MASS MOVEMENT AND REWORKING OF LATE GLACIAL AND POSTGLACIAL SEDIMENTS IN NORTHERN SENECA LAKE, NEW YORK

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ABSTRACT: Over 100 km of high-resolution (2-12 kHz) seismic reflection profiles, collected during 1995 and 1996 from northern Seneca Lake, the largest Finger Lake in central New York, are used to delineate the upper stratigraphy, as well as depositional and erosional processes in the survey area. Four main acoustic packages were identified in the upper 30 meters of section based on acoustic character and correlation with short (1 to 3 m) piston cores and surface grab samples where the sequence was close to or outcropped on the lake floor. Sequence 1 and 2 are interpreted as glacial drift and proglacial rhythmites (pink clays), respectively. They are believed identical to sequences III and IV described by Mullins et al. (1996). Sequence 3, differentiated with our higher-resolution equipment for the first time, is interpreted as mass-movement deposits of the proglacial rhythmites. These mass movement events occurred during the waning phases of deglaciation (~ 14 ka). Sequence 4 images the overlying massive brown muds and younger postglacial sediments. Mullins et al. (1996) placed these two lithologies into two separate sequences, V and VI, however one sequence is more consistent with our seismic profiles and minimal sediment variability at the brown mud / postglacial mud contact. Holocene marls, although rare, are detected in water depths less than 20 meters and are associated with gas (biogenic methane?) wipeouts on the seismic sections.

The seismic profiles reveal erosional truncation of reflections at the lake floor to water depths of 50 to 60 meters. The erosional truncation is interpreted to reflect: (1) wind-driven surface waves and currents in shallow-water regions (<20 m water depth); (2) currents related to internal seiche activity along the thermocline in isolated deep water regions (down to 60 m); (3) mass wasting and gravity slides along the steep slopes that descend to the flat lake floor; and, (4) subaerial erosion during a hypothesized lowstand of Seneca Lake. Unfortunately, chronologic control is lacking to determine the timing of the lowstand event.

INTRODUCTION

High-resolution seismic reflection surveys are indispensable to investigate sedimentation processes in large lakes that often exhibit complex depositional histories (e.g., Johnson et al. 1987; Scholz and Rosendahl 1988; Shilts and Clague 1992; Scholz et al. 1993; Mullins et al. 1996). These findings impact numerous fields of study. For example, rapid facies transitions impact the exploitation of ancient sequences for their economic potential, and the dynamics of many pollutants like heavy metals, PCB's and DDT. Lake deposits are also important archives of climatic change, because they are typically more continuous and easier to date than other continental paleoclimatic proxies.

Surprisingly, no seismic surveys with the vertical resolution presented here are in the literature from the Finger Lakes of New York besides the deep-penetration (up to 300 m) Uniboom (1 kHz) surveys of Stephens (1986), Mullins and Hinchey (1989), and Mullins et al. (1996). In this paper, we present first-order results of high-resolution (2-12 kHz), shallow-penetration (up to 30 m) seismic reflection profiles of the sediments accumulating in northern Seneca Lake, and begin to address the paucity of high-resolution subsurface geophysical data from the Finger Lakes, refine our knowledge of the late glacial to recent history of the basin, and investigate the extent of post-depositional reworking of the sediments in the basin.

SENECA LAKE - GEOLOGIC SETTING

Seneca Lake is the largest (by volume) and deepest of the eleven elongated Finger Lakes in central New York (Fig. 1). It is approximately 57 km long and 5 km wide with a maximum depth of 186 m. The basin is eroded into Devonian shales and carbonates that dip gently to the south. Large-scale glacial erosion aided by large volumes of glacial meltwater has been hypothesized as the erosional agents for these basins (Coates 1968). Recent Uniboom seismic data are consistent with the later hypothesis, i.e., large volumes of southward flowing glacial meltwater confined beneath the retreating Laurentide Ice sheet first scoured the lake basins in the Finger Lakes region, then filled in the basins with ice-proximal and distal sediments (Stephens 1986; Mullins and Hinchey 1989; Mullins et al. 1996).

Short cores and grab samples reveal a number of sediment types within the basin (Woodrow et al. 1969; Woodrow 1978; Mullins et al. 1996). Glacial drift, poorly sorted and unstratified coarse materials (sands), and pink to gray, organic-poor, laminated (cm-scale) muds, that are interpreted as proglacial rhythmites (pink clays), outcrop in the northern and other shallow-water margins of the basin. Lacustrine marls, muds with photosynthetically induced microcrystalline carbonate, shells and plant fragments are also observed in the littoral zone. The deep, flat-floored basin contains olive-gray to black, laminated, fossil poor, organic rich muds. Massive brown muds are observed between the postglacial sediments above and pink clays below, where the postglacial sequence is condensed enough to recover older sediments. Occasionally the recovered pink clays are folded, faulted and chaotic, suggesting post-depositional flowage or disturbance by coring (Woodrow et al. 1969; Ciszkowski 1996).

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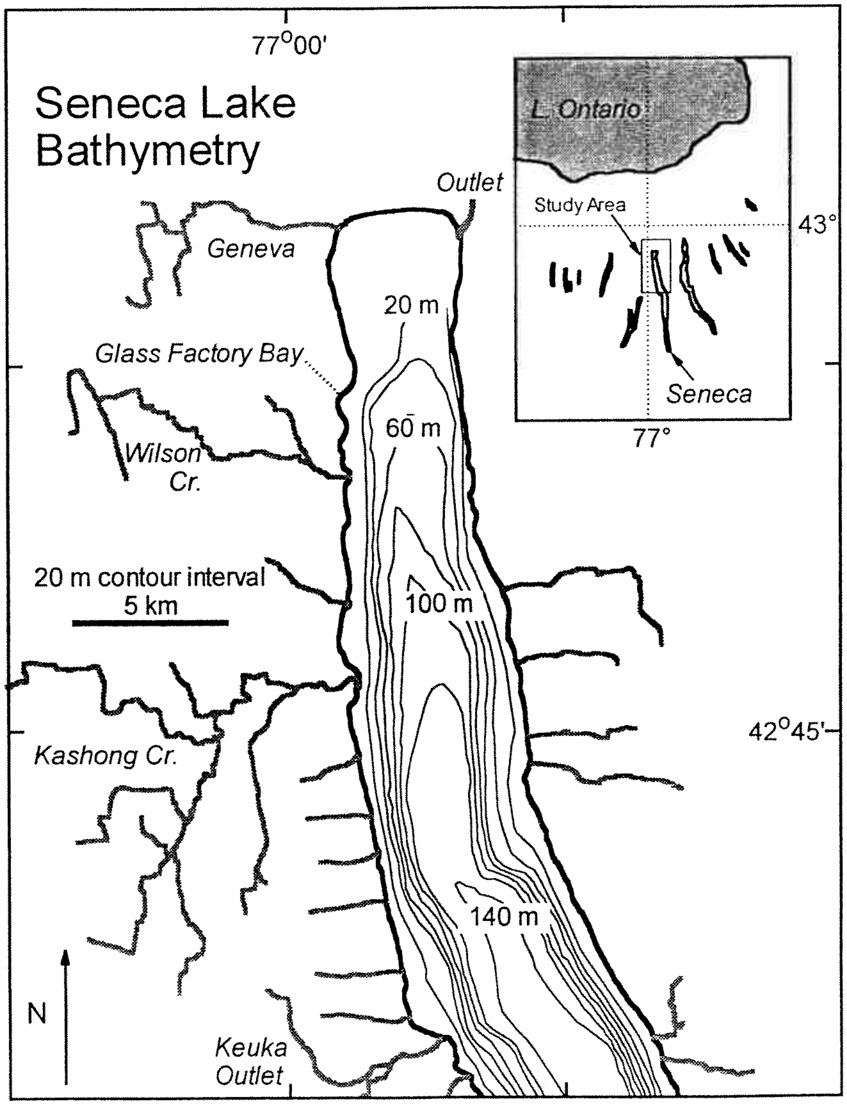

Figure 1. Bathymetric map of the northern half of Seneca Lake (modified from Mullins et al. 1996). The insert shows the location of Seneca Lake and the study area in relation to the other Finger Lakes and Lake Ontario.

