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Maximum-Limiting Ages of Lake Michigan Coastal Dunes: Their Correlation With Holocene Lake Level History

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ABSTRACT. *Coastal geomorphology along the Great Lakes has long been linked with lake-level history. Some of the most spectacular landforms along the eastern shore of Lake Michigan are high-relief dunes that mantle lake terraces. It has been assumed that these dunes developed during the Nipissing high stand of ancestral Lake Michigan. This hypothesis was tested through stratigraphic analyses and radiocarbon dating of buried soils at four sites between Manistee and Grand Haven, Michigan.*

At each site, thick deposits of eolian sand overlie late-Pleistocene lacustrine sands. Moderately developed Spodosols (Entic Haplorthods) formed in the uppermost part of the lake sediments are buried by thick dune sand at three sites. At the fourth locality, a similar soil occurs in a very thin (1.3 m) unit of eolian sand buried deep within a dune. These soils indicate long-term (~ 4,000 years) stability of the lake deposits following subaerial exposure. Radiocarbon dating of charcoal in the buried sola indicates massive dune construction began between 4,900 and 4,500 cal. yr B.P. at the Nordhouse Dunes site, between 4,300 and 3,900 cal. yr B.P. at the Jackson and Nugent Quarries, and between 3,300 to 2,900 cal. yr B.P. at Rosy Mound. Given these ages, it can be concluded that dune building at one site occurred during the Nipissing high stand but that the other dunes developed later. Although lake levels generally fell after the Nipissing, it appears that dune construction may have resulted from small increases in lake level and destabilization of lake-terrace bluffs.

INDEX WORDS: *Lake level, age dating, ^{14}C, dune, Nipissing, Lake Michigan.*

BACKGROUND AND PROBLEM DEFINITION

Coastal dunes are common along the Great Lakes (Leverett and Taylor 1915, Farrand and Bell 1982, Fig. 1), providing dramatic vistas, recreational opportunities, and economic development. Dunes also support a suite of unique ecosystems that are highly valued by the Great Lakes basin's 35,000,000 residents. As human impacts on these sensitive landscapes increase, however, they may be destabilized and extensively mobilized (Santer 1993, Harding 1994). Thus, critical habitats may be lost and significant dollars spent by various agencies and landowners to control dune erosion (Harding 1994). To plan for protection and use of coastal dunes in Michigan their natural evolution must be fully understood. In terms of genesis, Great Lakes coastal dunes have been broadly classified in two ways: 1) as foredunes or beach-margin dunes (Olson 1958a); and 2) as "perched" dunes (Olson 1958, Marsh and Marsh 1987).

Of the two categories, beach-margin dunes have been studied the most, particularly in association with beach ridges and late Holocene lake-level change. Beach ridges form when lake level falls and sand from the new (lakeward) beach is deflated and deposited on the wider back beach such that a sublinear dune a few meters high is constructed. Further fall in lake level builds a similar ridge lakeward and parallel to the first and, eventually, in a

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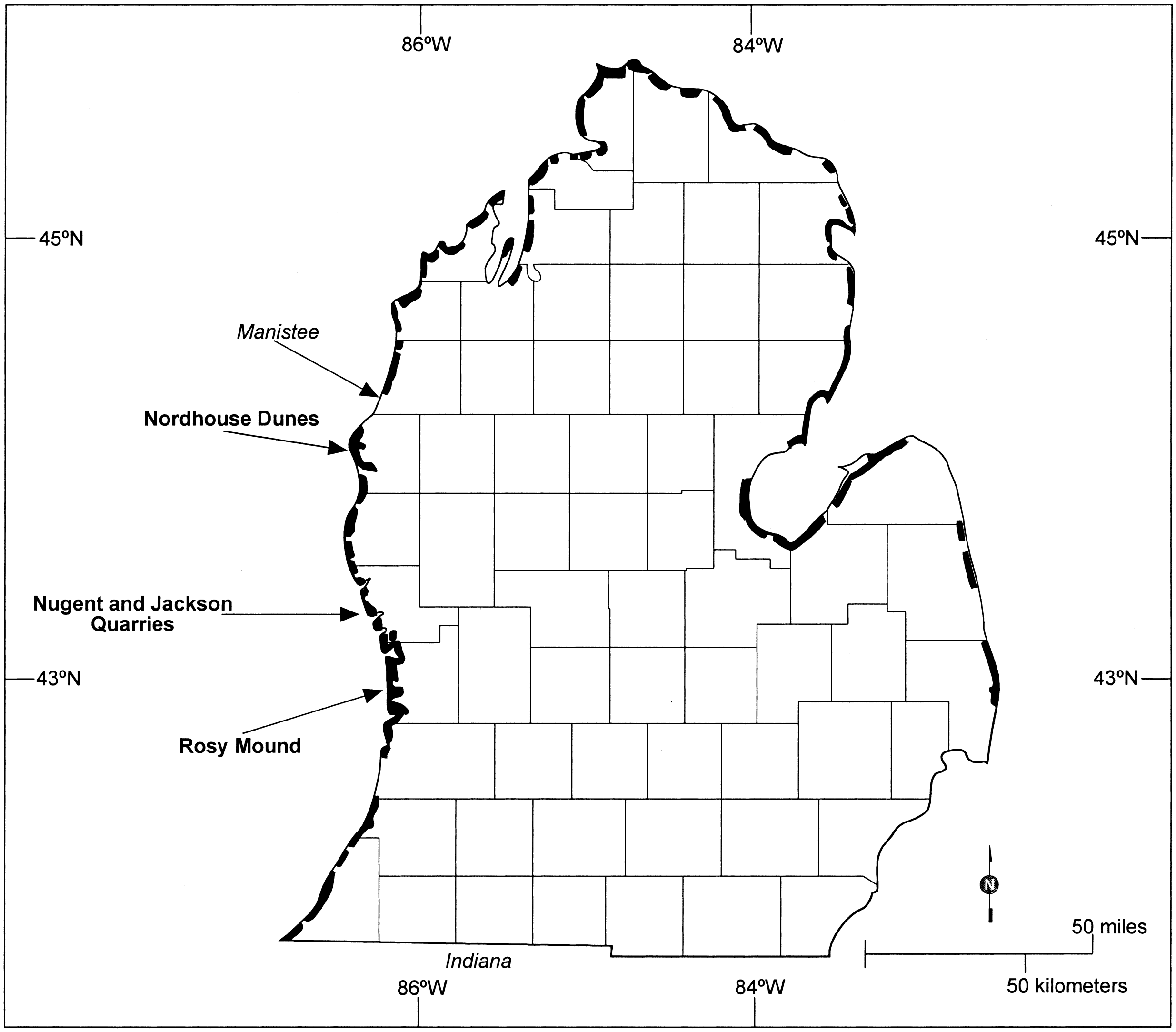

