STRATIGRAPHY, SEDIMENTOLOGY, AND GEOCHEMISTRY OF SENECA LAKE, NEW YORK

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INTRODUCTION

This field trip investigates the stratigraphy, sedimentology and geochemistry of Seneca Lake. The field trip is aboard the H-WS Explorer, and focuses on representative sediments that have accumulated in the northern part of the lake since deglaciation, which are typical of the other Finger Lakes. The trip also highlights ongoing efforts to collect and interpret high-resolution (2 - 12 kHz) seismic reflection profiles that image down to the glacial drift, and our recent understanding of the chloride and calcium concentrations/budgets in Seneca Lake in comparison to the other Finger Lakes.

The Finger Lakes of central New York State consist of 11 elongated, north-south trending basins just south of Lake Ontario (Fig. 1). The basins are glacially scoured into the northern edge of the Appalachian Plateau (Coates, 1968, 1974). At Seneca Lake, the bedrock is primarily Devonian shales (Hamilton Group in the northern end of the lake), and lesser amounts of sandstones and carbonates that gently dip to the south-southwest. Silurian carbonates, shales and most importantly evaporites (mostly halite) are found below the Devonian section.

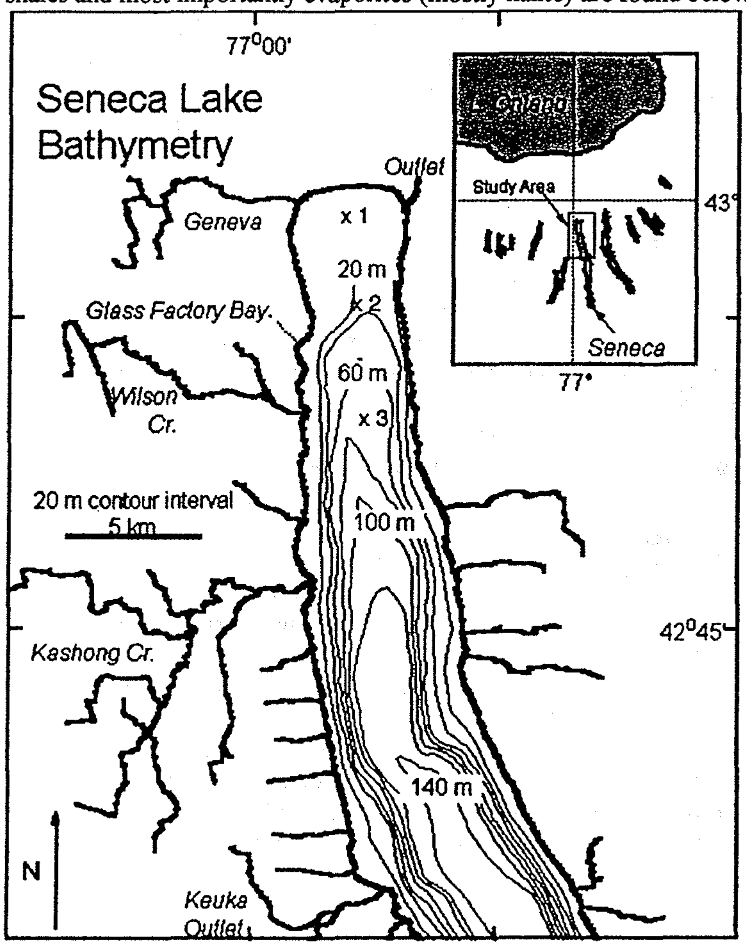


Fig. 1. Bathymetric map of northern Seneca Lake with station locations for this field trip (e.g., x 1). Th insert shows the location of Seneca Lake in relation to the other Finger Lakes.

Seneca Lake is the largest (by volume) and deepest of the Finger Lakes (Fig. 1, Table 1). Only Cayuga Lake immediately to the east of Seneca is longer (61 km) and almost as deep (132 m). The other basins are smaller, ranging in length from 5 to 32 km and maximum water depth from 9 to 84 m. The present day lake is fed by over 30 streams and major creeks and drains to the north-northeast through the Seneca River (New York State Cayuga-Seneca Barge Canal).

DEGLACIATION OF THE FINGER LAKES REGION

Deglaciation of the Laurentide Ice Sheet, as recorded by recessional moraines and kame deposits, is linked to the present day erosional and depositional geomorphology of the Finger Lakes Region (Fig. 2, Muller and Cadwell, 1986), and specifically, the excavation and subsequent filling of the Finger Lake Basins. The best developed moraines are the East-West trending moraines near Geneva (north of Geneva near the Freeway and south of Geneva intersecting the lake near Glass Factory Bay), and the kame moraines immediately to the south of each Finger Lake. The kame moraines are collectively known as the Valley Heads Moraine that dams each lake at their southern margins, are restricted to the valleys and reveal evidence for deposition by moving water. It suggests that glacial erosion aided by large volumes of glacial meltwater during the occupation of the Valley Heads Moraine were the erosional agents for the Finger Lake Basins (Coates, 1968) and is consistent with Mullins' interpretations of recent Uniboom seismic reflection profiles of the basins.