Uniboom seismic profiles reveal up to 270 m of sedimentary fill in Seneca Lake (Stephens 1986; Mullins and Hinchey 1989; Mullins et al. 1996). The profiles are interpreted to represent late glacial sediments with a relatively thin (< 10-15 m) cover of postglacial sediment based on acoustic character and correlation to short piston cores and on-land drilling (Wellner et al. 1996). Within the sedimentary package, six seismic stratigraphic sequences are identified in Seneca Lake that are contemporaneous to the sedimentary fill in the other Finger Lakes (Mullins et al. 1996). The lower three sequences (I – III) are ice-contact and water-lain sands and gravels that fine upward to ice-proximal lacustrine muds related to the retreat of the Laurentian Ice Sheet from the Valley Heads Moraine (~ 14.4 ka) at the southern margin of the lake to the Geneva Moraine at the northern edge of the lake. The fourth sequence (IV) is correlated to the pink clays, and was deposited during a proglacial, high lake-level phase when the ice front blocked today's outlets to the north. The ice front subsequently retreated farther to the north beyond the northern limit of the drainage basin and exposed a lower outlet to the north. Subsequent rapid lowering of lake level to near modern day levels triggered the deposition of sequence five (V), the profundal brown muds. The uppermost, sixth, sequence (VI) is interpreted as postglacial muds that have accumulated in the lake following the establishment of "modern" lake levels and drainage. Mullins et al. (1996) estimated that the glacial sediments were deposited from approximately 14.4 ka to 13.9 ka (radiocarbon years). The older date estimates the stratigraphic onlap of younger sediments onto the Valley Heads Moraine. The younger date is based on a radiocarbon-date near the contact between the brown muds and younger postglacial sediments.

The present day lake floor gradually deepens from north to the south in the survey area (Fig. 1). Transverse profiles gently deepen to the central portion of the lake to the north of Glass

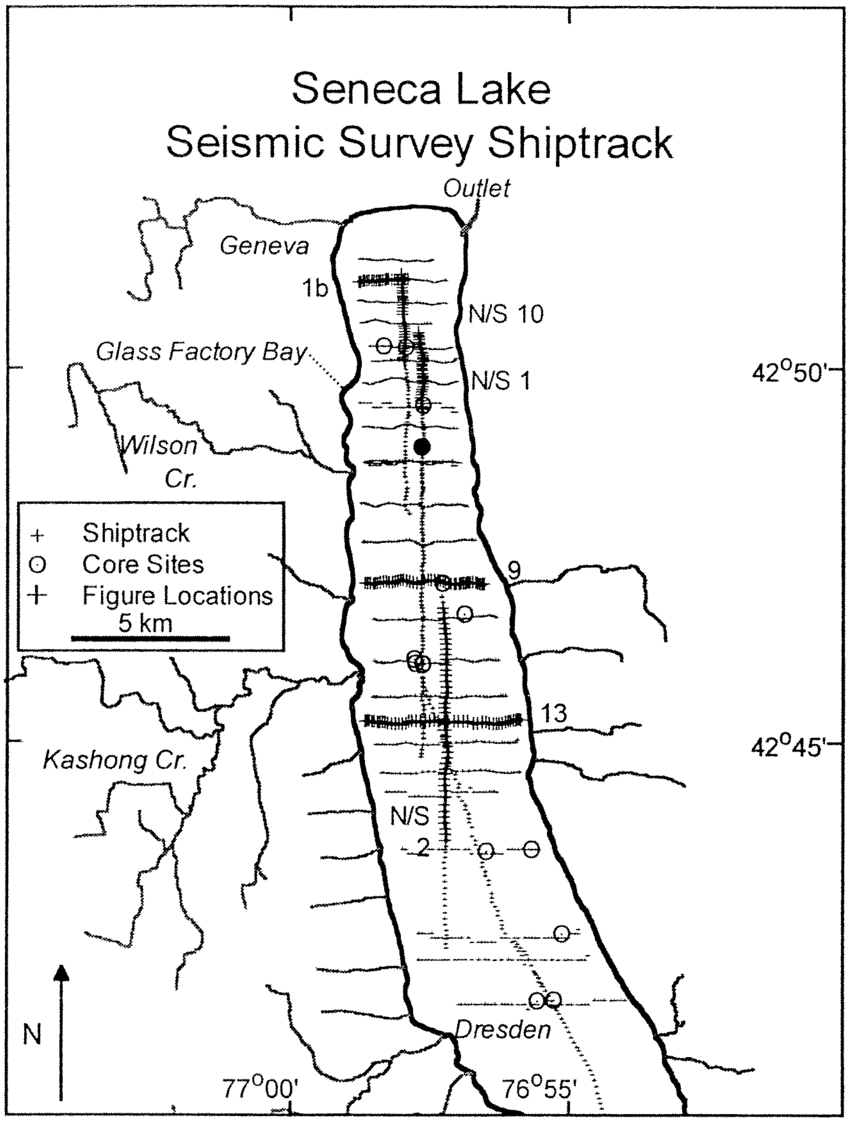

Figure 2. Trackline and piston core site map. Locations of profiles illustrated in subsequent figures are identified by profile number. The solid circle identifies the core site that recovered deformed pink clays discussed in the text.

Factory Bay. Farther south, the lake bottom gently deepens in nearshore locations, then abruptly descends to a flat-lying, deep-water basin in the central part of the lake. A grade of 10% or more for the steepest slopes is not uncommon south of Wilson Creek. The present day U-shaped lake-bottom topography is interpreted to reflect glacial meltwater erosion of the bedrock into a V-shaped basin, the bedrock forming the steep walls of the present day basin. Subsequent deposition of glacial and postglacial sediments within the basin formed the relatively flat lake floor (Stephens 1986; Mullins and Hinchey 1989).

METHODS

Over 100 km of high-resolution seismic reflection data were collected from the northern portion of Seneca Lake using EG&G's (EdgeTech) X-Star subbottom profiling system that employs chirp technology, sweep frequencies of 2 to 12 kHz and a SB-216S tow vehicle. The survey grid consists of 25 east-west oriented (E/W), transverse lines (~1 km separation), and 5 north-south oriented (N/S), longitudinal lines (Herrick and Halfman 1996; Fig. 2). The signal was digitally recorded on magnetic (DAT) tape. Profiles were plotted on an EPC graphic recorder (Model GSP-1086) with a time-varying gain that increased linearly (0.4 dB/m) below the lake floor. Besides data playback at two different scales, no additional post-cruise processing was performed. The fish was towed approximately 3 to 5 meters below the water's surface at approximately 1.5 to 2 meters/second (3 to 4 knots). Navigation fixes supplied by shipboard satellite navigation (non-differential GPS) were recorded with each seismic trace.

The X-Star system typically resolves reflections in the upper 30 to 50 meters of the sediment column with a decimeter-scale

Table 1. Seneca Lake High-Resolution Acoustic Sequences.

Sequence	Acoustic Character	Sediment Correlation	Seismic Sequence Correlation*
4	Low-amplitude surface and low-amplitude internal reflections Onlaps onto older sediments Extensively reworked by waves, currents and internal seiche activity in shallow water (< 60 m) settings	Postglacial Muds & Brown Clays	Sequence VI & Sequence V?
3	Transparent packages with intermediate-amplitude surface reflections Restricted to deepest basin	Mass-Movement of Pink Clays	Not previously differentiated (Sequence V?)
2	High-amplitude subparallel to parallel reflections on decimeter scale Typically acoustic basement is within this sequence.	Proglacial Rhythmites locally known as Pink Clays	Sequence IV
1	High-amplitude surface reflection with local internal point reflectors.	Glacial Drift	Sequence III
Other	Transparent package with gas wipeouts and strong water-bottom multiples	Nearshore marls	No previous delineation

*from Mullins et al., 1996.

vertical resolution. Penetration depth; however, also depends on the physical properties of the subbottom sediments. Sediment thicknesses and water depths discussed in the text and displayed on the figures assume a water-column sound velocity of 1.5 km/s measured from the tow fish. However, the actual speed of sound in water may be as low as 1.455 km/s and as high as 2.0 km/s for the oldest sediments detected in our profiles (Mullins et al. 1996).

Grab samples and short (< 3 m), 3.4-cm diameter, piston cores were collected along selected profiles (Fig. 1). These sediments were lithologically described and sediment cores analyzed for magnetic susceptibility, carbonate content, organic carbon content and water content for purposes of correlation of the different acoustic packages and internal reflections to the sediment lithologies and other variations in the sediments. Magnetic susceptibility was measured every 2 cm down unopened cores using a Bartington Instruments MS-2 meter and a MS-2C, low-field, 7-cm diameter, 2-cm wide loop sensor. Water content was measured every 6 cm down core, determined by weight loss after freeze drying and reported as percentage of the wet mud. Total organic carbon and bulk carbonate were measured using the freeze-dried samples, determined by "loss on ignition" at 550°C and 1000°C, respectively, and reported as a percentage of the dry sediment (Dean 1974). Multiple (2 to 5) measurements at selected depths for both "loss-on-ignition" techniques were within 0.2% of the mean value at that depth (Ciszkowski 1996).

