character of the

***TABLE 1. Site averages and standard deviation of duplicate sediment analyses of multiple Ponar grabs at each site. Sites are arranged from nearshore to offshore locations. Bulk/Top/Bottom: Bulk sediment samples were analyzed from each Ponar grab unless separate subsamples could isolate the lake floor sands (top) from the underlying glaciolacustrine muds (bottom).***

| Location | Location (degrees) | | Sand (wt.%) | | | Silt (wt.%) | | | Total Organic Carbon (wt.%) | | | Carbonate (wt.%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth (m) | Latitude | Longitude | Bulk | Top | Bottom | Bulk | Top | Bottom | Bulk | Top | Bottom | Bulk | Top | Bottom |
| **Olcott** | | | | | | | | | | | | | | |
| 01–30 m | 43.35833 | 78.75703 | 5 ± 1 | — | — | 64 ± 11 | — | — | 2.6 ± 0.7 | — | — | 11.6 ± 0.7 | — | — |
| 01–55 m | 43.36983 | 78.75617 | 18 ± 3 | — | — | 64 ± 8 | — | — | 3.9 ± 1.9 | — | — | 12.6 ± 1.1 | — | — |
| 01–75 m | 43.38282 | 78.75002 | 11 ± 2 | — | — | 71 ± 9 | — | — | 3.2 ± 0.4 | — | — | 9.2 ± 0.5 | — | — |
| 01–95 m | 43.39703 | 78.74610 | 13 ± 1 | — | — | 69 ± 3 | — | — | 3.1 ± 0.2 | — | — | 6.6 ± 0.6 | — | — |
| 01–110 m | 43.40915 | 78.74168 | 14 ± 1 | — | — | 67 ± 8 | — | — | 3.0 ± 0.1 | — | — | 6.7 ± 1.3 | — | — |
| 01–130 m* | 43.43903 | 78.76250 | 28 ± 9 | 74 ± 1 | 10 ± 2 | 62 ± 20 | 8 ± 3 | 50 ± 22 | 1.5 ± 0.6 | 0.7 ± 0.0 | 1.3 ± 0.1 | 2.7 ± 0.7 | 1.9 ± 0.0 | 4.4 ± 0.1 |
| 02–130 m* | 43.43913 | 78.76225 | — | 79 ± 1 | 6 ± 1 | — | 9 ± 3 | 56 ± 17 | — | 0.6 ± 0.0 | 1.3 ± 0.1 | — | 2.1 ± 0.6 | 6.0 ± 0.7 |
| 01–150 m* | 43.46960 | 78.72228 | 21 ± 8 | 76 ± 5 | 5 ± 1 | 70 ± 21 | 12 ± 8 | 34 ± 21 | 1.2 ± 0.4 | 0.6 ± 0.0 | 0.9 ± 0.0 | 4.0 ± 2.5 | 1.6 ± 0.1 | 8.5 ± 0.0 |
| 02–143 m* | 43.46998 | 78.82795 | — | 39 ± 12 | 4 ± 1 | — | 59 ± 19 | 87 ± 3 | — | 0.8 ± 0.2 | 1.3 ± 0.1 | — | 2.8 ± 2.3 | 5.4 ± 4.5 |
