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High-Resolution Seismic Reflection Evidence for Middle Holocene Environmental Change, Owasco Lake, New York

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Approximately 70 km of new decimeter-resolution seismic reflection profile data from Owasco Lake, New York define a middle Holocene (~4600 ^{14}C yr B.P.) erosion surface in the north end of the lake at water depths as great as 26 m. Beneath the lake, postglacial sediments are up to 9 m thick and represent about 10% of the total sediment fill. Early to middle Holocene sediments, ~6 m thick, contain biogenic gas at the south end of the basin and a large (4 km × 300 m × 15 m) subaqueous slide deposit along the east-central portion of the lake. Late Holocene sediments are thinner or absent, particularly at the north end of the lake. The middle Holocene erosion surface may have been produced by a drop in lake level. Alternatively, it may represent a change in climate during the transition between the relatively warm Holocene hypsithermal and cool neoglacial. At this time (~4600 ^{14}C yr B.P.) circulation in Owasco Lake appears to have evolved from sluggish to active. The increased circulation, which persists today, probably resulted from atmospheric cold fronts with strong southwesterly winds that piled up water at the north end of the lake. The increased water circulation may have been ultimately driven by decreasing insolation, which produced an increased pole-to-equator thermal gradient and, thus, stronger global winds that began at the transition between the hypsithermal and neoglacial.

Key Words: **erosion surface; Owasco Lake; middle Holocene; climate change; seismic reflection data; atmospheric circulation.**

INTRODUCTION

Sediments in glacial lake basins can record environmental changes that occurred at middle and high latitudes during the current interglacial. Seismic reflection surveys can help decode these records of continental environmental change by showing their three-dimensional stratigraphic framework.

At New York's Finger Lakes (Fig. 1), for example, a 1000-joule UNIBOOM survey using a sound source with a dominant frequency of ~1 kHz defined the entire sediment fill of the lakes (Mullins *et al.*, 1996) and was subsequently correlated to onshore drill-core data (Wellner *et al.*, 1996). Six (I to VI; oldest to youngest) Finger Lake depositional sequences were defined and mapped within sediment sections up to 275 m thick (Mullins and Hinchey, 1989). In addition, an ultra-high frequency (2 to 12 kHz) seismic reflection profile system extracted previously unrecognized information on the latest postglacial history of Seneca Lake (Halfman and Herrick, 1998).

This paper presents new results and interpretations of a recent (1998) decimeter-resolution seismic reflection profile survey of Owasco Lake, one of New York's Finger Lakes (Fig. 1). These new data allow for further refinement of the seismic stratigraphy presented by Mullins *et al.* (1996) as well as a more detailed assessment of postglacial processes, including middle Holocene environmental change during the transition between the relatively warm hypsithermal and cool neoglacial.

REGIONAL SETTING

The Finger Lakes of central New York State occupy elongate lake basins that originated as preglacial stream valleys which were subsequently deepened by a combination of ice and subglacial meltwater erosion ~14,500 ^{14}C yr B.P. (Mullins and Hinchey, 1989; Mullins *et al.*, 1996). Owasco Lake is 18 km long and ~1–2 km wide (Fig. 1) and has the largest drainage area to surface area ratio (17) of any Finger Lake (Mullins *et al.*, 1996). Two major streams enter Owasco Lake today; one at its southern end and the other at Burtis Point in the northeast quadrant of the lake (Fig. 2). Outflow of surface waters is at the north end of the lake where Muller and Cadwell (1986) have mapped regionally continuous moraines. Water residence times for the Finger Lakes range from 1 to 12 years, with that for Owasco Lake being less than 3 years (Michel and Kraemer, 1995). Outflow

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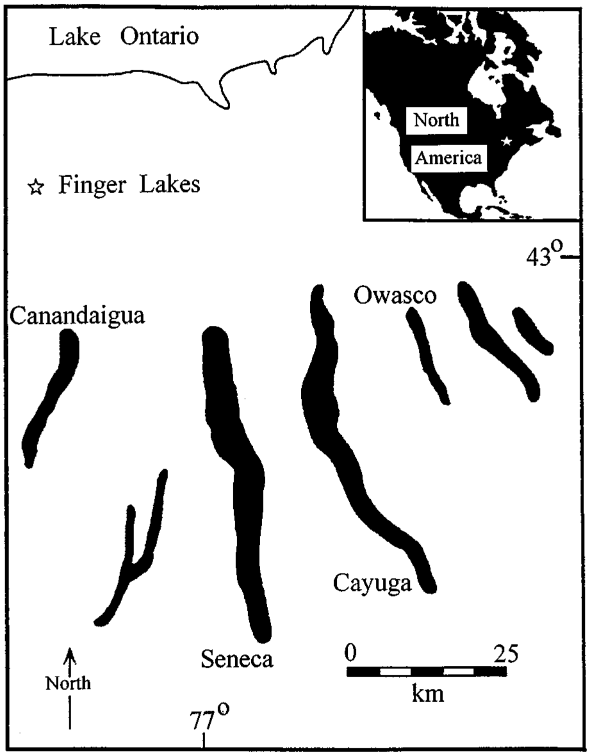

FIG. 1. Index maps.

from all the Finger Lakes ultimately flows into Lake Ontario to the north.

Owasco Lake is dimictic; it has two annual episodes of turnover and thermal stratification (Schaffner and Oglesby, 1978; Effler *et al.*, 1985). It is also a moderately productive (mesotrophic), hardwater lake that seasonally precipitates calcite during "whiting events" (Effler *et al.*, 1985, 1987). Like the other Finger Lakes, Owasco Lake has symmetrical, steep, rocky, western and eastern walls that extend down to a flat muddy bottom (Fig. 2). The maximum water depth of 52 m is located near the midpoint of the lake just south of Long Point. The north–south bathymetric profile slopes more gradually into deep water at the north end of the lake than at the deltaic south end. Owasco Lake has long snowy winters and warm, humid summers. At the south end of neighboring Cayuga Lake, average annual precipitation is 92 cm/yr, and average monthly temperatures range from −4.4°C in January to 20.5°C in July. Winds blow mainly from the west, and strong southwesterly winds accompany the passage of cold fronts (Schaffner and Oglesby, 1978; Eichenlaub, 1979).