RESULTS AND DISCUSSION

The seismic profiles reveal a variable sediment thickness from zero to over 30 m of sediment in the area surveyed. The thinnest sediment accumulations in the survey area are in shallow-water areas and along the steep slopes that descend

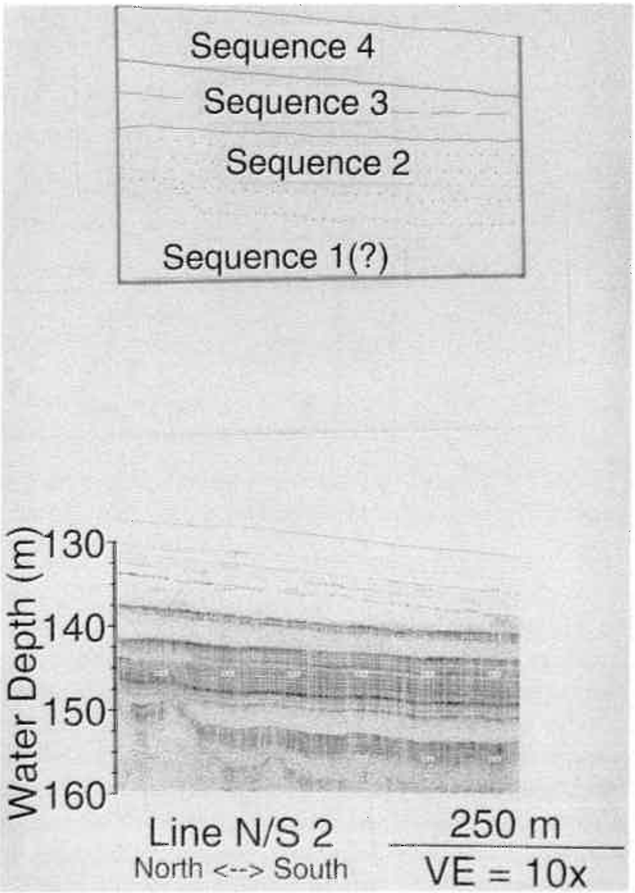

Figure 3. An example of the upper three seismic sequences discussed in the text from profile N/S 2. See Figure 2 for profile location for this and subsequent figures. The line drawings in this and subsequent figures outline the major sequences identified in the text and are drawn to the same scale as the profile.

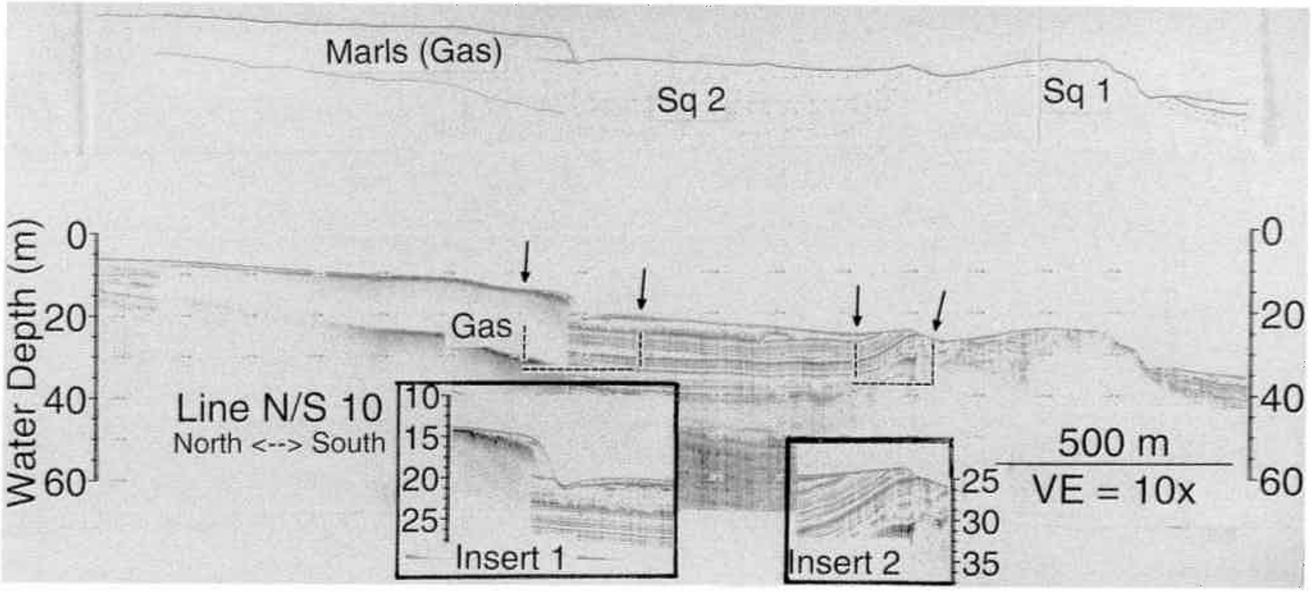

Figure 4. Profile N/S 10 reveals glacial drift (Sequence 1) outcropping at the southern side, erosional truncation of pink clays (Sequence 2), gas at the northern side and a bathymetric scarp in the middle of the profile. Postglacial sediments (Sequence 4) onlap onto older sediments at the extreme southern end of the profile. Insert 1 (scarp) and Insert 2 (truncation of the pink clays) are enlarged at exactly twice the scale of the main profile. The boxes and arrows on the main profile indicate the location of the respective inserts.

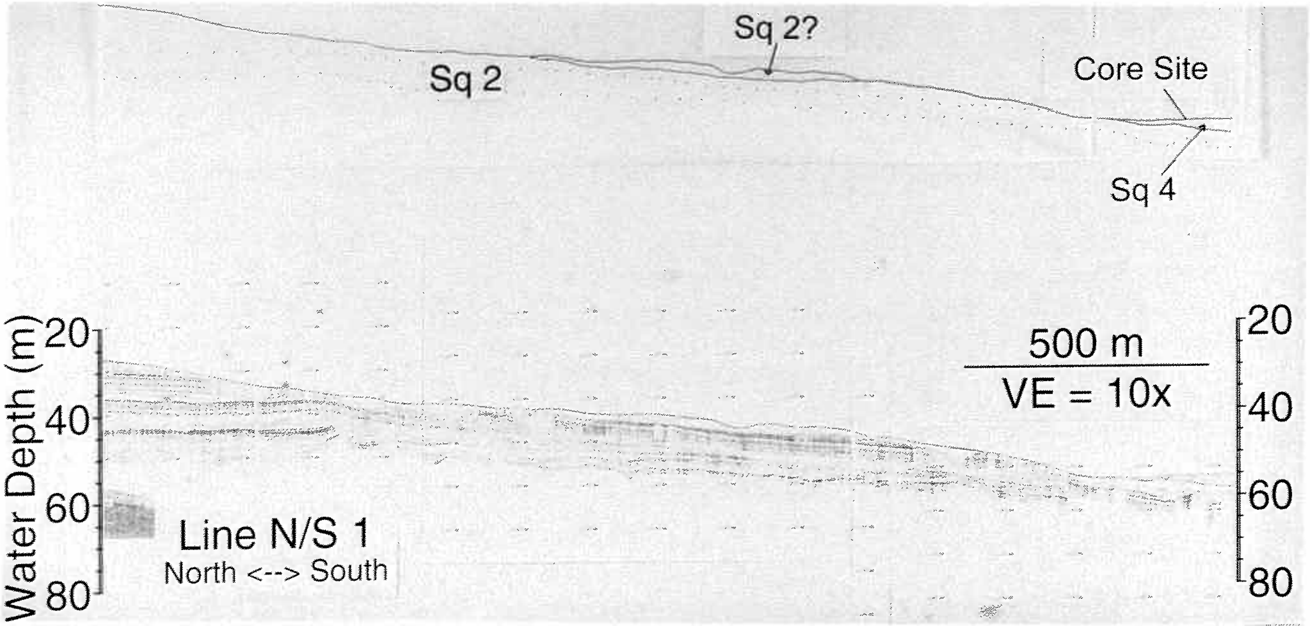

Figure 5. Profile N/S 1 reveals truncation of the pink clays (Sequence 2) in water depths of 50 meters and onlapping postglacial muds (Sequence 4) at the southern margin of the profile.

down to the lake floor where acoustic basement (glacial drift and/or bedrock) is near the surface. In other nearshore areas, coarse sediment and/or biogenic gas attenuated the acoustic signal and preclude estimation of sediment thickness. The thickest accumulation of sediment in our survey area occurs in the central, flat-floored, deep-water, portion of the lake basin (Stephens 1986). We believe that the 30 meter limit of our seismic system is a result of equipment limitations because the Uniboom seismic profiles (Stephens 1986; Mullins and Hinchey 1989; Mullins et al. 1996) revealed over 50 meters of Late Pleistocene/Holocene sediment in the northern basin and over 270 m of fill farther south in the lake.

