The timing of regional Lateglacial events and post-glacial sedimentation rates from Lake Superior

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Abstract

We analyze both new and previously published paleomagnetic records of secular variation (PSV) from Lake Superior sediment cores and compare these records to correlated rhythmite (varve) thickness records to determine post-glacial sedimentation rates and to reassess the termination of glaciolacustrine varves in the basin. The results suggest that offshore sedimentation rates have exhibited considerable spatial variation over the past 8000 years, particularly during the mid-Holocene. We attribute offshore, mid-Holocene sedimentation changes to alterations in whole basin circulation, perhaps precipitated by a greater dominance of the Gulf of Mexico air mass during the summer season. Nearshore bays are characterized by high sedimentation rates for at least 1000 years after varve cessation and during a period between around 4500 and 2000 cal. BP. After 2000 cal. BP, sedimentation rates subsided to earlier rates. The increases between 4500 and 2000 cal. BP are probably due to lake level fall after the Nipissing II highstand.

The older glaciolacustrine varve thickness records suggest that the influx of glacially derived sediment ended abruptly everywhere in the lake, except near the Lake Nipigon inlets. Multiple sediment cores reveal 36 anomalously thick varves, previously ascribed to the formation of the Nakina moraine, which were deposited just prior to varve cessation in the open lake. The PSV records support the observation that the cessation of these thick varves is a temporally correlative event, occurring at 9035 ± 170 cal. BP (calibrated years before 1950, ca 7950–8250 14C BP). This date would correlate to the eastern diversion of Lake Agassiz and glacial meltwater into Lake Ojibway.

1. Introduction

The sediments of Lake Superior include a sequence of glaciolacustrine rhythms that very likely hold an annually resolvable record of regional ice margin dynamics and Lake Agassiz discharge for a period between 10,800 and 9000 cal. BP (Fig. 1). Farrand (1969a, b) was the first to describe the rhythms and interpret them as varves. A date on a wood fragment from basal sediments in Beaver Lake, MI suggests rhythmite deposition began around 9480 ± 60 14C BP (ca 10,550–11,100 cal. BP) (Fisher and Whitman, 1999). Rhythmite (glacial) deposition ended when the ice sheet receded north out of the Lake Superior watershed, after which time, meltwater and Lake Agassiz outflow were routed east into Lake Ojibway (Teller and Thorleifson, 1983). Post-glacial sediments in Superior are non-calcareous, homogenous clays (Dell, 1971) and sedimentation rates are at least an order of magnitude lower than the calcareous glaciolacustrine rhythms (0.03 vs. 0.5 cm/yr). There have been few successful attempts to date Lake Superior sediments with radiocarbon analyses. Macrofossils are almost non-existent and dates on bulk carbon or pollen separations are too old. By contrast, dating sediment cores with paleomagnetic records of secular variation (PSV) has been very successful. Mothersill (1988) reported that the cessation of rhythms was asynchronous across Lake Superior, ending first in southeastern regions of the lake, and 1200 years later in the northern reaches of the lake.

In an attempt to refine late-glacial events in Superior we combine PSV data and rhythmite thickness
measurements to conclude that rhythmite cessation was synchronous, except near the glacial meltwater inlets. Furthermore, we find that the sedimentation rates during the Holocene have not been constant. In agreement with Mothersill (1979, 1985) we find that sedimentation rates in some of the bays peaked between 2000 and 4500 cal. BP. Offshore, sedimentation rates show considerable spatial variation, but widespread changes occurred as early as 5000 cal. BP.