METHODS

During July 1998, we collected ~70 km of decimeter-resolution reflection profiles from Owasco Lake. Thirty-eight east–west profiles were tied together by a single north–south line (Fig. 2). Reflection data were collected from a 6-m-long vessel using an Edge-Tech X-Star sub-bottom profiling system that has sweep frequencies of 2 to 12 kHz. The combined sound source and receiver was towed at a depth of ~1 m at 3 to 4 knots. Data were graphically displayed on an EPC model GSP-1086 recorder and were also digitally recorded on magnetic tape. A time-varying gain of 0.4 db/m was applied to the graphic field records. Navigation was by a GPS receiver interfaced and digitally recorded with each seismic trace. This X-star system typically allows penetration of up to 50 m in soft sediment with decimeter-scale resolution. A constant P-wave velocity of 1500 m/s was assumed for both the water column

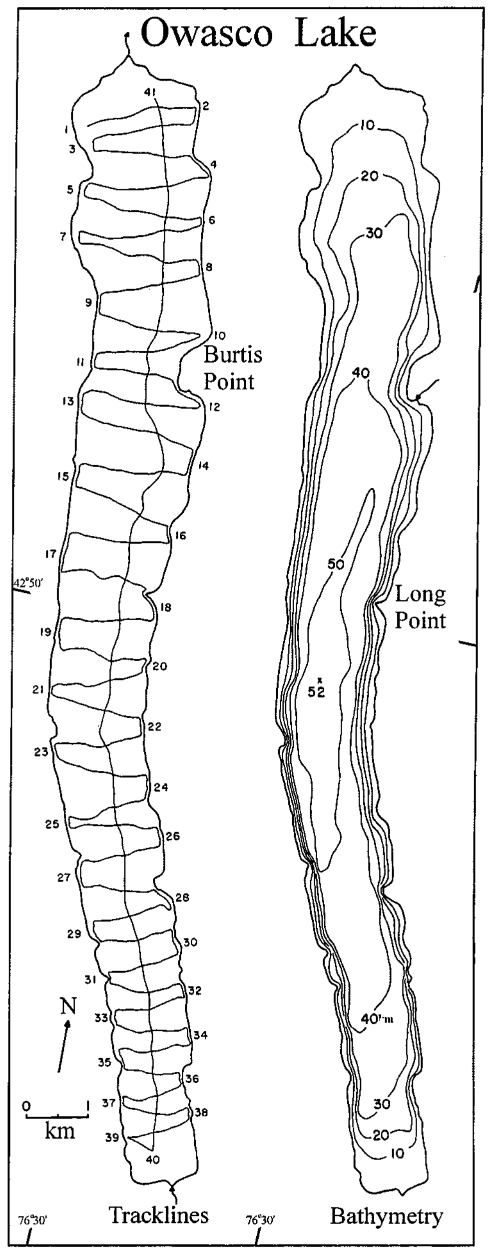

FIG. 2. Seismic reflection tracklines (left) and bathymetry (right) of Owasco Lake.

and near surface sediments, consistent with near-surface velocities previously measured by wide-angle reflection experiments in the Finger Lakes (Mullins *et al.*, 1996). Bathymetric, special feature, and isopach maps were constructed by digitizing each seismic reflection profile with measured values plotted on a base map and contoured.

Although no sediment cores were recovered directly as part of this study, box-core (<1 m) data for Owasco Lake are available from the New York State Department of Environmental Conservation in Albany (C. Rowell, personal communication, 1996) and nine radiocarbon-dated (<12,000 ^{14}C yr B.P.) cores up to 9 m in length have previously been recovered from the wetland and dry lake valley south of Owasco Lake (Dwyer *et al.*, 1996). In addition, a 120-m-long drill-core from the south end of Canadaigua Lake has established the regional seismic stratigraphic (depositional sequences I to VI) and chronostratigraphic framework for the Finger Lakes (Mullins *et al.*, 1996; Wellner *et al.*, 1996).

RESULTS

Previous UNIBOOM seismic reflection surveys have identified six depositional sequences (I–VI) beneath Owasco Lake that have a maximum total sediment thickness of 95 m (Mullins *et al.*, 1996). Because the X-Star high-resolution profiler used here is capable of much higher resolution imaging of the postglacial section, we will restrict our presentation to the youngest unit—sequence VI. Depth to bedrock, total sediment thickness, and sequences I to V were described by Mullins *et al.* (1996).

Sequence VI

Sequence VI was originally defined as a thin (<10 m), acoustically transparent unit of postglacial sediment in the Finger Lakes (Mullins *et al.*, 1996). Piston cores recovered from nearby Cayuga and Seneca lakes showed that sequence VI consists of dark-gray, organic-rich mud <13,900 ^{14}C yr B.P. (Mullins *et al.*, 1996; Anderson *et al.*, 1997). However, the new high-resolution data shows that sequence VI also contains low-amplitude, continuous reflections, particularly in the lower two-thirds of the sequence (Fig. 3). Using these reflectors we divided sequence VI into two subunits (VIA and VIB) that are mappable throughout most of the Owasco basin (Fig. 4). Although the origin of the reflections in subunit VIA is unknown, they may be related to four small-scale (<5 m) lake-level lowerings that occurred in nearby Cayuga Lake between 11,000 and 4000 ^{14}C yr B.P. (Mullins, 1998a) and/or to variations in calcium carbonate content known from Seneca and Cayuga lakes between 13,900 and 4500 ^{14}C yr B.P. (Anderson *et al.*, 1997; Mullins, 1998b; Halfman and Herrick, 1998). Regardless of their origin, these reflections distinguish VIA from overlying subunit VIB, which