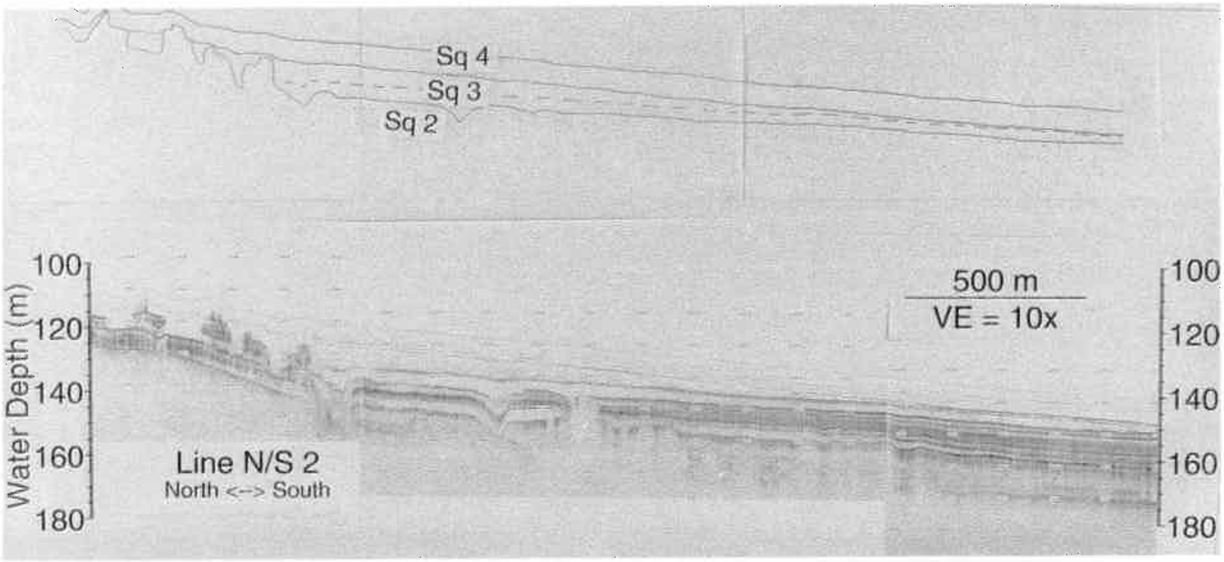

Figure 6. Profile N/S 2 reveals remnants of pink clays (Sequence 2) encased in basin-scale mass movement sediments (Sequence 3). Each package of Sequence 3 thins to the south and the transparent nature gradually gains internal reflections that are characteristic of Sequence 2.

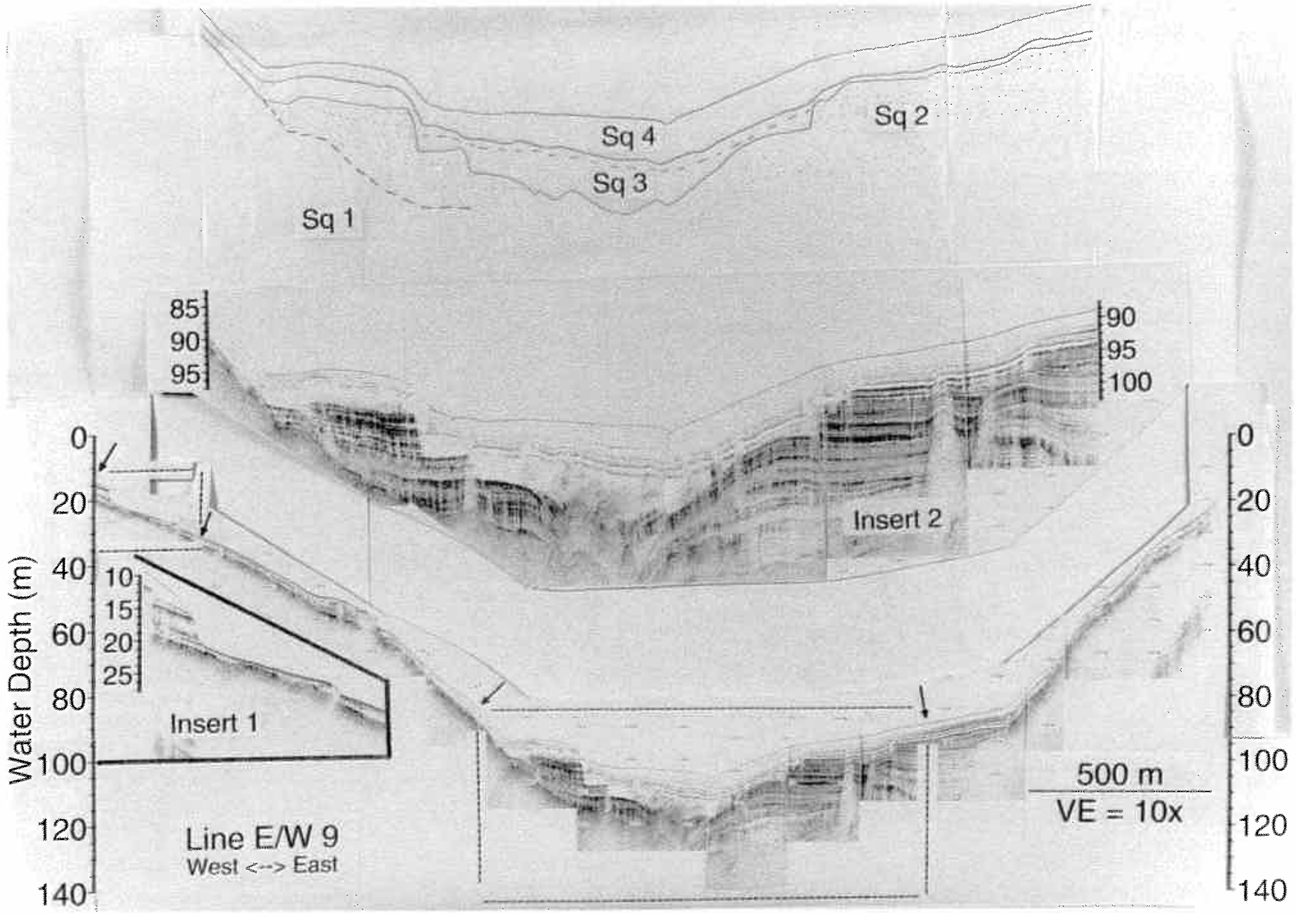

Figure 7. Profile E/W 9 reveals steep slopes with minimal sediment accumulations on either side of the deep basin, remnants of pink clays (Sequence 2) with adjacent mass movement sediments (Sequence 3) buried below postglacial muds (Sequence 4) in the deep basin, and a possible wave-cut notch in 20 m of water. Insert 1 (wave-cut notch) and Insert 2 (deep basin floor) are enlarged at exactly twice the scale of the main profile. The boxes and arrows on the main profile indicate the location of the respective inserts.

Four sequences (1 - 4) are interpreted on the basis of seismic sequence analysis and correlation to sediment samples (Table 1, Fig. 3). The sequence is most complete in the flat-floored, deep-water portions of the lake, south of Glass Factory Bay. Elsewhere, one or more of these sequences may be absent. Sequence 1 is the oldest and consists of a high-amplitude, diffuse, upper-most reflection with localized internal point reflections, where the sequence is near the surface or exposed at the lake floor (Fig. 4). This sequence becomes difficult to image if it is buried below 20 meters of sediments (below acoustic basement). Sequence 2 has high-amplitude, decimeter-scale, parallel to subparallel reflections that drape the underlying topography defined by the upper boundary of sequence 1 (Figs. 5 and 6). Sequence 3 is split into two primary transparent packages that are separated by a diffuse, moderate-amplitude reflection. The sequence is restricted to the southern part of the deep, flat-floored basin in the survey area (Figs. 6, 7 and 8). Sequence 4 has low-amplitude surface and low-amplitude, parallel to subparallel internal reflections. The sequence is found primarily in deep-water portions of the survey area where it onlaps onto the older sequences (Figs. 7 and 8).

Sequence 1 - Glacial Drift

Sequence 1 (Sequence III of Mullins et al. 1996) is the deepest package resolved by the X-Star system in this survey. An exception is a high-amplitude reflector that is locally observed below sequence 1, but only at the margins of the deep basin, especially where the slope of the lake floor is very steep (Fig. 8, Insert). We interpret this lowest high-amplitude reflector as bedrock. Sequence 1 is not typically imaged in our seismic profiles from Seneca Lake. In the shallow water regions north of Glass Factory Bay, attenuation of the seismic signal is facilitated by a high amplitude surface reflector, gas (biogenic methane) wipeouts and/or water bottom multiples (Figs. 4 and 9). In the deep basin and elsewhere, the absence of sequence 1 is probably due to the attenuation of the high frequency, seismic signal within 20 or more meters of younger sediments, because thick sequences of ice-contact and ice-proximal deposits were previously identified in the Uniboom seismic profiles at these locations.