| 02–144 m* | 43.47595 | 78.79960 | — | 63 ± 14 | 8 ± 2 | — | 24 ± 29 | 74 ± 14 | — | 0.6 ± 0.1 | 1.1 ± 0.1 | — | 2.8 ± 2.6 | 5.1 ± 0.3 |
| 02–148 m* | 43.48175 | 78.77753 | — | 69 ± 2 | 33 ± 6 | — | 13 ± 7 | 49 ± 21 | — | 0.7 ± 0.1 | 1.0 ± 0.2 | — | 2.3 ± 0.1 | 4.6 ± 1.5 |
| 02–154 m | 43.52957 | 78.78947 | — | 6 ± 3 | 4 ± 1 | — | 45 ± 17 | 57 ± 18 | — | 3.4 ± 1.2 | 2.8 ± 0.7 | — | 6.9 ± 1.9 | 5.9 ± 0.8 |
| **Rochester** | | | | | | | | | | | | | | |
| 01–30 m | 43.30220 | 77.56413 | 37 ± 3 | — | — | 43 ± 13 | — | — | 0.9 ± 0.1 | — | — | 6.4 ± 0.3 | — | — |
| 01–55 m | 43.33252 | 77.54940 | 17 ± 4 | — | — | 60 ± 20 | — | — | 2.2 ± 0.9 | — | — | 7.0 ± 0.5 | — | — |
| 01–80 m | 43.35993 | 77.53228 | 55 ± 10 | — | — | 24 ± 10 | — | — | 1.5 ± 0.7 | — | — | 3.5 ± 2.4 | — | — |
| 01–95 m | 43.36543 | 77.52938 | 30 ± 6 | — | — | 56 ± 7 | — | — | 1.1 ± 0.2 | — | — | 2.2 ± 0.6 | — | — |
| 01–95D | 43.38552 | 77.64407 | 55 ± 1 | — | — | 35 ± 1 | — | — | 3.3 ± 0.4 | — | — | 7.4 ± 1.1 | — | — |
| 01–110 m | 43.36803 | 77.52828 | 27 ± 6 | — | — | 52 ± 11 | — | — | 1.8 ± 0.4 | — | — | 3.4 ± 1.1 | — | — |
| 01–130 m | 43.37602 | 77.52213 | 11 ± 3 | — | — | 69 ± 4 | — | — | 2.9 ± 0.3 | — | — | 5.2 ± 1.4 | — | — |
| 01–150 m* | 43.38595 | 77.51603 | 13 ± 3 | 10 ± 1 | 8 ± 1 | 71 ± 12 | 63 ± 4 | 63 ± 6 | 3.2 ± 0.8 | 4.0 ± 0.9 | 2.9 ± 0.3 | 5.3 ± 0.8 | 7.0 ± 1.0 | 5.8 ± 0.3 |
| 02–134 m* | 43.39567 | 77.56723 | 13 ± 3 | — | — | 41 ± 5 | — | — | 2.1 ± 0.4 | — | — | 4.3 ± 0.7 | — | — |
| 02–158 m* | 43.46672 | 77.64832 | 19 ± 8 | 80 ± 4 | 26 ± 15 | 20 ± 25 | 7 ± 1 | 51 ± 34 | 1.4 ± 0.1 | 0.7 ± 0.1 | 1.2 ± 0.3 | 4.0 ± 0.2 | 1.7 ± 0.4 | 3.7 ± 0.2 |
| 02–164 m* | 43.50010 | 77.68673 | 16 ± 6 | — | — | 28 ± 4 | — | — | 2.1 ± 1.1 | — | — | 4.6 ± 0.3 | — | — |
| 02–160 m* | 43.53417 | 77.72412 | 7 ± 2 | — | — | 52 ± 29 | — | — | 1.5 ± 0.2 | — | — | 4.1 ± 0.1 | — | — |
| 02–150 m* | 43.57535 | 77.77460 | 32 ± 12 | — | — | 38 ± 11 | — | — | 3.9 ± 0.9 | — | — | 12.2 ± 5.7 | — | — |