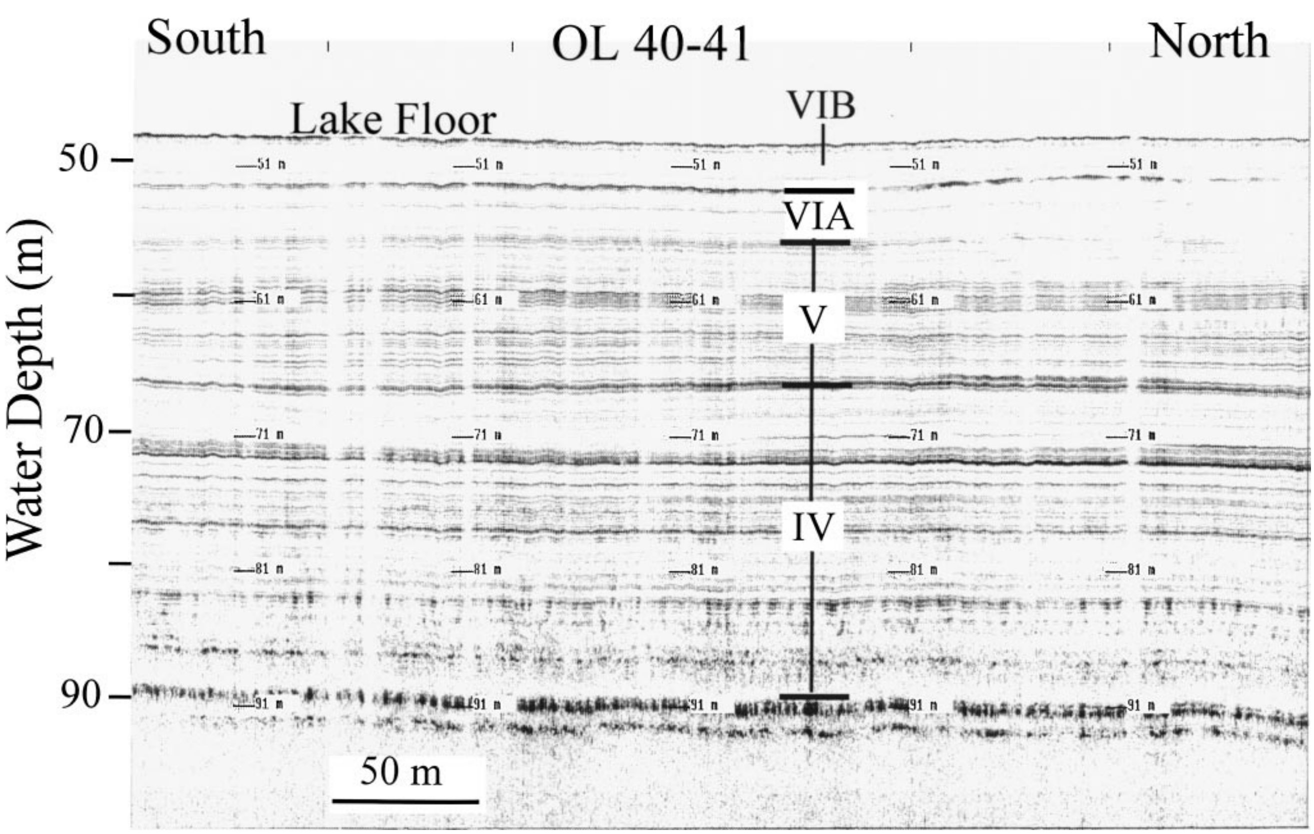

FIG. 3. Part of seismic reflection profile 40–41 (Fig. 2) illustrating depositional sequences VIA and VIB.

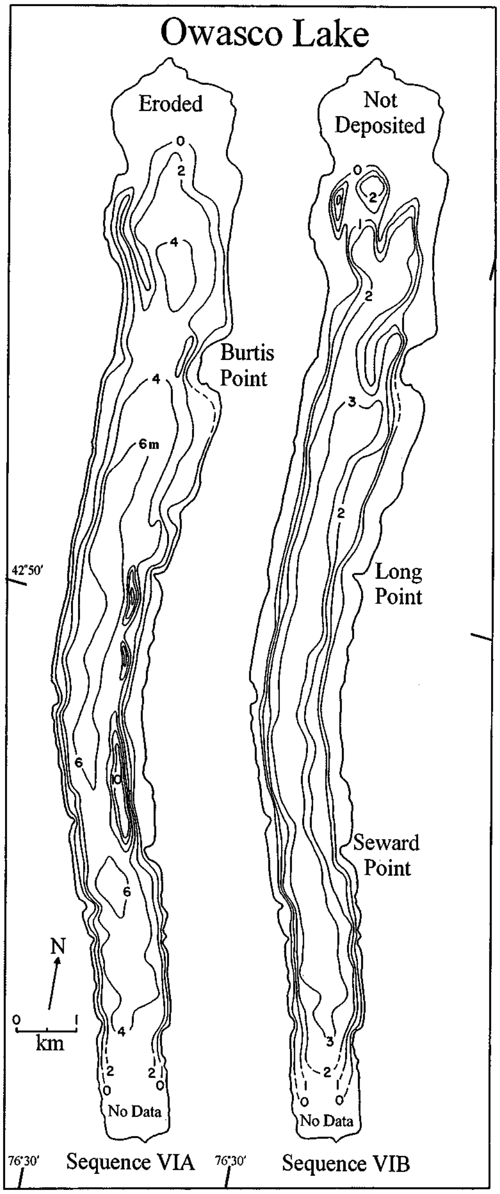

FIG. 4. Isopach maps of seismic sequences VIA (left) and VIB (right) in Owasco Lake.

is acoustically transparent even in our high-resolution profiles (Fig. 3).

Isopach mapping (Fig. 4) of sequence VI reveals that overall it has a maximum thickness of 9 m (6 m in VIA and 3 m in VIB) with the exception of localized slide deposits (see next section on special features). Sequence VI is thickest in the middle of Owasco Lake (Fig. 4), where water depth is greatest. This coincidence suggests that sediment deposition has been focused in deep water (Lehman, 1975) during postglacial time. Sequence VI sediments are absent from the northern end of Owasco Lake (Fig. 4) due to a combination of erosion of VIA and nondeposition of VIB (see next section).