FIG. 1. Coastal dunes in lower Michigan and the location of study sites (shading indicates coastal dune areas along the shoreline). Map modified from Santer 1993 and Farrand and Bell 1982.

series of ridges roughly paralleling the shore. Whenever a new ridge begins to build the older ridge stabilizes and peat begins to develop in the poorly drained, intervening swale. The base of these peats can then be radiocarbon dated, which provides an estimate of when building of the more lakeward ridge in a ridge couplet began. This age, in conjunction with the elevation of foreshore deposits buried by the more lakeward ridge, can thus be used to reconstruct lake elevation at the time of ridge formation. Using this approach, extensive beach ridge sequences (100 + ridges) have been used to develop late Holocene hydrographs of Lake Michigan (Larsen 1994, Thompson 1992, Johnson *et al.* 1990, Dott and Mickelson 1995, Lichter 1995, Thompson and Baedke 1997).

Some details regarding the geomorphic evolution of perched dunes have recently emerged. Two prominent perched dune systems in Michigan, Sleeping Bear Dunes and Grand Sable Dunes, are located leeward of lake-facing bluffs that are approximately 90-m high (Santer 1993). In contrast to the low-lying beach ridges, the sediment source for perched dunes is the upper part of the adjacent bluffs, which destabilize when the lower bluff is undercut during high water. This disruption subsequently makes eolian transport of sediment (from the upper bluff face) more likely (Olson 1958, Snyder 1985, Marsh and Marsh 1987). At the Grand Sable dune field, Anderton and Loope (1995) correlated episodes of dune building and stability with the late-Holocene lake hydrographs reconstructed from beach ridge studies (Thompson and Baedke 1997). They argued that dunes began to develop as the rising waters of ancestral Lake Nipissing cut a bluff into a high forested plateau of unconsolidated sand about 6,000 radiocarbon years before present (yr B.P.) Subsequently, between four and eleven major periods of dune building buried former stable surfaces (represented by soils). This model supports previous research (Olson 1958, Marsh and Marsh 1987) linking building and immobilization of perched dunes to high and low water, respectively. According to unpublished reports by Snyder (1985) and Loope *et al*. (1995), the Sleeping Bear Dunes on Lake Michigan probably evolved in a similar manner.

In addition to the well-defined beach-margin and perched dunes, another type of dune system exists along the eastern shore of Lake Michigan that is unique but poorly understood. These dunes are similar to beach-margin dunes because their base is relatively close to the shore when compared to dunes perched on high bluffs. The dunes are much larger (> 30 m) than beach ridges, however, and are parabolic rather than sublinear in plan view. These dunes are also comparable to classic perched dunes because they mantle elevated surfaces. In contrast to high plateaus (Sleeping Bear, Grand Sable), however, these surfaces are much lower pro-glacial lake terraces (Taylor 1990). Overall, these *lake-terrace* dunes are easily the most common dune type along the eastern shore of Lake Michigan, extending from Manistee, Michigan to Indiana (Fig. 1). Contained within this belt of dunes are some of the most spectacular parks in the region, including Indiana Dunes, Warren Dunes and Saugatuck.

With few exceptions (Calver 1946, Tague 1946), it is believed that lake-terrace dunes formed during the Nipissing transgression of ancestral Lake Michigan (Dorr and Eschman 1970, Buckler 1979), between 6,000 and 4,000 yr B.P. (Hansel *et al*. 1985). This hypothesis however, has not been systematically tested by radiocarbon dating. In fact, only one radiocarbon age has been reported along the full length of the eastern shore of Lake Michigan from the lowermost part of a lake-terrace dune. This age, approximately 3,700 yr B.P., was obtained by Gutschick and Gonsiewski (1976) from a buried soil in the top of the lowermost eolian unit at the Indiana Dunes National Lakeshore. According to Gutschick and Gonsiewski (1976), this age implied that the underlying sediments are Nipissing in age. Given the detailed hydrographs available, it is now possible to test the hypothesis that dune building along the western coast of central lower Michigan occurred primarily during the Nipissing transgression.

Purpose

In this paper, the hypothesis that lake-terrace dunes along the western coast of central lower Michigan originated during the Nipissing transgression and high stand is tested. This test centers upon the analysis of four stratigraphic sections that include radiocarbon ages from the lower part of lake-terrace dunes at scattered sites along the shore of Lake Michigan in central lower Michigan.

STUDY AREA

The study area is located along an approximately 150-km-long section of coastline extending from Grand Haven north to the Nordhouse dunes within the Huron-Manistee National Forest (Fig. 1). In this part of Michigan, dunes mantle lacustrine deposits (Farrand and Bell 1982) that accumulated during various high lake stages (Calumet, Nipissing, Hansel *et al.* 1985) in the basin. Although dunes are very common on this shore, they extend only about 1 km inland as a semi-continuous band. The dunes are parabolic in plan view, with limbs that are basically oriented to the west/southwest (~ 260%; Fig. 2), which is largely perpendicular to the coast. The base of most dunes lies at an elevation of approximately 191 m above mean sea level (MSL, 1929), whereas the modern datum for the Great Lakes is 176 m above MSL (IGLD, 1985). The crests of the largest dunes exceed 230 m above MSL (Grand Haven, Mich. 7.5 minute quadrangle, 1972).

Climate data for the region was obtained from the weather station at Muskegon, which lies within the study transect. The local climate is classified as mixed marine, continental. Mean annual temperature ranges from approximately –5° C in January to about 21°C in July. The area receives about 81 cm of precipitation throughout the year. Although winds are multidirectional, the strongest annual winds are northwesterly in winter and southwesterly in summer (Eichenlaub *et al.* 1990).