Table 1. Seneca Lake Statistics (Bloomfield, 1978)	
Length	57 km
Maximum Width	5.2 km
Surface Elevation	136 m above mean sea level
Water Volume	15.54 km^3
Surface Area	175 km^2
Maximum Water Depth	186 m
Water Residence Time	18-20 years

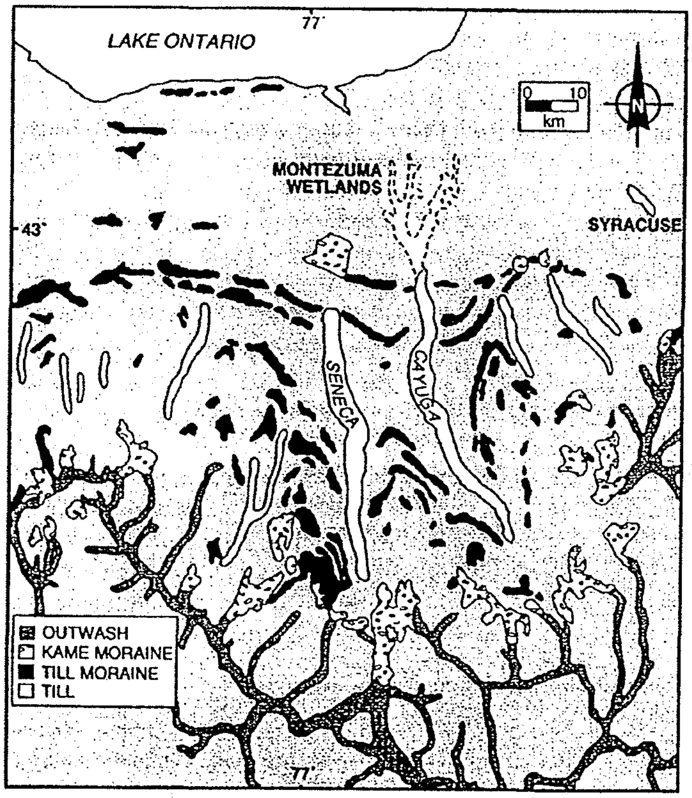


Fig. 2. Generalized geomorphology of the Finger Lakes region (redrawn from Muller and Cadwell, 1986 by Mullins et al., 1996).

In Seneca Lake, Uniboom seismic reflection profiles reveal a deep V-shaped notch cut into the bedrock with up to 270 m of sediment fill onlapping onto the erosional bedrock surface (Mullins and Hinchey, 1989; Mullins et al., 1996). It is deep enough to erode into the Silurian evaporites, which is important to the Chloride geochemical story presented below. Mullins proposed that pressurized meltwaters flowing under the ice excavated the basin when the ice occupied the Valley Heads moraine. Mullins links the majority of the sedimentary fill to deglaciation of the region. The seismostratigraphy of the sediment fill is interpreted as late glacial sediments with a thin cover of postglacial sediments based on acoustic character and correlation to short piston cores and on-land drilling. Mullins and coworkers differentiated 3 lower seismic sequences of ice-contact and water-lain sands and gravels fining upward to ice-proximal lacustrine muds that are related to the retreat of the Laurentian Ice Sheet from the Valley Heads moraine at the southern margin of the lake to the Geneva Moraine at the northern extent of the lake. The upper sequences are relatively thin and are interpreted to correspond to the proglacial rhythmites, locally known as pink clays, which were deposited during a proglacial, high, lake-level phase of Seneca Lake when the ice front blocked the present day outlet to the north, massive brown muds, which are related to the rapid lowering of lake level when the lower, modern-day outlet opened to the north, and profundal postglacial, black to gray, stratified muds, which have accumulated in the lake since deglaciation. Timing of these events is not well constrained. Limited number of radiocarbon dates suggest that the Valley Heads moraine was occupied about 14.4 ka, and the brown mud - postglacial transition was 13.9 ka and suggests that the retreat of the ice sheet and deposition of the ice-related sediments occurred in a rapid period of time (Mullins et al., 1996).

The basin bathymetry is similar to a steep-sided (bedrock cut), flat-floored trough (sediment fill). The lake floor gradually deepens from north to south before shoaling at the southern end of the lake near Watkins Glen. East/West profiles gently deepen to the central portion of the lake, north of Glass Factory Bay. Farther south, the lake bottom gently deepens in nearshore locations, then quickly descends to a flat lying basin in the central part of the lake. A grade of 10% or more is not uncommon on the steepest slopes south of Wilson Creek. Farther to the south, the nearshore areas are narrower and the steep slopes are steeper.

STRATIGRAPHY - ICE-CONTACT, ICE-PROXIMAL AND POSTGLACIAL SEDIMENTS (after Woodrow et al., 1969 & Woodrow, 1978)

Short cores and surface grab samples reveal a number of sediment types within the basin (Woodrow et al., 1969; Woodrow, 1978; Mullins et al., 1996; Halfman and Herrick, 1998). Glacial drift (ice-contact and ice-proximal) fine sands and silts underlie proglacial rhythmites (pink clays). Both outcrop in the northern and other shallow water margins of the lake. Lacustrine marls, muds with photosynthetically-induced microcrystalline carbonate with fossil mollusk layers and macroscopic plant fragments are also sporadically observed in water depths shallower than 20 m. The deep profundal zone contains olive-gray to black, laminated, fossil poor, organic rich muds. Massive brown muds are found between the younger postglacial muds and older pink clays. Halfman and Herrick (1998) recently detected evidence for basin-scale mass movements of the pink clays during the waning stages of pink clay deposition (see below).