no sample
*winnowed sites

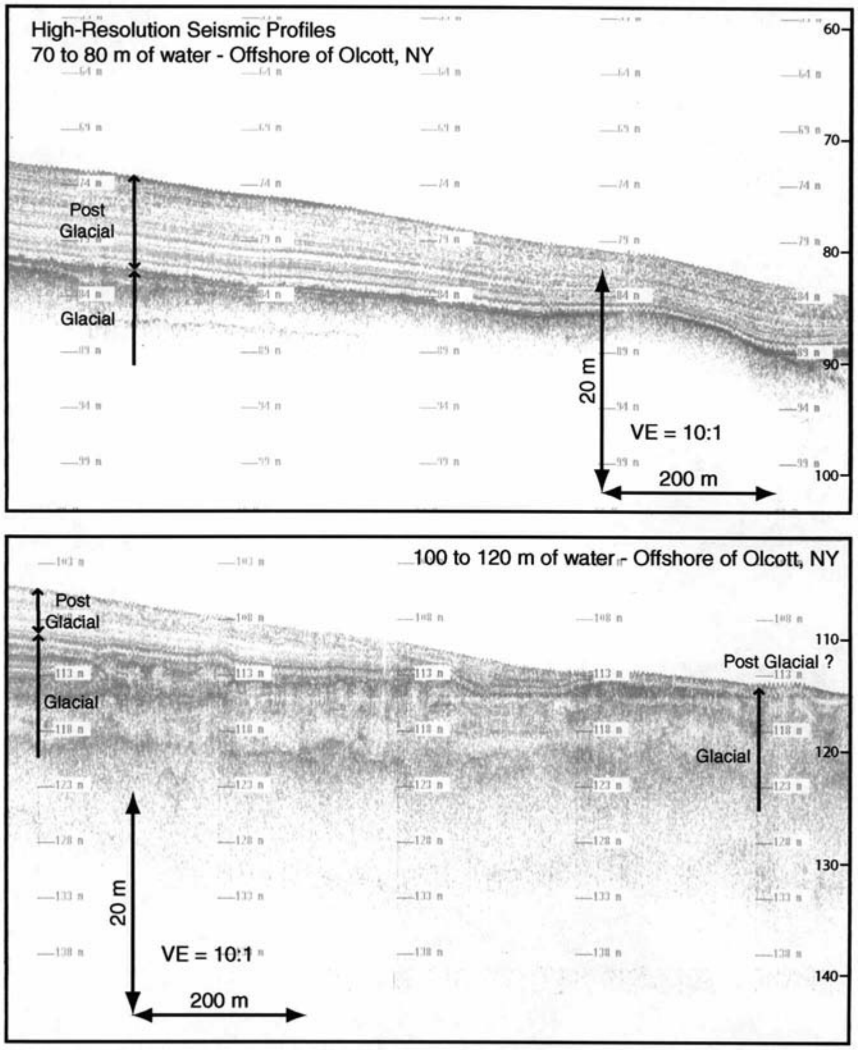


***FIG. 2. Representative high-resolution seismic profiles from offshore of Olcott, NY, along a north-northeasterly shiptrack, nearly perpendicular to the bathymetric contours. The first high-amplitude acoustic reflector below the lake floor is interpreted as the base of the postglacial sequence. Top: A profile from 70 to 80 m of water revealing the thick accumulation of postglacial muds. Bottom: A profile from ~100 to 110 m of water revealing the thinning of postglacial sediments to deeper water. Depths assumed a conventional speed of sound of 1,500 m/s.***

isolated pods is similar to the postglacial muds sampled elsewhere.

### Side Scan Sonar Profiles

Side scan sonar profiles reveal a nearshore to offshore transition of higher to lower amplitude background scatter, with occasional acoustic backscatter anomalies and lineations in water depths greater than 90 m (Fig. 4). The high to low amplitude transition from shallow water to 90 m parallels the observed decrease in surface sediment acoustic reflectivity and the increase in postglacial sediment thickness observed in the high-resolution seismic reflection data.

Acoustic backscatter anomalies (ABAs) were superimposed on the background scatter. These ABAs