2. Methods

2.1. Rhythmite stratigraphy

The rhythmite thickness records originate from a variety of Kullenberg piston cores (suffixed with “P”, e.g. BH02-5P), taken over four cruises aboard the R/V Blue Heron in 1999–2002 (cores prefixed with LS99, LS00, BH01, and BH02) (Fig. 2). The Kullenberg coring system is capable of recovering 9-m piston cores in Lake Superior. Accompanying every Kullenberg core is a 2-m Benthos piston-gravity core (suffixed with “PG”, e.g. LS99-3PG) that penetrates the sediments with much less force and recovers the sediment–water interface. Each site was selected with the aid of a 28 kHz Knudsen reflection profiler to help ensure only sites with undisturbed glacial stratigraphies were cored. The bathymetry of Lake Superior is complex, faults within the sediment are not uncommon (Wattrus et al., 2003), and non-depositional zones occur at all depths. For these reasons the reflection profiler is critical when selecting coring sites. Cores were logged with a Geotek multi-sensor core logger and split at the Limnological Research Center (LRC) in Minneapolis. Both working and archive halves are stored at 4°C at the Large Lakes Observatory (LLO).

Rhythmite thickness measurements were made on photographs of split cores. LS99-1P/2P, -3P, LS00-3P, BH01-6P/8P were photographed with a digital camera at the LLO and BH01-11P and BH02-3P, -5P were photographed with a flatbed digital core scanner at the LRC. Black and white photographs (taken by W. Farrand in the 1960s) of cores S62-8 and S67-108, -134, -154, -156, and -163 were scanned and these digital images were utilized. Sigma Scan Pro image analysis software was used to make the thickness measurements on the digital images. The Superior rhythmites are typically graded in color, having a light-colored basal layer that grades upward into a darker top layer (Fig. 3). The contact between the top dark layer and succeeding light layer of the next couplet is sharp. Rhythmite thickness is defined as the shortest distance between these sharp light/dark contrasts.

2.2. Records of Paleomagnetic Secular Variation (PSV)

PSV records document local variations in inclination and declination, which reflect the variations in the earth’s magnetic field with time. Ferromagnetic grains, commonly magnetite, align themselves with the local magnetic field during or shortly after deposition. With consolidation of the sediments, the motion of these grains is constrained. Any magnetization acquired by the magnetic grains long after deposition is thought to be removed in the laboratory by alternating field (AF) demagnetization at low fields. In contrast, the remanent magnetization removed at higher demagnetization fields is assumed to have resulted from burial in the presence of the local magnetic field (for a complete discussion see Butler, 1992). The top 1–2 cm of sediment is usually bioturbated in Lake Superior (Evans et al., 1981), so the PSV records from the post-glacial sediments are 10–100 year averages of the regional field. By correlating PSV records from Superior with PSV records from regional, well-dated sites, ages can be assigned to sediment cores.

Previously published PSV records were reanalyzed from eight sediment cores (Fig. 4): LU77-4 (Mothersill, 1979, 1988), LU83-15 (Mothersill, 1985, 1988), LU83-5, -8, -11 (Mothersill, 1988), L78-40G (Johnson and Fields, 1984), and L78-24P (Halfman and Johnson, 1984). In addition we obtained new PSV data from a core recovered from Caribou basin, LS99-3PG. Older
measurements were all of discrete samples (8 cm$^3$) sampled at 3-cm intervals and measured with a fluxgate spinner magnetometer (see Mothersill, 1988).

We sampled LS99-3PG for paleomagnetic analyses in the fall of 2002. Magnetically cleaned, plastic boxes (8 cm$^3$) were oriented with the aid of a Plexiglas template and pushed directly into the core. Similar to previous studies, the core was sampled at 3.3-cm intervals, which allowed for a 1-cm spacing between each sample. Magnetic susceptibility and NRM were measured with a superconducting rock magnetometer at Michigan Tech University. Samples were AF demagnetized at 5–10 mT steps, up to 100 mT. Paleomagnetic directions for each sample were determined via a principal component analysis (Kirschvink, 1980). Some samples had a weak secondary magnetization component removed at low fields, so only demagnetization steps greater than 10 mT were included in the analysis. The best fit-line for the vector data was forced through the origin. The average maximum angular deviation is 1.7°, and the largest value is 5.1°. As with previous studies, declination data are reported as the angle relative to a mean value rather than the degree measured because the Kullenberg coring system cannot be oriented to the local magnetic field.

