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Paleoecology of a Northern Michigan Lake and the Relationship among Climate, Vegetation, and Great Lakes Water Levels

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We reconstructed Holocene water-level and vegetation dynamics based on pollen and plant macrofossils from a coastal lake in Upper Michigan. Our primary objective was to test the hypothesis that major fluctuations in Great Lakes water levels resulted in part from climatic changes. We also used our data to provide temporal constraints to the mid-Holocene dry period in Upper Michigan. From 9600 to 8600 cal yr B.P. a shallow, lacustrine environment characterized the Mud Lake basin. A *Sphagnum*-dominated wetland occupied the basin during the mid-Holocene dry period (∼8600 to 6600 cal yr B.P.). The basin flooded at 6600 cal yr B.P. as a result of rising water levels associated with the onset of the Nipissing I phase of ancestral Lake Superior. This flooding event occurred contemporaneously with a well-documented regional expansion of *Tsuga*. *Betula* pollen increased during the Nipissing II phase (4500 cal yr B.P.). Macrofossil evidence from Mud Lake suggests that *Betula alleghaniensis* expansion was primarily responsible for the rising *Betula* pollen percentages. Major regional and local vegetational changes were associated with all the major Holocene highstands of the western Great Lakes (Nipissing I, Nipissing II, and Algoma). Traditional interpretations of Great Lakes water-level history should be revised to include a major role of climate.

Key Words: **Holocene climate; dry period; paleohydrology; paleoecology; Upper Michigan; Nipissing I; Nipissing II; Algoma; Great Lakes water levels; *Betula alleghaniensis*.**

INTRODUCTION

Holocene climate change in the western Great Lakes region of North America is well documented from paleoecological and paleolimnological studies (Webb *et al.*, 1983; Bartlein *et al.*, 1984; Baker *et al.*, 1992; Davis *et al.*, 2000). These studies reveal that latitudinal and longitudinal climatic and vegetational gradients have shifted position within the region during the Holocene. Although the mid-Holocene was characterized by a warm, dry climate in the region (Bartlein *et al.*, 1984), the period of maximum warmth and drought was asynchronous across the region (Webb *et al.*, 1983; Baker *et al.*, 1992; Yu *et al.*, 1997). Dramatic fluctuations in the water levels of the western Great Lakes also occurred during the Holocene, and recent work in coastal sedimentology and shoreline behavior has improved our understanding of the timing, rate, and magnitude of Great Lakes water-level fluctuations (Thompson and Baedke, 1997; Baedke and Thompson, 2000). However, especially in the early to mid-Holocene, the lack of precise temporal constraint of Great Lakes water-level phases and terrestrial proxy climate data has hindered direct comparisons among vegetation, climate, and Great Lakes water levels.

The northwestern Great Lakes region (Minnesota, Upper Michigan) was particularly dry between approximately 8800 and 5700 cal yr B.P. (8000–5000 ^{14}C yr B.P.) (McAndrews, 1966; Brubaker, 1975; Webb *et al.*, 1983), while the southwestern Great Lakes region (eastern Iowa, southern Wisconsin, northern Indiana, southern Michigan) experienced maximum dryness later, between 6600 and 3200 cal yr B.P. (5800–3000 ^{14}C yr B.P.) (Manny *et al.*, 1978; Winkler *et al.*, 1986; Baker *et al.*, 1992, 1996; Singer *et al.*, 1996). Mid-Holocene climate change in the region was related to changes in atmospheric circulation that are still not well understood. However, recent studies point to changes in precipitation seasonality and/or source (Yu *et al.*, 1997; Denniston *et al.*, 1999).

Contemporaneous with the mid-Holocene shift from wet to dry in southern Michigan and from dry to wet in Upper Michigan, *Tsuga* (hemlock) expanded its range westward over a large portion of the Upper Peninsula (Brubaker, 1975; Woods and Davis, 1989; Davis, *et al.*, 1986; Davis, 1987; Brugam *et al.*, 1997). At the same time, prairie vegetation invaded mesic forests in Iowa (Baker *et al.*, 1992, 1996), and forest expanded westward into prairie in central Minnesota (McAndrews, 1966). In the southern Lake Michigan region, oak savanna replaced more

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mesic forests, while water levels in lakes and wetlands dropped (Winkler *et al.*, 1986; Singer *et al.*, 1996).

Unlike the climate shift that occurred between 5700 and 6800 cal yr B.P., which was antipodal in northern and southern portions of the western Great Lakes region, the entire region shows evidence of increasing effective moisture after about 3200 cal yr B.P. *Tsuga* resumed westward expansion in Upper Michigan and northern Wisconsin (Brugam *et al.*, 1997), accompanied by expansion of other mesic and cool–temperate taxa (*Betula, Fagus, Acer saccharum*) (Brubaker, 1975; Woods and Davis, 1989; Davis *et al.*, 2000). Oak savanna replaced prairie in eastern Iowa (Baker *et al.*, 1992, 1996), while mesic taxa (*Fagus, Acer*) increased in southern Michigan, southern Wisconsin, and northern Indiana (Webb *et al.*, 1983). Water levels of lakes and wetlands increased throughout the region (Futyma and Miller, 1986; Winkler *et al.*, 1986; Singer *et al.*, 1996; Brugam and Johnson, 1997).

The western Great Lakes themselves underwent dramatic fluctuations in water levels during the Holocene, which are generally ascribed to geological processes (isostatic rebound, outlet incision, outlet switching). The highest Holocene water levels of the western Great Lakes (Nipissing phase) were attained after transgressions from extreme low water levels of the early Holocene (Chippewa, Stanley, and Houghton low phases, respectively in the Lake Michigan, Huron, and Superior basins). The Nipissing transgression, conventionally attributed to isostatic uplift of the North Bay outlet (Lewis, 1970), occurred in two phases (I and II). The Nipissing I high-water phase probably occurred between ca. 6800 and 5700 cal yr B.P. (6000–5000 ^{14}C yr B.P.) (Lewis, 1969, 1970), although bracketing dates and interpretations differ among sites and studies (Hansel *et al.*, 1985; Larsen, 1985a; Chrzastowski and Thompson, 1992). The Nipissing II high-water phase is better constrained, occurring between 4600 and 4400 cal yr B.P. (Thompson and Baedke, 1997; Baedke and Thompson, 2000). Water-level drops from these highstands are attributed to incision of outlets at Port Huron (Lewis, 1970). Water-level fluctuations of higher frequency and lower magnitude during the past 4500 yr probably represent hydrological responses to climatic variation (Fraser *et al.*, 1975, 1990; Larsen, 1985a,b; Thompson and Baedke, 1997), and Larsen (1985a) has suggested a role for climate change in the major mid-Holocene highstands. The role of climatic change in driving the high-magnitude water-level changes of the mid-Holocene can be assessed by comparing the lake-level records with temporally constrained paleohydrological and paleoclimatic data from the western Great Lakes region.