The only sediment core available from Owasco Lake is a 60-cm-long box core recovered during 1996 in 40 m of water from subunit VIB in the northern half of the lake off Burtis Point. This near-surface core consists of massive dark-gray mud with high (>70%) water content, up to 10 weight % total organic matter, and up to 25 weight % calcite (C. Lajewski, personal communication, 1999). A maximum ^{137}Cs peak at 12 cm in the core (C. Rowell, personal communication, 1996) corresponds to A.D. 1963, the peak of atmospheric nuclear weapons tests (Krishnaswamy *et al.*, 1971). The sedimentation rate thus averaged 0.36 cm/yr between 1963 and 1996. If extrapolated to the entire Holocene, this rate predicts 36 m of sediment in sequence VI, compared with the 9 m maximum observed on our seismic profiles. Perhaps the high rate of sediment accumulation in the late 1900s is a legacy of clear cutting and soil erosion, which occurred in the watershed during the 1800s (Schaffner and Oglesby, 1978).

Special Features

In addition to defining subdivisions of sequence VI, our new high-resolution seismic reflection data revealed a number of other features (Fig. 5) that may be related to postglacial environmental change.

Subaqueous slide. The profiles show that a large subaqueous slide occurred in eastern Owasco Lake near the end of sequence VIA (middle Holocene) time (Fig. 6). The slide is a wedge-shaped deposit of acoustically chaotic debris having a hummocky top that produces many diffractions (Fig. 6). It extends north–south more than 4 km with a width of up to 300 m and maximum thickness of 15 m (volume up to 18,000 km^3). The slide deposit shows up distinctly on the isopach map of sequence VIA as elongate accumulations of sediment 10–15 m thick (Fig. 4). In addition, a steep slope immediately east of the VIA slide deposit (Figs. 5 and 6) is probably the slide's headscarp.

Erosion surface. The north end of Owasco Lake has a distinct surface of erosion and/or nondeposition (Fig. 7) that extends down to water depths as great as 26 m. Here, sequence VI is uncommonly thin and truncates deposits of sequence V, and perhaps sequence IV, that are widely exposed at the lake floor. These features require an erosional event later than sequence V. The timing of this erosion is further constrained, in profile 5–6 (Fig. 8), by truncation of sequence VIA reflections that are overlain by sequence VIB sediments. There, erosion appears to have been initiated at, or about, the time of the sequence VIA/VIB boundary.

Acoustically impenetrable zones. Acoustically impenetrable zones border Burtis Point and the south end of the lake (Fig. 5). On our reflection profiles these zones appear as chaotic, high-amplitude reflections (termed "seismic smears" by Mullins and Nagel, 1983) that obscure or completely cover underlying stratigraphy. Such acoustic responses, widely observed in marine as well as lacustrine sediments, result from interstitial gas (methane) of either biogenic (Schubel and Schiemer, 1973) or

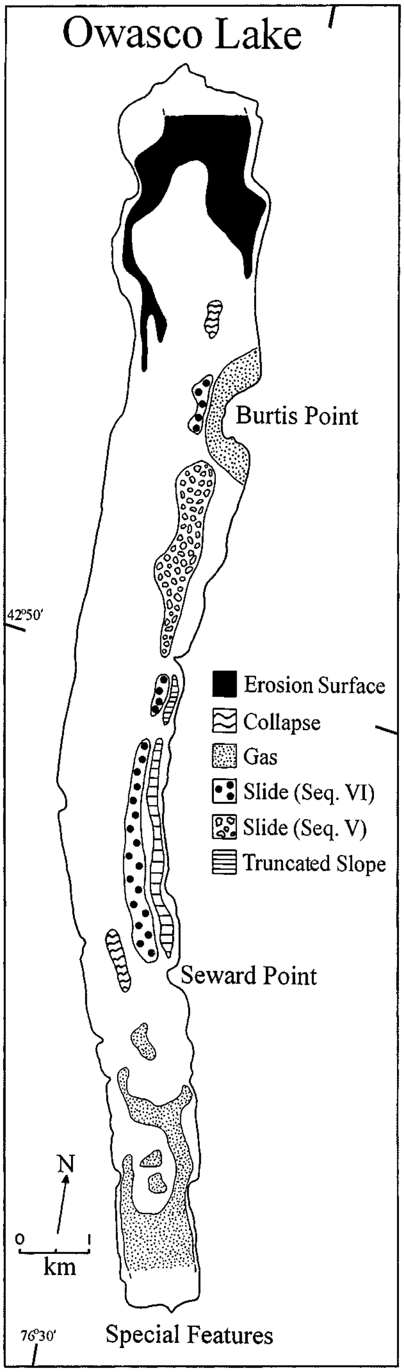

FIG. 5. Map of special features defined seismically in Owasco Lake and discussed in text.

thermogenic (Mullins and Nagel, 1983) origin. In the case of Owasco Lake, the occurrence of these acoustically impenetrable zones at the mouths of major inlet streams argues that the gas is of biogenic origin, being due to the anaerobic bacterial decay (methanogenesis) of terrestrial organic material transported to the lake basin by streams.

Although parts of the acoustically impenetrable zones in Owasco Lake are so high in the section that they may represent modern methane production, most of the acoustic anomalies occur within sequence VIA. Near the south end of the lake for instance, several seismic smears occur along the sequence VIA/VIB boundary (Fig. 9). Because gas can only migrate upward, this position indicates greater subsurface methane production during the early Holocene (sequence VIA) than in more recent times (sequence VIB).

DISCUSSION

Sequence VI represents deposition in Owasco Lake after final ice retreat ~13,900 ^{14}C yr B.P. (Mullins *et al.*, 1996). These postglacial sediments are at most only 9 m thick—a small fraction of the total sediment fill, which is as much as 95 m thick. Sediments within Owasco Lake sequence VI accumulated at an average rate of ~0.65 m/1000 ^{14}C yr compared with an average rate of ~170 m/1000 ^{14}C yr for sequences II through V (Mullins *et al.*, 1996).

