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Stratigraphy of the mid-Holocene black bands in Lakes Michigan and Huron: Evidence for possible basin-wide anoxia

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Abstract

The post-glacial history of the Great Lakes has involved several changes in lake levels throughout the latest Pleistocene and Holocene, resulting from the changing position of the retreating Laurentide ice sheet, outlet incision and isostatic rebound. The final lowering of lake levels occurred at approximately 7600 ^{14}C yr BP, after which lake levels began to rise again to the Nipissing highstand at approximately 4700 ^{14}C yr BP. During this time of rising lake levels, black bands of iron sulfide were being formed in the sediments of all five of the Great Lakes. These bands signify suboxic to anoxic conditions, at least within the sediments and possibly at the sediment-water interface, during the middle Holocene warm interval. During this interval, the climate was warmer and drier than present, possibly resulting in the occasional absence of seasonal turnover in the lakes. We examined a series of piston cores from northern Lakes Michigan and Huron and found that the black bands are correlatable among cores taken from within the same basin. The observation that the banding can be correlated suggests a basin-wide cause, near-bottom or sub-bottom anoxia in the northern Michigan and northern Huron sediments during the mid-Holocene warm period. The sedimentary and geochemical processes in the Great Lakes during the middle Holocene warm interval are good indicators of possible future scenarios for the lakes as a result of global warming, as 21st-century temperatures are predicted to reach similar levels due to increased concentrations of greenhouse gases.

Introduction

The Laurentian Great Lakes first formed as periglacial lakes within the scoured and depressed crust exposed by the retreat of the Laurentide ice sheet. The sedimentary deposits found in these lakes contain a record of their glacial and post-glacial depositional and paleoclimatic history, including latest Wisconsinan periglacial events, episodes of early Holocene draining, and the middle Holocene warm period (Rea et al. 1994a). Numerous studies have contributed to our understanding of the depositional and paleoclimatic history of the Laurentian Great Lakes (e.g., Leverett and Taylor (1915), Stanley (1938), Hough (1958), Lineback et al. (1979), Rea et al. (1981, 1994a, 1994b), Lewis and Anderson (1989), Colman et al. (1990, 1994a, 1994b, 1994c, 2000), Teller (1990), Moore et al. (1994, 2000), Lewis et al. (1994), Dobson et al. (1995), Godsey et al. (1999), Safarudin and Moore (1999)).

During their post-glacial history, the Great Lakes have undergone several changes in lake levels. The changing levels and areal extent of the lakes have been a result of retreats and readvances of the Laurentide ice sheet, changing outlets for the upper lakes at Duluth, Chicago, North Bay, and Port Huron, and isostatic rebound as a result of unloading of the ice (Lewis and Anderson 1989; Colman et al. 1994a; Rea et al. 1994a; Lewis et al. 1994).

From their largest areal extent (the Main Algonquin stage), a series of lake level drawdowns began about 10,200 ^{14}C yr BP. The initial drawdown was the result of the opening of the North Bay outlet upon further retreat of the ice sheet. The ensuing lowstands and intervening Mattawa highstands occurred over the next 2500 years, with the most recent lowstand occurring at approximately 7,600 ^{14}C yr BP (Lewis et al. 1994). Here we follow the nomenclature of Lewis et al. (1994) in using the name Stanley for the three main lowstands, Early, Middle, and Late, in the Huron-Michigan Basins.

The final major lowering of lake levels, the Late Stanley lowstand, marked the end of the main Mattawa highstand and the beginning of the Nipissing phases in the upper Great Lakes. Beginning about 7400 ^{14}C yr BP, lake levels in the Michigan and Huron basins rose toward the Nipissing highstand at about 4700 ^{14}C yr BP. Lake Michigan became confluent with Lake Huron through the Straits of Mackinac before the peak of the Nipissing phase. Evidence of erosion and thin sediment accumulations in the area near the Straits of Mackinac indicates that Lake Huron likely flowed westward into Lake Michigan during the higher lake levels of the Nipissing highstand around 4000 years ago when the southern outlet through Chicago was active (Lewis and Anderson 1989; Dobson et al. 1995). Water levels have been falling slowly ever since the Nipissing highstand as a result of erosion at the Port Huron outlet (Lewis and Anderson 1989). Sedimentation rates also dropped markedly during and after the Nipissing highstand (Rea et al. 1980; Colman et al. 2000). Since the final lowstand, sedimentation has been generally confined to the basin floors, with accumulations in the deep basins, and erosion of the interbasin highs and around the margins common (Dobson et al. 1995; Safarudin and Moore 1999).

The history of deposition and lake level fluctuation in the Great Lakes is revealed in the stratigraphy displayed by high-resolution seismic reflection profiles and about 80 sediment cores. Seismic sequence reflectors are associated with intervals of coarser grain size and abrupt changes in bulk density of the sediments, and are interpreted as unconformities representing lowstands (Rea et al. 1994a; Moore et al. 1994). These unconformities, traced throughout most of the study area, are used to define boundaries of sedimentary sequences in the Great Lakes using the principles described by Vail et al. (1977) in interpreting seismic records (Moore et al. 1994).

The basis for assigning ages to the sequences and boundaries within the Great Lakes is a master time scale developed for a core in northwestern Lake Huron, core LH91-37P, which is discussed by Rea et al. (1994b). This time scale was produced from a cross correlation among the dated cores from *R/V Laurentian* cruise LH91 (Rea et al. 1994a; Moore et al. 1994) and a well-dated core in southern Lake Michigan by Colman et al. (1990). These radiocarbon dates have been corrected for hard-water effects found in the Great Lakes (Rea and Colman 1995; Moore et al. 1998). The seismic character of the northern Michigan basin is entirely comparable to that seen in the Huron basin, Georgian Bay, and North Channel (Moore et al. 1994), which have been correlated to sequence boundaries in Lake Michigan through seismic records (Safarudin and Moore 1999).

Oxygen isotope data determined on ostracodes from Lake Michigan cores (Colman et al. 1990, 1994c; Moore et al. 2000) shows large isotopic fluctuations occurring in Lake Michigan between 5000 BP and 12000 ^{14}C yr BP. Core 9V, collected from the southern basin of Lake Michigan by Colman et al. (1990, 1994c), has relatively negative isotopic values between approximately 9200 and 8500 ^{14}C yr BP, indicating the whole-system mixing during the main Mattawa highstand (Colman et al. 1990; Rea et al. 1994b). Beginning at approximately 8500 ^{14}C yr BP, the oxygen-isotopic values from southern Lake Michigan became significantly heavier, remaining fairly constant until 5000 ^{14}C yr BP (the young end of the record). Colman et al. (1990) suggested that evaporation accompanying warming and increasing TDS (total dissolved solids) levels explain these heavier values.