The reflection associated with the top of sequence 1 is highly irregular and characterized by localized highs and depressions

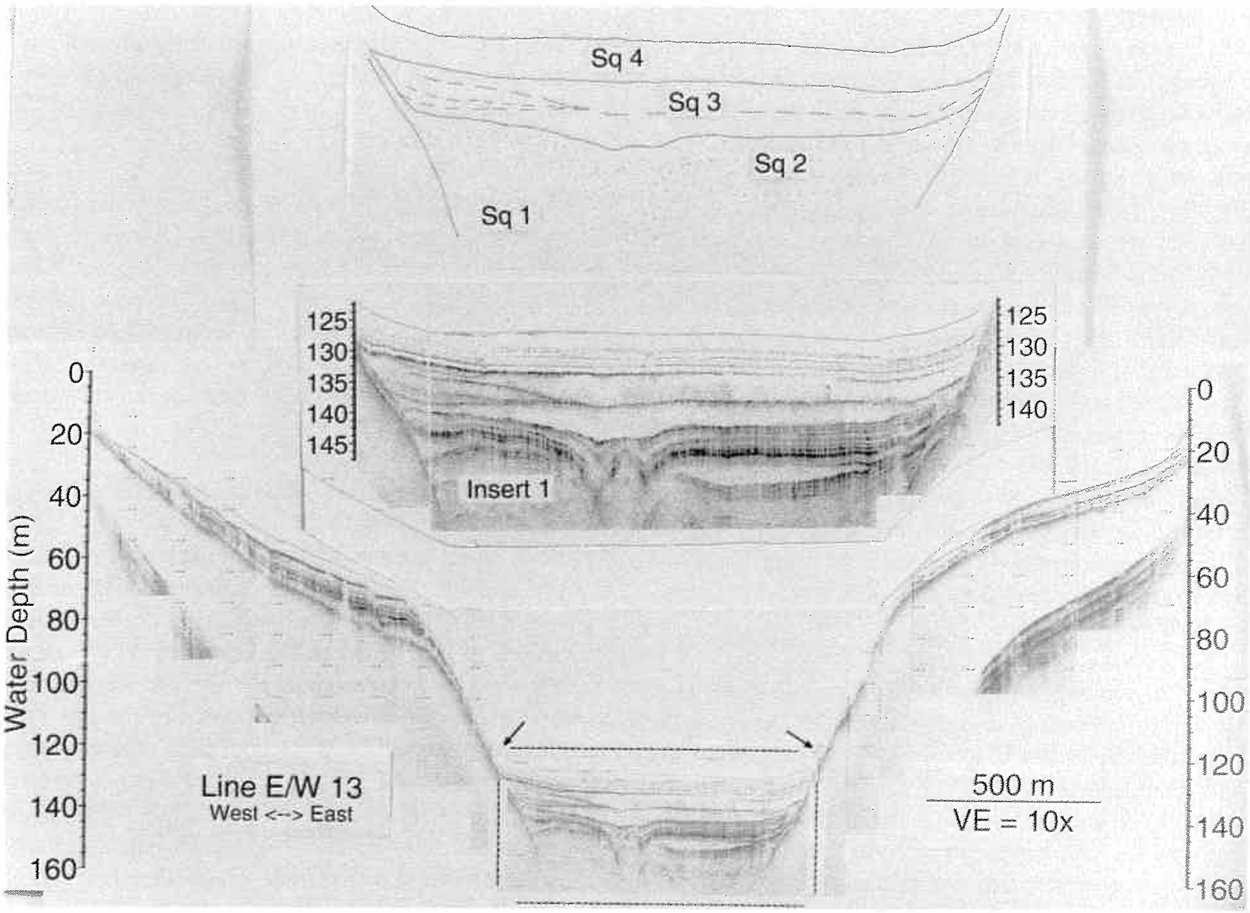

Figure 8. Profile E/W 13 reveals the expansion of the mass movement sediment (Sequence 3) to the entire deep basin and onto lower sections of pink clays (Sequence 2), incomplete sections of pink clays (Sequence 2) and postglacial muds (Sequence 4) on the basin shoulders before the abrupt deepening of the lake floor into the deep basin, and a possible wave-cut notch in 20 m of water at both margins of the lake. The insert (deep basin floor) is enlarged at exactly twice the scale of the main profile. The box and arrows on the main profile indicates the location of the respective inserts.

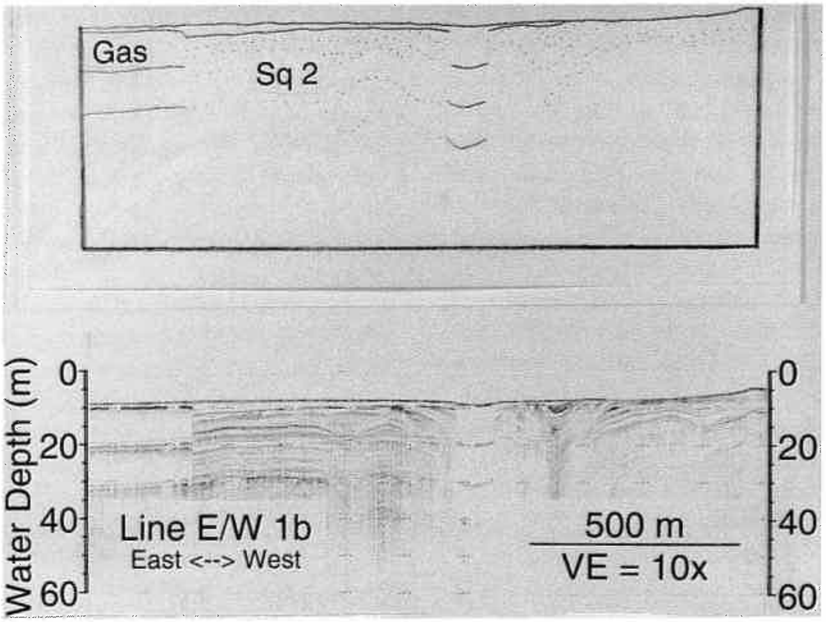

Figure 9. Profile E/W 1b reveals folding of the pink clays and possible buried channels in the northern end of the lake. A lake-floor multiple obscures the image between water depths of 15 to 20 meters.

that are typically a few tens of meters across or less with less than 2 meters of local relief. In two locations, sequence 1 is much closer to or is exposed at the lake floor, and delineates two elongated ridges in map view orientated in an east-west direction (e.g., Fig. 4). One ridge is just to the north of Glass Factory Bay, outcrops at the lake floor along the western side of the lake, and segregates the shallow-water region to the north from the deep-water basin to the south. This feature projects towards a recessional moraine previously identified on land (Muller and Cadwell 1986; Muller and Calkin 1993). Another ridge is observed in the seismic profiles offshore of Kashong Creek and is buried below younger sediments. A second, but significantly smaller moraine is detected onshore near Kashong Creek (MacKey 1975; Woodrow 1978). The alignment indicates that these ridges are subaqueous extensions of recessional moraines previously delineated on land. Our interpretation is consistent with elongated bathymetric hills observed in the Uniboom surveys (Stephens 1986; Mullins et al. 1996).

Localized depressions are observed in the surface of sequence 1, i.e., surface reflections disappear downward and younger sediment drape over and fill into the holes. The bottom-most fill within the depressions is typically chaotic. The depressions are typically ten to a few hundred meters across but individual depressions are not traceable to adjacent lines. The features lack evidence for erosional truncation of underlying strata with onlap of younger strata and mapped linear trends that are typical of a buried channel. We interpret the depressions as subaqueous ice-meltout features or dead-ice sinks (e.g., Fleischer 1986) that formed when stagnant ice melted after the deposition of younger sediments. The resulting depression and chaotic fill was then blanketed by postglacial sedimentation. Our interpretation is consistent with similar features observed in Keuka Lake (Mullins et al. 1996) and a detailed investigation of a large depression north of Glass Factory Bay (Preston 1994).

We interpret the geometry and seismic character of sequence 1 as ice-contact or ice-proximal drift (Table 1). Similar features are observed in seismic profiles from many other lakes in glaciated terrains (e.g., Johnson 1980a; Larocque and Shilts 1986). Grab samples of sequence 1 recovered poorly sorted gravely sand and silt, which is consistent with this interpretation. Sequence 1 is believed equivalent to sequence III of Mullins et al. (1996).

Sequence 2 - Proglacial Rhythmites (Pink Clays)

Sequence 2 (Sequence IV of Mullins et al. 1996) is characterized by high-amplitude, decimeter-scale, parallel to subparallel reflections. The sequence drapes over the topography defined by the surface of sequence 1. Sequence 2 is thinner over the highs and thicker over the lows. The thinner sections are typically condensed versions of the thicker sections. Vertically, the high-amplitude, multiple internal reflectors of sequence 2 may give way abruptly to relatively thinner sections of transparent sediments. Yet, the entire package appears conformable, i.e., the transparent sections are sandwiched between two sections of high-amplitude reflectors (e.g., Fig. 3 at a depth of 150 m). Acoustically, the transparent sections of this unit are very similar to sequence 3.