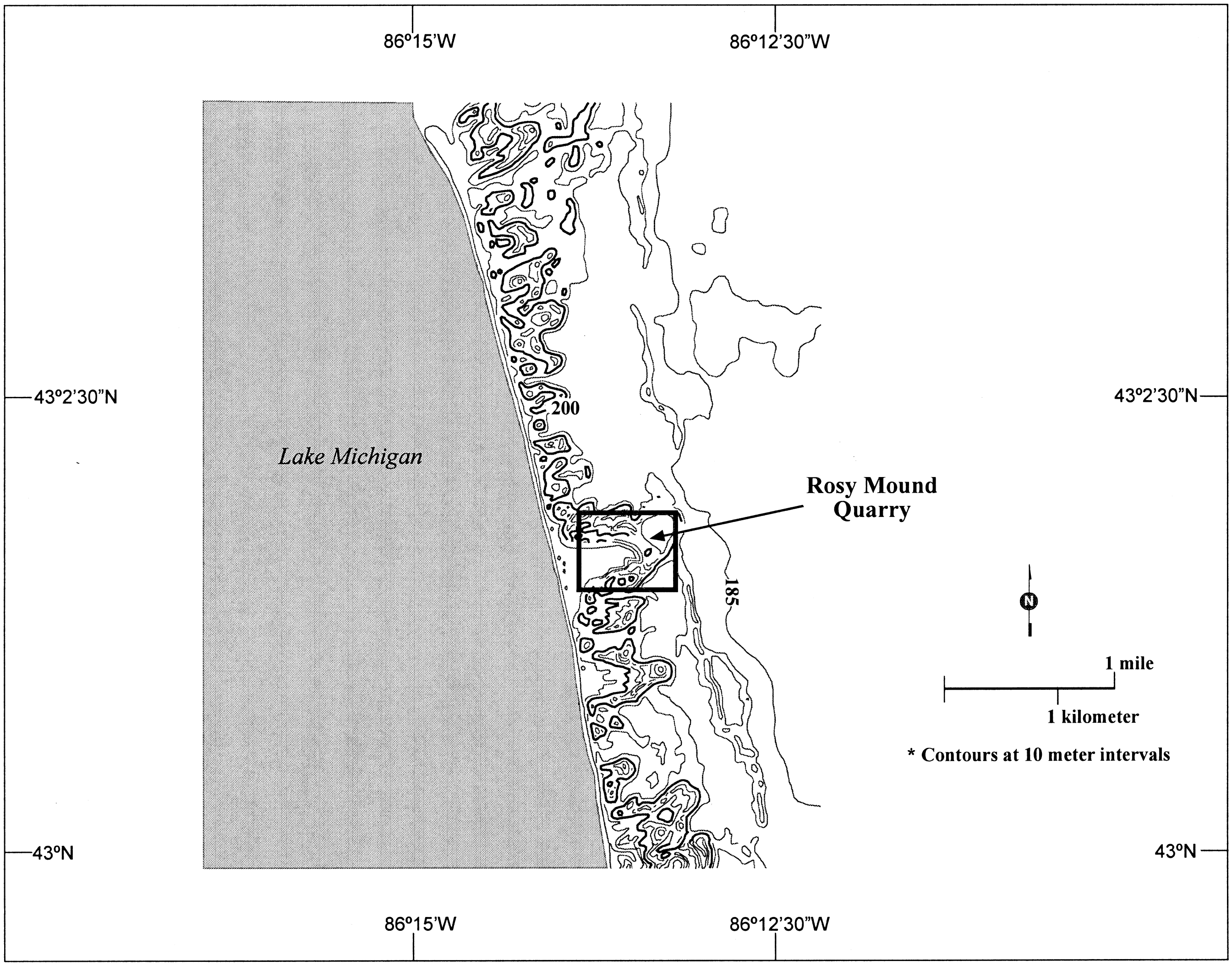

FIG. 2. Topographic map in the vicinity of Grand Haven. Note the narrow width of the dune field and the orientation of individual parabolic dunes (from the Grand Haven, Michigan Quadrangle 1972).

METHODS

Four sites were investigated. Three of the sites are exposures discovered and sampled in sand quarries during May, 1997. At two of the quarry sites, the stratigraphy was particularly well exposed and the contact between the dunes and the underlying sediments was clear. At the third quarry site, however, the stratigraphic relationships were less visible, thus they were explored with a bucket auger and shovel. The fourth site was located at a narrow vegetated dune ridge within the Nordhouse Dunes, and was accessed using a bucket auger to penetrate the landward toe of the dune. The overall height of the dunes at all sites was established with a hand level. All land elevations are relative to mean sea level as established by the National Geodetic Vertical Datum (MSL, 1929), whereas lake elevations are based on the International Great Lakes Datum (IGLD 1985).

Soils were described according to standards outlined by the Soil Survey Division Staff (1993). Radiocarbon ages were derived from charcoal fragments (apparently resulting from fire) contained within soils formed in the uppermost part of basal lacustrine sediments at the three quarry study sites (Fig. 3). These soils reflect internal organization of the lacustrine sediment into distinct horizons (O/A/E/Bs/C) by prolonged weathering before the dunes began to build. The radiocarbon ages derived from these soils provide maximum-limiting esti-