Oxygen isotopic data has also been presented by Moore et al. (2000) for core LH95-16PC from northern Lake Michigan (Figure 1) discussed in detail below. A timescale for this core was established by correlating grain size variations in it to those of the previously-dated core 9V from Colman et al. (1990). All radiocarbon dates for this core were converted to calendar years using the CALIB program (4.1.2) of Stuiver et al. (1998). After approximately 8500 cal yr BP [approximately 7700 ^{14}C yr BP (Lowell and Teller 1994)], LH95-16PC shows a similar δ^{18}O profile to core 9V of Colman et al. (1990) during the mid-Holocene; the δ^{18}O values become significantly heavier, averaging between -5.0 and 0‰. These heavy values last until at least 5000 BP. This time interval coincides with the mid-Holocene warm interval, also commonly referred to as the Holocene Altithermal or Hypsithermal (Antevs 1948; Deevey and Flint 1957; Cooper 1958; Wright 1976; Bartlein et al. 1984; Kutzbach and Guetter 1986; Webb et al. 1987; Pielou 1991; Wright 1992).

In this study, we focus on the sediments of the Surface Sediment sequence, located above the unconformity caused by the youngest lake level fall prior to the Nipissing highstand, the Late Stanley lowstand (Moore et al. 1994). This youngest sequence is characterized in its middle portion by a series of irregularly-spaced black bands (Rea et al. 1981, 1994a), which are believed to be composed of minute particules of iron-sulfide (Figures 2 and 3). These black bands are found in the basins of all five of the Great Lakes (Hough 1958). Kindle, the first geologist to study the deep-water sediments of any of the Great Lakes, was also the first to report the presence of the black bands (Kindle 1925). He reported samples from Lake Ontario as ''stratified throughout in alternating bands of black and buffish grey mud which apparently differ only in colour. When dry the colour is a uniform ash grey. The banding disappears after a half hour's exposure to the air. . . . The bands of black vary from the thickness of a sheet of coarse paper to 1/8 of an inch or a little more. The grey buffish bands between these vary from 1/16 to 1 inch in thickness'' (Kindle (1925), pp. 78). Kindle also noted that evidence of benthic [macroscopic] life was practically absent throughout these sections. The black bands in Lake Ontario have also been described by Thomas et al. (1972). The first report of the black bands in Lake Michigan was by Hough (1958) in which he reported that the gray clay comprising approximately the upper ten feet of a sample core was essentially homogeneous in texture but contained jet-black color bands alternating with gray zones. He reported that the black color disappeared within an hour after exposure to the air, similar to those seen by Kindle. Differential thermal analysis of the black material showed no appreciable organic matter to be present, but did indicate the presence of iron-sulfide. Hough reported the jet-black color to be due to a state of reduction of the sediments. Other investigators have reported the presence of the black iron-sulfide bands in Lake Michigan, including Lineback et al. (1970, 1979), Gross et al. (1970), Rea et al. (1980). Black bands containing iron-sulfide have also been described in Lake Huron (Hough 1962; Thomas et al. 1973), Lake

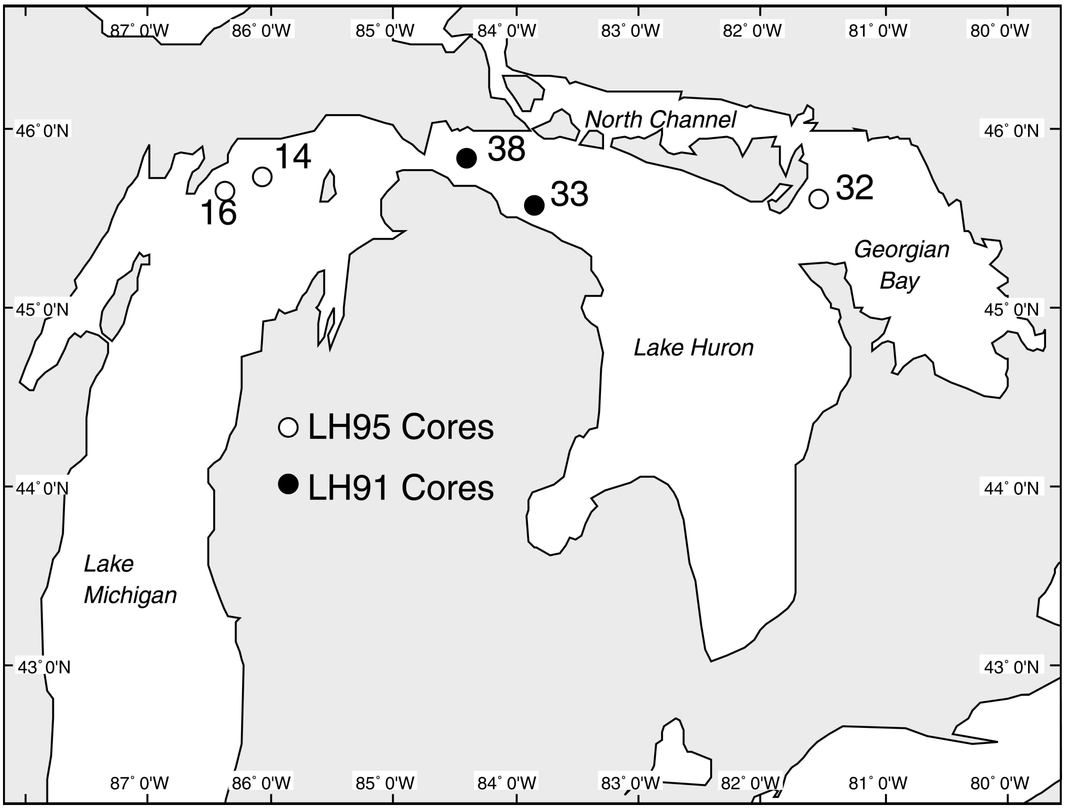

Figure 1. Map of the Great Lakes showing locations of cores from research cruises LH91 and LH95 used in this study.

Superior (Farrand 1969; Dell 1972, 1974; Lineback et al. 1979) and Lake Erie (Lewis 1969).