Sequence 2 is typically more than 10 m thick but may be thicker in the deep portion of the basin because acoustic basement is typically within this sequence. When the thickness of the sequence is observed, the thicker sections are located north of Glass Factory Bay (Figs. 4, 5, and 9) and in the northern part of the deep basin (Figs. 7 and 8). Less complete sections of sequence 2 are observed elsewhere in isolated locations. For example, fragments of sequence 2 are better preserved under isolated patches of nearshore marl or in other nearshore areas where the lake floor is relatively flat in shallow water regions. In the deep basin, sequence 2 is thinner or absent towards the center of the basin. Where sequence 2 is thinner, its upper sections are noticeably missing. A more complete sequence is observed south of Dresden.

Short piston cores and grab samples of the upper portions of sequence 2 recovered proglacial rhythmites, the pink clays. This sequence could only be sampled where sequence 3 was not imaged in the seismic profiles because the overlying strata were too thick to sample sequence 2 elsewhere. Each light/dark couplet is no more than a few centimeters thick, whereas individual acoustic reflections in our seismic sections are decimeters apart. The difference indicates that individual reflections in sequence 2 correspond to changes in physical properties across a bundle of couplets or are acoustic interference patterns. Our interpretations are consistent with similar high-amplitude, multiple-reflection, acoustic packages that are imaged in other lakes (e.g., Johnson et al. 1980a; Shilts et al. 1992). Sequence 2 is believed equivalent to sequence IV of Mullins et al. (1996).

One core recovered 3 meters of pink clays under a condensed postglacial section (Ciszkowski 1996). The thick section is unusual because the pink clays are typically very stiff and often represent the basal sediment recovered by the corer or the clays are buried under more postglacial sediment than our piston core can recover. The recovered pink clays exhibit deformation near the top of the section but little or no deformation at the base. This relationship is inconsistent with sediment disturbance by coring. We hypothesize that the deformed (folded and faulted) pink clays lack the internal consistency to generate internal reflections that are typical of undeformed pink clays, and instead result in the transparent acoustic package conformable with the pink clays. Proglacial varves, deposited in Glacial Lake Iroquois, reveal a meter-scale section of folded and faulted varves within a larger sequence of undisturbed varves (Woodrow et al. 1990). Proglacial rhythmites from Cayuga Lake are occasionally folded and faulted as well (Mullins et al. 1996). The distorted varve packages are interpreted as soft-sediment deformation due to an isolated mass-movement event during the deposition of the proglacial sediments.

The pink clays in Seneca Lake reveal multiple evidence for post-depositional reworking. Onlapping fill on curved erosional surfaces are detected within the pink clay sequence. The largest of these features are traceable across two or more lines and interpreted as buried distributary or meltwater channels (Fig. 9). The pink clays are folded, tilted, and the surface is severely truncated north of Glass Factory Bay. The folding and faulting is not observed farther to the south (Fig. 9). Perhaps small re-advances of the Laurentide Ice sheet into the northern portion of the Seneca Lake basin folded, faulted and truncated the strata. Additional evidence for erosion of the pink clays, but without the severe folding and tilting, is observed in water depths of 20 to 30 meters through out the lake (Fig. 4, Insert 2), and in the northern end of the deep basin down to water depths of 50 to 60 meters (Fig. 5). This suggests that waves and currents are actively reworking lake floor sediments, and/or a lake level that was lower in the past.

The erosional surfaces discussed above are parallel or nearly parallel to the lake floor. In contrast, one or more "vertical" cliffs, that abruptly truncate the pink clays of sequence 2, are observed in the deep-water (to water depths of 110 m) portion of the flat-floored basin from Wilson Creek to Kashong Creek (Fig. 7). These sequence 2 remnants are not exposed at the lake floor but are buried beneath younger sediments. Reflections in underlying and overlying strata are not faulted or deformed, rather they drape over the vertical cliffs. Along east-west transects, erosional remnants of sequence 2 are observed on either side of the deep-water section. Individual reflections can be jump-correlated from one side of the basin to the other across the erosional gap.

Sequence 3 - Mass-Movement Deposits

Sequence 3 is composed of two stacked transparent packages that occupy approximately 25 km^2 of lake floor (Fig. 10). Individual packages are separated by a diffuse moderate-amplitude reflection. At some locations, the boundary is composed of two to five high-amplitude subparallel reflections similar to those that characterize sequence 2. The geometry changes from north to south between sequence 2 and 3. Between Glass Factory Bay and Kashong Creek, sequence 3 is thickest (>10 m thick) and is located between the erosional remnants of sequence 2 (e.g., Line E/W 9, Fig. 7). The internal reflectors of sequence 3 are hummocky and appear to drape into a depression within the underlying sequence. Near line E/W 13, sequence 3 covers the entire deep-water basin and is detected above thinner sections of sequence 2 (Fig. 8). Sequence 2 is much thinner at this location because the upper portions of sequence 2 are missing from the sediment column. Farther south, the two primary packages of sequence 3 thin and slowly gain additional high-amplitude reflections characteristic of those in sequence 2. Sequence 3 is absent from the sediment column in the deep-portion of the lake south of Dresden.

Near the northern end of Line N/S 2, isolated erosional remnants of sequence 2 are laterally encased in sediments of sequence 3 (Fig. 6). Each remnant is ~100 m across. The transition between sequence 2 and sequence 3 is abrupt, and the top and bottom of a remnant is typically conformable to the adjacent package of sequence 3. As an analogy, remnants of parent material are observed in the Tully Landslide, a subaerial mudflow incorporating early Holocene muds and proglacial

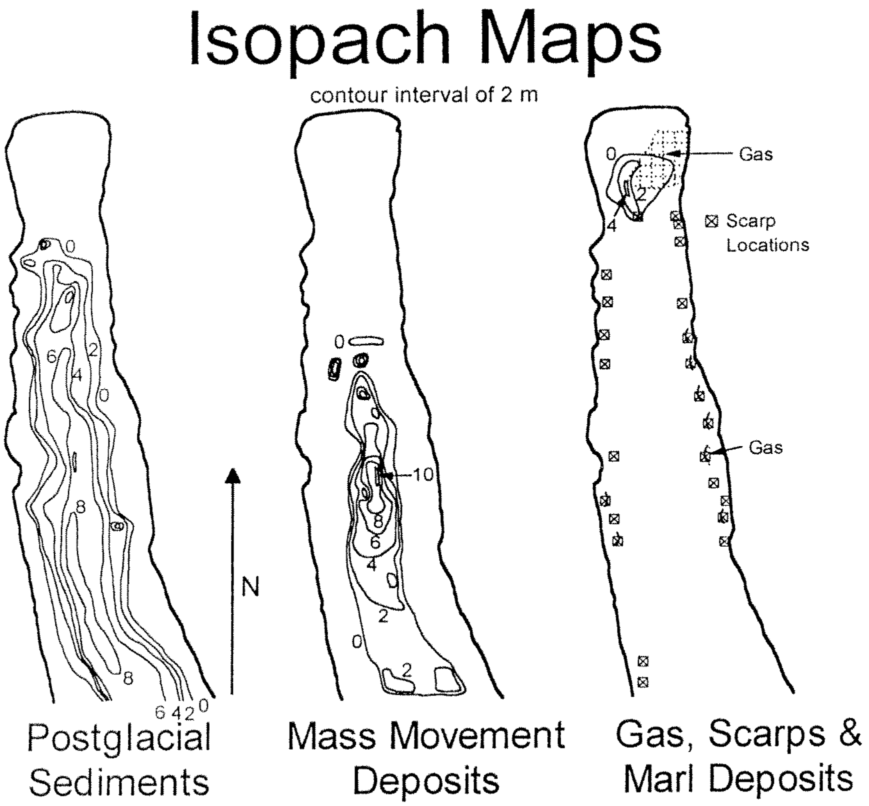

Figure 10. Isopach maps of the postglacial sediments (left), mass-movement deposits (center) and nearshore marls (right). Occurrences of gas and wave-cut scarps imaged in this high-resolution survey are also shown (right). An isopach map was not determined for the proglacial rhythmites because acoustic basement was typically within this sequence. Thickness is measured in meters assuming a sound velocity of 1.5 km/s.

rhythmites (Jager and Wieczorek 1994). We infer that the isolated remnants of sequence 2 are relatively undeformed, coherent, blocks of sequence 2 that are encased within sequence 3 sediment.

Woodrow and co-workers (1969) described deformed pink clays recovered from the margins of the deep basin in > 80 m of water. They hypothesized that they were products of downslope movement of pink clays from the neighboring steep sides of the lake. This interpretation is consistent with the smaller, isolated packages of sequence 3 observed along the margin of the basin in this survey. However, the two primary packages of sequence 3 have not been sampled because they are always buried beneath more sediment than our piston corer can recover.