All PSV data were compared to multiple North American records correlated in Lund (1996), but our comparison ultimately relied on age models from Minnesota Lakes St. Croix and Kylen. We identified features from the Lake Superior records noted by Lund (1996) in all North American PSV records (Figs. 4 and 5), and used the St. Croix ages and associated errors for each feature to construct site specific age-depth profiles, thereby independently correlating both inclination and declination profiles. Lund (1996) suggests that the St. Croix ages for inclination feature 14 and declination features 16 and 17 are too old, so ages for these features from Lake Kylen were used instead. Only those features that are clearly apparent in each PSV record were utilized in constructing an age-depth model. Ages were originally given in radiocarbon years, but we have converted the St. Croix...
and Kylen ages for these features to calibrated years before 1950, and used 1-σ error values (Oxcal v3.5, Ramsey, 1995).

3. Results

3.1. Rhythmite thickness records: the 36 correlative rhythmites

Rhythmite thickness measurements reveal a correlative sequence of 36 anomalously thick rhythmites found across the basin: an isochronous stratigraphic unit (Fig. 6). Except for locations near Nipigon, ON (near the meltwater inlets), continuous rhythmite sedimentation ends shortly after these 36 rhythmites. We believe these are the same rhythmites found near the top of a core from Dorion, ON (Teller and Mahnic, 1988) and interpreted by Thorleifson and Kristjansson (1993) as a period of anomalously high meltwater discharge during the formation of the Nakina moraine (Fig. 1). Following the thick rhythmite sequence in BH01-11P are 142 couplets that are thicker than couplets deposited prior to the thick rhythmite sequence. Mothersill (1988) describes a sequence of 238 thick rhythmites at the top of LU83-8 (located north of any available core). We suspect that the lowest 36 of these 238 rhythmites correlate with the 36 rhythmites found basin-wide: indicating that closer to Nipigon there are thicker and more numerous rhythmites in addition to the 36 correlative rhythmites.

3.2. The PSV records and Holocene sedimentation rates

A polynomial regression provides an age model for each site (Fig. 7). We estimated errors with similar regressions on age minima and maxima. The PSV records (Fig. 4) are redrawn versus age and the features that we use to construct the age-depth models are labeled (Fig. 8). The polynomial regressions applied to each age-depth profile (Fig. 7) are redrawn to show sedimentation rates at each site (Fig. 9). Sedimentation rates have changed substantially through the Holocene. Sedimentation rates slow rapidly following the cessation of rhythmites, but rates remain relatively high and it is difficult to assess how quickly a low stable post-glacial rate is reached. Certainly in LU83-15 and L78-24P, the transition was gradual; high sedimentation rates seem to persist for 2000 years following rhythmite cessation. At the other sites, stable rates were established by at least 8000 cal. BP (up to 1000 years after rhythmite cessation).

Within the nearshore bays, sedimentation rates markedly increase between 4500 and 2000 cal. BP. These patterns are nearly identical in LU83-8 and LU83-15. The pattern in LU77-4 (Thunder Bay) is similar but not identical, however this core has a comparatively poor PSV record: inclination features 9 and 10 are not apparent and no features younger than 2000 cal. BP are available. It is certainly possible that the increases in sedimentation rates in Thunder Bay, which are slightly older than those in LU83-15 and LU83-8, are solely attributed to errors associated with the poorer PSV record.

Even the offshore sites (LU83-11, LS99-3PG, and L78-24P) show changes in sedimentation rates beginning as early as 5000 cal. BP. Between 5000 and 2000 cal. BP, rates decrease from 0.25 to 0.15 mm/yr in LS99-3PG and increase from 0.28 to 0.38 mm/yr in LU83-11. Rates also seem to increase at L78-40G, although a potential gravity flow at around 2000 cal. BP probably distorts these increases.