The character of the black bands is similar in Lakes Michigan and Huron. In Lake Huron, the uppermost Surface Sediment sequence of these lakes is up to 3 m thick and consistently comprises gray clay with the black bands, topped with 1–2 cm of brown oxidized sediment. The base of the sequence becomes uniformly dark gray (Rea et al. 1994a). The main difference between the Lake Huron and Lake Michigan upper sequence is that the cores from Lake Michigan have a background brownish color instead of the gray color seen in Lake Huron.

No one has determined the exact lake conditions that gave rise to the development of these bands. Were such anaerobic to suboxic conditions only present within the sediments themselves, or were the bottom waters at least seasonally anoxic or suboxic? Did these conditions occur throughout a given basin during a given time, or was their occurrence controlled by local conditions of biologic productivity or sedimentation? In this paper we begin to address these questions by comparing the black bands first between cores from the same basin and then between different basins. In this effort we hope to determine if the periods of suboxic-anaerobic conditions were basin-wide events, and whether these conditions extended throughout both basins simultaneously for as much as 4000 years.

Methods of analysis

We analyzed sediments taken from the northern Lake Michigan, northern Lake Huron and Georgian Bay basins (Figure 1). Piston and trigger weight cores were recovered from 81 stations in Lake Michigan, Green Bay, northern Lake Huron, including North Channel, and Georgian Bay during cruises of the *R/V Laurentian* in 1991 and 1995 (cruises LH91, LH95). Cores were taken to sample both the distinct reflecting horizons which are associated with lowstands and the sedimentary sequences between them. The *Laurentian* cores are stored at the Geological Survey of Canada Atlantic facility at the Bedford Institute of Oceanography, Dartmouth, Nova Scotia. Description and interpretation of the 1991 cores has been discussed by Rea et al. (1994a), Moore et al. (1994).

From these cores we selected two from each of the northern Michigan (LH95-14PC and LH95-16PC; Figure 2) and Huron basins (LH91-33PC and LH91-38PC; Figure 3) as representative of the black bands in each basin. One core from the Georgian Bay basin was also examined, LH95-32PC (Table 1, Figure 1).

Magnetic susceptibility and bulk density measurements were made on the unopened cores. Once the cores were opened, they were photographed, described, and their acoustic velocity and shear strength were measured and recorded. Samples for grain-size analysis were typically taken at every 5 to 8 cm along each core. For this project, grain-size analysis using a Coulter Counter was performed on ten of the cores from LH95, using the techniques described by Joseph et al. (1998). Grain-size analyses already completed from two cores from LH91 were also used.

The method of graphic correlation established by Shaw (1964) was adopted to correlate between cores within each basin, based on grain size and lithostratigraphy, and checked using the whole core magnetic susceptibility and bulk density measurements. This method involves creation of a cross-plot of the depths of correlative levels in two cores. For the northern Lake Michigan basin, a correlation plot of LH95-14PC versus LH95-16PC was constructed, using median grain size data for correlation (Figure 4). Once this plot was made, the depths of banding pattern changes were added to the chart and compared between cores. The same method was used to correlate LH91-33PC and LH91-38PC for the northwestern Lake Huron basin (Figure 5). The cores were then correlated between basins using the same techniques. The purpose of this exercise was to establish a stratigraphy independent of the black banding, and then to determine if the band-forming conditions were contemporary both within and among basins during the Nippising Stage of the Great Lakes.

Results

The uppermost sedimentary unit, the Surface Sediment sequence, lies between the lake floor and the most recent (7600 ^{14}C yr BP) major lowstand of the Great Lakes, the Late Stanley lowstand (Moore et al. 1994; Lewis et al. 1994). These sediments are the gray and brownish-gray clays that cover the floor of the upper Great Lakes. This is the part of the section is characterized by pronounced black iron-sulfide banding, which fades away almost completely within 30 to 60 minutes upon exposure to air due to oxidation of