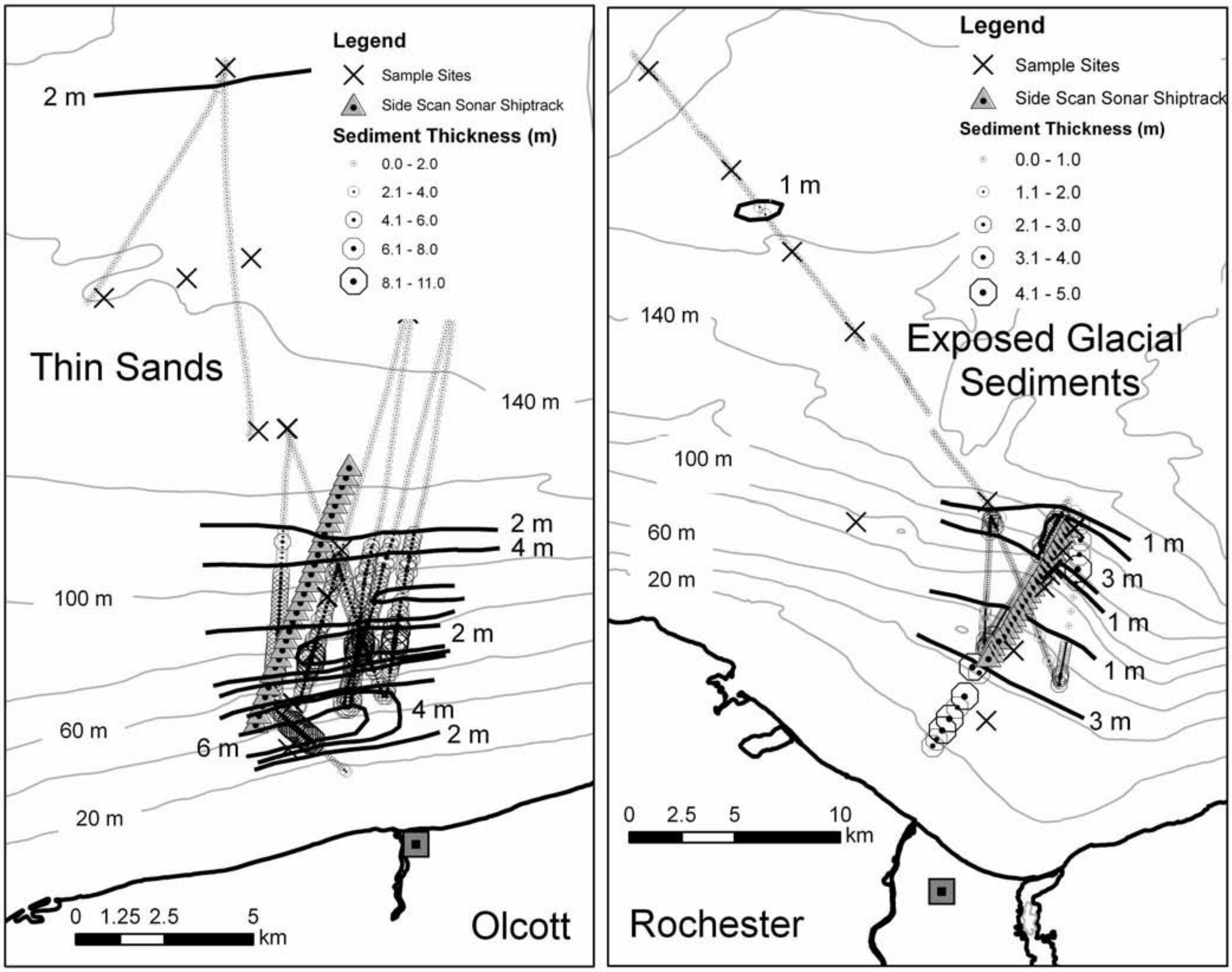


***FIG 3. Postglacial sediment thickness maps in the survey area. Both areas reveal thin, if any, postglacial sediments in the deepwater portions of the surveys. Left/Right: Sediment thickness data offshore of Olcott and Rochester, respectively (2 m contour interval).***

were up to 5 to 10 m across, irregular to oval in shape, and did not reveal any topographic relief at the displayed scale and frequency of sound. Up to 15 or 20 ABAs are observed over an area of 250 $m^2$, typically in random distributions. These acoustic backscatter anomalies (ABAs) may be patches of ship-derived debris (coal, taconite and/or coal clinkers) or patches of *Dreissena* spp. The former were observed in side scan data, ROV images and box cores from the western portion of Lake Ontario (Ferrini and Flood 2001) under shipping lanes. However, our study areas are removed from major shipping lanes and clinkers were not abundant in the sediment grabs collected in this study. Our grabs recovered 0 to a few thousand individuals/$m^2$ *Dreissena* spp. in water depths greater than 75 m (Dittman *et al.* 2005). The observations indicate that the ABAs in these surveys are most likely patchy groups of *Dreissena* spp. ABAs in eastern Lake Ontario also have been attributed to patch distributions of *Dreissena* spp. (Charles McClennen, personal communication).

Lineations were observed in the records at water depths of 90 m to the deepest portion of the side-scan sonar survey (~130 m). These lineations are parallel or slightly subparallel to the bathymetric contours