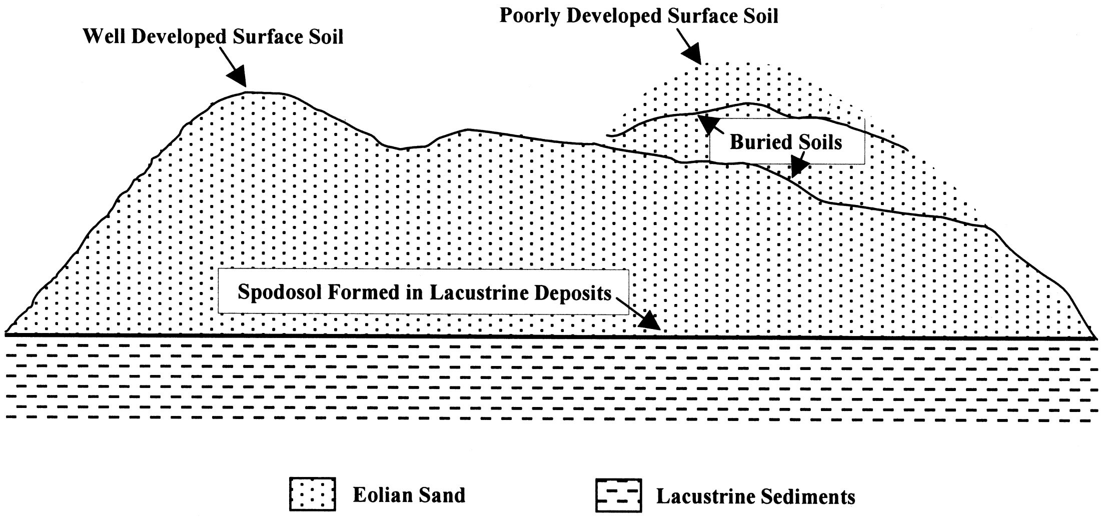

FIG. 3. Schematic crossection (not to scale) of deposits examined in this study. Thick deposits of eolian sand overlie lake sediments deposited by ancestral Lake Michigan. Well developed soils are present in the upper part of lacustrine sediments at 3 of the 4 sites studied. Overlying dunes are very large, with some greater than 50 m tall. Some dunes contain weakly developed buried soils, which indicate brief periods of landscape stability as the dune was constructed.

mates for the beginning of dune construction because they approximate the date when the former stable (lacustrine) surfaces were buried by eolian sand. At the Nordhouse site, a radiocarbon age was derived from charcoal in a soil developed into the surface of a thin eolian deposit buried deep within a dune. A total of five samples were collected from the study sites for age determination (Table 1). Three of the samples were small (< 10 gm) and were thus assayed by Accelerator Mass Spectrometry (AMS) at the INSTAAR Laboratory at the University of Colorado (Boulder). The remaining samples were much larger and could thus be analyzed by conventional methods; one was processed at the radiocarbon laboratory at the University of Texas (Austin) and the other at the Beta Analytic Laboratory in Miami, Florida. In order to correct for long-term variations in the radiocarbon time scale (due to fluctuations in production of the radiocarbon isotope over time) all dates were calibrated to the tree-ring curve established by Stuiver and Reimer (1993). This calibration allows radiocarbon dates (reported in yr B.P.) to be adjusted to calendar years before present (cal. yr B.P.)

TABLE 1. Radiocarbon ages presented in this study.

Location	Stratigraphic Position[1]	Horizon (depth)	Lab No.	δ^{13}C-corrected ^{14}C Age[2]	δ^{13}C (‰)	Calibrated Age[3] (2σ)
Rosy Mound Quarry	ls	6Ab (~ 55 m)	Tx-8608	2,890 ± 60	–25.8	3,270–2,940
Rosy Mound Quarry	ls	6Ab (~ 55 m)	NSRL-3518	2,920 ± 60	–27.0	3,270–2,940
Nugent Quarry	ls	2Ab (~ 5.4 m)	NSRL-3676	3,720 ± 50	–29.3	4,350–4,060
Jackson Quarry	ls	2Ab (~ 20 m)	NSRL-3677	3,730 ± 50	–22.7	4,250–3,920
Nordhouse Dunes	ds	2Ab (~ 22 m)	Beta-106928	4,030 ± 50	–26.5	4,820–4,410

1: ls = lacustrine sand; ds = dune sand
2: For a discussion of the ^{13}C-correction procedure, see Stuiver and Polach (1977) and Taylor (1987).
3:Calibrated from conventional ^{13}C-corrected radiocarbon age to calendar years using a tree-ring curve. All calibrations reported here were based upon the 20-year atmospheric curve (Linick *et al.* 1985, Stuiver *et al.* 1986). Program used is discussed in Stuiver and Reimer (1993).

RESULTS AND DISCUSSION

Site Stratigraphy

In the following text the stratigraphic relationships at each site are described. The order of presentation is based upon geographic location, beginning with the southernmost site (Rosy Mound) and ending at the most northerly site (Nordhouse dunes).

Rosy Mound Quarry

The Rosy Mound Quarry is located approximately 2 km south of Grand Haven, Michigan (Fig. 1). Sand mining at this site (Fig. 2) has resulted in several excellent exposures of buried soils. The best exposure, one where the underlying sediments are also visible, was on the western end of the quarry.

The stratigraphy at the Rosy Mound Quarry consists of eolian sand overlying stratified lacustrine sands that lie at an elevation of approximately 191 meters above MSL (Fig. 4). Formed within the top of the lacustrine unit is a moderately developed soil, with A/E/Bs/C horizonation (solum thickness is 80 cm). This soil apparently formed through podzolization, which results in the eluviation of sesquioxides and organic matter in an acidic environment by percolating water (Rourke *et al.* 1988). Given its development, the soil is classified as an Entic Haplorthod. Charcoal was scattered throughout the A horizon of the soil and two age determinations were conducted. One sample provided a conventional radiocarbon age of 2,890 ± 60 yr B.P. (Tx-8608), whereas the other yielded an AMS date of 2,940 ± 60 yr B.P. (NSRL-3518). Each estimate essentially correlates to the same calibrated age at 2σ of 3,270 to 2,940 cal. yr B.P.

Overlying the lacustrine unit is approximately 55 m of eolian sand. Contained within the upper part of the dune (from ~ 9.8 to 16.5 m below the dune surface) are four buried soils. These soils dip steeply to the north, are weakly developed (A/C horizonation; the A horizons are ~ 5-cm thick), and indicate very brief periods of landscape stability as the dune evolved. Given the steep dip of the soils, burial likely occurred because sand originated on the windward side of the dune and accumulated in the lee. Thus far, dateable material has not been recovered from these soils. The surface soil of the dune is morphologically consistent (Deer Park series; Pregitzer 1972) with the buried soils in the dune, indicating that the dune has been stable for a brief period of time.

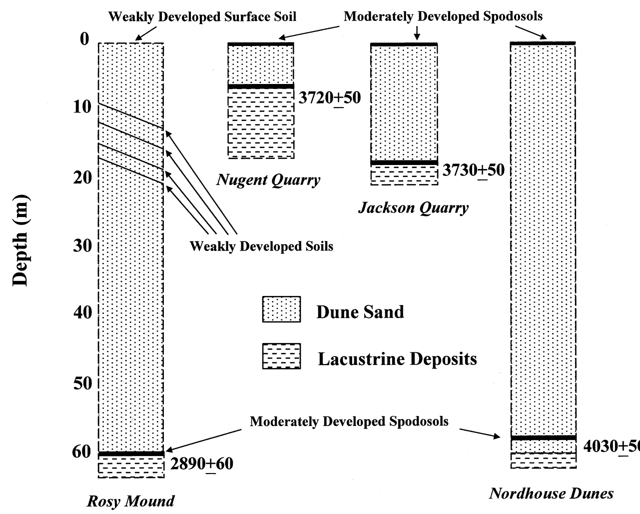

FIG. 4. Site stratigraphy at the Rosy Mound, Nugent, and Jackson quarries, and the Nordhouse Dunes site.