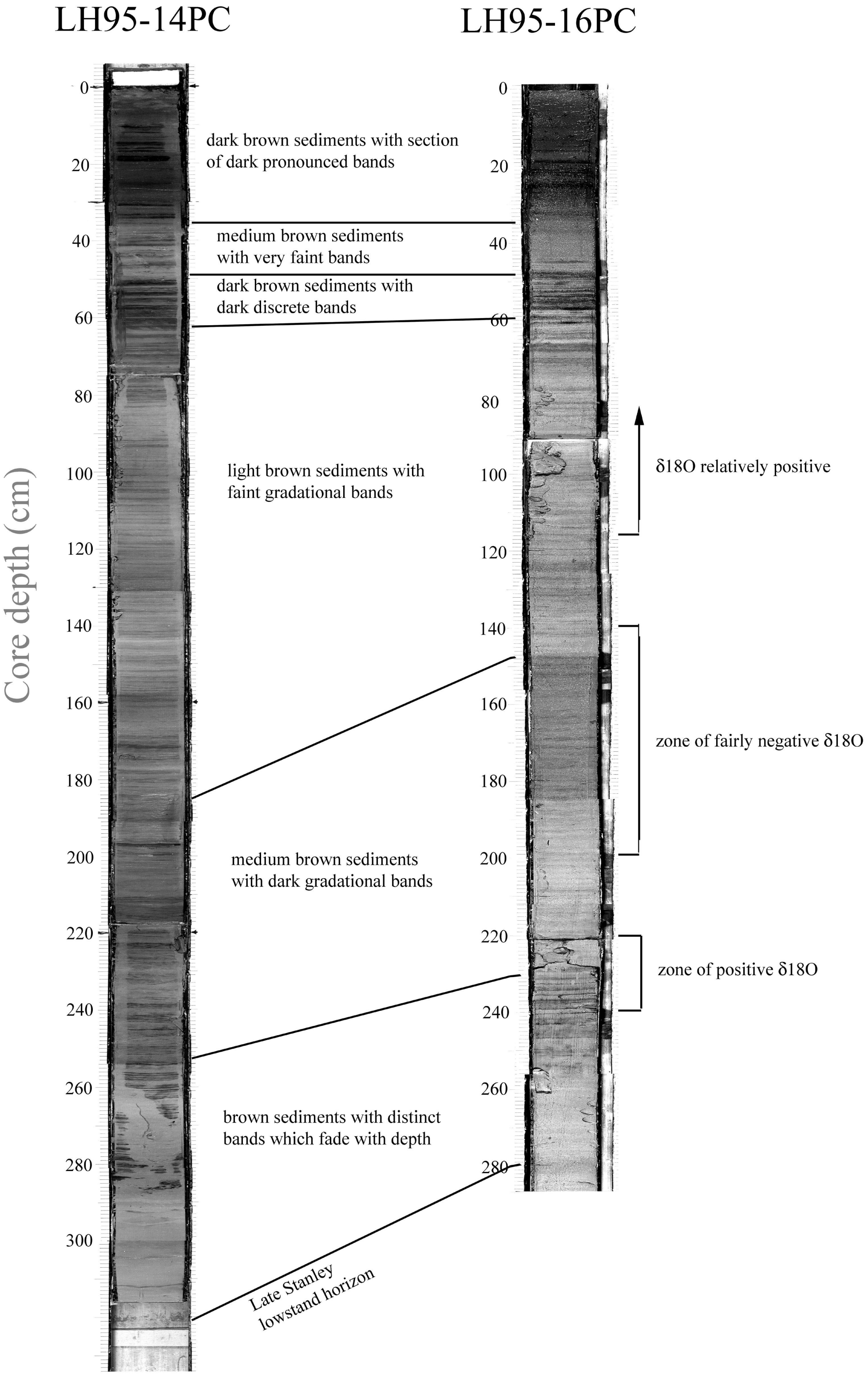

Figure 2. Photographic montage of cores LH95-14PC and LH95-16PC from Lake Michigan with banding correlations indicated. Cores have been stretched horizontally to appear wider.

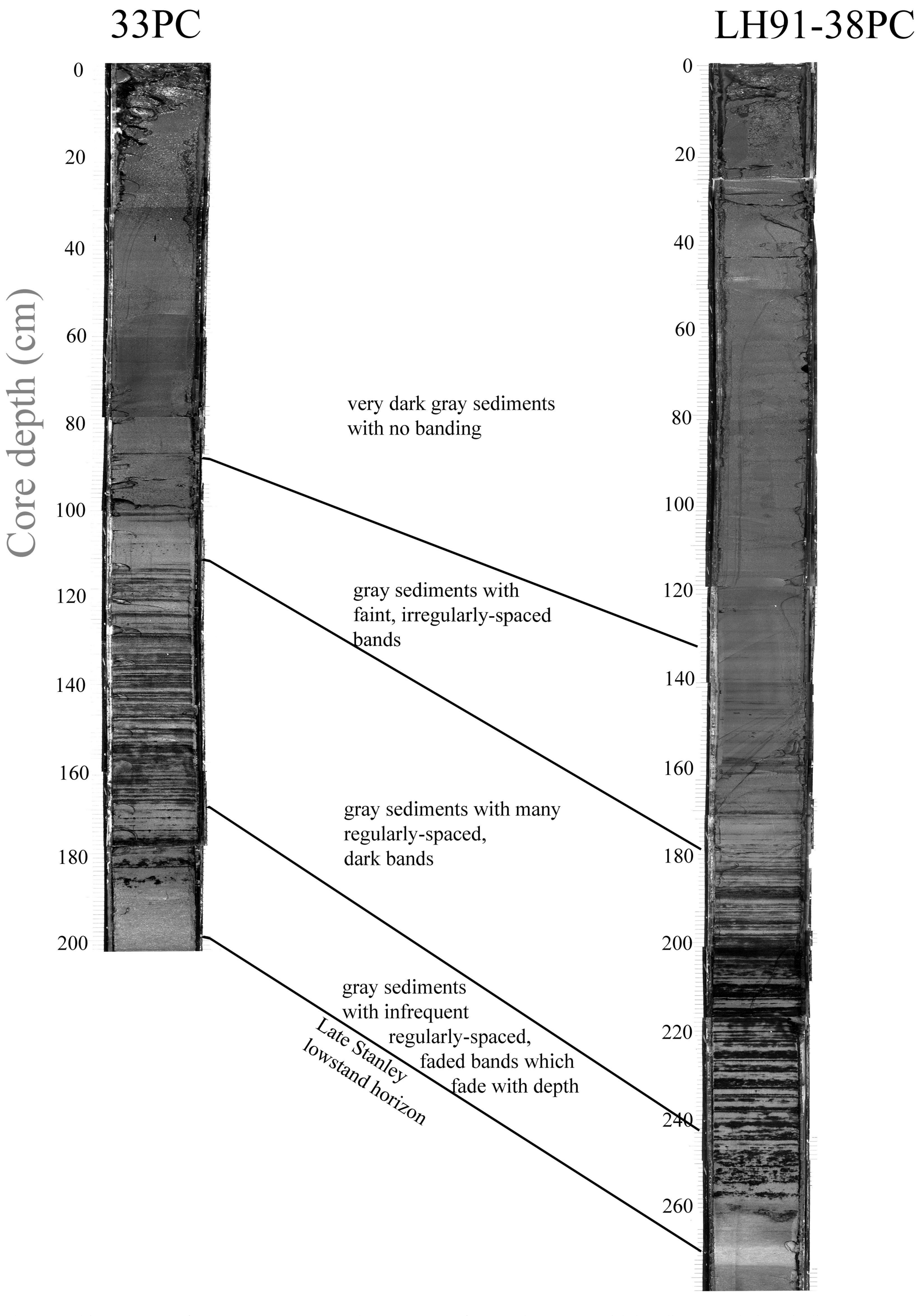

Figure 3. Photographic montage of cores LH91-33PC and LH91-38PC from Lake Huron with banding correlations indicated. Cores have been stretched horizontally to appear wider.

Table 1. Location, depth and length of cores used in this study

Core	Latitude N	Longitude W	Depth (m)	Length (cm)
LH91-33	45°31.70′	83°51.00′	70	485
LH91-38	45°49.90′	84°15.80′	64	524
LH95-14	45°43.81′	86°01.86′	101	471
LH95-16	45°39.79′	86°14.17′	93	379
LH95-32	45°36.72′	81°30.55′	67	557

the iron sulfides (Hough 1958). The nature of the banding varies between sharp distinct layers and more gradational boundaries (Figures 2 and 3).