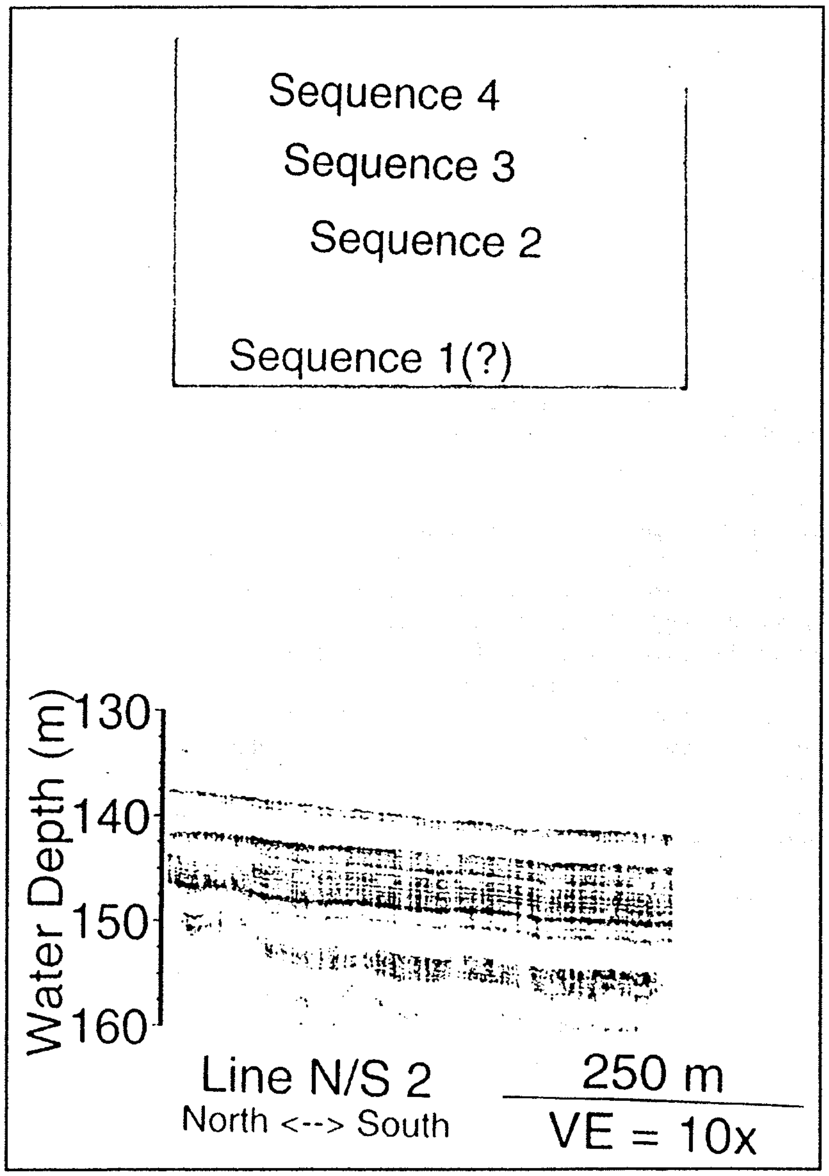


Fig. 3. An example of the acoustic stratigraphy of the upper 30 m of sediment in the deeper portion of Seneca Lake (from Halfman and Herrick, 1998). The line drawing outlines the major sequences identified in the text.

SEDIMENTOLOGY - HIGH-RESOLUTION SEISMIC REFLECTION PROFILES (after Halfman and Herrick, 1998)

Over 100 km of high-resolution (2 - 12 kHz) seismic reflection profiles, collected from the northern end of the lake delineate the upper stratigraphy and investigate the depositional and erosional processes in the basin (Halfman and Herrick, 1998). The seismic system images up to 30 meters of section. Four major acoustic sequences encompassing the upper part of the glacial drift to the postglacial sediments were identified based on acoustic character and correlation with short (1 to 3 m) piston cores and surface grab samples (Fig. 3, Table 2).

The high-resolution seismic reflection profiles shown in this field guide focus on evidence for: (1) mass movement of the pink clays, and (2) sediment reworking to water depths of 60 m by wind-driven surface waves and currents, wind-driven internal waves and currents associated with seiche activity along the thermocline, and a possible 20 m lowstand of the lake during the Holocene.

Table 2. High-Resolution Seismostratigraphic Sequences (from Halfman and Herrick, 1998)

Sequence	Acoustic Character and Interpretation
4	Low amplitude surface and internal reflectors that onlap onto older sequences. Postglacial laminated muds & underlying brown muds
3	Two and locally more transparent units with surface reflectors similar to sequence 2. Mass movement deposits of pink clays
2	High-amplitude surface and parallel to subparallel internal reflectors on decimeter scale. Proglacial rhythmites (pink clays)
1	High-amplitude surface and occasional internal point reflectors. Glacial drift
Others	Transparent section, the seismic signal is typically attenuated by gas (biogenic methane?). Lacustrine early-Holocene marls (detected in isolated nearshore areas, water depths < 20 m)

MASS MOVEMENT OF THE PINK CLAYS

Sequence 3 is a previously unidentified seismostratigraphic unit, and is interpreted as two main and locally more mass movement deposits of the pink clays. A number of observations support our hypothesis. The sequence is found abruptly between and above the pink clays, filling the bathymetric lows in the lake (Fig. 4). The sequence thins to the south, and slowly gains additional high-amplitude internal reflectors that are characteristic of the older pink clays. Isolated "pods" of pink clays are laterally encased in a package of sequence 3 and suggests that the pods are parent material caught in a flow of proglacial rhythmites (Fig. 5). Woodrow and coworkers (1969) described folded and faulted pink clays recovered from the margins of the deep basin. They hypothesized that the deformed strata were the product of down slope movement of pink clays from the neighboring steep sides of the basin. Halfman and Herrick (1998) hypothesize that sequence 3 is a subaqueous, down slope movement of upper portions of pink clays. Movement was towards the center of the basin and towards the south along the long axis of the lake. They infer that the movement was intense enough to disturb the internal stratigraphy of the pink clays but the intensity of disturbance decreased to the south. Timing of the two main flows is stratigraphically restricted to the waning stages of pink clay deposition in the basin about 14 ka. The triggering mechanisms could be pulses of meltwater or meltwater sediments, rapid drawdown of the lake as a lower outlet was opened to the north, melting of stagnant ice within the glacial drift along the central portion of the basin, and/or earthquake activity.