In this study we examine the macrofossil, pollen, and sedimentary record of a coastal lake on the Keweenaw Peninsula in Upper Michigan. The lake was chosen because it is shallow (∼3 m deep) and is located within late Holocene coastal features and deposits. Therefore, it should have been hydrologically sensitive to both the Holocene dry period and the Nipissing I transgression. We assess the local and regional effects of the Holocene dry period in the Upper Peninsula and briefly discuss the rate and characteristics of the effective moisture increase between 5700 and 6800 cal yr B.P. We also test the hypothesis that the major water-level phases of the western Great Lakes were associated with changes in climate by comparing the timing of regional and local records of vegetational and hydrological change with that of western Great Lakes water levels. Although the mid-Holocene was characterized by a warm, dry climate in the region (Bartlein *et al.*, 1984), the period of maximum warmth and drought was asynchronous across the region (Webb *et al.*, 1983; Baker *et al.*, 1992; Wright, 1992; Yu *et al.*, 1997).

STUDY SITE

Mud Lake occupies a shallow, 72-ha depression on the eastern side of the Keweenaw Peninsula in Upper Michigan (47°08′N, 88°19′W) (Figs. 1a and 1b). The lake is 1.25 km inland from Lake Superior, and the water surface is at approximately 189 m elevation, which is ∼6 m above Lake Superior (Fig. 1b). Inflow and outflow streams function seasonally. Surface materials are dominated by coarse- to medium-grained sands, presumably eroded and redeposited from the numerous outcrops of Jacobsville Sandstone in the eastern Keweenaw Peninsula (Johnston *et al.*, 2000). Forest vegetation around the lake is dominated by *Pinus strobus* (white pine), *Picea mariana* (black spruce), *Picea glauca* (white spruce), *Acer saccharum* (sugar maple), *Betula papyrifera* (paper birch), and *Betula alleghaniensis* (yellow birch). *Myrica gale* (wax myrtle) and *Alnus rugosa* (alder) are common around the lake border. Abundant aquatic plants (e.g., *Pontedaria cordata, Potamogeton* spp., *Nymphaea odorata, Carex* spp.) inhabit shallower areas of the lake.

METHODOLOGY

Field Methods

A 5.96-m sediment core was obtained from the deepest area (∼3 m) of the lake in July 1999 (Fig. 1c). The top 53 cm was recovered using a 5.1-cm-diameter Plexiglas piston corer, so that the sediment–water interface could be clearly differentiated. The top 24 cm was sampled in the field at 1-cm intervals. The remainder of the core was retrieved in 1-m drives using a 7.6-cm diameter square-rod piston corer. Core increments were extruded in the field.

Macrofossil Analyses

Ninety macrofossil samples spanning the length of the core were collected in 2-cm slices. Macrofossils were isolated from core samples and sorted according to standard methods (Jackson, 1999), although we analyzed only macrofossils from the 710-μm sieve fraction. Taxonomic identifications were made by comparison with herbarium specimens and modern collections. Taxonomy follows Voss (1972, 1985, 1996). Numbers of each macrofossil morphotype were tallied and expressed as numbers per 65 cm^3 of sediment (the average sample volume of all samples from the core). Macroscopic charcoal particles were

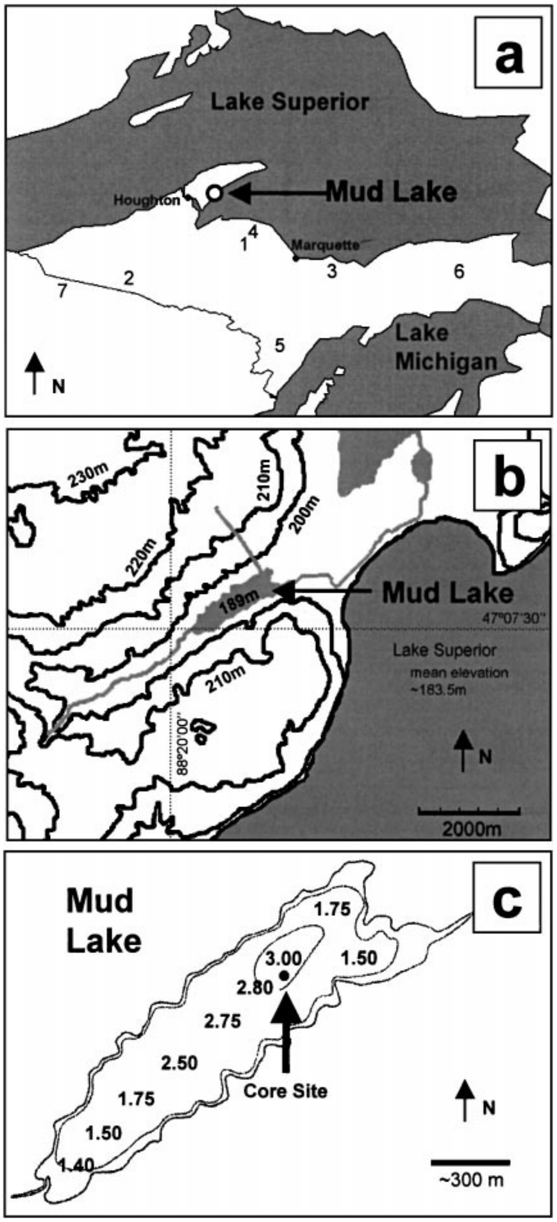

FIG. 1. (a) Location of Mud Lake and selected regional fossil pollen sites. 1: Yellow Dog Pond, Lost Lake, Camp 11 Lake (Brubaker, 1975). 2: Crooked Lake, Glimmerglass Lake (Brugam *et al.*, 1997). 3: Spirit Lake (Woods and Davis, 1989). 4: Canyon Lake (Davis, 1978). 5: Kitcher Lake (Woods and Davis, 1989). 6: Wolverine Lake (Futyma, unpublished data). 7: Lake Mary (Webb, 1974). (b) Topography of Mud Lake and vicinity. (c) Bathymetry (depth in meters, contours at 2.8 m and 1.4 m) of Mud Lake showing the core location.

picked, dried, and weighed. A few samples contained small amounts of sand, and this was also dried and weighed. Concentrations of macroscopic charcoal and sand were expressed as weight per 65 cm^3 of sediment.