Lake Michigan cores

The two cores from Lake Michigan, LH95-14PC and LH95-16PC, approximately 17 km apart, were collected from the northern basin of the lake from 101 m and 93 m depth, respectively (Figure 1, Table 1). By comparing the changes in median grain size and color patterns of the two cores, close correlations were identified between LH95-14PC and LH95-16PC, indicating a similar depositional history (Figures 4 and 6). Near the surface of both cores are dark gray-brown sediments containing a section of dark, pronounced bands. The discrete bands vary in thickness from 2–10 mm. At approximately 35 cm depth, both cores lighten in color to medium brown with very faint bands, and simultaneously decrease in grain size (Figures 2 and 6). At around 50 cm depth in each core there is a sharp increase in darkness of the sediments, which persists to about 60 cm depth. In both cores this section contains dark, discrete bands and shows a down-core increase in grain size. Within the section of dark discrete bands near the surface of both cores down to about 60 cm, individual banding patterns are similar in intensity and spacing and can be correlated to each other. Beneath this section of concentrated bands down to approximately 190 cm in LH95-14PC and 150 cm in LH95-16PC the sediments are lighter in color and the banding is gradational and less pronounced (Figures 2 and 6). At these depths in LH95-14PC and LH95-16PC the sediments and bands

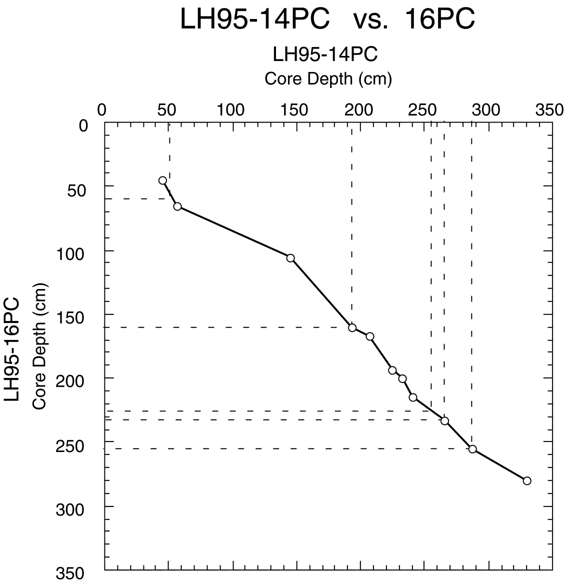

Figure 4. Cross-plot of features in the Lake Michigan cores. The correlation line was established using sediment grain-size values (circles), following which similar patterns of banding were plotted (dashed lines) to confirm their correlative nature.

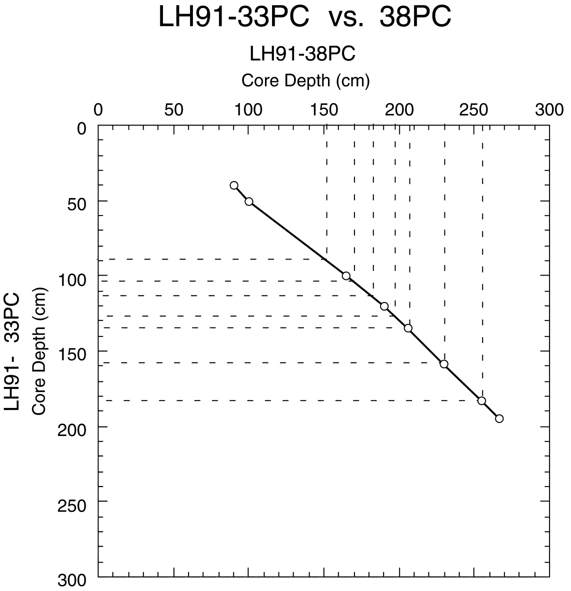

Figure 5. Cross-plot of features in the Lake Huron cores. The correlation line was established using sediment grain-size values (circles), following which similar patterns of banding were plotted (dashed lines) to confirm their correlative nature.

darken, although the bands remain more gradational than further upsection. This change in color coincides with an increase in median grain size in both cores. These gradational bands continue for about another 60–70 cm down core to about 220 cm. In this interval of the sedimentary section, an identical grain size profile is seen in both cores, with two more coarse peaks in grain size observed (Figures 2 and 6). At approximately 255 cm in LH95-14PC and 230 cm in LH95-16PC, there is a change in the character of the banding, which occurs simultaneously with a decrease in median grain size. The bands become more distinct at this depth, with sharper boundaries. From this point downward to the Late Stanley lowstand horizon the bands in LH95-16PC gradually lighten in color and disappear altogether just above the sequence boundary at 280 cm (Figures 2 and 6). The lower boundary of the banded interval cannot be determined from the photographs of core LH95-14PC due to oxidation of the core just above the unconformity related to the Late Stanley lowstand at approximately 330 cm (likely due to a water and air leak into the core after recovery). As has been observed in all the other cores, there are no black bands beneath the this unconformity.

Moore et al. (2000) established a timescale for core LH95-16 by correlation of grain size variation with that of the dated core 9V (Colman et al. 1990). By using this timescale for core LH95-16 (Table 2), we were able to convert the depth interval at which the black bands were found into an age interval of approximately 8500 to 4600 cal yr BP (Figure 7).

The oxygen-isotope data derived from ostracodes for core LH95-16 from Moore et al. (2000) may be used to determine the δ^{18}O values of the lake waters during the deposition of the black bands (Figure 7, Table 2). The major negative oxygen-isotope excursions seen between 9000 and 8400 cal yr BP records the large influxes of meltwater in the area during the time of the Late Stanley lowstand (Rea et al. 1994b). From approximately 8400 BP to at least 5000 BP, the oxygen isotope values become significantly heavier, with a secondary negative excursion at about 7700 BP. This upper portion of the Lake Michigan record, which shows the heaviest δ^{18}O values reported for Great Lakes biogenic calcite, $+0.4$ to -2‰ (Colman et al. 1990, 1994c; Moore et al. 2000), is the time interval where the sulfide banding is common.