SEDIMENT REWORKING AND POSSIBLE LOWER LAKE LEVELS

The postglacial muds are 5 to 8 meters thick and blanket the profundal portions of the basin. The thickness of postglacial sediments decreases rapidly on the steep slopes, where normal faults, slumping, accurate glide planes, and other evidence for episodic down slope movement of sediments is evident. The postglacial muds only form a thin veneer of material that unconformibly covers pink clays and glacial drift in shallow water areas, down to water depths of 60 m in the northern part of the lake. Surface waves and associated currents rework shallow-water sediments. Theoretical calculations for Seneca Lake suggest that surface waves from sustained 50 kph winds can erode fine sands at water depths up to 20 meters in the lake (Johnson, 1980). This 20-meter depth is a maximum estimate because parameters like effective fetch were deliberately overestimated in the calculations.

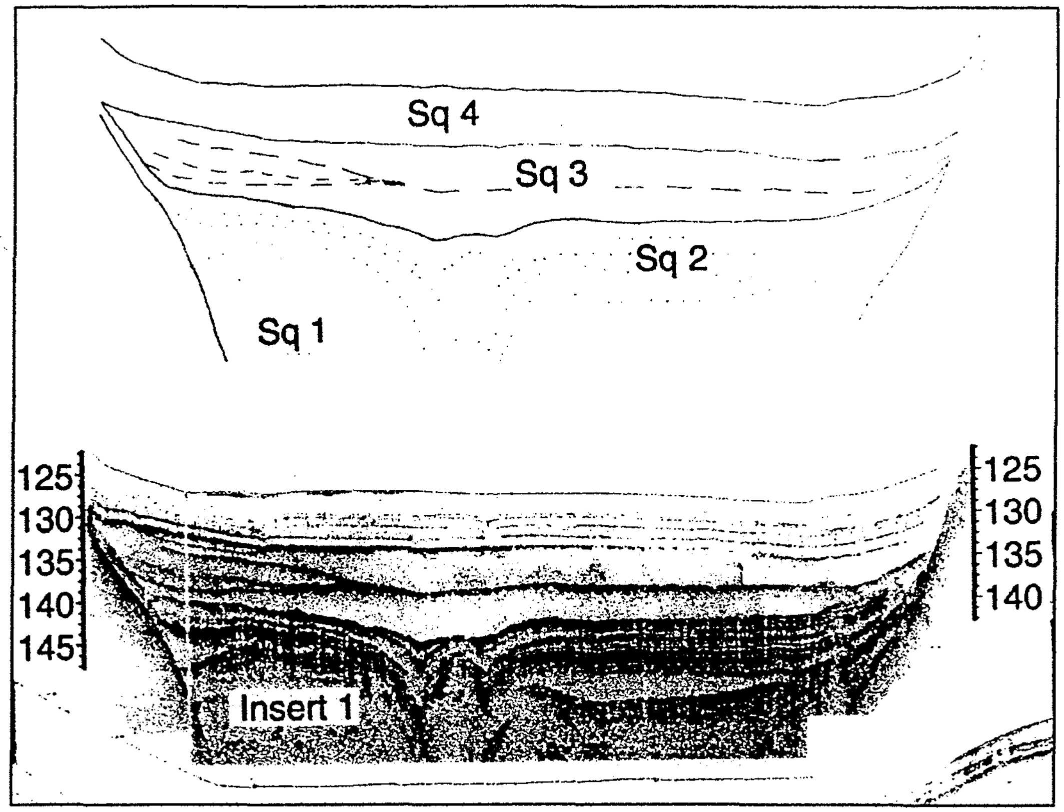


Fig. 4. East/West seismic profile from the lake with Sequence 3 found between and above the pink clays (after Halfman and Herrick, 1998).

Twenty years of current meter data collected by Bill Ahrnsbrak (Hobart and 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). For example, current velocities of 30 cm/s have been recorded 1 meter above the lake floor at a water depth of 66 m this past Fall (1996) but only immediately after strong southerly wind events associated with the passage of a front. These currents must impact sedimentation in the lake at water depths deeper than 20 m, apparently down to 60 m. The strong seiche activity is probably enhanced by the elongated nature of the basin.

A lake-floor scarp, where the lake bottom quickly descends from approximately 15 to 20 meters, is observed in Seneca Lake (Fig. 6). We are presently investigating the following hypotheses for its origin (1) The scarp may be the result subaqueous sediment redistribution and deposition by the reworking processes mentioned above, and the reworked sediments have prograded lakeward with time. (2) The scarp could be the lakeward extent of marl deposition. (3) The scarp may be a wave-cut feature, i.e. the result of sediment truncation by surface, wind-driven waves during a lowstand of the lake sometime after the deposition of the early-Holocene marls. The preliminary data favor the later hypothesis but additional data are required to confirm our tentative hypothesis.