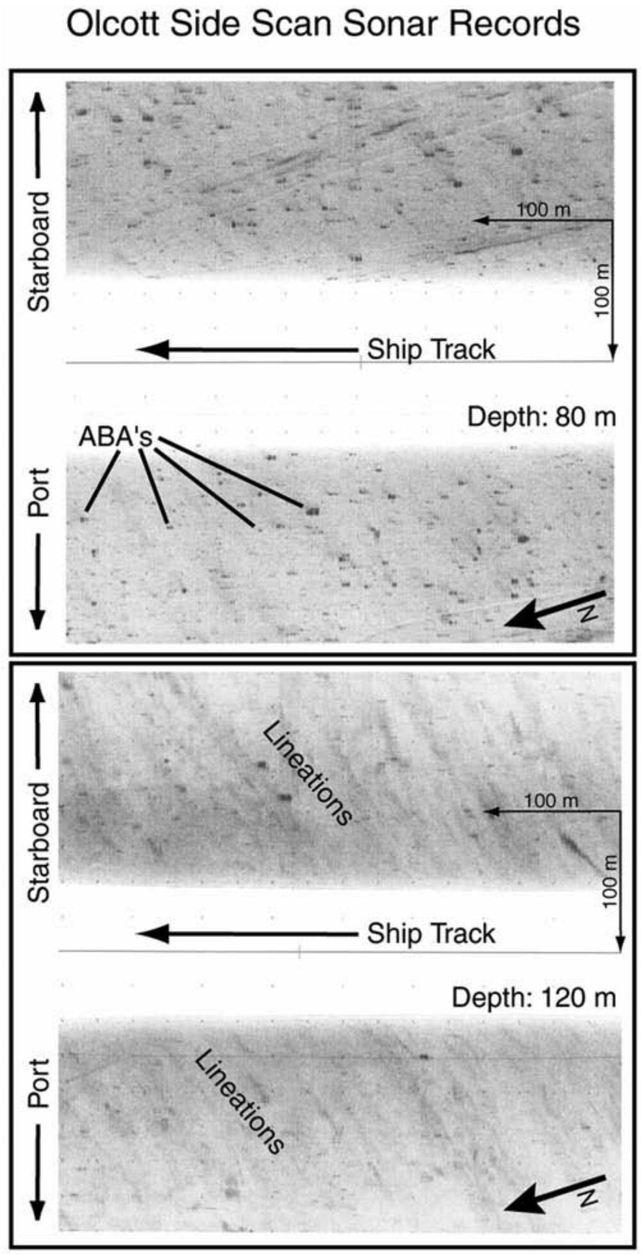


***FIG. 4. Representative side scan sonar profiles from offshore of Olcott, NY. Top/Bottom: A nearshore profile in a water depth of 80 m, and an offshore profile at 120 m, respectively. The deepwater profile reveals well-developed lineations along the lake floor that are indicative of bottom current activity.***

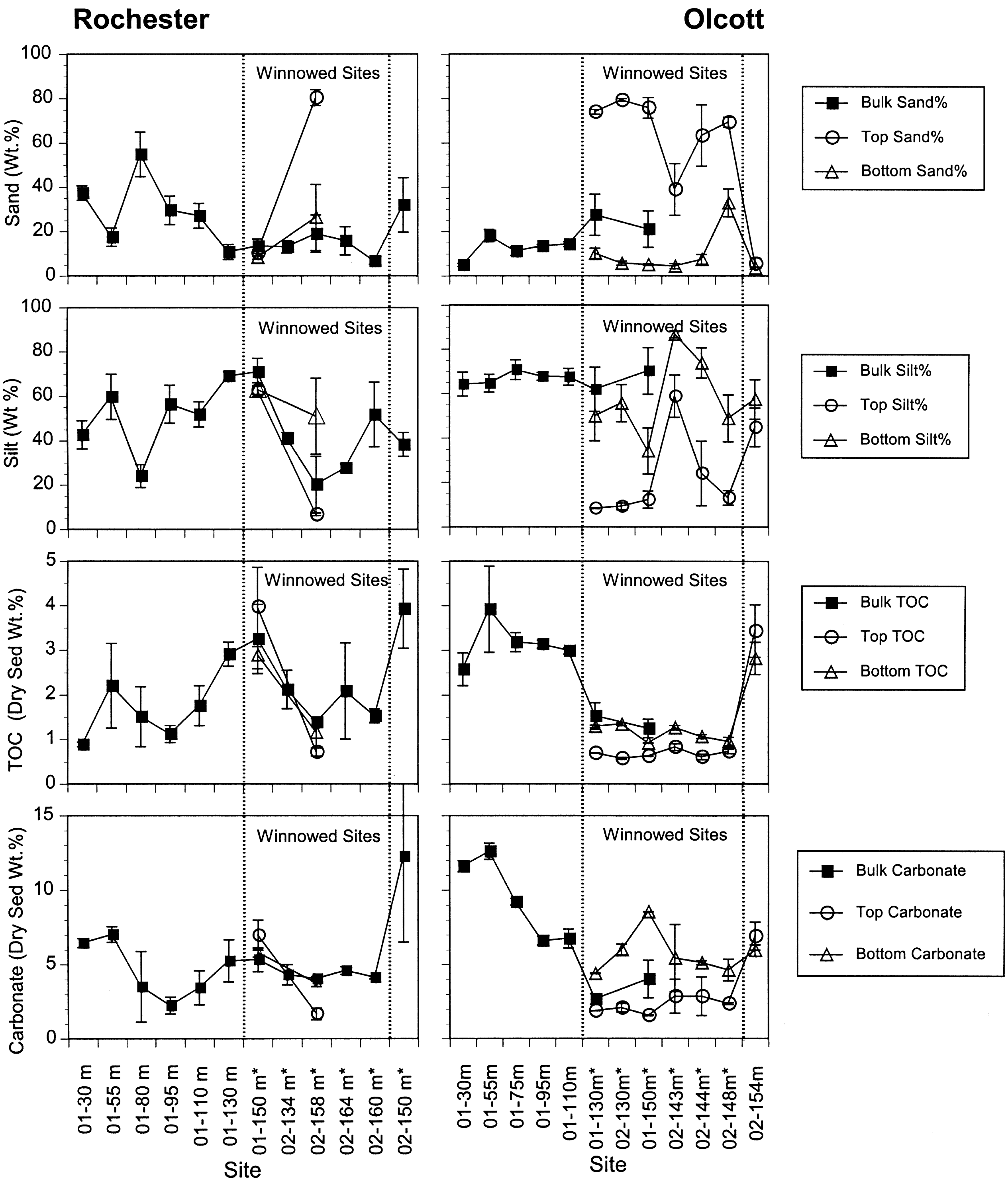
and lack discernable bathymetric relief at the displayed scale and frequency of sound. The lineations are more pronounced towards deeper water along both profiles, and are more pronounced offshore of Olcott than Rochester at the same water depths.