Palynological Analyses

Fifty-five pollen samples (1 cm^3 each) were collected from across the core, each spanning 1 cm. Samples were processed according to standard procedures (Jackson, 1999). Pollen counts were continued until at least 250 arboreal grains were tallied. Pollen percentages were calculated using an arboreal pollen sum for arboreal taxa and a total pollen sum for all other pollen taxa. A sum of all palynomorphs was used to express the abundance of *Peridinium,* a freshwater dinoflagellate. Stratigraphically constrained cluster analysis, using the program CONISS (Grimm, 1987), was performed on the arboreal pollen data to aid in pollen zonation. Microscopic charcoal fragments were counted and assigned to size classes using an ocular grid (nine 50-μm^2 classes spanning 50 to 500 μm^2), and data were expressed as square micrometers per 250 arboreal pollen grains.

Radiocarbon Dating

Eight accelerator mass spectrometry (AMS) radiocarbon dates were obtained from the Mud Lake sediment core. All dates were from terrestrial plant material (Table 1). Radiocarbon ages were converted to approximate calendar-year ages using CALIB 4.1 (Stuiver and Reimer, 1993).

RESULTS AND DISCUSSION

Chronology and Sediment Stratigraphy

One young date (NSRL-11620) from near the top of a drive increment was rejected because of its age and unusual pollen composition. The sample was probably contaminated by material pushed downward when the corer was reinserted. An age–depth model was constructed using the seven other radiocarbon dates and the *Ambrosia* pollen-rise (ca. A.D. 1850), assuming a constant rate of sedimentation between dated horizons (Fig. 2). Sedimentation rates ranged from 0.34 to 1.26 mm/yr (Fig. 2). Sedimentation rates are highest at the top and base of the core and lowest between 300 and 400 cm depth (approximately 7800 to 5400 cal yr B.P.).

The sediment stratigraphy of the core is characterized by several conspicuous changes (Fig. 3). An organic-rich, brown gyttja began accumulating in the Mud Lake basin about 9600 cal yr B.P. The gyttja gradually becomes more fibrous upward, and a variably fibrous peat occurs from 460 to 353 cm (∼8500–6700 cal yr B.P.). Above the peat there is a relatively abrupt transition to gyjtta. Small amounts of silt and sand are present in lower portions of this gyttja.

Paleohydrology, Wetland Vegetation, and Effects of the Mid-Holocene Dry Period

The Minong phase, the last of the proglacial lakes in the Lake Superior basin, began about 11,000 yr ago when ice advanced southward (Marquette advance) to the northern Upper Peninsula (Farrand and Drexler, 1985), effectively dividing the basin into two lakes. These lakes coalesced to occupy the entire basin following final deglaciation of the Keweenaw Peninsula ∼10,500 yr ago. Elevation of the Minong phase lake was controlled by a morainal sill crossing from Nadoway Point, Michigan, to Gross Cap, Ontario. Minong waters were

TABLE 1
Radiocarbon Dates Obtained from the Mud Lake Sediment Core

Depth (cm)	Material dated	Lab number	^{14}C yr B.P.	Calibrated yr B.P.[a]
108–110	*Betula alleghaniensis* (seeds) and *Pinus strobus* (bud scales)	NSRL-11614	1400 ± 30	1298 (1347–1275)
184–186	*Betula* spp. (seeds) and *Pinus strobus* (bud scales)	NSRL-11615	2530 ± 70	2713 (2775–2356)
295–297	*Betula papyrifera* (seeds) and *Pinus strobus* (bud scales)	NSRL-11616	4640 ± 45	5439, 5420, 5321 (5568–5297)
337–339	*Pinus strobus* (bud scales)	NSRL-11617	5830 ± 50	6659, 6647, 6653 (6775–6495)
395–397	*Larix laricina* (needles)	NSRL-11618	6990 ± 50	7815, 7813, 7790 (7936–7678)
437–439	*Betula payrifera* (seeds), *Picea* sp. (needles), and *Viola* sp. (seeds)	NSRL-11619	7460 ± 40	8326, 8305, 8303, 8259, 8248, 8238, 8215 (8368–8175)
469–471	*Larix laricina* (needles)	NSRL-11620	7040 ± 55[b]	7919, 7901, 7857 (7964–7737)
593–595	*Picea* sp. (needles) and *Pinus banksiana* (needles)	NSRL-11241	8700 ± 90	9677, 9667, 9662, 9646, 9629 (10147–9528)

[a] Means and 2σ ranges (in parentheses) are shown. Calculated using CALIB version 4.1 (Stuiver and Reimer, 1993).
[b] Date rejected because it is young, from near the top of a core drive, and has an anomalous pollen assemblage.

approximately 40 m higher than today (Farrand and Drexler, 1985). Successive influxes from Lake Agassiz to the west eroded the Nadoway sill down to bedrock at Sault Sainte. Marie (Saarnisto, 1975). The ensuing low-water period, the Houghton phase, lasted from 10,000 to 8200 cal yr B.P. Differential uplift between the outlet at North Bay (Ontario) and the Sault sill caused water to rise in the Lake Superior basin until the elevation of the Nipissing I phase was reached. Nipissing I waters near the Sault outlet were about 14 m higher than today. At this time Lakes Superior, Michigan, and Huron were confluent, and three outlets at North Bay, Port Huron, and Chicago were active. Continued uplift of the North Bay outlet made it inactive by 5500 cal yr B.P., transferring control to the southern outlets (Lewis, 1969). Farrand (1962) suggested that the Sault Sainte Marie outlet rebounded above the elevation of the Port Huron outlet at ~2100 cal yr B.P. Recent work by Johnston