Nugent Quarry

The Nugent Quarry is a very large quarry (~ .75 km^2), located on the southwestern side of Muskegon, Michigan (Fig. 1). As at the Rosy Mound Quarry, the stratigraphy at the Nugent Quarry consists of eolian sand overlying laminated lacustrine sands that lie at an elevation of about 191 m above MSL (Fig. 4). Formed within the uppermost part of the lacustrine sediments is a moderately developed buried soil. This soil is quite consistent (A/E/Bs/C horizonation; solum thickness is 75 cm) with the basal soil at the Rosy Mound Quarry, indicating that it formed by podzolization and is classified as an Entic Haplorthod. Given the large size of the Nugent Quarry, the soil was traceable as a horizontal surface for several hundred meters. The Ab horizon of the soil contained a moderate amount of charcoal, which provided an AMS estimate of 3,770 ± 50 yr B.P. (NSRL-3676) and a calibrated age at 2σ of 4,350 to 4,060 cal. yr B.P.

Overlying the basal lacustrine unit and soil at the Nugent Quarry is approximately 5.4 m of eolian sand. In contrast to the Rosy Mound Quarry, which contained several buried soils, the exposures at the Nugent Quarry are devoid of buried sola. In addition, the surface soil at the Nugent Quarry is an Entic Haplorthod (A/E/Bs/C horizonation; Rubicon Series; Pregitzer 1972), which is significantly more developed than its counterpart at the Rosy Mound

Quarry. Overall, the lack of buried soils and the relatively strong development of the surface soil imply that eolian sand accumulated quickly at the Nugent Quarry and the dune has largely been stable since that time.

Jackson Quarry

The Jackson Quarry is located approximately 1.5 km north of the site where the Nugent Quarry was sampled (Fig. 1). Unlike the Rosy Mound and Nugent Quarries, mining at the Jackson Quarry has not exposed the sediments underlying the dune. Thus, the sub-dune relationships at this site were explored with a bucket auger and shovel. Results indicated that the stratigraphy is essentially the same as at the other sites, with dune sand overlying lacustrine sediments that lie at an elevation of approximately 191 m above MSL. In addition, a buried soil is present in the uppermost part of the basal lacustrine unit. This soil is morphologically consistent (A/E/Bs/C horizonation) with the other basal soils (Fig. 4) and was traced throughout the quarry. The Ab horizon contained charcoal, which provided an AMS radiocarbon age of 3,720 ± 50 yr B.P. (NSRL-3677) and a calibrated estimate at 2σ of 4,250 to 3,920 cal. yr B.P. These ages are consistent with the ages estimated in the nearby Nugent Quarry.

Overlying the basal soil is approximately 20 m of eolian sand. Consistent with the nearby Nugent Quarry, the dune at the Jackson Quarry is devoid of buried soils. Here too, the surface soil is moderately developed, consisting of an Entic Haplorthod with A/E/Bs/C horizonation (Rubicon Series). Overall, the lack of buried soils coupled with the development of the surface soil indicates that the eolian deposit accumulated quickly and has been stable for a relatively long period of time.

Nordhouse Dunes Site

The Nordhouse Dunes site is located at the western edge of the Huron-Manistee National Forest, along Lake Michigan, approximately 90 km north of the Jackson Quarry (Fig. 1). Dunes at this site are well vegetated; thus, the basal stratigraphy was explored with a bucket auger and shovel. Given the large size of the dunes in this area and the lack of exposures, investigations focused on the lee slope of a single dune at its interface with the lacustrine surface.

The stratigraphy at the Nordhouse dunes site is generally consistent with the stratigraphy at the sites to the south, consisting of dune sand overlying lacustrine deposits of unknown depth (Fig. 4). There are three significant differences, however, between this site and the others: 1) the top of the lacustrine unit lies at an elevation of approximately 200 m above MSL as opposed to 191 m above MSL; 2) a soil is not present in the upper part of the lacustrine sediments; and 3) the top of this depositional unit is marked by a thin (< 5 cm) zone of rounded pebbles. At the Nordhouse Dunes site, the lowermost paleosol is developed within a thin (1.3 m) eolian unit very near the base of the dune. This buried soil is fairly well developed (A/E/Bs/C horizonation; solum thickness = ~ 80 cm) and is consistent with the basal soils to the south. Thus, this soil is also classified as an Entic Haplorthod. Charcoal was recovered in the upper part of the A horizon that provided an AMS age of 4,030 ± 50 yr B.P. (Beta-106928) and a calibrated age at 2s of 4,820 to 4,410 cal. yr B.P.

Overlying the basal Haplorthod is approximately 10 m of eolian sand. No buried soils were found in this portion of the section. The surface soil is a weakly to moderately developed Entic Haplorthod with A/E/Bw/C horizonation. Overall, the lack of buried soils in the upper section, coupled with the development of the surface soil, indicates that the 10-m-thick uppermost eolian deposit accumulated quickly and its surface has been stable for a relatively long period of time.

Timing for the Initiation of Dune Formation

Analysis of site stratigraphy and radiocarbon ages reveals a chronology for the onset of dune mobilization at scattered sites along the shore of central lower Michigan. All of the dunes overlie lacustrine terrace deposits that lie at elevations ranging from approximately 191 m above MSL [1929 (Mean Sea Level, 1929)] at Rosy Mound and the Nugent and Jackson Quarries to 200 m above MSL at Nordhouse Dunes. These elevations are much higher than the modern [lake] elevation of ~ 176 m above MSL for Lake Michigan and the highest Nipissing stage of 183.5 m above MSL (Hansel *et al*. 1985), which occurred during the middle Holocene (Table 2). Thus, the terrace sediments must have accumulated when lake level was much higher during an earlier stage, either the Glenwood (~ 12,900 to 12,700 yr B.P.) or Calumet (~ 11,800 to 11,200 yr B.P.)