### Sediment Analyses

The sediments recovered by the Ponar grabs grade from stiff sandy silts at 30 m to olive-gray, flocculent (water-rich) muds at 80 to 120 m. This transition parallels the absent to 5–10 m thick postglacial sediment transition, the high to low amplitude surface reflection, and published trends (e.g., Thomas *et al.* 1972). In contrast, the sediments recovered at 130 m and farther offshore of Olcott (Sites 01-130 m, 01-150 m, 02-143 m, 02-144 m, 02-148 m, and 02-154 m) revealed a 1 to 5 cm thick, lake floor sand layer overlying stiff glaciolacustrine silty clays. The sands were massive, lack graded bedding, and the basal contact was sharp. The sands at Site 02-154 m, the site farthest offshore of Olcott, contained more silt and was a few cm thicker than the other deepwater sands. The Rochester sediment samples lakeward of Site 01-150 m also recovered minimal, if any postglacial sediment. The grabs typically recovered up to 100 sand grains, dispersed on top of stiff and eroded (dimpled surface) glaciolacustrine silty clays. Sites 01-150 m and 02-158 m recovered a lake floor sand layer, ~1 cm thick, overlying the glaciolacustrine muds.

Site averaged grain size of the surface sediments ranged from silty sands to clayey silts with sand percentages ranging from 3 to 80%, silt from 8 to 86%, and clay from 9 to 61% (Table 1, Fig. 5). The standard deviation of the sand percents at each site ranged from < 1 to 15%. The average standard deviation is 3% after excluding the standard deviations from the deepwater sites as these subsamples may have mixed different percentages of sand and underlying glaciolacustrine clays. Among the Olcott sites, sediments with the largest sand concentrations were detected in the sand layers recovered from the 130 m and deeper sites, and the smallest sand concentrations were detected in the underlying glaciolacustrine muds. Among the Rochester sites, the largest sand concentrations were detected in the sediments shallower than 110 m, at Site 02-160 m, and from the surface sand lens recovered at Site 02-158 m. The percent clay and silt data lacked spatial trends and lacked significant correlations between each other, except significantly less clay and silt was detected in the deepwater sand lenses.

Site averaged total organic carbon concentrations ranged from 0.6 to 4.0% (Table 1, Fig. 5). The standard deviation of the TOC concentrations at each site ranged from 0.1 to 1.3%. The largest deviations at any one site were detected in the nearshore sites



Nearshore <=======> Offshore

*FIG. 5. Average grain size (sand wt. % and silt wt. %), total organic carbon content (dry wt. %), and carbonate content (dry wt. %) at each Ponar grab site. Left/Right: Graphs of the sediment data from offshore of Rochester and Olcott, respectively. Bulk/Top/Bottom: Bulk sediment subsampled from each Ponar grab or separate subsamples isolating the lake floor sand (top) and underlying glaciolacustrine mud (bottom). Averages and standard deviations of the duplicate analyses of multiple sediment grabs at each site are shown. The sites, from left to right, correspond to nearshore to offshore locations at each survey area. The winnowed designation and, e.g., 01-150 m* asterisk, identifies those sites influenced by bottom currents.*

and Site 02-154 m, and may reflect TOC patchiness at the site. Among the Olcott sites, the largest TOC concentrations were detected in the sediments shallower than 100 m, and the farthest offshore site (Site 02-154 m). Among the Rochester sites, TOC increased slightly from 30 to 150 m and then returned to lower values in the sites farther offshore. The exception was at Site 02-150 m, the site farthest from the survey area with TOC concentrations similar to the largest values along the 30 to 150 m transect. Each deepwater sand had less TOC than the underlying glaciolacustrine clays by approximately 0.5%, except at Site 02-154 m and 01-150 m offshore of Olcott and Rochester, respectively.