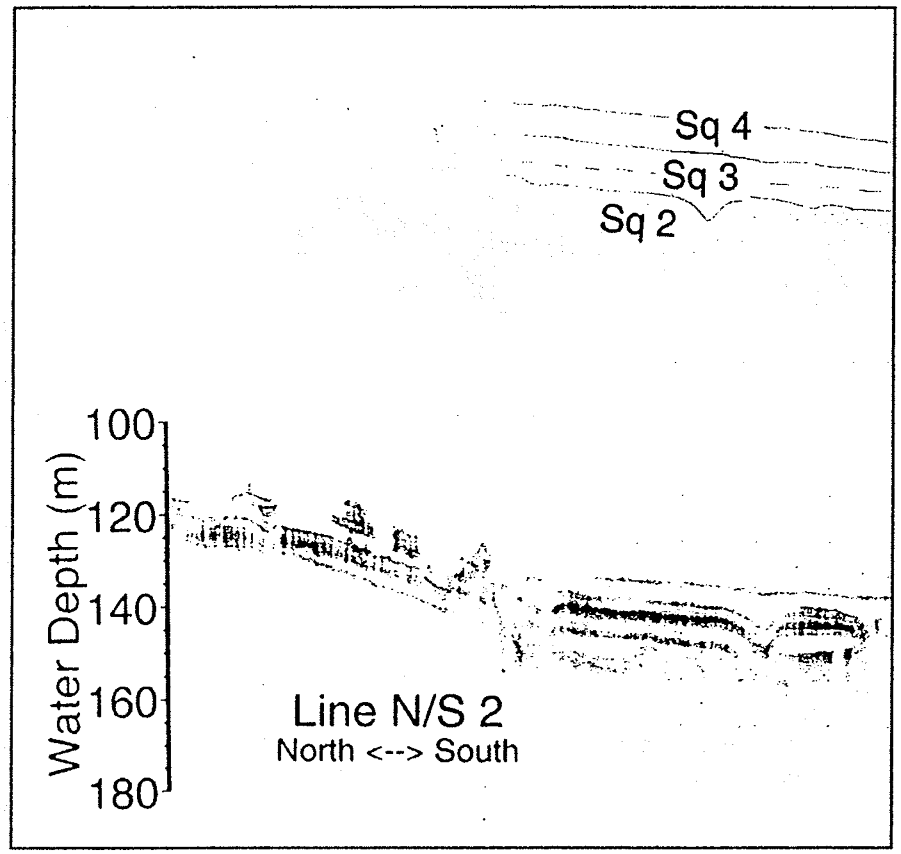


Fig. 5. Pods of pink clay encased in a package of Sequence 3. It suggests that Sequence 3 is a mass movement of pink clays during the waning stages of deglaciation in the basin (after Halfman and Herrick, 1998).