An environmental change likely occurred at or near the sequence VIA/VIB boundary. Its age is middle Holocene, based on the boundary's position about one-third (3 m) of the way down into the postglacial sediment section. Assuming constant sediment accumulation rates in sequence VI over the past ~13,900 ^{14}C yr B.P., we estimate an age of ~4600 ^{14}C yr B.P. (13,900 yr × 0.33) for the boundary. This age estimate is similar to that of the boundary between carbonate-rich and carbonate-poor sediments, which has been dated by AMS at ~5500 ^{14}C yr B.P. in Seneca Lake (Anderson *et al.*, 1997) and at ~3500 ^{14}C yr B.P. in Cayuga Lake (Mullins, 1998b).

Sequence VIA in Owasco Lake is characterized by extensive interstitial gas at the south end of the basin (Fig. 9), a large subaqueous slide deposit along the eastern margin of the lake (Fig. 6), and erosional truncation along its top in the northern end of the lake (Figs. 7 and 8). The biogenic gas implies greater burial of organic matter and methanogenesis in the lake during the early Holocene than during the late Holocene. Potential explanations include primary aquatic productivity, flux of terrestrial organic matter, and dissolved oxygen concentrations in deep water that favored the preservation of organic matter. Although we have no direct data on the first two options, historic oxygen data may provide insight to early Holocene environmental conditions. Today, deep waters (hypolimnion) in Owasco Lake are sufficiently oxygenated throughout the year to support a deep, cold-water sport fishery, consistent with data collected in 1910 as well as from 1971 to 1973 (Effler *et al.*, 1985). However, data from the summer of 1942 reveal that "oxygen concentrations were substantially lower (up to 2 mg/l less) in the hypolimnion" (Effler *et al.*, 1985). Interestingly, historic meteorological data indicate that summer temperatures (June, July, August) in the Finger Lakes region during the 1940s were unusually warm, compared to those of the 1910s or 1970s (National Climate Data Center). Relative to the 1895–1997 average, summer temperatures during the decade of the 1940s were as much as 2–3°C above normal.

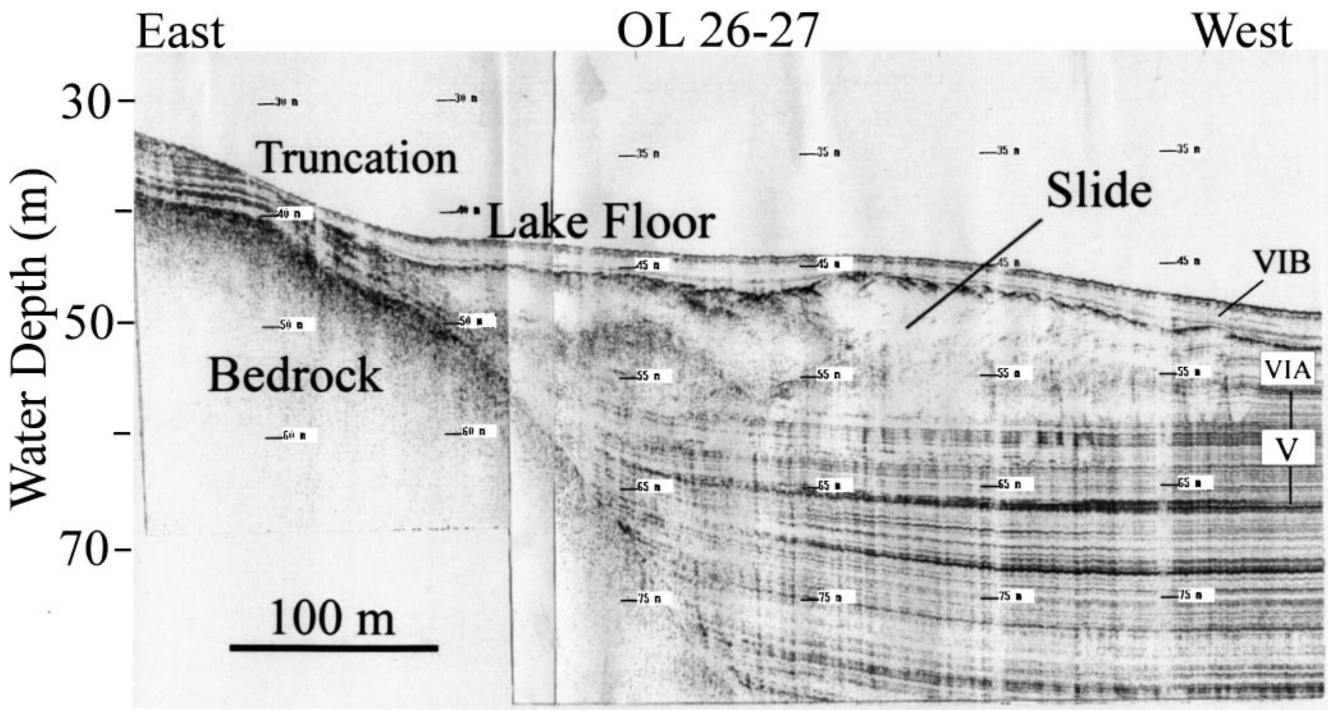

FIG. 6. Part of seismic reflection profile 26–27 (Fig. 2) illustrating subaqueous slide deposit at or near the sequence VIA/VIB boundary.