3.3. Dating the 36 correlative rhythmites

The age models (Fig. 7) are used to estimate a date for the glacial/post-glacial contact at each site (Table 1). We use these dates to estimate an age for the top of the 36
Fig. 4. PSV data, A (top): inclination, B (bottom): declination. A 3-pt running mean (line) is applied to the raw data from each core. Core depth (m) is scaled to help convey the similarities in the records. PSV features (after Lund, 1996) are noted with bold numbers (see Fig. 5). Correlated features are connected with a dashed line. Note that a long dash denotes the absence of a feature. Glacial sediments (rhythmites) are shaded gray.
4. Discussion

4.1. The 36 correlative rhythmites (varves)

The 36 correlative rhythmites must be varves. The mechanisms responsible for the Superior rhythmites have been discussed (Dell, 1971, 1973) and their annual nature previously asserted (Farrand, 1969a, b; Dell, 1971, 1973; Teller and Mahnic, 1988). While the evidence presented in support of annual couplings has been less than absolute, the total number of rhythmites observed in Caribou Basin (1604) matches the age differences quite well between the top of the rhythmite sequence (9035 cal. BP) and the age for the onset of rhythmite sedimentation in Beaver Lake (10,550–11,100 cal. BP) (Fisher and Whitman, 1999). (Note that rhythmite sedimentation should have begun at the Caribou Basin site only after ice retreat north of Beaver Lake: a distance of about 120-km.) This study is the first attempt to correlate rhythmite stratigraphies between multiple cores from Lake Superior, and there can be no doubt that at least the 36 correlative thick rhythmites are annual couplets. In a basin as large and bathymetrically complex as Lake Superior, the notion that these correlative rhythmites may be created by sub-annual gravity flow events can be ruled out. These couplets are very thick (up to 14-cm near Isle Royale),
Homogenous clay (h.c.) generally thin when flows (4 cm thickness scale) persist in northern Lake Superior. Homogenous clay (h.c.) follows rhythmite cessation in most localities. Rhythmites persist in northern Lake Superior.

Northern Lake Superior (near Nipigon, ONT)

<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>Thunder Bay Trough</th>
<th>Caribou Basin</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 4 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogenous clay (h.c.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h.c. over debris</td>
<td></td>
<td>h.c.</td>
<td></td>
</tr>
<tr>
<td>No recovery</td>
<td></td>
<td>No recovery</td>
<td></td>
</tr>
<tr>
<td>h.c.</td>
<td></td>
<td>h.c.</td>
<td></td>
</tr>
<tr>
<td>Correlative thick varves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generally thin rhymites</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 6.** Sediment stratigraphy and the correlative thick varve sequence. (A) (top): Sediment stratigraphy, including rhythmite thickness versus count in the upper part of the rhythmite sequence. Within most of the basin, varve deposition occurs shortly after a 36-yr sequence of correlatable varves (shaded). Near the Nipigon inlets, rhymites persist after the 36 thick varves. "Dorion" refers to the interpolated varve thickness by Thorleifson and Kristjansson (1993) from a core originally reported in Teller and Mahnic (1988). (B) (middle): The rhythmite stratigraphy extends well below the thick varves, but the 36 thick, correlative varves are some of the thickest in the entire record. "Caribou Basin" is a stacked record, which includes measurements from S62-8, BH02-3P, and BH02-5P. (C) (bottom): Correlated rhythmite thicknesses from seven cores, displaying similar thickness trends.
often composed of multiple layers that are graded in color (see Fig. 3), and almost entirely clay-sized sediment (Dell, 1971). Because they are correlatable between separate intra-lake basins, much of the sediment must have circulated around the lake during the ice-free season. The presence of very faint, sub-annual layers in cores near sediment influxes into the lake suggests there were multiple pulses of sediment during the ice-free season. The exact mechanism responsible for the formation of the light-dark couplets continues to be investigated, but dissolution of light-colored carbonates in a lake undersaturated with respect to calcium carbonate during the ice-covered season (which yields dark layers), remains the probable mechanism for formation (Dell, 1973). Rhythmite formation and the significance of the rhythmites deposited prior to the 36 correlative varves (see Fig. 6b) will be discussed in a subsequent publication.