We hypothesize that sequence 3 is the result of sub-aqueous, downslope movement of the upper portion of sequence 2 that has slid over lower sections of sequence 2. Movement was towards the center of the basin and south along the longitudinal axis of the lake. We do not propose that significant flowage continued as far south as Dresden. Instead, we believe that movement towards the center of the basin in the north may have sufficiently disturbed the pink clays to the immediate south to disrupt the laminar structure and retard the generation of internal reflections. The intensity of disturbance decreases southward, explaining the gradual increase in the number of sequence 2 type reflections in sequence 3. Such a hypothesized motion was not apparently severe enough to disrupt the pink clays south of Dresden. The two primary units of sequence 3 indicate at least two main flow events down the main axis of the lake. The reflection character of this sequence is similar to the transparent packages within the pink clays and provides additional support to the hypothesis that these transparent packages are the result of postdepositional mass-movement of pink clays.

The mass movement deposits are identified in subbottom profiles for the first time in Seneca Lake. They do not have a sequence/lithology counterpart previously identified by Mullins et al. (1996) unless his sequence V, which he correlated to the brown muds, actually imaged these flows (see additional support for this conjecture below). The higher-resolution data probably enabled the differentiation of this sequence. We suggest renaming the sequence nomenclature of Mullins et al. (1996) to sequence IV for the rhythmites and sequence V for the flow deposits.

The timing of the flow events is stratigraphically restricted to the waning stages of pink clay deposition in the basin (~ 14 ka, Mullins et al. 1996), when ice retreated north of the drainage basin. The proglacial pink clays must have accumulated prior to flow, yet the overlying sediments are not disturbed by the motion and instead blanket the pink clays and mass-movement deposits. This timing is approximate because the movement may have lost a thin veneer of younger sediment. The two primary packages within sequence 3 suggest, but do not dictate, two triggering events within a short period of time.

Plausible mechanisms to induce flow are: (1) Pulses of meltwater, meltwater sediments or just additional accumulation of the pink clays may have provided sufficient loading of the pink clays to initiate downslope movement (e.g., Lane 1967). (2) Retreat of the glacier, opening of the lower outlet to the north, and rapid drawndown of lake levels may have temporarily left high pore pressures in slowly draining pink clays to induce downslope motion (Schuster 1979). (3) Melting of stagnant ice within the glacial drift along the thalweg of the basin initiated flow into the lake's thalweg, which in turn, initiated flow towards the center of the lake and southward to disturb the pink clays to the south. (4) Earthquake activity, which occurs historically to the west (Buffalo) and north (St Lawrence Seaway) of Seneca Lake but may have been more frequent during glacial retreat than today as the melting ice unloaded the crust, may have initiated the movement of the already unstable clays (e.g., Shilts and Clague 1992). The present seismic coverage supports our stagnant-ice hypothesis but does not exclude the other possibilities.

Up to 5 additional but smaller packages of sequence 3 are observed locally on several E/W seismic profiles (e.g., western side of the deep basin in Line E/W 13, Fig. 8). These packages are < 1 m thick at the intersection of the steep-basin walls and deep-basin floor and thin towards the central portion of the basin with surface areas less than a few km^2. Subaqueous, downslope movement could explain the deposition of these smaller packages. The source of sediments is probably the steep slopes adjacent to the deep basins, but a more detailed grid of seismic profiles is required to more clearly delineate the variation in sediment thickness and probable source of these smaller packages. These additional units flowed at approximately the same time as the larger packages of sequence 3 because the additional packages are stratigraphically imbedded within the two main packages of sequence 3 sediment.

Sequence 4 - Postglacial Sedimentation

Sequence 4 (Sequence V? and VI of Mullins et al. 1996) is the uppermost acoustic sequence in the seismic survey and is typically restricted to the deepest locations within the basin (Fig. 10). Sequence 4 is characterized by a very low-amplitude surface reflection and a number of low-amplitude internal reflections that onlap older sediments. The internal reflectors within the lower half of the package are slightly higher-amplitude than those in the upper half, and can be traced

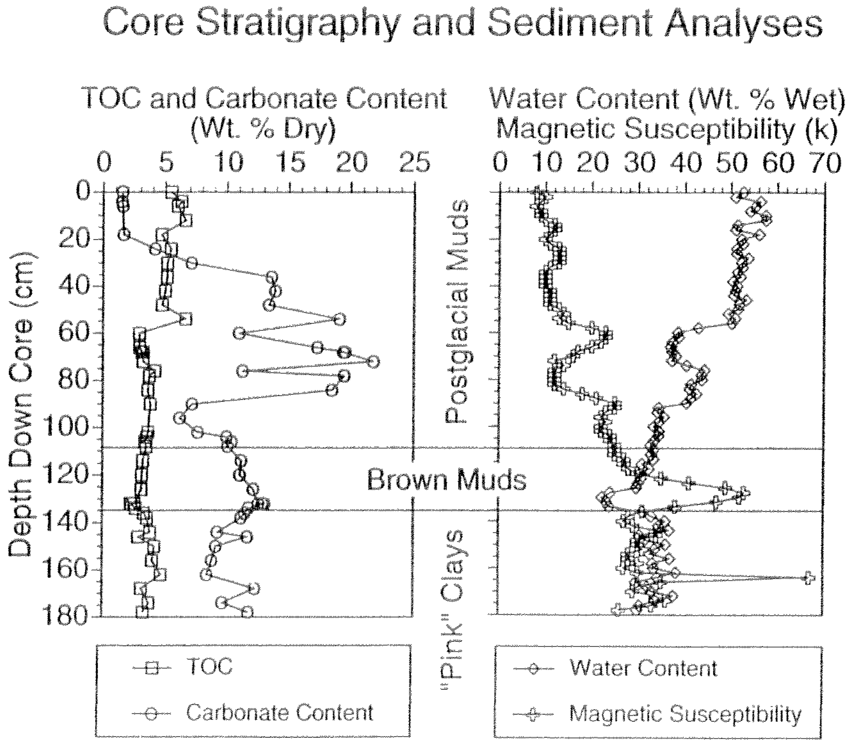

Figure 11. Water content, total organic carbon content (TOC), bulk carbonate content, and magnetic susceptibility (κ) of sediments recovered by piston corer from the deep basin of the lake to associate changes in sediment character and reflections in the seismic profiles. Sequence 3 is not detected at this site; elsewhere it is buried below too much mud to be recovered by our corer. See Figures 2 and 5 for the core site.

throughout the survey area (Figs. 3 and 4).

Cores of sequence 4 recovered olive-gray to black, laminated mud that overlies postglacial massive brown muds. Where the postglacial section is condensed, proglacial pink clays are recovered immediately below sequence 4; however, sequence 3 is not imaged in the seismic profiles at these core sites. The faint internal reflectors in the seismic profiles probably correspond to down-core variability in bulk carbonate content, magnetic susceptibility, water content and perhaps other sedimentological parameters that influence bulk density and acoustic velocity of the sediments (Fig. 11). The down-core variability in any parameter is largest in the lower portion of the postglacial / brown mud record and probably corresponds to the greater definition of the lowermost internal reflectors in sequence 4.

Sequence 4 is similar but not identical to sequence VI identified earlier by Mullins et al. (1996). Sequence 4 incorporates both the older brown muds and overlying postglacial muds, whereas Mullins placed the brown muds into sequence V and the postglacial muds into sequence VI. The sediment analyses reveal minimal downcore variability at the postglacial / brown mud contact (Fig. 11). This suggests that the contact is not an acoustic boundary in the seismic profiles. A reinterpretation of Mullins' Sequence V to correspond with sequence 3, the mass-movement deposits, and Mullins' Sequence VI to correspond with sequence 4, the massive brown and postglacial muds, is more consistent with seismic, lithologic and sediment thickness data presented here.

Postglacial sediments are 5 to 8 meters thick in the deep basin where they blanket older strata (Figs. 3, 6, 7, 8, and 10). They thicken toward the largest tributaries that enter the northern half of Seneca Lake, Kashong Creek and Keuka Outlet. Thicker accumulations of postglacial sediments also fill small isolated lows in the underlying topography. The thickness of postglacial sediments decreases rapidly on the steep slopes of the basin, where the existing sediments reveal normal faults, arcuate glide planes, hummocky to chaotic internal reflectors, downslope stacking of sedimentary packages and other evidence for episodic downslope movement (e.g., Figs. 7 and 8). In shallower areas (< 50 m of water), postglacial muds form a thin (< 0.2 m) veneer of material that blankets older sediments along an unconformable contact (Figs. 4, 5, and 9). These observations suggest episodic downslope movement or non-deposition of postglacial muds on the steep slopes of the basin, and active reworking of the postglacial muds in shallow water areas.