Following the Lake Calumet high stand, lake levels dropped significantly, falling to Chippewa stage

TABLE 2. Elevations of the stratigraphic contact between the lacustrine and eolian deposits, relative to the highest Nipissing level and the modern lake datum, at the four study sites.

Location	Contact Elevation (m above modern datum)[1]	Contact Elevation (m above NGVD, 1929)[2]	Highest Nipissing Level (m above NGVD)[3]
Rosy Mound Quarry	190.8	191	183.5
Nugent Quarry	190.8	191	183.5
Jackson Quarry	190.8	191	183.5
Nordhouse Dunes	190.8	200	183.5

[1]Elevations referenced to the International Great Lakes Datum 1985 (IGLD 85) are 0.04 m lower than elevations referenced to the North American Vertical Datum 1988 (NAVD 88) in this part of Michigan. The datums are treated as approximately equivalant at these sites.
[2]National Geodetic Vertical Datum, 1929, equivalent to Mean Sea Level 1929
[3]From Hansel *et al.* 1985.

at approximately 9,800 yr B.P. Thereafter, lake elevation rose slowly during the Nipissing transgression, peaking at approximately 5,200 cal. yr B.P. (Hansel *et al*. 1985). The interval between the Calumet and Nipissing high stands was largely a period of stability for the modern shorezone, as indicated by the moderately developed Spodosols (Entic Haplorthods) that are deeply buried by dunes (Fig. 3). At Rosy Mound and the Nugent and Jackson Quarries (Fig. 1), these soils formed in the top of the lacustrine terraces. At Nordhouse Dunes, the soil developed in an extremely thin (1.3 m) eolian unit that directly overlies the lake terrace sediments. In northwestern lower Michigan, where environmental conditions (heavy snowpack, sandy textures, pine forest, low pH) are especially suitable for Spodosol development (Schaetzl and Isard 1991), Entic Haplorthods are thought to form in approximately 3,000 years (Barrett and Schaetzl 1992). In all probability, the development of the basal soils studied here was relatively slow in comparison to northwestern lower Michigan (i.e., the primary Spodosol zone) because the environmental variables are less favorable for Spodosol development. The presence of the soils suggests that no continuous band of dunes was present in this part of the study area for an extended period of time in the early to middle Holocene. Instead, the zone of dune construction was probably farther to the west, wherever the active coastline was located during the low lake stage. If this is true, dunes deeper in the basin would have subsequently been destroyed as lake level rose during the Nipissing transgression.

Although the buried Spodosols indicate long-term stability along the prehistoric coastal zone, they cannot be used to estimate the onset of dune construction along the modern shorezone. To shed light on this issue, calibrated radiocarbon ages obtained here were compared with the calibrated lake-level curve (derived from beach ridges at Sturgeon Bay) reported by Thompson and Baedke (1997). The oldest part of this curve (Fig. 5) dates to the latter part of the Nipissing interval. Although the curve is not corrected for isostatic rebound, which exaggerates the amount of lake-level fall in the middle Holocene, the age correlation is nonetheless valid.

The correlated dune/lake-level curve reveals that extensive mobilization of eolian sand occurred along the shore of ancestral Lake Nipissing at only the Nordhouse Dunes site, where massive dune construction (burying the thin basal unit of eolian sand) began sometime between 4,900 and 4,500 cal. yr B.P. Although the early part of this interval is beyond Thompson and Baedke's (1997) data, the latter half falls within the prominent rise in lake level that peaks approximately 4,600 cal. yr B.P. This correlation suggests that dune construction began because lake level rose and sand was supplied through wave erosion of the high lake-terrace bluffs as described in the perched-dune model (e.g., Marsh and Marsh 1987, Anderton and Loope 1995).

Burial of basal soils in lacustrine sediments at quarry sites to the south of Nordhouse dunes apparently occurred sometime after the Nipissing interval. At the Nugent and Jackson quarries, burial by eolian sand occurred between 4,300 and 3,900 cal. yr B.P. Still farther south, at the Rosy Mound Quarry, initial sand deposition happened between about 3,300 and 2,900 cal. yr B.P. This last interval correlates nicely to a higher lake phase, possibly the Algoma (Larsen 1985, Dott and Mickelson 1995), and suggests that sand supply increased due to bluff destabilization as lake level rose. An obvious ques-