Site averaged carbonate concentrations ranged from 1 to 13% (Table 1, Fig. 5). The standard deviation of the carbonate concentrations at each site ranged from < 0.1 to 4.5%, and lacked spatial trends. Offshore of Olcott, the carbonate concentrations decreased with water depth until the deepest water sites. Offshore of Rochester, carbonate concentrations did not change in a systematic manner. Each deepwater sand lens, when present, had approximately 3% less carbonate than the underlying glaciolacustrine clays, except at the site farthest offshore of Olcott (Site 02-154 m) where carbonate was 1% larger in the sand lens, and Site 01-150 m offshore of Rochester. Carbonate content weakly co-varied with TOC content ($r^2 = 0.53$).

## DISCUSSION

The classic lacustrine depositional model dictates that nearshore sediments are winnowed of fine-grained, TOC-rich materials by surface waves and epilimnetic currents leaving behind coarse, TOC-poor sediments. The winnowed material is selectively deposited below wave base as thick, undisturbed, accumulations of TOC-rich muds (Thomas *et al.* 1972, Kemp and Harper 1976, Sly 1980, Rea *et al.* 1981, Johnson 1984). In Lake Ontario, the nearshore sediments offshore of Olcott are also influenced by easterly transport of Niagara River sediments due to the strong, storm-induced, eastward flowing currents that occasionally extend down to water depths of 100 m when the lake is isothermal (Scrudato and DelPrete 1982, Hawley *et al.* 1996). The sediments from 30 to 100 m at Olcott and 30 to 130 m at Rochester follow this general pattern, especially if the previously published data from the deepest basins in the lake (thickness > 12 m, silty clays, 4 to 5% TOC) are included. However, the deepwater sediments from 130 to 155 m offshore of Olcott and 140 to 160 m offshore of Rochester consisting of thin, if any, postglacial sediments, lake floor sediment lineations, sand lags over glaciolacustrine clays, and small TOC concentrations are clearly anomalous to the overall trend and the focus of this discussion.

Previous workers speculated without elaboration that these offshore sites may be sediment starved (e.g., Thomas *et al.* 1972, Kemp *et al.* 1974, Kemp and Harper 1976, Hutchinson *et al.* 1993). In support, they noted the minimal accumulations of postglacial muds at these sites and indicated that these sites are located along "sills" between the Niagara, Mississauga, and Rochester basins. They proposed that the bathymetric relief was sufficient to prevent the accumulation of postglacial sediments. However, their bathymetric data revealed more relief than more recent data (Virden *et al.* 1999).

We propose that the thin (1 to 5 cm-thick), massive, sand-rich postglacial sediment implies sediment deposition and subsequent reworking at these deepwater sites. Fine-grained organic rich sediments are accumulating at shallower and deeper water depths. The accumulation of sands and pods of postglacial muds in the area suggests postglacial sediments are deposited in the area as well. It indicates that the fine-grained, organic rich materials must be removed from these sites, except from isolated depressions on the lake floor, to leave behind the sands. The areas with no postglacial sediments offshore of Rochester revealed dimpled glaciolacustrine muds and a dusting of sand grains at the surface, indicative of active and perhaps more intense erosion offshore of Rochester than Olcott. Finally, the lineations in the side scan sonar profiles are consistent with sediments that are reworked and winnowed by bottom currents. Bottom currents leave ribbons of coarser sediments, with the lineations parallel to the current flow (e.g., Flood 1981, Flood and Johnson 1984). More ribbons were detected offshore of Olcott, because Olcott had more sand on the lake floor to be modified by bottom current activity. The lineations increased in intensity toward the deepest portion of both transects, and imply more intense reworking of the lake floor toward progressively deeper water. This interpretation is consistent with the high-resolution seismic data and recovered sandy or missing postglacial sediments, and thus extends the anomalous character of the sediments lakeward through the remainder of both transects.

Resuspension by surface and/or internal waves or associated epilimnetic currents brought about by large storms is an unlikely means to impact sedimentation at these deepwater sites. The nearshore transition between the single, hard reflector to discernable postglacial sediments occurs at water depths of ~25 m, and suggests that surface waves and current activity decreases its influence on the lake floor at these water depths. This water depth is consistent with models of wave erosion based on the effective fetch, water depth, and typical storm-induced winds in Lake Ontario (e.g., Johnson 1980). The accumulation of thicker and more flocculent sediments at 80 to 100 m suggests that surface and/or internal waves and other surface processes do not influence the lake floor at these and deeper sites. Neither is ice-rafted debris nor fish burrows consistent with these continuous, thin, massive, sandy sediments, and the lake floor lineations. No ice-rafted dropstones were observed, nor were burrow structures detected in the side scan sonar and Ponar grab samples.