As previously noted, Thorleifson and Kristjansson (1993) attribute the upper unit of thick varves in the Dorion core to an episode of increased sediment supply during the formative period of the Nakina moraine (Fig. 1). This connection was based on the suggestion that the gravel-dominated moraines of northern Ontario (including the Nakina) originated during periods of increased meltwater supply (Sharpe and Cowan, 1990). The Nakina moraine also straddles the watershed divide between Lake Superior and Hudson Bay. Retreat of the ice sheet north of the Nakina moraine allowed meltwater to be diverted east into Lake Ojibway, which would have led to a drastic reduction in sediment supply to Lake Superior and diminished varve deposition. As mentioned previously, the thick varves occur just prior to varve cessation in most localities. We suggest that the thick varves are associated with the gravel-rich Nakina moraine and that meltwater discharge that created the Nakina moraine occurred in as few as 36 years, ending at 9040 ± 170 cal. BP (five varves succeed the 36 correlative varves in Caribou Basin).

Radiocarbon dates on ice margin positions during the retreat of the LIS across Northwestern Ontario are limited. The ice sheet is typically depicted some distance north of the Nakina-Agutua moraines by 9500 cal. BP (8500 14C BP) (Dyke et al., 2003). The PSV dates from
the Superior cores suggest that this date has been overestimated by at least 400 years. Based on the rhythmite thickness record there is no indication that the ice margin backed far enough northward to allow meltwater to divert east into Lake Ojibway before the deposition of the thick varves. This implies that ice sheet recession stopped or slowed dramatically at the Hudson Bay drainage divide. Regional studies support this conclusion. Björck (1985) used sediment cores from small lakes in northwestern Ontario to conclude that the ice remained at or near the Agutua moraine for perhaps 600 years (9700–9100 cal. BP, 8700–8200 ¹⁴C BP). Bajc

Fig. 8. Lake Superior PSV profiles after correlation with Lakes St. Croix and Kylen, (A) (top): inclination, (B) (bottom): declination. Features used to construct the age models are identified and numbered. Glacial sediments (rhythmites) shaded gray.
et al. (1997) also dated a proximal deltaic deposit associated with a meltwater channel from Lake Nakina into Superior as early as 8975 \( \pm 7325 \) cal. BP (8070 \( \pm 7180 \) \(^{14}\)C BP). Both studies put the ice sheet at the Hudson Bay drainage divide at around 9000 cal. BP.

Furthermore, we suggest the impact of the anomalously great meltwater discharge that created the thick varves has already been documented in ostracodes from Lakes Michigan and Huron, as recognized by extremely negative oxygen isotopic excursions, dated around 8900 cal. BP (Rea et al., 1994a, b; Moore et al., 2000). In Huron and Michigan, these isotopic values are as light as any in the record (nearly \(-2\%\) PDB in Huron, \(-17\%\) PDB in Michigan), and the 15\(^{\text{th}}\) shift is abrupt (Moore et al., 2000). Moore et al. (2000) calculated that this negative isotopic anomaly corresponds to a total meltwater discharge of around 0.035 Sv (an increase of around 0.025 Sv), however their model did not distinguish between Lake Agassiz and glacial meltwater. Prior to this event Huron’s ostracodes were isotopically heavy (\(-5\%\) PDB), but Agassiz baseline flux into the Great Lakes at this time is estimated to have been 0.05 Sv (Licciardi et al., 1999; Teller et al., 2002), therefore Lake Agassiz waters may have been much heavier than glacial meltwater (see also Buhay and Betcher, 1998). If Agassiz baseline flux even approached 0.05 Sv at this time, then the amount of glacial meltwater necessary to produce an abrupt \(-15\%\) isotopic shift would have been far greater than the 0.025 Sv predicted by Moore et al. (2000). Until this matter is clarified, it remains unclear how much water correlates to this meltwater event and therefore the potential impact on the North Atlantic is speculative. A \(^{\delta^{18}}\)O minimum on the Laurentian Fan at around 7900 cal. BP (7100 \(^{14}\)C BP) was hypothesized to correlate to glacial meltwater discharge from the Great Lakes, as recognized in Lake Huron (Keigwin and