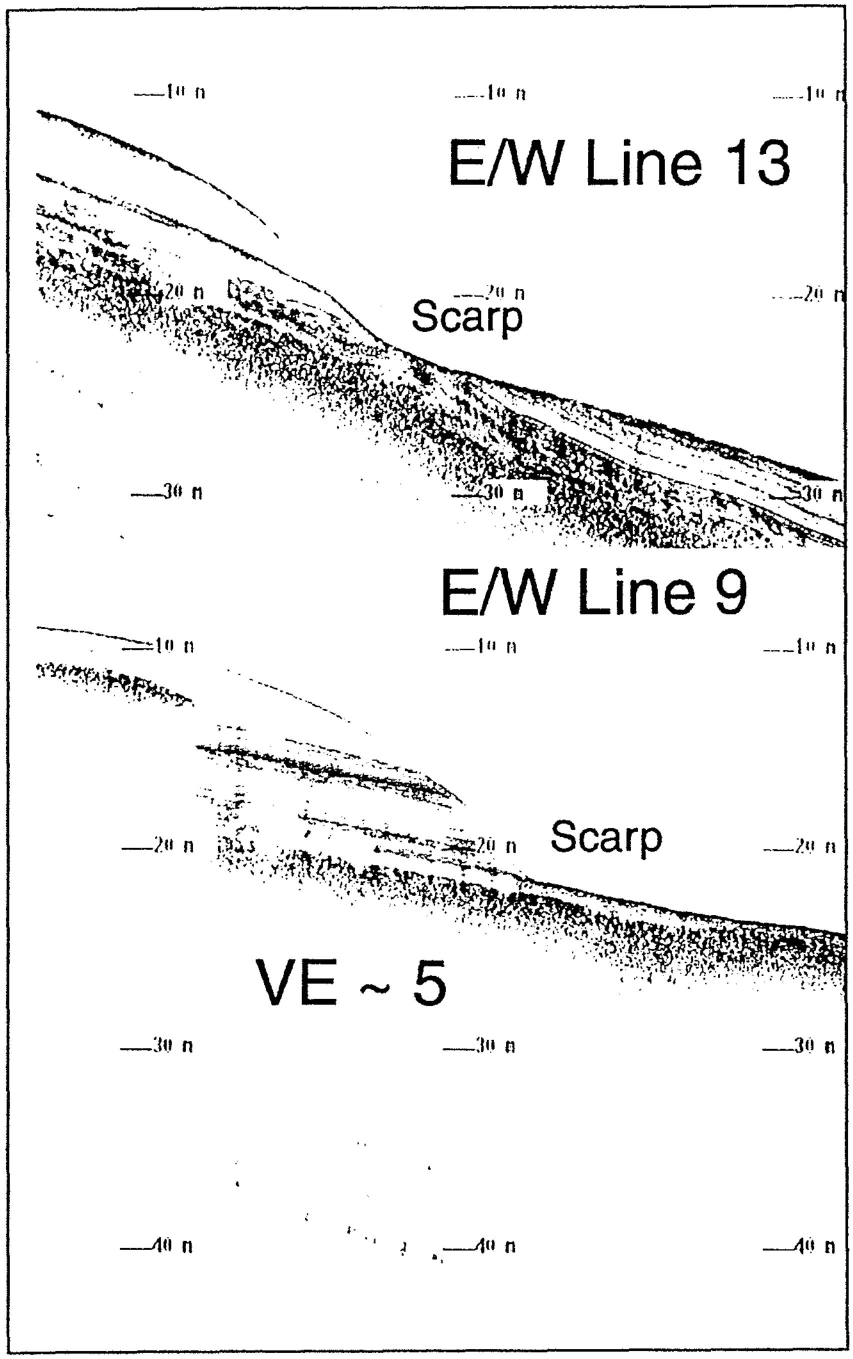


Fig. 6. A scarp at 20 meters of water is found through out the basin. Its origin is currently being investigated.

GEOCHEMISTRY - SENECA LAKE CHLORIDE AND CALCIUM CONCENTRATION

CHLORIDE
(after Wing et al., 1995)

Seneca Lake is the water supply for many of the inhabitants within its drainage basin. Thus, water quality of the lake is a concern to many. Chloride concentrations are 8 to 10 times higher in Seneca Lake (approximately 150 ppm) than they are in the other Finger Lakes (5 to 20 ppm, and 80 ppm in Cayuga Lake), high enough to pose a long-term health hazard for individuals prone to heart disease and newborns who use Seneca Lake water for drinking. The higher concentration is not the result of landuse or mining practices in the basin, because the annual chloride loading to Seneca Lake by streams and local mines is similar to those found at the other Finger Lakes, and more importantly, is deficient by an estimated 170 x 10^6 kg of salt. The deficiency suggests an interesting hypothesis. Seneca Lake is the only Finger Lake (with the partial exception for Cayuga Lake) with a deep enough basin to intersect the Silurian evaporites. Thus, the great depth of the bedrock floor provides a conduit to an extra source of Chloride, which is not available to the other shallower Finger Lakes. Cayuga Lake is the exception to this rule. Wing and coworkers (1995) propose that its second deepest status is consistent with its second highest chloride concentrations among the Finger Lakes.

Field data support this hypothesis. Chloride concentrations were observed to increase in the hypolimnion, the water mass below the thermocline, during the summer. The saltier water was mixed into the rest of the lake in early winter when the lake became isothermal (isopycnal). Sediment pore waters reveal large regions of higher salinity water several meters below the sediment-water interface, where chloride concentrations as high as 30 ppt have been found. Analysis of pore waters from piston cores reveal increasing Chloride concentrations with increasing burial depth.

CALCIUM HARDNESS
(After Halfman et al., submitted)

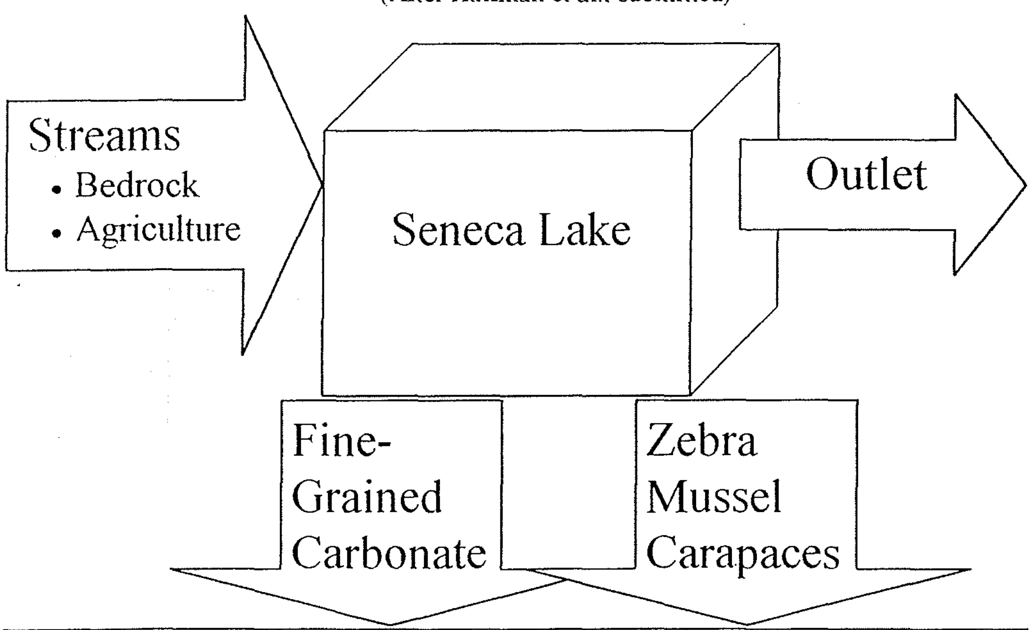
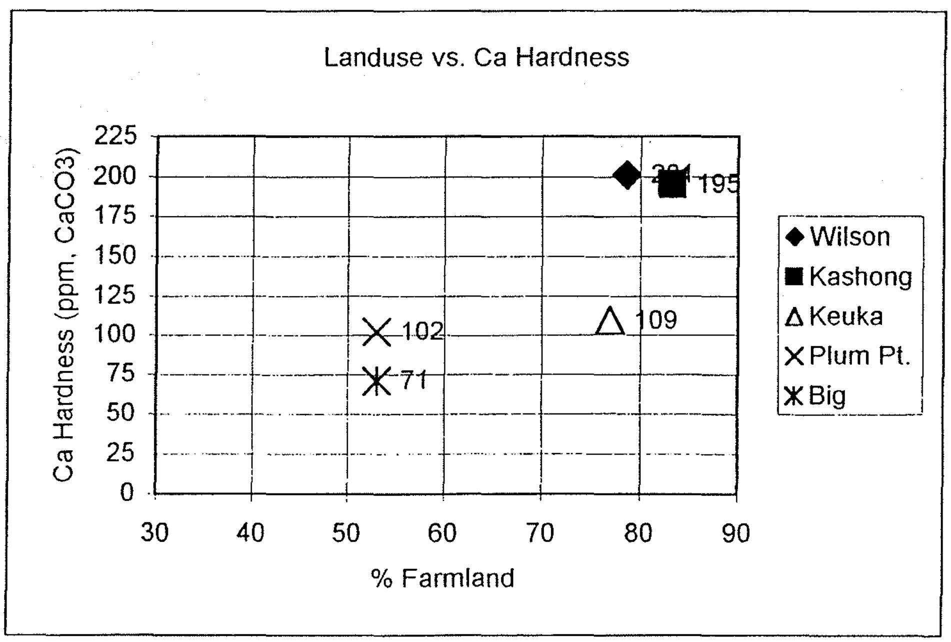