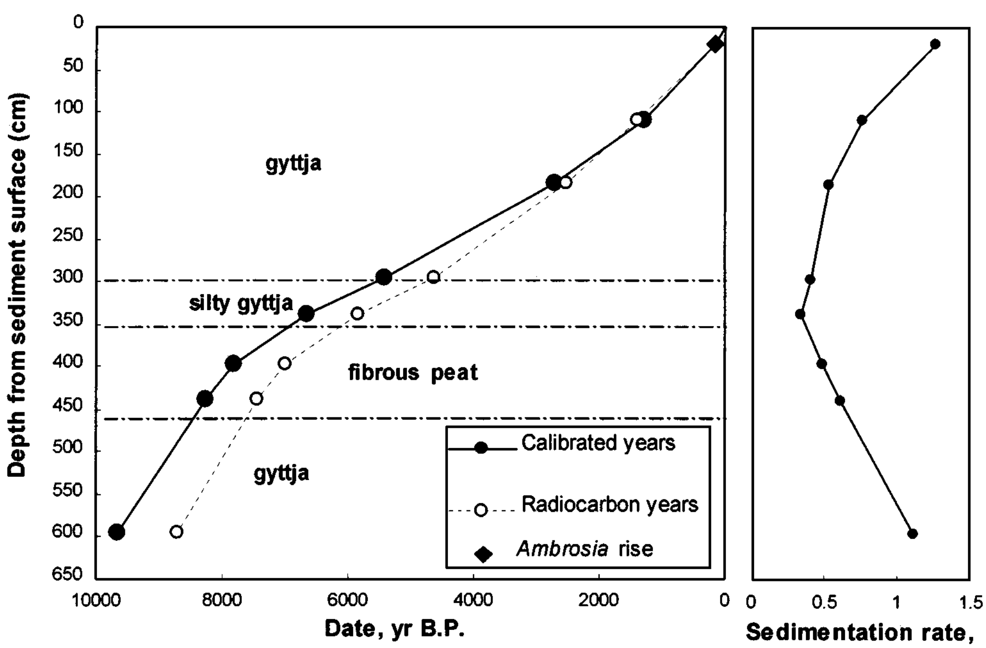

FIG. 2. Age–depth curve and sedimentation rates for the Mud Lake sediment core.

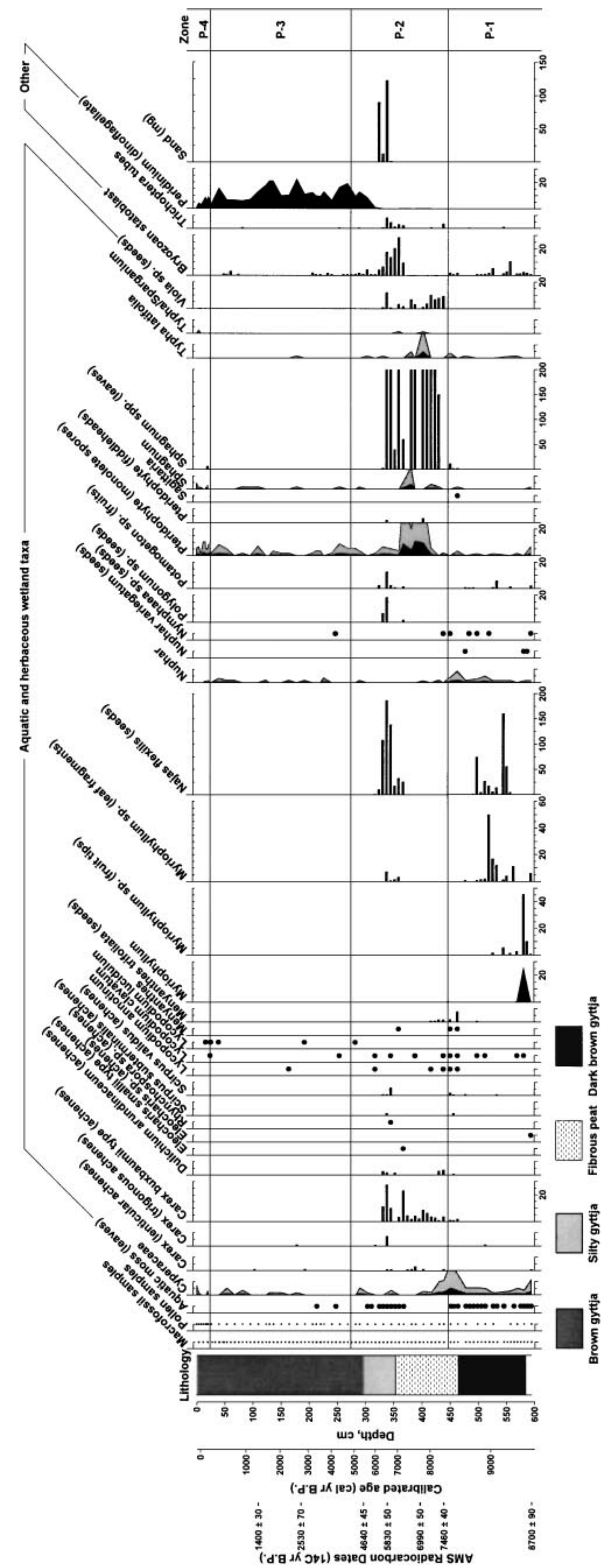

FIG. 3. Aquatic and herbaceous wetland pollen and plant macrofossil diagram for Mud Lake. Accelerator mass spectrometry (AMS) radiocarbon dates, corresponding calibrated ages, depth, and lithology are on the left side of the diagram. Shaded silhouettes show palynomorph percentages, with fivefold exaggeration (gray) shown for infrequent taxa. Histograms are shown for macrofossil and sand concentrations (numbers/65 cm^3 and mg/65 cm^3, respectively). The presence of infrequent or low-abundance taxa is indicated by closed circles.

et al. (2000) suggests that this separation may be closer to 1200 yr ago.

During the Minong phase, the level of Lake Superior would have been more than 24 m higher than the current elevation of Mud Lake. Lowering of the lake to the Houghton phase dropped Lake Superior roughly 31 m, and in 9600 cal yr B.P. an isolated lake formed in the Mud Lake basin. Macrofossils and pollen of the lowest sediments of Mud Lake indicate a shallow lake dominated by aquatic plants (*Myriophyllum, Najas flexilis, Nuphar, Nymphaea, Potamogeton*, and aquatic moss) from about 9600 to 8600 cal yr B.P. (Fig. 3). *Myrica gale, Larix laricina*, and *Salix* grew along the edges of the basin (Fig. 4).

A drying trend around 8800 cal yr B.P. is indicated by the disappearance of submersed aquatic species like *Myriophyllum* and *Najas flexilis* (Fig. 3). This drying trend marks the beginning of the mid-Holocene drought in the region. Floating-leaved aquatic species (e.g., *Nymphaea, Nuphar, Potamogeton*) persisted longer than *Myriophyllum* and *Najas*, although they were eventually replaced by emergent and rich-fen species (e.g., *Menyanthes trifoliata, Carex buxbaumii* type, *Dulichium arundinaceum, Scirpus subterminalis, S. validus*). Consistent with further drying, *Sphagnum*-dominated peat and macrofossils of other bog and fen species (e.g., *Viola* sp., *Chamaedaphne calyculata, Kalmia/Andromeda, Larix laricina*) appear by 8200 cal yr B.P. Many of the rich-fen and emergent species (e.g., *Menyanthes trifoliata, Dulichium arundinaceum, Scirpus subterminalis, S. validus*) also disappear at this time. Fragments of pteridophyte fiddleheads and abundant monolete spores indicate the local abundance of ferns. The abundance of *Sphagnum* and other bog-fen species indicate that that average water levels were at or below the surface of the wetland, indicating that Mud Lake basin water levels were at least 7 m lower than today.