Evidence for post-depositional reworking of sediments at water depths significantly below the summer thermocline is expanding in the literature. For example, wavy bedforms, sediment thinning, and other features suggest that bottom currents are active in Lake Malawi despite the permanent water-column stratification in these lakes (Johnson and Ng'ang'a 1990). The majority of the deepwater sands, gravels, and erosional channels on the lake floor, however are the result of turbidity current activity (Scholz *et al.* 1993, Soreghan *et al.* 1999). Turbidites are not consistent with the Lake Ontario deepwater sands, as the sands do not reveal graded bedding. They lack a significant sediment source, the lake floor lacks distributary channels closer to shore, and distal turbidites are not reported from the sediments recovered from the deepest basins of the lake.

Bottom contour-current modified structures were found along the deep lake floor (> 200 m of water) just north of the Keweenaw Peninsula in Lake Superior (Flood and Johnson 1984, Johnson *et al.* 1984, Viekman *et al.* 1992). The authors proposed that the strong surface currents offshore of the peninsula generated by major storms may extend down to the lake floor and winnow and resuspend the sediments when the lake is isothermal. We suggest a similar but slightly modified scenario to influence the deepwater sediments at our two survey sites. Specifically, we hypothesize that surface currents generated by major storms in Lake Ontario extend down to the lake floor at these deepwater sites, reworking and winnowing the lake floor sediments when the lake is isothermal. However, an offshore extension of the coastal current system is an unlikely mechanism for the sediment reworking at 130 and 150 m in Lake Ontario because sediments are meters thick and thus less influenced by bottom current activity in shallower water between these sites and the coastal current system.

Theoretically, wind stress sets into motion a two-gyre surface flow in Lake Ontario (Csanady 1978). The gyre locations are dictated by the geometry of the basin and bathymetry of the lake floor. In Lake Ontario, both gyres flow eastward along the northern and southern shorelines of the lake and the return limbs combine, intensify, and flow westward down the middle and deepest reaches of the lake. Current meter records, along with geophysical and sedimentological evidence from the nearshore regions, confirm the nearshore flow of these gyres (e.g., Lewis and Sly 1971, Sutton *et al.* 1970, Rukavina 1976, Simons *et al.* 1985). However, current meter measurements are lacking offshore along the lake floor. Models of current flow indicate that the location for the westward return flow follows the deepest portions of the lake and travels over the deepwater sites in our two study areas (Csanady 1978), and are supported by mean circulation patterns observed in surface-water current meter records (Beletsky *et al.* 1999).

Benthic nepheloid layers and resuspension of bottom sediments have been detected in Lake Ontario and the other Great Lakes (e.g., Mudroch and Mudroch 1992, Sandilands and Mudroch 1983, Eadie *et al.* 1984, Rosa 1985, Hawley *et al.* 1996). In Lake Ontario, the height and suspended sediment concentration of the benthic nepheloid layer increased from the summer to the early winter months. The trend suggests that the seasonal decay of the thermocline and associated water column stratification coupled with lower biological productivity and increased frequency and intensity of storm activity as time progresses into the winter months may promote lake floor resuspension of the sediments. In fact, storm-induced bottom sediment resuspension events were documented for western Lake Ontario due to easterly nearshore currents in water depths down to 100 m when the lake was isothermal (Hawley *et al.* 1996). Therefore, the sedimentologic evidence suggests that westward flowing surface currents extend from the surface to the lake floor during larger storms when the lake is isothermal, and the events are sufficient to occasionally resuspend and rework sediments in the study area. Furthermore, the sedimentological evidence suggests that these deepwater currents have the largest influence on sediment accumulation and redistribution at the "sill" locations in this survey. Perhaps these currents intensify while constricted over these sills between the deepest basins of Lake Ontario.

## CONCLUSIONS

High-resolution seismic profiles, side scan sonar profiles, and sand-rich sediment lags or no postglacial sediment accumulation indicate that bottom currents resuspend and rework the sediments at the deepwater sills that separate the deepest bathymetric basins of Lake Ontario. We hypothesize that the suspected bottom currents result from the western confluence of the two-gyre surface current system in the lake that extends down to the lake floor and influences sedimentation processes at these deepwater sites when the lake is isothermal during storm-driven events.

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