Table 1

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth to contact (m)</th>
<th>Post-glacial contact (cal. BP)</th>
<th>End of thick varves (cal. BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated age</td>
<td>Minimum age</td>
<td>Maximum age</td>
</tr>
<tr>
<td>LU83-8</td>
<td>6.8</td>
<td>8859</td>
<td>8515</td>
</tr>
<tr>
<td>LU83-15</td>
<td>5.7</td>
<td>8994</td>
<td>8583</td>
</tr>
<tr>
<td>LU77-4</td>
<td>8.85</td>
<td>9033</td>
<td>8761</td>
</tr>
<tr>
<td>LU83-11</td>
<td>2.81</td>
<td>8899</td>
<td>8555</td>
</tr>
<tr>
<td>LU83-5</td>
<td>8.40</td>
<td>8738</td>
<td>8497</td>
</tr>
</tbody>
</table>

Weighted mean age for the cessation of the thick varve sequence:

\(^{a}\)LU-83-5 not included in the weighted mean calculation because the number of varves after the 36-yr thick varve sequence is not well known.
These two signals are difficult to connect given the age discrepancies, however more recent data from the Laurentian Fan suggests that the meltwater signal occurred closer to 8500 cal. BP. (Keigwin, 2003; L. Keigwin, pers. comm.).

Finally, because rhythmites continue near the Nipigon inlets after varve cessation in the greater lake, glacially derived sediment continued to enter the lake, although at greatly reduced fluxes. We propose that the younger rhythmites near Nipigon may be the result of drainage of abandoned Glacial Lakes Kelvin (Nipigon) and Nakina, located south of the Hudson Bay drainage divide, which persisted for a short time following the eastern diversion of meltwater (Lemoine and Teller, 1995; Leverington and Teller, 2003). Subsequent analyses that further identify the similarities and differences between these younger rhythmites and the longer set of rhythmites found basin-wide, will be necessary to determine their significance.

4.2. Holocene sedimentation rates

Holocene sedimentation rates have not remained constant throughout the lake since varve deposition ceased. Cores from the nearshore bays (LU83-8, LU83-15, and LU77-4) all show rises to maximum sedimentation rates between 2000 and 4500 cal. BP. This is in complete agreement with Mothersill’s earlier assessments of cores LU77-4 (1979) and LU83-15 (1985). Post 4000 cal. BP sedimentation increases in the large bays have been attributed previously to a drop in water level following the Nipissing II highstand (Mothersill, 1988), when sill incisions at the Port Huron outlet lowered lake levels in Superior and Huron (which were connected basins). Lake levels stabilized by 2000 cal. BP when Huron levels fell below the outlet at Sault Ste Marie (Larsen, 1985; Baedke and Thompson, 2000). Shoreline studies from Tahquamenon Bay (Fig. 1) suggest lake levels fell 12-m between 4000 and 2400 cal. BP (Johnston et al., 2001). These dates correlate well with the sedimentation increases observed in the nearshore cores, and the rise and subsequent declines in sedimentation can be attributed solely to the reworking and export of shallow water sediments within the embayments during lake level fall.

Offshore cores from near Superior Shoals (LU83-11), within Caribou Basin (LS99-3PG), and off the Keweenaw Peninsula (L78-24P) also show changes in sedimentation rates. Sedimentation rates increased in LU83-11 and L78-24P between 5000 and 2000 cal. BP, but decreased in LS99-3PG during the same interval. These changes are not exactly synchronous. We suggest that there were changes in whole basin circulation that altered sedimentation patterns offshore, because new sedimentation rates are established rather than a rise and fall, and because the amount of sediment reworked with a 12-m drop in lake level is not likely to have a significant impact in the large basins offshore. Multiple factors determine mean circulation patterns in Lake Superior, but wind and internal temperature distributions are the primary time transient factors. Mid-Holocene climatic change is well documented in the region, and we suggest these changes are responsible for shifts in sedimentation patterns.