Many of the previously extirpated aquatic species (e.g., *Myriophyllum, Najas flexilis, Potamogeton, Scirpus subterminalis, S. validus*) recolonized the basin as water levels rose after 7200 cal yr B.P. The trend toward wetter conditions culminated 6600 cal yr B.P. when the entire site was flooded by rising Lake Superior water levels during the post-Houghton transgression to the Nipissing I maximum. At the Nipissing I maximum, the level of Lake Superior was about 6.5 m above the current elevation of Mud Lake. The transition to an open-water estuary is marked by replacement of peat by gyttja and by the appearance of *Peridinium*, a planktonic freshwater dinoflagellate (Fig. 3). Lowermost gyttja sediments are characterized by a mixture of aquatic, wetland, and terrestrial macrofossils, although

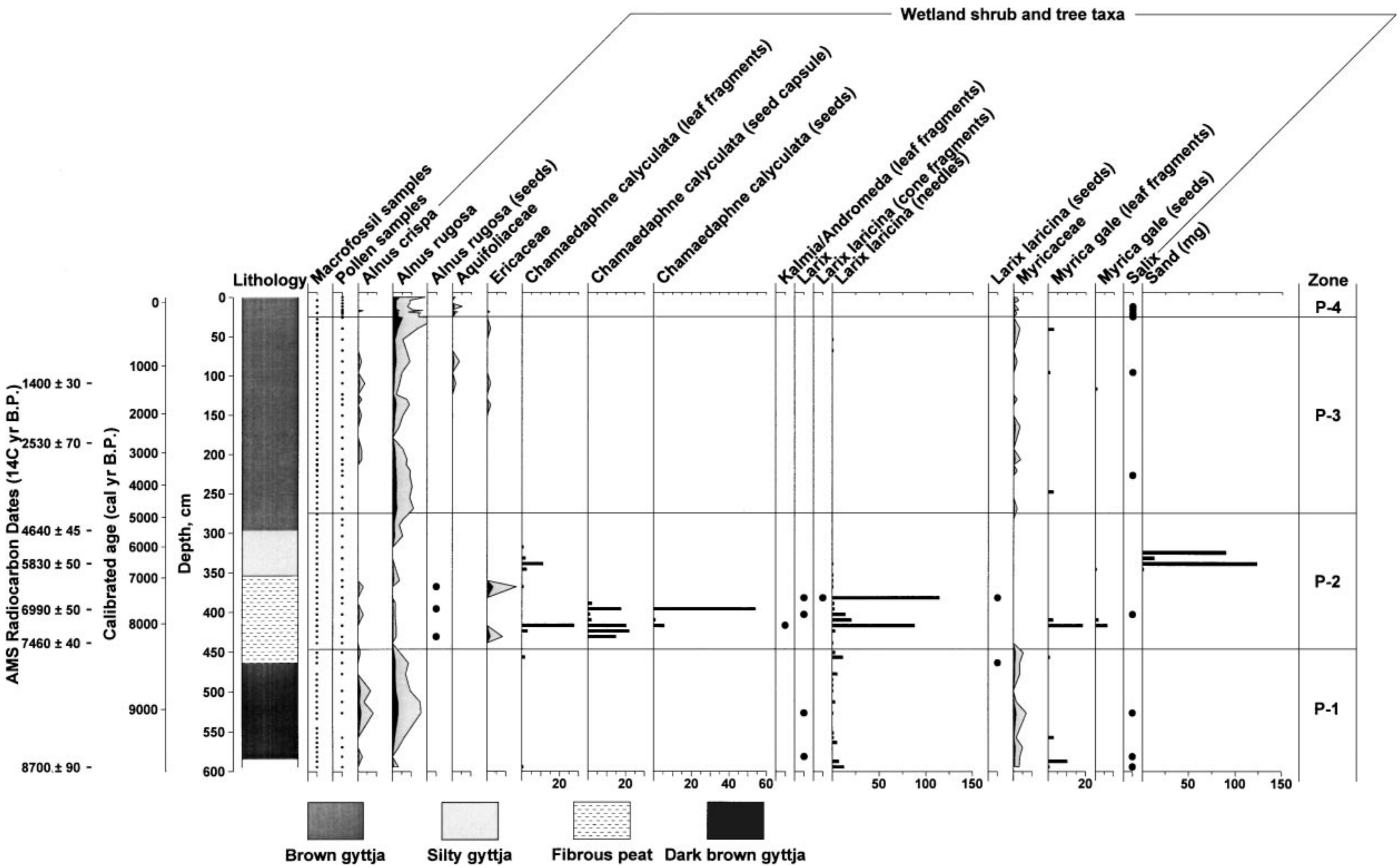

FIG. 4. Wetland shrub and tree pollen and plant macrofossil diagram for Mud Lake. Accelerator mass spectrometry (AMS) radiocarbon dates, corresponding calibrated ages, depth, and lithology are on the left side of the diagram. Shaded silhouettes show pollen percentages, with fivefold exaggeration (gray) shown for infrequent taxa. Histograms are shown for macrofossil and sand concentrations (numbers/65 cm^3 and mg/65 cm^3, respectively). The presence of infrequent or low-abundance taxa is indicated by closed circles.

littoral-zone taxa are especially well represented (Trichoptera (caddis fly) tubes, Bryozoan statoblasts, *Polygonum*). Some macrofossils are slightly abraded in the lowermost gyttja , and small amounts of sand and silt occur. Sand and silt are absent from the gyttja after about 5500 cal yr B.P., suggesting that the Mud Lake basin became isolated from Lake Superior at this time. Water-level fluctuations during the lake phase (5500 to 0 cal yr B.P.) are impossible to discern from our data.

Timing and Effect of the Nipissing I Great Lakes Water-Level Phase

Rising Great Lakes water levels, eventually culminating in the Nipissing I highstand, created an estuary or embayment in the Mud Lake basin. This inference is consistent with hypothesized elevations and age estimates for the Nipissing I highstand (Lewis, 1969, 1970; Hansel *et al.*, 1985). Increased wave action related to connection of the basin with Lake Superior led to transport of sand and macrofossils from the littoral zone to the coring site. Although sedimentation rates are lowest during this high-water period, rates (0.34 mm/yr) are still nearly three times those considered to indicate a possible hiatus (Webb and Webb, 1988). Also, the pollen stratigraphy of Mud Lake is similar to other pollen diagrams from lakes in the western Upper Peninsula (Brubaker, 1975; Woods and Davis, 1989; Brugam *et al.*, 1997) and northwest Wisconsin (Webb, 1974), indicating continuous deposition.