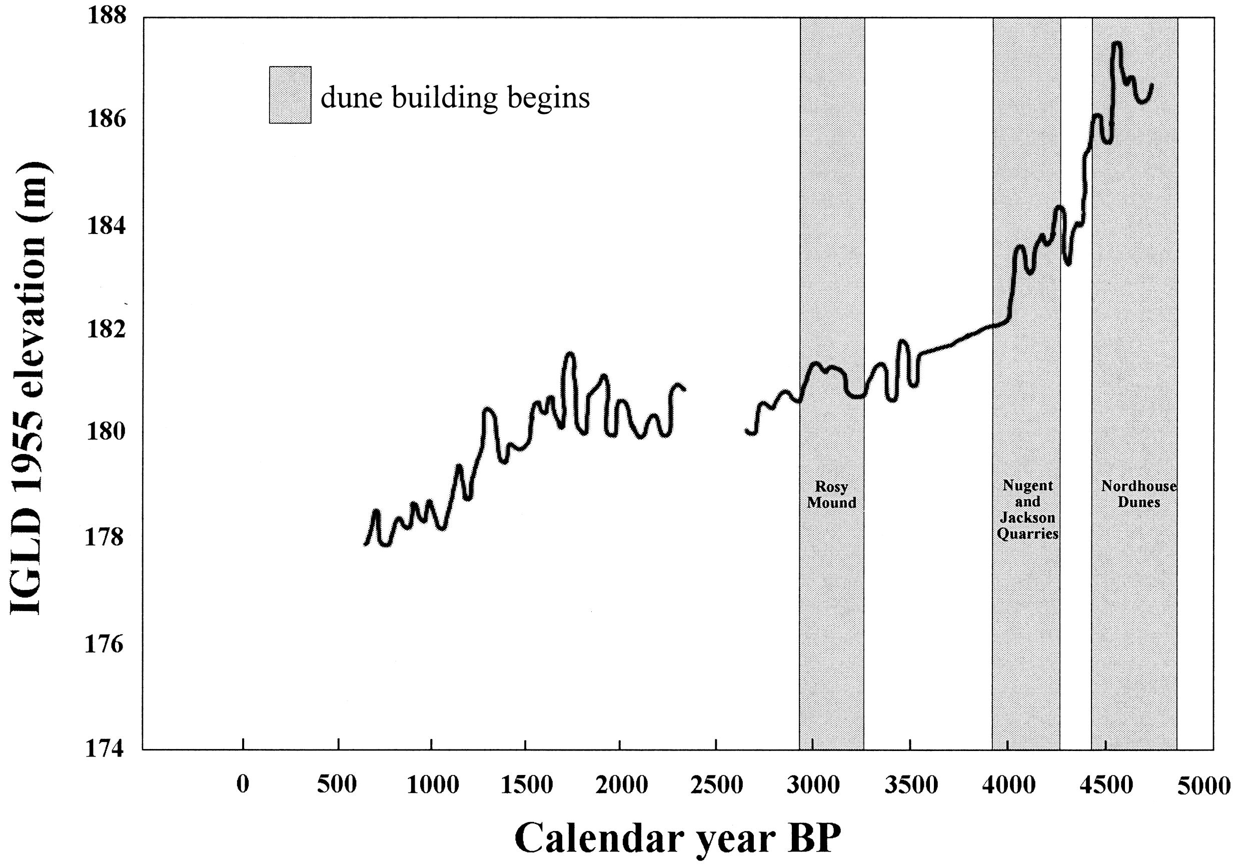

FIG. 5. Comparison of calibrated radiocarbon ages for commencement of dune-building at the four sites with the late-Holocene lake level curve for Lake Michigan (modified from Thompson and Baedke 1997).

tion is the timing of dune construction at Rosy Mound relative to Nordhouse Dunes. Why are the dunes at Rosy Mound so much younger (i.e., not Nipissing) in age? The most logical answer is that the Nipissing high stand caused limited retreat of the relatively high bluff at Nordhouse Dunes (allowing for substantial deflation of the bluff by wind), but the lower bluff at Rosy Mound retreated rapidly (yielding little eolian sediment). Once the position of this lower bluff was established, it then became a source for eolian sand during the later (but lower) Algoma rise.

Although terrace burial at the Nordhouse and Rosy Mound sites chronologically correlates well to rising lake levels, the relationship between dune construction and lake level at the Nugent and Jackson quarries is less clear. It is initially tempting to ascribe dune construction at these sites to beach enlargement and increased sand supply during the general drop from the Nipissing high. Development of low-lying ridges during the Nipissing regression is well documented (Larsen 1994, Thompson 1992, Dott and Mickelson 1995, Lichter 1995, Thompson and Baedke 1997).

When viewed more closely, the burial of a densely-forested lake terrace by massive dunes using the beach-ridge model is problematic. Olson's (1958) model suggests that the more inland members in a beach-ridge sequence become more protected and thus receive less sand with each incremental drop in lake level. Because the source of sand (the unvegetated beach) would have migrated continually away from these forested terraces, it seems unlikely that the sand required to build enormous dunes (Olson 1958) could originate from enlarged beaches. Instead, it is most logical that high quantities of sand could be provided to one place (i.e., a dune) through undercutting of an established lakeward-facing exposure of sandy terrace sediments, consistent with the perched-dune model (Olson 1958, Marsh and Marsh 1987) and what apparently occurred at the Nordhouse and Rosy Mound sites. In that context, it is possible that dune building at the Nugent and Jackson quarries is related to the minor peaks in lake level from 4,300 to 3,900 cal. yr B.P. that occurred during the Nipissing regression. Moreover, the impact of these mini-peaks was probably greater than implied because the curve is not corrected for isostatic rebound. In this scenario, the position of the bluff was quickly established during the Nipissing high stand and was then destabilized during subsequent (but lower) lake level rises, such as occurred at the Rosy Mound Quarry.

CONCLUSIONS

This study tested the hypothesis that lake-terrace dunes along a portion of the eastern shore of Lake Michigan are Nipissing landforms. Soils buried under three dunes and a soil buried deeply within one dune were analyzed and dated. The dunes overlie lacustrine deposits that accumulated either during the Glenwood or Calumet stages of glacial Lake Chicago (Hough 1958), between 12,900 and 11,200 yr B.P. Ice retreat from the Great Lakes basin and falling lake levels during the Chippewa low stage subsequently led to a long-term period of stability at the four sites, allowing moderately developed Spodosols to develop on the former lake terraces.

At the Nordhouse Dunes site, dune-building commenced between 4,900 and 4,500 cal. yr B.P., possibly due to a lake rise during the Nipissing interval (Thompson and Baedke 1997) that destabilized the lakeward edge of the terrace. At the remaining sites, the extant dunes began to form sometime after the Nipissing stage. Radiocarbon ages from buried soils at the Nugent and Jackson quarries suggest that dune construction began as lake level generally fell, but may have been caused by bluff destabilization during lake-level peaks within the regression. At the southernmost site (Rosy Mound Quarry), burial of the basal soil occurred much later, perhaps during the Algoma high stand. Overall, these results imply that many lake-terrace dunes along the central east shore of Lake Michigan began to form after the peak of the Nipissing high stands. Younger buried soils (as yet undated) at the Rosy Mound Quarry site suggest that post-Algoma lake level change may have caused some dune building at that site. Current models for the history and behavior of lake-terrace dunes require much refinement. At this point, more radiocarbon ages are essential to further test hypotheses of lake-terrace dune behavior relative to lake levels.

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REFERENCES

Anderton, J. B., and Loope, W. L. 1995. Buried soils in a perched dunefield as indicators of Late Holocene lake-level change in the Lake Superior basin. *Quat. Res.* 44:190–199.

Barrett, L. R., and Schaetzl, R. J. 1992. An examination of podzolization near Lake Michigan using chronofunctions. *Canadian J. of Soil Science* 72:527–541.

Buckler, R.W. 1979. *Dune inventory and barrier dune classification study of Michigan's Lake Michigan shore.* Michigan Department of Natural Resources, Geological Survey Division: Investigation 23, Lansing.

Calver, J. L. 1946. *The glacial and post-glacial history of the Platte and Crystal Lake depressions, Benzie County, Michigan.* Occasional Papers on the Geology of Michigan, Publication 45, Michigan Dept. of Conservation, Geological Survey Division.