Fig. 7. A first-order calcium mass balance model for Seneca Lake showing the major source and sinks of calcium to and from the lake.

Calcium hardness concentrations average 95 ppm (as $CaCO_3$), and total hardness concentrations average 150 ppm (as $CaCO_3$). These values approach the 80 (100) ppm concentration minimum that defines the boundary between soft (lower concentrations) and hard water (higher concentrations). Hard water is a nuisance in domestic water supplies because is prevents the lathering of soaps and deposits a whitish scum on pots, pans and plugs plumbing in hot water heaters. Calcium is also a vital "nutrient" for the zebra mussel (*Dreissena polymorpha*), a recent exotic. It first appeared in Seneca Lake during the summer of 1992. Since then, it has quickly invaded all of the suitable habitats in the lake, and significantly impacted water clarity, plankton concentrations, nutrient concentrations and other facets of the lake's limnology. Here we will report on the zebra mussel's impact on the calcium budget of the lake.

Stream, sediment and limnological data are sufficient for back-of-the-envelop calculations on the calcium budget in the lake and to assess the impact by the recent invasion of zebra mussels. The primary source of calcium to the lake is from streams whereas the primary removal mechanisms of calcium from the lake are precipitation of an authigenic carbonate (whiting), flow through the outlet, and precipitation of zebra mussel shells. We assume that groundwater has a negligible impact (Fig. 7).

The calcium input by streams was extrapolated from the available stream discharge and calcium concentration data collected from 6 streams since 1995. We extrapolated the different fluxes of calcium by each stream to the entire watershed after assuming stream discharge is proportional to subwatershed area and calcium concentration is proportional to bedrock geology and a lesser extent agricultural activity in the subwatershed (Fig. 8). It yields an annual influx of 34,400 metric tonnes of calcium per year. The outflow removes 31,000 metric tonnes of calcium/year by multiplying the Ca concentration in the lake by the annual discharge through the outlet. The pre-zebra mussel efflux by authigenic calcite precipitation was estimated from the mean concentration of calcium in the sediments (0.03 g Ca/g mud), the sediment porosity (0.82), sediment accumulation rates over the entire lake floor (0.20 cm/year) and sediment density (2.65 g/cm^3). The result is 4,000 metric tonnes / year. The estimated pre-zebra mussel inputs (34,400) balance the pre-zebra mussel outputs (31,000 + 4,000). The flux of calcium to zebra mussels was estimated from the average mass of calcium in the zebra mussels collected in a number of sediment dredge samples (1.2 g Ca/dredge), a zebra mussel average life span of 3 years, and extrapolating this result over the entire lake floor where zebra mussels accumulate (50 km^2). This yields a flux of 200 metric tonnes/year or 5% of the total calcium flux to the lake floor. This redirection of calcium from the authigenic carbonate fraction to the zebra mussel fraction is confirmed by a most recent decrease in carbonate content in the uppermost 1 or 2 cm of sediment.



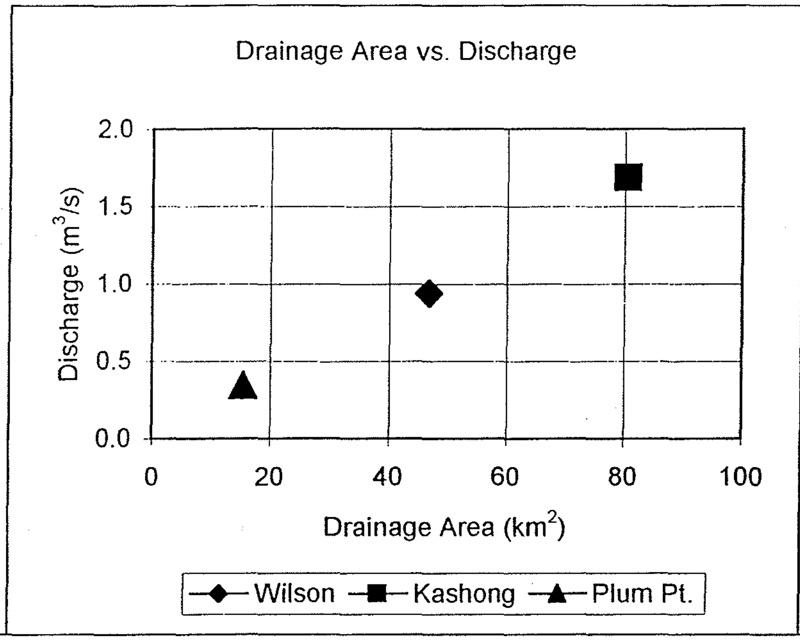


Fig. 8. Mean annual discharge and mean calcium concentrations vs. subwatershed area for selected streams. The data suggest that stream discharge is proportional to watershed area, whereas calcium concentration must reflect other factors besides watershed area. Landuse and bedrock geology are two plausible options. Mean annual calcium concentrations vs. percentage of agricultural land do not reveal a linear trend. Limestone and calcium rich soils underlie Reeder, Wilson, and Kashong Creeks than other creeks in the survey and the bedrock correspond to the high calcium concentrations.