Lake Huron cores

The two cores from the Mackinaw Basin of Lake Huron, LH91-33PC and LH91-38PC, approximately 47 km apart, were collected from 64 m and 70 m depth, respectively (Figure 1, Table 1). The black bands found in these cores vary in thickness between approximately 1–10 mm, with a few as thick as 15 mm, and appear much darker and generally thicker than in the Lake Michigan cores. The upper portion of both Huron cores contains very dark gray sediments with no banding for the first 90 cm in core LH91-33PC and 135 cm in core LH91-38PC (Figures 3 and 8). At this depth very faint, irregularly-spaced bands begin to appear in both cores. This coincides with an increasing down-core median grain size. A peak in grain size occurs at approximately 100 cm in core LH91-33PC and 165 cm in core LH91-38PC. A change in the character of the banding is seen at approximately 113 cm in core LH91-33PC and 180 cm in core LH91-38PC, with the down-core onset of regularly-occurring, darker bands in both cores. These dark bands continue down core and coincide with a decrease in grain size and another peak in grain size at approximately 140 cm in core LH91-33PC and 220 cm in core LH91-38PC (Figures 3 and 8). Beneath this peak, at approximately 170 cm in LH91-33PC and 240 cm in LH91-38PC, both cores show a change in the characteristics of their banded layers. Here, the regularly-spaced bands become less frequent and more faded. Below this point, a decrease in median grain size begins in both cores. The bands become increasingly faded until they reach the Late Stanley unconformity, where they disappear. This occurs at approximately 200 cm in core LH91-33PC and 270 cm in core LH91-38PC, and coincides with an interval of relatively coarse median grain size (Figures 3 and 8). No black bands are present beneath the Late Stanley lowstand reflective horizon.

By comparing the changes in median grain size, color and banding patterns of the two cores, close correlations were identified between LH91-33PC and LH91-38PC, indicating a close stratigraphic relationship between the two cores and a similar depositional history (Figures 5 and 8). Individual bands can often be correlated to each other between the two cores.

Georgian Bay core

Core LH95-32PC from Georgian Bay was also examined in an attempt to correlate it with the Huron basin cores. This core was collected from a depth of 67 m from the northwestern portion of the bay (Figure 1, Table 1). The upper 165 cm of the core is dark-gray

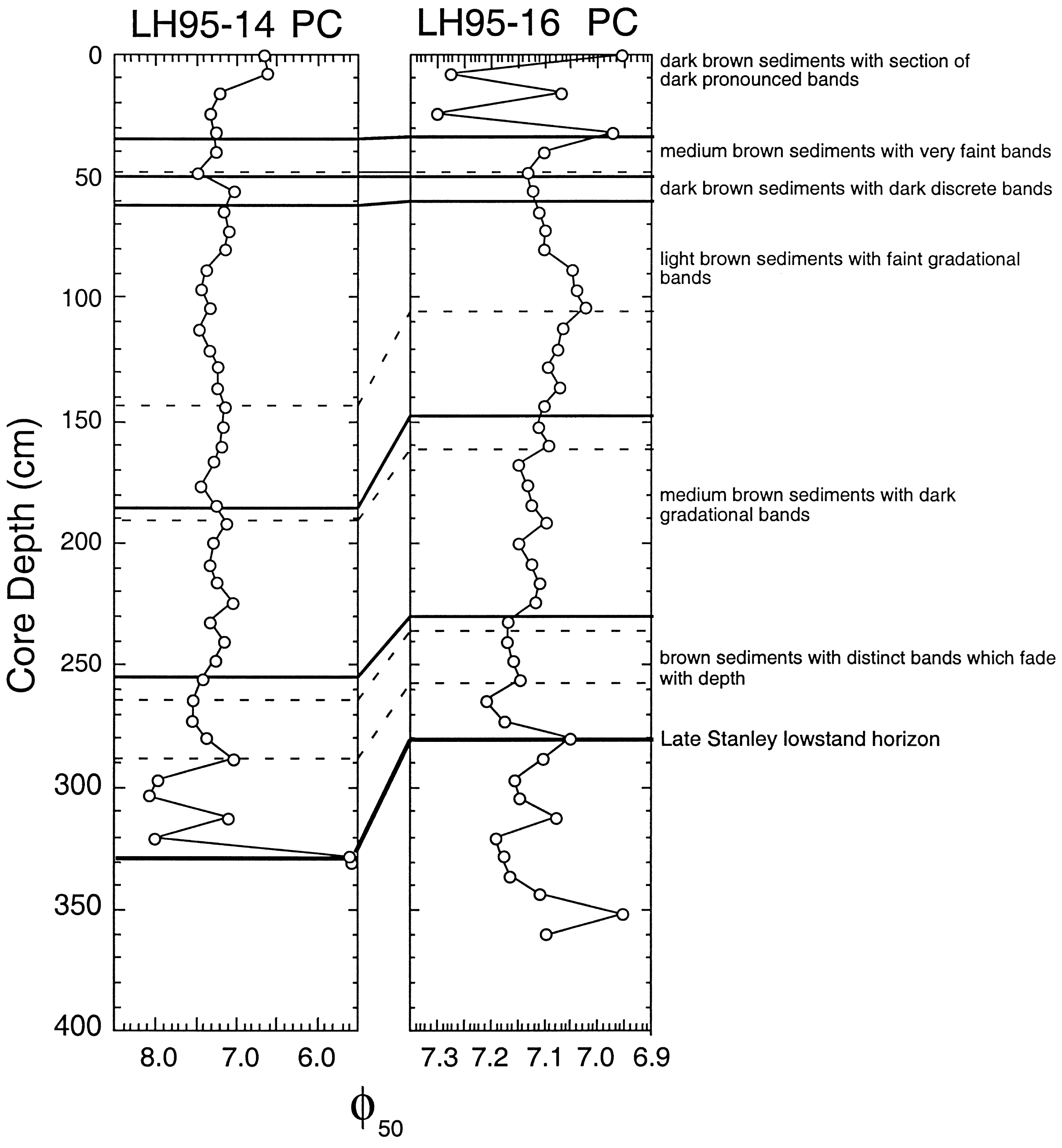

Figure 6. Grain-size, in phi units, and banding correlations in the northern Michigan Basin. Solid lines represent banding correlations and dashed lines represent grain-size correlations.

and contains no bands. Below 165 cm, the black bands are distinct and nearly continuous, with no fading. Although the grain-size, magnetic susceptibility, and bulk density records of these cores could be correlated, LH95-32PC does not share banding patterns similar in appearance to those seen in either the Huron or Michigan basins.

Inter-basin comparison

In order to compare the cores between the Michigan and Huron basins, one core from each basin, LH95-16PC and LH91-33PC respectively, were chosen to compare with each other. The black bands located just above the Late Stanley unconformity, from 229-247

Table 2. Oxygen isotope data for LH95-16PC from Moore et al. (2000).