Dorr, J. A. Jr., and Eschman, D. F. 1970. *Geology of Michigan*. Ann Arbor, Michigan: University of Michigan Press.

Dott, E. R., and Mickelson, D. M. 1995. Lake Michigan water levels and the development of Holocene beach-ridge complexes at Two Rivers, Wisconsin: stratigraphic, geomorphic, and radiocarbon evidence. *Geol. Soc. of America Bull*. 107:286–296.

Eichenlaub, V. L., Harman, J. R., Nurnberger, F. V., and Stolle, H. J. 1990. *The Climatic Atlas of Michigan*. Notre Dame, IN: University of Notre Dame Press.

Farrand, W. R., and Bell, D. L. 1982. *Quaternary geology (map) of southern Michigan with surface water drainage divides.* 1:500,000 scale. Dept. of Geological Sciences, University. of Michigan, Ann Arbor.

Grand Haven, Michigan Quadrangle. 1972. United States Geological Survey Topographic Map: 1:24,000 scale.

Gutschick, R. C., and Gonsiewski, J. 1976. Coastal geology of the Mt. Baldy Area, Indian Dunes National Lakeshore. In *Coastal Sedimentation and Stability in Southern Lake Michigan*, ed. W. L. Wood, pp. 38–90. West Lafayette, Indiana: Purdue Great Lakes Coastal Research Laboratory.

Hansel, A. K., Mickelson, D. M., Schneider, A. F., and Larsen, C. E. 1985. Late Wisconsinan and Holocene history of the Lake Michigan Basin. *Geol. Assoc. of Canada, Special Paper* 30:39–53.

Harding, R. J. 1994. *Sand dune protection and management*; part 353 of the Natural Resources and Environmental Protection Act, PA 451.

Hough, J. L. 1958. *Geology of the Great Lakes*. Urbana, IL: University of Illinois Press.

IGLD. 1985. Establishment of International Great Lakes Datum. Coordinating Committee on Great Lakes Basin Hydraulic and Hydrologic Data. December, 1985.

Johnson, T. C., Stieglitz, R. D., and Swain, A. M. 1990. Age and paleoclimatic significance of Lake Michigan beach ridges at Baileys Harbor, Wisconsin. *Geol. Soc. of America, Special Paper* 251:67–74.

Larsen, C. E. 1985. Lake level, uplift, and outlet incision, the Nipissing and Algoma Great Lakes. In *Quaternary Evolution of the Great Lakes*, eds. P. F. Karrow and P. E. Calkin, pp. 63–77. St. John's, Newfoundland: Geological Association of Canada.

______. 1994. Beach ridges as monitors of isostatic uplift in the upper Great Lakes. *J. Great Lakes Res.* 20: 108–134.

Leverett, F., and Taylor, F. B. 1915. *The Pleistocene of Indiana and Michigan and the history of the Great Lakes*. U. S. Geol. Surv. Mono. 53.

Lichter, J. 1995. Lake Michigan beach-ridge and dune development, lake level, and variability in regional water balance. *Quat. Res.* 44:181–189.

Linick, T. W., Suess, H. E., and Becker, B. 1985. La Jolla measurements of radiocarbon in south German oak tree-ring chronologies. *Radiocarbon* 27:20–32.

Loope, W.L., Snyder, F. S., and Anderton, J. B. 1995. *Tentative correlation of lake level, soil burial and vegetation cover in perched dune fields of the upper Great Lakes: a preliminary report.* Report prepared for the National Park Service (1443PX632092115).

Marsh, W. M., and Marsh, B. D. 1987. Wind erosion and sand dune formation on high Lake Superior bluff. *Geografiska Annaler* 69A:379–391.

Olson, J. S. 1958. Lake Michigan dune development, 3: lake-level, beach, and dune oscillations: *Jour. Geol.* 66:473–483.

Pregitzer, K. E. 1972. *Soil Survey of Ottawa County, Michigan*. United States Department of Agriculture, Soil Conservation Service.

Rourke, R.V., Brasher, B. R., Yeck, R. D., and Miller, F. T. 1988. Characteristic morphology of U.S. Spodosols. *Soil Science Soc. of America J.* 52:445–449.

Santer, R. A. 1993. *Geography of Michigan and the Great Lakes Basin.* Dubuque, Iowa: Kendall/Hunt Publishing.

Schaetzl, R.J., and Isard, S. A. 1991. The distribution of Spodosol soils in southern Michigan: a climatic interpretation. *Annals of the Assoc. of American Geog.* 81:425–442.

Snyder, F.S. 1985. A spatial and temporal analysis of the Sleeping Bear Dunes complex, Michigan. PhD dissertation. University of Pittsburgh.

Soil Survey Division Staff. 1993. *Soil Survey Manual.* USDA Handbook 18. US Govt. Printing Off., Washington, D.C.

Stuiver, M., and Polach, H. A. 1977. Reporting of ^{14}C data. *Radiocarbon* 19:355–363.

______, and Reimer, P. J. 1993. Radiocarbon calibration program revision 3.0. *Radiocarbon* 35:215–230.

______, Pearson, G. W., and Braziunas, T. 1 986. Radiocarbon age calibration of marine samples back to 9000 cal. yrs B.P. *Radiocarbon* 28:980–1021

Tague, G.G. 1946. *The post-glacial geology of the Grand Marais embayment, Berrien Co., Michigan.* Occasional Papers on the Geology of Michigan, Publication 45, Michigan Dept. of Conservation, Geological Survey Division. pp. 1–82.

Taylor, L. D. 1990. Evidence for high glacial-lake levels in the northeastern Lake Michigan basin and their relation to the Glenwood and Calumet phases of glacial Lake Chicago. In *Late Quaternary History of the Lake Michigan Basin*, eds. A. F. Schneider and G. S. Fraser, pp. 91–110. Geol. Soc. Amer. Spec. Paper 251.

Taylor, T. L. 1987. *Radiocarbon Dating—An Archaeological Perspective*. Orlando, FL: Academic Press.

Thompson, T. A. 1992. Beach-ridge development and lake-level variation in Lake Michigan: *Sed. Geol.* 80:305–318.

______, and Baedke, S. J. 1997. Strand-plain evidence for late Holocene lake-level variations in Lake Michigan. *Geol. Soc. of America Bull.* 109:666–682.

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