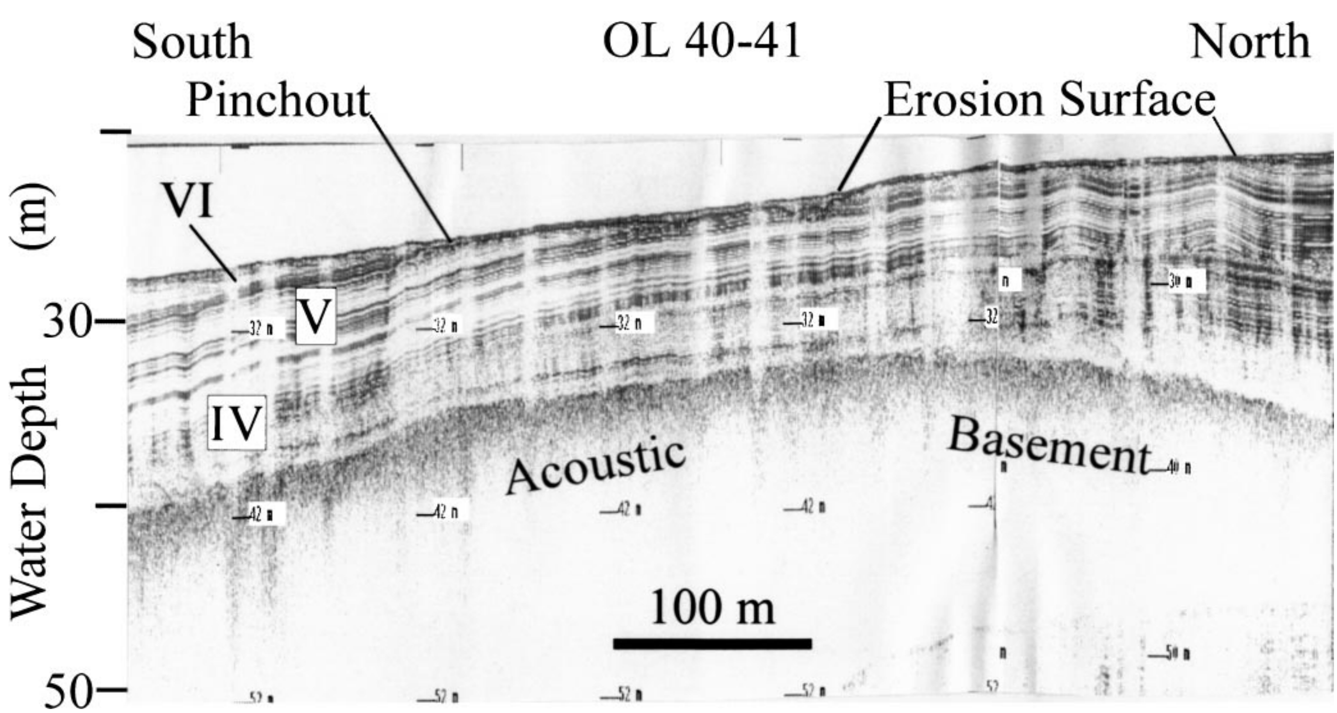

FIG. 7. North part of axial seismic reflection profile 40–41 (Fig. 2) illustrating pinchout (onlap) of sequence VI against erosion surface that truncates reflectors in sequence V.

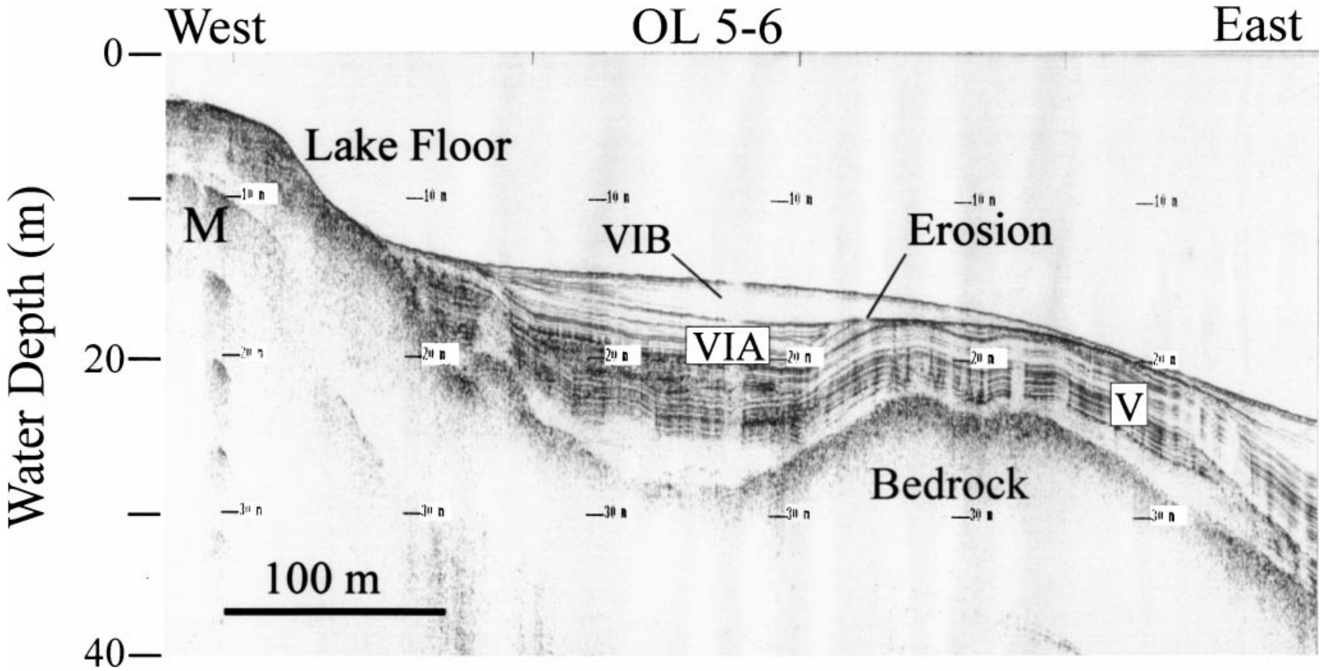

FIG. 8. Western part of seismic reflection profile 5–6 (Fig. 2) illustrating erosion surface along the sequence VIA/VIB boundary. This position implies a middle-Holocene age for the start of erosion. M indicates multiple reflection.