Depth in core (cm)	δ^{18}O, PDB	4.1.2 CAL AGE (yr BP)
57.5	−0.44	5139
65.5	−0.31	5324
73.5	−0.40	5508
81.5	0.03	5693
89.5	0.42	5878
97.5	−0.37	6063
105.5	−0.61	6248
113.5	−0.94	6433
121.5	−2.03	6617
129.5	−2.36	6802
137.5	−1.59	6987
145.5	−3.69	7172
185.5	−9.50	7708
193.5	−5.38	7791
201.5	−1.94	7872
209.5	−1.60	7950
217.5	−1.65	8025
225.5	−1.80	8096
233.5	−1.88	8165
241.5	−2.39	8231
249.5	−2.49	8294
257.5	−3.23	8354
265.5	−4.89	8411
273.5	−10.43	8466
281.5	−16.06	8517
289.5	−5.44	8565
297.5	−6.63	8611
305.5	−11.28	8653
313.5	−15.26	8693
321.5	−7.72	8729
329.5	−7.30	8763
337.5	−7.17	8794
345.5	−10.33	8821
361.5	−1.29	8868

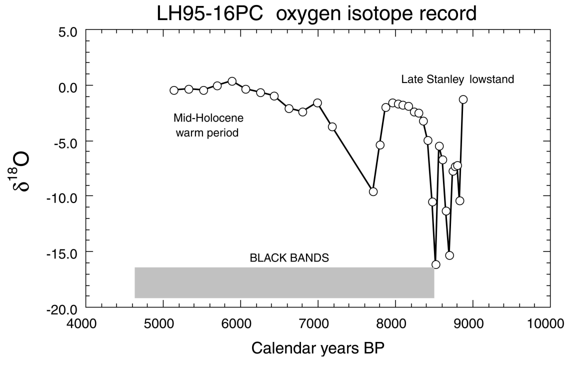

Figure 7. Oxygen isotopic data (Table 2) and the age of black bands in Lake Michigan core LH95-16PC.

cm in core LH95-16PC and 168–183 in core LH91-33PC, showed similar banding patterns, and can be correlated to each other. This small interval where banding in both cores matched coincided with a minimum in grain size immediately above the maximum representing the Late Stanley reflector in both cores. However, this lower portion of the black bands is the only section that can be matched convincingly between the basins. Although downcore grain size distributions are similar in cores from the two basins, the banding patterns in the majority of the sediment sequence are unique to each basin and cannot be specifically correlated between the basins.

Discussion

The Late Stanley lowstand horizon in the seismic-reflection profiles marks the erosional event caused by the final major lowstand in the Great Lakes as a result of ice retreat preceding isostatic rebound (Lewis et al. 1994). This final lowstand began about 7800 ^{14}C yr BP (Lewis and Anderson 1989; Lewis et al. 1994). Beginning about 7400 ^{14}C yr BP, lake levels in the Michigan and Huron basins started to rise toward the Nipissing highstand in response to continuing rebound of the outlets. This time of rising and high lake levels corresponds approximately to the middle Holocene warm epoch or Hypsithermal (Deevey and Flint 1957). Heavy δ^{18}O lake values in both northern and southern Lake Michigan during this time suggest enhanced evaporation associated with the warmer climate. Palynological, geochemical and sedimentological data from Elk Lake, a small lake located at a similar latitude in Minnesota, provides a clear indication of this warming and drying during the middle Holocene between 8000 and 4000 BP (Bradbury et al. 1993). This warming has been documented throughout all of the Midwest U.S. during this time interval (Webb et al. 1983; Webb 1985; Lewis et al. 2001).

Forester et al. (1994) reported evidence from ostracode assemblages and oxygen-isotope values of biogenic carbonate that the waters of southern Lake Michigan became more chemically concentrated (higher total dissolved solids [TDS]) after about 7000 ^{14}C yr BP. Colman et al. (1990) found a reduction in ostracodes around the same time, and proposed it may have been partly due to a decrease in dissolved oxygen in the bottom water. The lowered oxygen