Regional and Local Terrestrial Vegetation

We define four pollen zones at Mud Lake (Fig. 5). Zone P-1 (9600–8300 cal yr B.P.) is characterized by abundant pollen of *Pinus* subgenus *Pinus* and *Picea*. *Betula* pollen also occurs in relatively high percentages in this zone. High percentages of *Ulmus* occur at the base of the zone. The lower samples from this zone were the only ones from the core to contain macroscopic charcoal, suggesting local fires during this time period. *Pinus banksiana* needles are associated with high *Pinus* Subgenus *Pinus* pine percentages, supporting the hypothesis that forests in the region were dominated by jack pine at this time (Wright, 1964).

Zone P-2 (8300–4800 cal yr B.P.) is characterized by abundant *Pinus* subgenus *Strobus* pollen and marks the migration of *Pinus strobus* into the region. *Pinus strobus* bud scales also appear in the sediments at this time. Drier conditions may have promoted the expansion of *Pinus strobus* into the Upper Peninsula (Brubaker, 1975). Drier conditions are documented in northern Minnesota at this time (McAndrews, 1966; Wright and Watts, 1969). Coincident with *Pinus strobus* expansion into the region, water levels in the Mud Lake basin dropped, supporting the hypothesis that *Pinus strobus* expansion was related to inception of a mid-Holocene dry period in the northwestern Great Lakes region.

Zone P-2 is also characterized by low *Betula* and *Picea* percentages. The low *Betula* pollen percentages are associated with abundant *Betula papyrifera* seeds. This suggests that *Betula* tree abundance did not decrease appreciably when *Pinus strobus*, a prolific pollen producer, expanded. *Tsuga* pollen also increased within zone P-2, at 6600 cal yr B.P. The *Tsuga* pollen increase at Mud Lake is part of the rapid westward migration of *Tsuga* across the Upper Peninsula observed between 6800 and 5800 cal yr B.P. This rapid migration has been interpreted as a response to increasingly moist climate (Brugam *et al.*, 1997) and decreased fire frequency (Davis *et al.*, 1994).

Zone P-3 (4800–∼130 cal yr B.P.) is characterized by abundant *Betula* and *Pinus* Subgenus *Strobus* pollen. *Betula alleghaniensis* seeds first appear at 4100 cal yr B.P. and become more common after 3400 cal yr B.P. The appearance of *Betula alleghaniensis* coincides with increased *Betula* pollen percentages at Mud Lake and other lakes in the region (Brubaker, 1975; Woods and Davis, 1989; Davis *et al*., 2000). This suggests that yellow birch expanded or migrated into the region at this time and is responsible for the regional *Betula* pollen increase. However, the first macrofossil occurrence of *Betula alleghaniensis* at Mud Lake follows the local increase of *Betula* pollen by 700 yr. More macrofossil data are needed from throughout the region to determine the timing and spatial pattern of yellow birch expansion and how it was related to the regional birch pollen increase. *Picea* and *Tsuga* pollen also increase within this zone at about 2500 to 3000 cal yr B.P. The modern mosaic of northern hardwoods and conifers became established at this time (Brubaker, 1975; Davis *et al*., 1994).

Zone P-4 represents the historical period (∼1800–2000 A.D.). *Pinus* Subgenus *Strobus* pollen decreases markedly in this zone, consistent with historical records of *Pinus strobus* logging. Forest fires were common in Upper Michigan during the logging era (late 1800s), and the microscopic charcoal increase presumably records these regional fires.

Comparisons among Mud Lake Paleohydrology, Great Lakes Water-Level Phases, and Holocene Vegetation Changes

To facilitate comparison between the paleohydrological record of Mud Lake and other regional and local Holocene events, we created a relative water-level curve for Mud Lake. To do this objectively, we applied detrended correspondence analysis (DCA) to selected wetland and aquatic macrofossil data. Taxa included were present in at least seven samples. Because of the variability of macrofossil data, concentrations were converted to an abundance scale ranging from 1 to 5 (low to high concentration). These abundance categories were defined for each macrofossil type independently by dividing the highest observed concentration by five to determine the range of each abundance category. The species scores for the resulting DCA demonstrate that axis 1 generally corresponds to a water-level gradient (Fig. 6). Therefore, axis 1 sample scores were plotted against age to generate a relative water-level curve (Fig. 7). Similar methods have been applied to macrofossil assemblages from European peat bogs to compare late Holocene hydrological changes (Barber *et al.*, 2000).

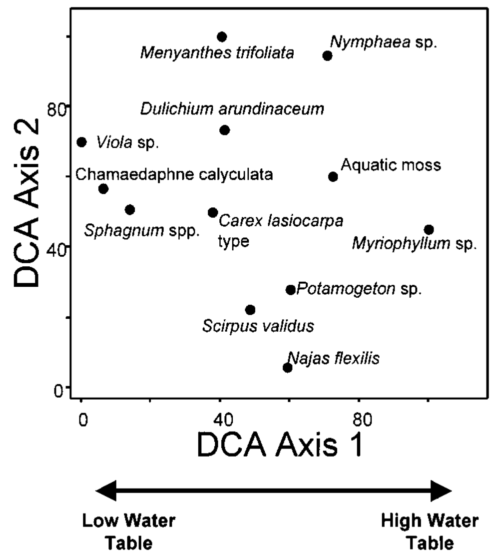

FIG. 6. Detrended correspondence analysis (DCA) species scores for macrofossil taxa used to generate the relative water-level curve shown in Figure 7. Note that axis 1 generally corresponds to a water-level gradient.

A comparison of Mud Lake paleohydrology, western Great Lakes water levels, and both regional and local vegetation events indicates that many of these changes correspond in time (Fig. 7). The onset of the mid-Holocene dry period in Upper Michigan converted the basin from a shallow lake to a *Sphagnum*-dominated wetland and promoted the expansion of *Pinus strobus* in the region. The mid-Holocene dry period ended at 6600 cal yr B.P., resulting in the well-documented expansion of *Tsuga* in Upper Michigan (Woods and Davis, 1989; Brugam *et al.*, 1997). The expansion of *Tsuga* and the end of the mid-Holocene drought also correspond temporally to rising western Great Lakes water levels associated with the onset of Nipissing I. Although rebound of the North Bay outlet is well documented, the rapid regional expansion of *Tsuga* suggests that increased effective moisture was at least partly responsible for the observed lake-level rise. The Mud Lake basin flooded as a result of these rising water levels.