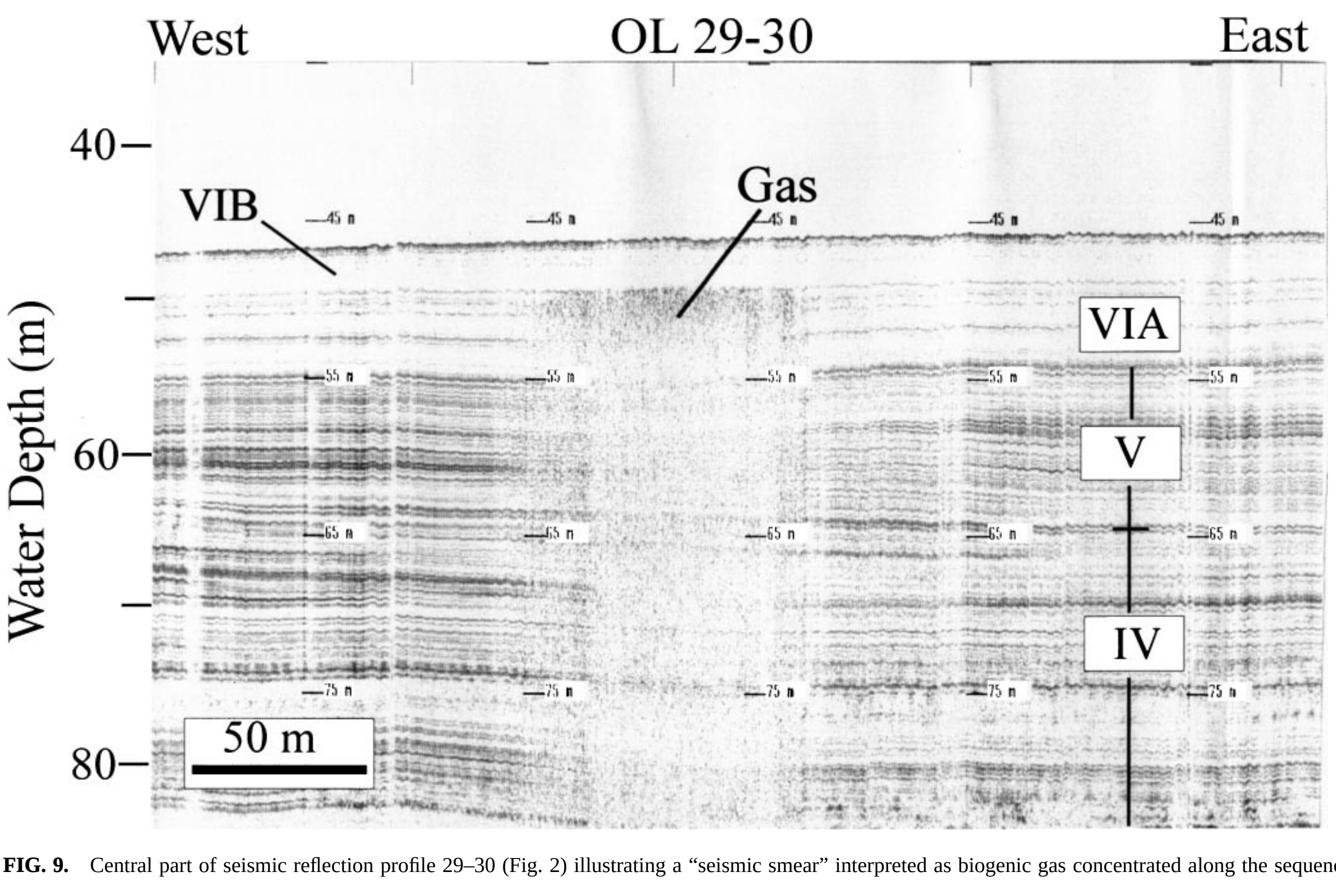

FIG. 9. Central part of seismic reflection profile 29–30 (Fig. 2) illustrating a "seismic smear" interpreted as biogenic gas concentrated along the sequence VIA/VIB boundary.

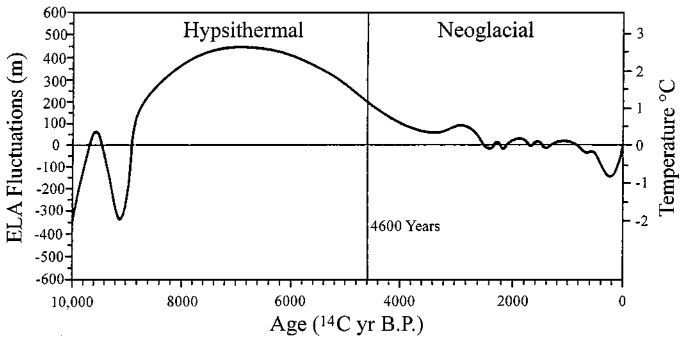

FIG. 10. Illustration of the age (~4,600 ^{14}C yr B.P.) of Owasco Lake erosion surface at the transition between the hypsithermal and neoglacial. The line surperimposed on the figure is from Nesje and Kvamme (1991) documenting Holocene equilibrium-line altitude (ELA) fluctuations and temperature variations relative to modern in Norway.

The early to middle Holocene has long been known to have had warmer Northern Hemisphere summers than today's, particularly between ~9000 and 4000 ^{14}C yr B.P., which is known as the Holocene hypsithermal (Pielou, 1991). Glacier reconstructions (Nesje and Kvamme, 1991) and general circulation models (Liao *et al.*, 1994; Ganopolski *et al.*, 1998) indicate that summer temperatures during the hypsithermal were 2–4°C warmer than today, as a result of increased insolation (~8%) due to variations in orbital precession and obliquity (COHMAP, 1988). Since the end of the hypsithermal ~4000 ^{14}C yr B.P. temperatures have fallen (except in the last 150 years), as illustrated by a variety of proxies including ice core oxygen isotope data from Greenland and Peru (Larsen *et al.*, 1995; Thompson *et al.*, 1995) as well as alpine glacier reconstructions from Norway (Nesje and Kvamme, 1991; Fig. 10) and western North America (Luckman *et al.*, 1993).