H-WS EXPLORER

H-WS Explorer is a steel hulled, single screw, diesel powered vessel built in 1954 for the United States Navy. Hobart and William Smith Colleges acquired the vessel in 1976 after it had also been used in, e.g., the lobster and fishing industries. The vessel is documented "Oceanographic" by the United States Coast Guard and meets all of the standards applicable to such a vessel. In 1989, major renovations resulted in the construction of a 20 by 10 ft laboratory on the main deck to compliment the growing list of standard oceanographic/limnologic equipment including 2 Sea Bird CTD's (Conductivity, Temperature, Dissolved Oxygen, pH, Turbidity and Depth sensors), EdgeTech (EG&G) X-Star high-resolution seismic reflection system, EdgeTech sidescan sonar, computers, flume hood, weather station and other equipment. The pilothouse has a full compliment of safety, navigation and communication equipment including up-to-date radar, satellite navigation, marine radio-telephone, cellular phone and other equipment. Most importantly, a licensed captain and mate operate the vessel. It provides a safe, well-equipped platform useful under most weather conditions experienced on Seneca Lake.

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CRUISE LOG

This field trip starts and stops aboard the H-WS Explorer, and investigates the sediment character and water chemistry at selected locations (Fig. 1). We will look at the X-Star seismic stratigraphy of the sediments while underway between stations. Surface grab samples will be collected at the first two stops, and a short piston core at the third stop. We will also deploy the CTD and collect water samples to analyze at the third station as well. We will not concern ourselves with the lacustrine marls because they compose a small fraction of the sediments in the lake. A road log is not provided for obvious reasons.

STATION #1. SHALLOW-WATER SANDY SILTS - NORTHERN END OF SENECA LAKE

The lake floor is covered by sandy silts, with the coarsest sediments in the northwest margin of the lake. Shell and plant debris and the occasional ice-raft pebble make up the other minor components. We believe that these sediments must be derived from the reworking of and erosion of glacial drift. Subbottom images suggests that the sand forms a thin wedge of sediment above the pink clays and/or glacial drift. In many places the seismic images are attenuated by gas (biogenic methane?).

Suitable substrate (coarse materials) is covered by zebra mussels. Zebra mussels are an exotic species that has been introduced in the lake during the past decade. They are prolific filter feeders, filtering, on average, a few liters of water each day, extracting the plankton from the water column. One possible measure of their impact is historical Secchi disc data. Secchi discs are used to measure water clarity. To a first approximation, deeper Secchi disc depths correspond to less turbid water (e.g., smaller plankton concentrations). Historical Secchi disc data have shown increasing Secchi depths over the past decade from a few meters to over 5 meters deep during the productive early summer months. This change is consistent with a decrease in chlorophyll concentrations. The exact reasons for the increase in water clarity (and decrease in chlorophyll) are not completely understood but the Secchi disc data suggests two hypotheses: that the burgeoning population of zebra mussels has become large enough to significantly reduce the standing crop of plankton, and/or an increase in the quality of sewage treatment by lake-shore residents has reduced the anthropogenic nutrient loading to the lake.

STATION #2. PROGLACIAL RHYTHMITES – MID-LAKE OFFSHORE OF BELHURST CASTLE

To the south of station 1, pink clays may be found below a thin veneer of postglacial material. The pink clays are well stratified, very cohesive and exhibit light red to pink colors. Single pebble to granule sized grains and ostracode shells are found widely scattered in the sequence. Well defined, parallel to subparallel reflectors characterize these clays in the subbottom profiles. The reflectors commonly outcrop onto the lake floor in shallow water. We interpret these clays as proglacial rhythmites, typical of many proglacial lakes. It is unclear whether the couplets are annual events (varves). In the northern part of the lake, the pink clays are folded. The subbottom profiles suggest that the pink clays collapsed into ice-block holes in the underlying drift and/or the ice front experienced small re-advances.

STATION #3. POSTGLACIAL MUDS & LAKE GEOCHEMISTRY – OFFSHORE OF CLARKS POINT

Moving south across exposures of glacial drift, the lake floor descends to a flatter floor typical of the deeper parts of the lake. At this location the uppermost sediments are very fine grained, black to gray, stratified and rich in organics. These sediments blanket the older materials with thicknesses up to 8 meters in the subbottom profiles. The sequence thins rapidly in water depths shallower than 60 meters and on the steep slopes on either side of the basin. They contain no shell material, a few coarse grains of silt and sulfide minerals. These muds are interpreted as the postglacial sediments deposited since deglaciation. The source is the suspension of fine material carried into the lake by streams and/or erosion of older, shallow-water bottom sediments by surface and internal waves.

We will also deploy the CTD and analyze the surface water for its chloride and calcium concentrations at this site to discuss the unique source of the "extra" chloride to Seneca Lake and the recent depletion of calcium from the lake by zebra mussels.