Nipissing II, which peaked at 4500 cal yr B.P. (Baedke and Thompson, 2000), is also associated with regional vegetation changes. *Betula* pollen increased at Mud Lake and other pollen sites in Upper Michigan record *Betula* expansion at a similar time (Webb, 1974; Brubaker, 1975; Woods and Davis, 1989). Macrofossils from Mud Lake indicate that this regional rise

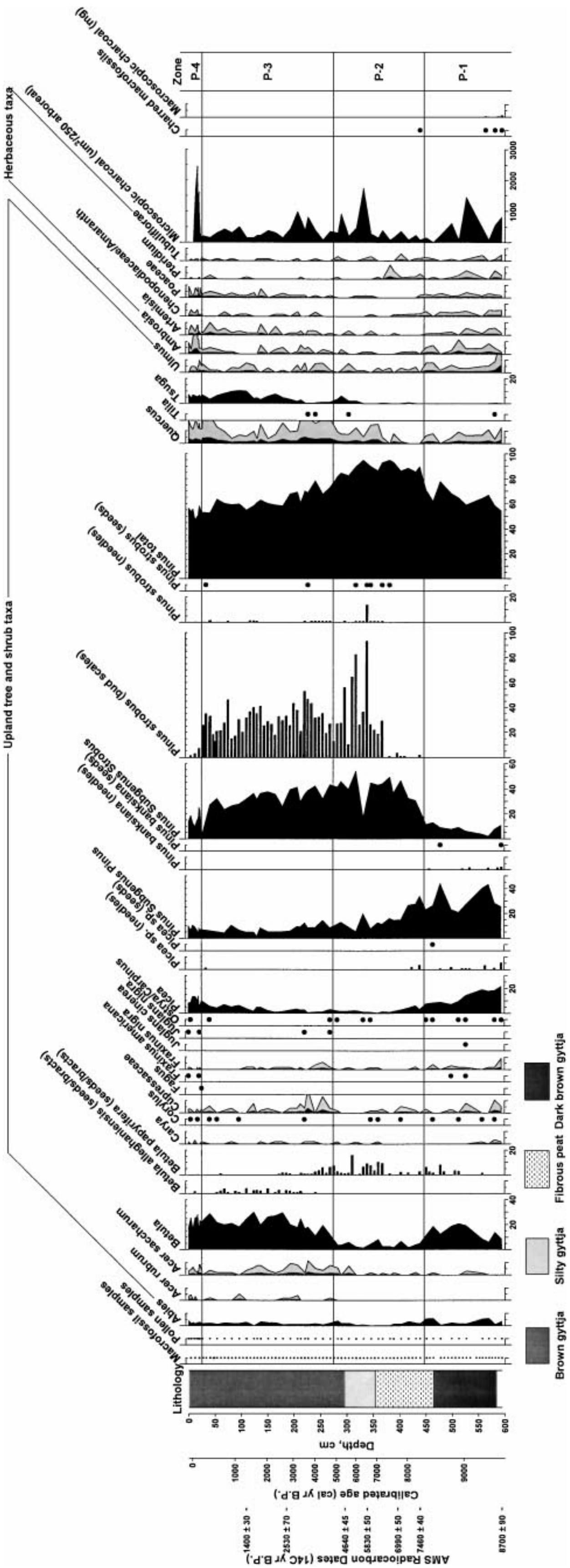

FIG. 5. Upland pollen and plant macrofossil diagram for Mud Lake. Accelerator mass spectrometry (AMS) radiocarbon dates, corresponding calibrated ages, depth, and lithology are on the left side of the diagram. Shaded silhouettes show pollen percentages, with fivefold exaggeration (gray) shown for infrequent taxa. Histograms are shown for macrofossil and sand concentrations (numbers/65 cm^3 and mg/65 cm^3, respectively). The presence of infrequent or low-abundance taxa is indicated by closed circles.