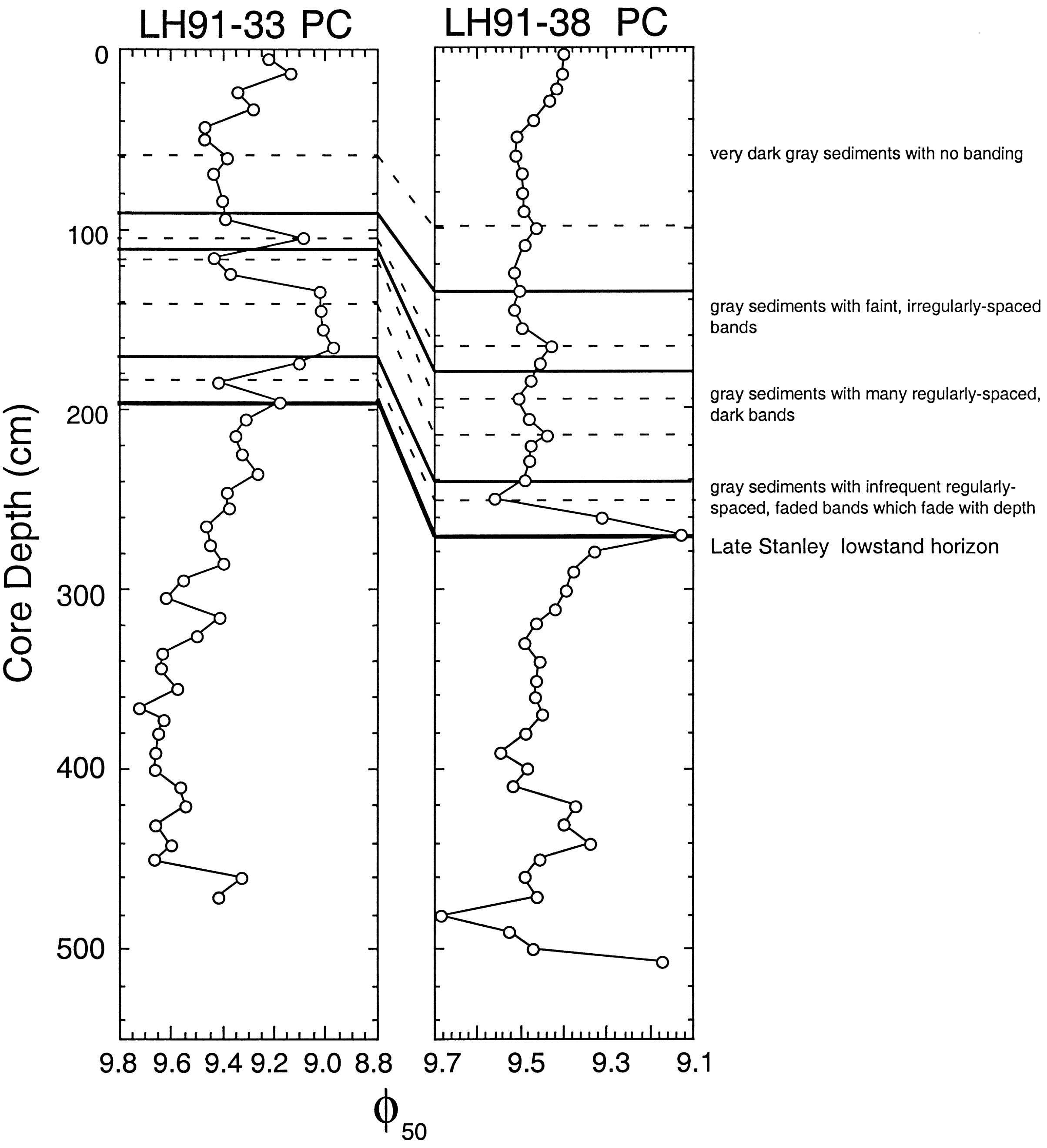

Figure 8. Grain-size, in phi units, and banding correlations in the northwestern Huron Basin. Solid lines represent banding correlations and dashed lines represent grain-size correlations.

concentrations in bottom waters, increased TDS values and heavier $\delta^{18}O$ values were likely brought on by stabilization of the water column and increased evaporation during the middle Holocene warm interval.

Rea et al. (1994a) proposed that it was during this warm and dry time that the black iron-sulfide bands seen in the Michigan and Huron basins were deposited. This suggestion is supported by our determination that the black bands were deposited between approximately 8500 BP and 4600 cal yr BP in a suboxic to anaerobic environment near the sediment-water interface. The formation of iron-sulfide bands during the middle Holocene warm interval implies a time with little or no oxygen present, either in bottom waters or in near-surface sediments. This was likely a result of the absence of turnover within the lake due to vertical stability caused by increased temperatures. The absence of turnover within these lakes would have resulted in nutrient depletion in near surface waters, decreased productivity, and loss of oxygen in the bottom waters due to decay of organic material.

The cores studied here show evidence that the conditions under which the black bands formed were affecting all three basins during the same time interval, coincident with the middle Holocene warm interval. There is evidence that the two lakes have been hydraulically connected since approximately 7500 ^{14}C yr BP (Rea et al. 1994b; Lewis et al. 1994). A lithologic correlation was identified between the Michigan and Huron basins for a short interval just above the Late Stanley lowstand unconformity. However, the black bands in the majority of the Surface Sediment sequence cannot be correlated between these two separate basins. Although both basins had an equivalent interval of recurring anoxic conditions that lasted approximately 4000 years, episodic anoxic-suboxic conditions are not precisely correlative between the basins following the initial rise in lake levels.

The inability to correlate the specific black bands of the Georgian Bay basin to those of the Huron or Michigan basins indicates that these basins were not under identical physical or geochemical conditions at the same time. Although water has flowed in both directions through the channel connecting Georgian Bay and Lake Huron over the last 7000 years (Dobson et al. 1995), the inability to correlate between these two basins is likely the result of the deep waters of the two basins not being hydraulically linked. During this time, the well-mixed epilimnion was free to flow through the channel connecting the two basins.

Correlations of the black bands within the northern Michigan and Huron basins suggest that the anoxic conditions (at least near the sediment-water interface) under which they formed were basin-wide events. Since the core pairs used in each basin for this study are located relatively close to each other, a possible mechanism to explain the inability to correlate between basins is wind-induced mixing as a control on productivity within each basin. This wind-induced control on productivity and the delivery of organic carbon to the lake floor, where it would decay and consume oxygen, may have differed somewhat from basin to basin depending on wind direction and basin morphology. Additional correlations of cores taken from different areas of the basins would help determine how widespread the conditions under which the black bands formed were.

The general occurrence of the black bands implies that the tendency toward similar near-anoxia likely occurred throughout all the Great Lakes basins during the ‘‘Hypsithermal’’ of the mid-Holocene. However, each basin responded differently to these climatic conditions based on differences in volume, water depth, sediment input and other comparatively local environmental conditions.

Computer models of the Great Lakes under conditions of slightly warmer climates have shown that a modest climatic warming could result in no winter turnover, which might result in near-anoxia in the deeper waters of the Great Lakes (McCormick 1989). Circulation models indicate that Northern Hemisphere summer temperatures were 2–3°C warmer during the middle Holocene warm interval than today (Liao et al. 1994), similar to the 1.5–4.5°C increase predicted by the year 2050 AD due to a doubling of atmospheric CO_2 concentration (Houghton et al. 1996). The sedimentary and geochemical processes in the Great Lakes during the middle Holocene warm interval may be good indicators of future scenarios for the lakes as they respond to global warming.

Conclusions

The sediments of the Great Lakes and their characteristics, such as grain size distribution, bulk density and color, are responsive to changing lake levels and sediment sources. The same seismic character and sedimentary sequences as found in Lake Huron are present in Lake Michigan and Georgian Bay. By analyzing sediments taken from northern Lake Michigan, northern Lake Huron and Georgian Bay, we have been able to correlate cores taken from these areas. Here we focused on the uppermost Surface Sediment sequence representing the time subsequent to the final lowstand of the Great Lakes at approximately 7600 ^{14}C yr BP. Black iron-sulfide bands which occur in these younger sediments were deposited during periods of likely anoxia near the sediment-water interface. These bands were deposited between approximately 8500 and 4600 BP, which coincides with the middle Holocene warm interval between approximately 8000 and 4000 BP. By detailed correlation of cores within these basins, we have been able to compare the iron-sulfide bands, and show that the bands were likely formed under conditions of basin-wide suboxic to anoxic conditions. Although low oxygen conditions may have occurred intermittently in all the Great Lakes basins during this interval, their existence appears to be controlled by conditions within each basin that are not exactly comparable from basin to basin within the Great Lakes. These results suggest the possibility of future basin-wide suboxic to anoxic conditions in the Great Lakes as a result of global warming.

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