The early to middle Holocene gas beneath Owasco Lake thus implies that bottom waters in Owasco Lake may have been oxygen depleted during the hypsithermal. The lake may have had longer periods of stable summer thermal stratification, less frequent or vigorous turnovers of the water column, and in general more sluggish water circulation during the early to middle Holocene than it does today.

The subaqueous slide along the eastern margin of Owasco Lake, near the sequence VIA/VIB boundary, requires a trigger close to ~4600 ^{14}C yr B.P. Subaqueous slides may be generated by lake-level drops that affect pore water pressures, by sediment overloading (gravitational instability) along delta fronts, or by earthquakes. A lake-level fall is the most likely explanation because sediment cores recovered from the wetland south of Owasco Lake (Dwyer *et al*., 1996), as well as nearby Cayuga Lake (Mullins, 1998a) and Fayetteville Green Lake (Hilfinger and Mullins, 1997), all indicate relative lake-level falls of 5 m or less beginning ~4500 ^{14}C yr B.P. near the close of the Holocene hypsithermal. Overloading along a delta front is less likely because the location of the slide (Fig. 5) does not coincide with major input streams. An earthquake origin also appears unlikely because of the intraplate setting of the Finger Lakes and the paucity of historical earthquakes (Ebel and Kafka, 1991), although infrequent Holocene earthquakes cannot be ruled out.

The erosion surface at the northern end of Owasco Lake (Figs. 7 and 8), which dates to the middle Holocene, also needs explanation. Halfman and Herrick (1998) have recently reported seismic reflection evidence for erosion extending to water depths as great as 60 m at the northern end of nearby Seneca Lake. Seismic reflection data have also revealed evidence for erosion at the north end of Canandaigua Lake (Mullins *et al.*, 1996). Halfman and Herrick (1998) discuss two likely mechanisms for the erosion at Seneca Lake: subaerial erosion during a lake level low-stand and bottom current erosion. Although as much as 5 m of relative lake-level fall occurred during the middle Holocene throughout the Finger Lakes region (Dwyer *et al.*, 1996; Hilfinger and Mullins, 1997; Mullins, 1998a), there is no independent evidence for a lake-level drop on the order of 26 m.

More probable is that the erosion was produced by bottom current activity that began ~4600 ^{14}C yr B.P. and continues today. For Seneca Lake, Halfman and Herrick (1998) suggested that lake floor erosion occurs by wind-driven waves and currents to depths of ~20 m, and by internal waves and currents related to seiches along the thermocline to depths as great as 60 m. This latter mechanism is supported by direct current meter data from Seneca Lake, which have recorded bottom current velocities of up to 30 cm/s at a water depth of 66 m following southerly winds associated with the passage of cold fronts (Ahrnsbrak *et al.*, 1996). In the Great Lakes region, historic meteorological data document strong southerly and southwesterly winds (Eichenlaub, 1979), which would be required to produce bottom current erosion at the north end of Owasco Lake.

We thus propose that erosion of the north end of Owasco Lake was initiated by an abrupt climatic change during the transition from the relatively warm Holocene hypsithermal to the cool neoglacial ~4600 ^{14}C yr B.P. (Nesje and Kvamme, 1991; Luckman *et al.*, 1993) and that it has persisted to historic times (Fig. 10). Associated changes in wind patterns may have thereby changed Owasco Lake from a warm, sluggish-circulation state during the early Holocene to a more physically active lake system during the late Holocene.

Independent evidence for a regional climate shift ~4600 ^{14}C yr B.P. comes from several kinds of data. Relative lake-level fell 5 m or less at Owasco, Cayuga, and Green lakes (Dwyer *et al*., 1996; Hilfinger and Mullins, 1997; Mullins, 1998a). Open water precipitation of calcite from surface waters of the Finger Lakes, which was common during the early to middle Holocene, abruptly ceased ~4500 ^{14}C yr B.P. (Anderson *et al.*, 1997; Mullins, 1998b). Calcite content of Cayuga Lake sediments during Holocene time correlates ($r = 0.93$) with oxygen isotope data from the Renland ice core in Greenland as well as with data on summer insolation at 43°N latitude; these correlations imply a temperature control (Mullins, 1998b). Cooling at the end of the hypsithermal may have thus increased thermal gradients, which in turn increased atmospheric circulation and strengthened winds that transformed Owasco Lake into a more physically active system ~4600 ^{14}C yr B.P. This hypothesis is consistent with lake sediment data from Ecuador that shows the modern ENSO (El Nino–Southern Oscillation) periodicity of 2–8 y becoming established ~4500 ^{14}C yr B.P. (5000 cal yr B.P.) coincident with the onset of stronger global wind patterns (Rodbell *et al.*, 1999). Steig (1999) has also argued that the middle Holocene was a period of profound climate change as land air temperatures declined across much of the globe, and atmospheric and oceanic circulation changed. In addition, Sandweiss *et al.* (1999) have argued, based on archaeological data, for increased interannual climate variability beginning ~5000 ^{14}C yr B.P. (5800 cal yr B.P.). Such variability further suggest a fundamental change in global climate about this time.

CONCLUSIONS

(1) A new, decimeter-resolution seismic reflection survey of Owasco Lake has allowed subdivision of the Holocene section into two depositional sequences. The older sequence contains biogenic gas, a subaqueous slide deposit, and an erosional unconformity at its upper boundary at the north end of the lake.

(2) This middle Holocene (~4600 ^{14}C yr B.P.) erosion surface, which extends to water depths as great as 26 m, probably developed because of a strengthening of southwesterly winds that accompany the passage of cold fronts.

(3) During the transition from the relatively warm Holocene hypsithermal to the cool Neoglacial (~4600 ^{14}C yr B.P.), Owasco Lake evolved from a warm, sluggish-circulation lacustrine system to a more physically active one seen today. This environmental change may have been induced by global changes in winds.

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