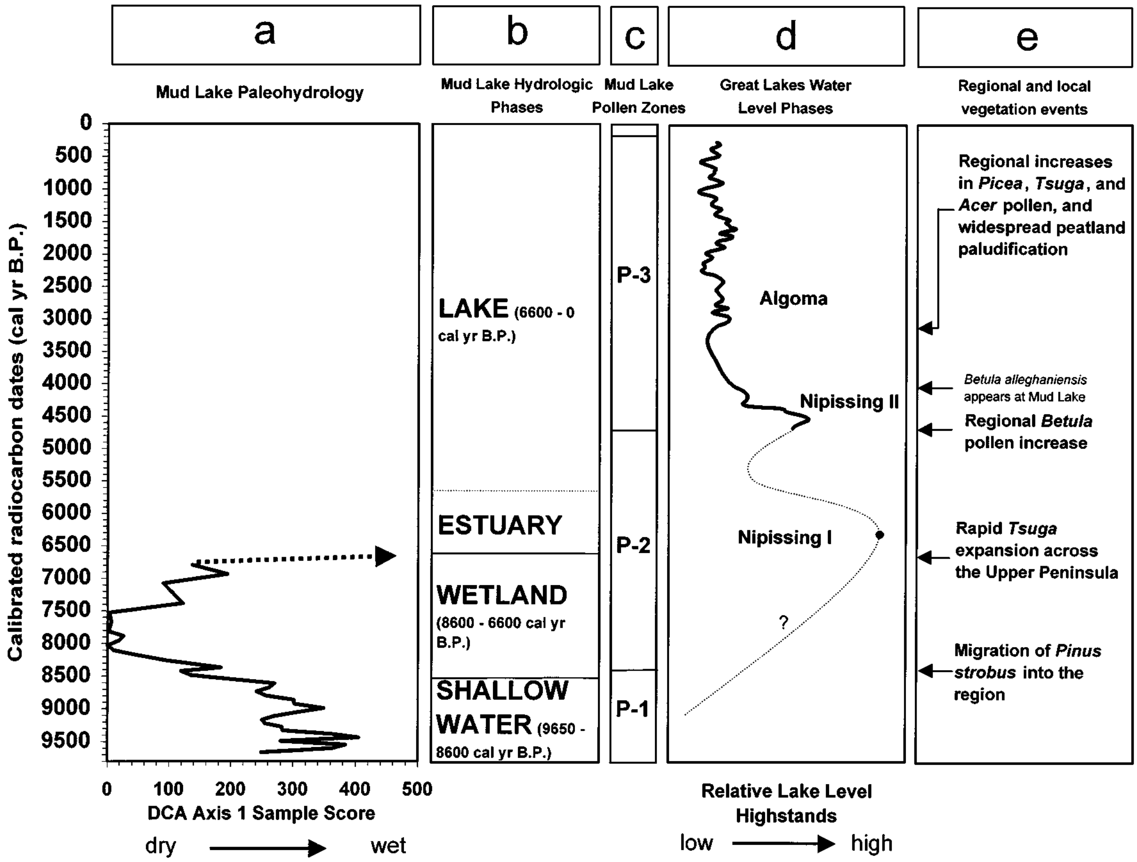

FIG. 7. Comparison of (a) Mud Lake paleohydrology, (b) Mud Lake hydrologic phases, (c) Mud Lake pollen zones, (d) upper Great Lakes water-level phases, and (e) regional and local vegetation changes. The solid portion of the upper Great Lakes water-level reconstruction is from the Lake Michigan record of Baedke and Thompson (2000). The dotted line is interpreted from the literature (e.g., Hansel *et al.*, 1985; Larsen, 1985a).

in *Betula* pollen resulted from migration and/or expansion of *Betula alleghaniensis*. Yellow birch saplings are particularly drought-intolerant (Godman and Krefting, 1960), so the *Betula* expansion may be connected with the inception of a relatively moist climatic regime.

Regional increases in *Picea, Tsuga,* and *Acer saccharum* pollen occurred at Mud Lake and other Upper Michigan pollen sites (e.g., Woods and Davis, 1989; Brubaker, 1975; Davis *et al.*, 2000) at about the same time as the Algoma highstand (2300–3200 cal yr B.P.; Baedke and Thompson, 2000). Widespread wetland paludification also occurred in northern Michigan during the past 4500 yr and was particularly rapid immediately preceding the Algoma highstand (Brugam and Johnson, 1997). However, more studies are needed to determine if wetland paludification rates correspond to the steplike pattern of increasing effective moisture suggested by pollen diagrams and the timing of the Nipissing and Algoma highstands. In summary, three major western Great Lakes water-level highstands, and the onset of the mid-Holocene drought, appear to be temporally correlated with major vegetation changes in the western Great Lakes region.

What Aspects of Climate Are the Great Lakes Water-Level Phases Recording?

The temporal correspondence between Holocene western Great Lakes water-level highstands and the regional onset of wetter conditions inferred from independent paleoecological and paleohydrological records indicates that the Nipissing I and II and Algoma phases were associated with regional climate change. These climate changes resulted in major population expansions of mesic tree species in the Upper Peninsula, with each climatic reorganization favoring a different species or group of species. The geographic extent of these climate changes also differed. For example, although increased effective moisture is evident from sites throughout the region since about 3200 cal yr B.P. (Algoma), the effective moisture changes of the mid-Holocene (Nipissing I) were antipodal in southern and northern portions of the western Great Lakes region.

The pattern of mid-Holocene climatic change in the region suggests that climatic changes in the northern portion of the western Great Lakes basin may have strongly influenced Great Lakes water levels. Between 5700 and 6800 cal yr B.P., water levels increased in northern Michigan wetlands (Miller and Futyma, 1987; Brugam and Johnson, 1997), while water levels decreased in wetlands of southern Wisconsin (Winkler *et al.*, 1986) and northwest Indiana (Singer *et al.*, 1996). At Portage Marsh in northwest Indiana, one of the few AMS-dated chronologies, a transition to drier conditions occurred rapidly at 6500 cal yr B.P. (Singer *et al.*, 1996). The timing of this drying is simultaneous with the shift toward wetter climate in Upper Michigan and with rising water levels of Nipissing I as recorded by Mud Lake. The simultaneous nature of these moisture changes implies that a major change in atmospheric circulation patterns occurred rapidly, and this change had opposite effects in northern and southern portions of the region. Thus, the high water levels of the Nipissing I highstand were probably partially a result of climatic changes that occurred in the northern part of the Great Lakes basin. Most of the western Great Lakes catchment is in the northern part of the basin, so lake level may be more sensitive to climate changes affecting that portion of the basin.

Although both Nipissing phases and the Algoma phase appear to be related to effective moisture increases, there is no terrestrial evidence for effective moisture decreases as water level dropped after these highstands. For example, after Nipissing II, high *Betula* pollen percentages continued until today, and yellow birch is still common in the Upper Peninsula. The persistence of high *Betula* and *Tsuga* pollen percentages suggests that the major lake-level highstands recorded the onset of major climatic shifts, and that each new climate regime persisted after the lake-level “event” ended. The lack of clear terrestrial evidence for effective moisture decreases after the major lake-level highstands supports the hypothesis that large-magnitude water-level declines resulted from outlet incision (Hough, 1958; Lewis, 1970). However, smaller magnitude fluctuations at higher frequencies probably record regional changes in effective moisture in both directions (Fraser *et al.*, 1990; Thompson and Baedke, 1997).

Increased water levels in the western Great Lakes, particularly large-magnitude changes like those of the Nipissing transgressions, may also have influenced climate by decreasing and/or moderating temperatures as well as increasing lake-effect precipitation. However, major climatic changes centering on 6500 cal yr B.P. are recorded on a subcontinental scale (e.g., Webb, 1988; Baker *et al.*, 2000). Although on a local and perhaps regional scale, high water levels may have directly influenced climate and vegetation, the onset of the major highstands appears to be related to major changes in atmospheric circulation patterns.

CONCLUSIONS

The Holocene dry period in Upper Michigan lasted from about 8600 to 6600 cal yr B.P., although the trend toward wetter conditions was initiated by 7200 cal yr B.P. The Mud Lake basin became a *Sphagnum*-dominated wetland during this period, and *Pinus strobus* populations expanded in Upper Michigan. Sediments indicate that rising western Great Lakes water levels associated with onset of Nipissing I converted the wetland into an estuary at 6600 cal yr B.P. Nipissing I, Nipissing II, and the Algoma phase are all temporally associated with periods of rapid regional vegetation change in the Upper Peninsula of Michigan. This association implies that climate, and not just differential rebound and outlet dynamics, played a major role in these lake-level events. However, water-level drops after these highstands appear to be unrelated to major climate changes. During Nipissing I, climatic changes that increased water levels were evidently concentrated in the northern part of the western Great Lakes basin. Traditional interpretations of Great Lakes water-level history should be revised to include a major role of climate.

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