Additional Acoustic Signatures - Biogenic Gas and Marls

Three additional acoustic signatures are observed in the study area (Fig. 10). The first unit reveals a diffuse, high-amplitude reflection less than 1 meter below the lake floor, and lacks deeper subbottom reflectors. Strong water bottom multiples are also pervasive for this unit. It is restricted to water depths shallower than 20 meters, primarily in the northeast corner of the lake, but also detected along the margins of the lake farther south within the marls described below. Lateral transition from this unit to other seismic units (i.e., those with subbottom penetration) is abrupt (e.g., Fig. 4). We suspect that these sediments have enough gas (biogenic methane?) to wipeout the subbottom seismic signal (e.g., Schubel and Schiemer 1973; Stephens 1986; Mullins et al. 1996).

The second unit reveals intermittent internal reflectors, and is restricted to water depths shallower than 20 meters along the east and west margins of the lake (Figs. 7 and 8). The unit is not continuous throughout the nearshore areas but is detected in isolated locations. It is typically a few meters thick and caps sections of pink clays. Marl deposits, muds with fine grained, photosynthetically induced, carbonate with shell and plant debris, have been recovered in grab samples from this unit (Brown 1985; Thompson and Ferris 1990).

Finally, a thin unit obscured by the gas is restricted to water depths less than 20 meters north of Glass Factory Bay and west of the first unit (Fig. 4). Where the gas is absent, parallel to subparallel internal reflectors are revealed, and the unit unconformably overlies pink clays. The unit gradually thickens lakeward to form a wedge of sediment up to 5 meters thick. Gas is observed in this unit and other isolated marl packages within Seneca Lake but not detected within other acoustic units, and grab samples recovered homogeneous, carbonate bearing muds, with some shell and plant debris. The evidence suggests that this unit is marl, and only distinguished from the previous units by location and presence of gas.

SEDIMENT REWORKING AND LOWER LAKE LEVELS

Erosional truncation of strata, minimal (if any) accumulation of postglacial sediments, and scarps in nearshore areas indicate a dynamic environment and perhaps lower lake levels in the past. Surface waves and currents rework shallow-water sediments in lakes (e.g., Johnson 1980a; Davis and Ford 1982). Theoretical calculations based on the work of Johnson (1980b) suggest that surface waves generated by 15 m/s (50 kph) winds blowing parallel to the long axis of the lake can erode silts and fine sands at water depths up to 20 m in the lake. This depth is a maximum estimate because parameters such as effective fetch were deliberately overestimated in the calculation. Yet, surface waves and currents can not explain the erosional features (e.g., truncation of the pink clays) observed in water depths of 60 meters, significantly below the calculated wave base (Figs. 4 and 5).

Twenty years of current meter data collected by Bill Ahrnsbrak (Hobart & William Smith Colleges) indicate that currents and internal waves associated with seiche activity are significant in Seneca Lake (e.g., Ahrnsbrak 1974; Ahrnsbrak et al. 1996). The activity is probably enhanced by the elongated nature of the basin, that is nearly parallel to the prevailing southwesterly winds when the lake is stratified. For example, current velocities up to 30 cm/sec have been recorded 1 meter above the lake floor at a water depth of 66 m but only immediately after a strong southerly wind event associated with frontal movement. These currents probably impact sedimentation on the lake floor. Redistribution of sediments by wind-driven waves, associated deep-water currents and internal seiche activity is observed in other lakes as well (e.g., Halfman and Johnson 1984; McManus and Duck 1988).

The lake bottom bathymetry quickly descends lakeward across a scarp from approximately 15 to 20 m of water along those profiles that extended into shallow water (Figs. 7 and 8). The scarp provides an interesting dilemma. The feature may be the result of subaqueous sediment redistribution and deposition by the reworking processes mentioned above, with the reworked sediment prograding out onto the deeper lake floor over time. The scarp could represent the lakeward extent of marl deposition or a detachment scarp from mass movement of sediments. Alternatively, the feature may be a wave-cut notch, i.e., the result of sediment truncation by surface, wind-driven waves during a lowstand of the lake.

The preliminary seismic data favor the wave-cut interpretation during a lowstand of the lake. The scarp truncates the internal reflectors, when gas does not obscure the subbottom record (Fig. 7). Shoreward of the scarp the internal reflectors are nearly parallel to the lake floor. This geometry is not consistent with a progradational sequence that is accreting onto the lake floor. The scarp truncates a number of different sediment types, e.g., marls, glacial drift and proglacial rhythmites. Thus, the scarp is not related to the deposition of the marls. Each wave-cut notch profiled in the seismic profiles is consistently at the same water depth, even though the scarps are from different locations in the lake and exposed to different fetches, prevailing winds, and associated wave activity (Fig. 10). Mass-movement deposits are not observed offshore of the scarps in Seneca Lake and correlation of internal reflections, identified nearshore and offshore of lake floor scarps in Otsego Lake, NY (Halfman and Fetterman 1998), suggest that the scarps are not detachment surfaces but rather erosional surfaces. However, additional seismic and sediment data, like lowstand deltas, incised streams, and submerged beach ridges, are needed to substantiate the lowstand hypothesis for Seneca Lake. Although we found no clear evidence for such features in the present survey, they are easily missed in this survey that focused on the deep-water portion of the basin. Alternatively, these features may not have developed if the lowstand event was short in duration.

If our wave-cut notch interpretation is correct, then lake level was at least 20 m lower in the past. Twenty meters is significantly lower than the present day sill depth (2 to 4 meters) for the outlet. Adjustments for glacial rebound of the crust are not important in this case because the outlet and the closest notch are within a kilometer or two. This difference in elevation implies that the lake was closed, i.e., had no outlet, sometime after deposition of the marls. The marls were deposited during the early to mid Holocene based on a published radiocarbon date of the marls, lithostratigraphic correlation to radiocarbon-dated and presently exposed marls at the southern end of the lake, and correlation to relative higher concentrations of fine-grained carbonate in the lower Holocene of the profundal sediments in Seneca and other Finger Lakes (Brown 1985; Dwyer et al. 1996; Anderson et al. 1997).

The lowstand hypothesis is consistent with a very small but growing database of lake-level information from the northeast. Within Seneca Lake, a sharp decrease in the water content and change in sediment geochemistry at mid-depth within the postglacial sediments of a piston core recovered from a water depth of 55 m is consistent with lower lake levels (Ciszkowski 1996). Deposition of the southernmost marls in Seneca Lake was abruptly discontinued after the mid-Holocene due to decreasing lake levels (Anderson et al. 1997). Erosional lags are identified within the marls elsewhere in the lake (Brown 1985). Holocene lowstands are proposed for a growing list of lakes in the northeast based on seismic, sedimentological, palynological and fossil macrophyte data (Harrison 1998; Wright et al. 1993; Wellner and Dwyer 1996; Anderson et al. 1997; Almquist-Jacobsen 1998; Halfman and Fetterman 1998; Newby et al. 1998; Retelle 1998; Shuman et al. 1998; Webb et al. 1998; Eyles, Mullins, and Halfman, unpublished data). However, more chronologic controls are necessary for the preliminary lowstand evidence from Seneca Lake before correlations are attempted with the emerging Holocene lake-level trends in the northeast.

CONCLUSIONS

The high-resolution seismic profiles improve our understanding of the sedimentation history in Seneca Lake. The upper sediment sequences includes, from oldest to youngest, sequence 1 - glacial drift, sequence 2 - proglacial rhythmites (pink clays), sequence 3 – mass-movement deposits and sequence 4 – massive brown muds and olive-gray to black postglacial muds. Sequences 1 and 2 correlate with sequences III and IV from Mullins et al. (1996). Our data delineate, for the first time, mass-movement deposits of pink clays within the deep basin of the lake on basin wide and smaller scales that may correspond to sequence V of Mullins et al. (1996). The seismic stratigraphy restricts the timing of these mass movements to just after the deposition of the pink clays and before the deposition of the massive brown muds, and is thus associated with the retreat of the glacier from the modern day drainage basin approximately 14 ka. Sequence 4 is correlated to the massive brown muds and postglacial muds. These lithologies were previously assigned to sequences V and VI by Mullins et al. (1996) but the reassignment proposed here is more consistent with the higher-resolution seismics and sediment character.

Truncation of strata, in places to glacial drift, minimal accumulation of postglacial sediments in shallow water areas, and scarps at 20 m of water indicate that sediments do not rain down uniformly onto a placid lake floor. They are subjected to episodic downslope movement on the steep slopes of the basin, sediment reworking by surface waves and currents, sediment reworking by internal waves and currents associated with seiche activity along the thermocline, and perhaps subaerial erosion during an earlier lowstand of the lake. Clearly, more work is required to substantiate the speculative lowstand hypothesis in Seneca Lake.

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