Unfortunately there is an absence of data that links decadal wind and temperature patterns to whole basin circulation or draws connections between basin circulation, sediment transport, and deposition patterns. However the anomalously strong Keweenaw current has been a focus of research that links surface winds, water temperature, and circulation (Van Luven et al., 1999; Chen et al., 2001, 2002; Zhu et al., 2001). LS99-3PG, located in Caribou Basin, likely receives the majority of its sediment flux from strong eastward currents that occasionally extend off the Keweenaw Peninsula. The decrease in sedimentation at LS99-3PG around 4000 cal. BP may have resulted from less sediment being moved offshore by the Keweenaw current. This interpretation is consistent with relatively high sedimentation rates during the same period in L78-24P, located just north of the Keweenaw Peninsula. The increasing sedimentation rates in L78-24P are coincident with smaller median silt grain size, and were interpreted as evidence for weaker bottom currents (Hallman and Johnson, 1984). Both weak temperature stratification (lower baroclinic pressure gradient) and more southerly and/or weaker winds favor decreases in the strength of the Keweenaw current (Chen et al., 2001; Zhu et al., 2001); the suggestion is that after 4000 cal. BP, cooler temperatures and/or weaker or less consistent westerlies created a relatively weaker Keweenaw current (and lower sediment flux into Caribou basin). Both effects are consistent with the present understanding of Holocene climatic patterns in central North America.

Regional increases in effective moisture are known to have occurred between 4000 and 3000 cal. BP. Elk Lake, in northwestern Minnesota, remains the most well-studied and accurately dated record for mid-Holocene environmental change in the Upper Midwest (Bradbury et al., 1993). Multiple proxies from Elk Lake (including pollen, elemental analyses, oxygen and carbon isotopes, and varve thicknesses) record the onset of a cooler and wetter climate beginning around 4000 cal. BP. Other records from Michigan, Minnesota, and Wisconsin substantiate these findings, although the interpretation regarding the exact timing of this transition varies (Webb et al., 1983; Winkler et al., 1986; Baker et al., 1992). Changes in atmospheric circulation may be partly responsible for this transition: specifically, the expansion of the Gulf of Mexico air mass relative to the Pacific air mass trends (Bryson, 1966; Bradbury et al., 1993; Yu et al., 1997; Denniston et al., 1999). These air masses are
controlled by the position of the jet stream and storm tracks. During the summer months, migration of the jet stream north of Superior leads to generally southerly winds over the lake. Conversely, a jet stream south of Superior (common between the fall and spring seasons) favors winds out of the west to northwest (NOAA-Climate Diagnostics Center, http://www.cdc.noaa.gov/).

An increase in the influence of the Gulf of Mexico air mass favors a longer season of southerly winds over Lake Superior and a decrease in the relative impact of the Keweenaw current on sedimentation in the Caribou basin.

With our limited understanding of whole basin changes in sedimentation patterns and the relationship between circulation and climate, connecting changes in sedimentation in LS99-3PG and LU83-11 to climate is highly speculative. The critical observation is that Holocene sedimentation rates in Superior are not uniform and that there appears to be a correlation between sedimentation rates and mid-Holocene climatic change. Predicting how the lake may respond to regional warming over the ensuing century is a present concern, yet modern whole basin circulation and sediment transport processes are relatively poorly understood. Given the possibility that basin circulation is not immune to climatic change, it seems paramount that we adequately describe modern circulation and sediment transport processes so that we can recognize potential changes when they occur.

5. Conclusion

The recognition that varve cessation was nearly synchronous in Superior led to a re-evaluation of multiple PSV records. The PSV records support the notion that varve cessation was abrupt in Superior, except near the Nipigon inlets. This conclusion differs from a previous notion that varve cessation ended ca 1200 years earlier in SE Superior than within the Nipissing II highstand. Offshore, patterns vary but suggest whole basin circulation processes may have permanently shifted between 4500 and 2000 cal. BP, probably in response to mid-Holocene climatic change. We suggest that the increasing dominance of the Gulf of Mexico air mass over Lake Superior during the mid-Holocene is consistent with our results, but drawing definite connections between climate and sedimentation in Lake Superior will require a greater understanding of both modern whole lake circulation and sedimentation processes and Holocene sedimentation patterns.

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