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Dominance of an ~150-Year Cycle of Sand-Supply Change in Late Holocene Dune-Building along the Eastern Shore of Lake Michigan

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Outcrops of buried soils on lake-plains and glacial headlands along Lake Michigan's eastern shore suggest that periodic dune-building has occurred there after relatively long (≥100 yr) periods of low sand supply. We located, described, and radiocarbon dated 75 such buried soils that crop out in 32 coastal dune fields beside the lake. We assume that peaks in probability distributions of calibrated ^{14}C ages obtained from wood, charcoal, and other organic matter from buried A horizons approximate the time of soil burial by dunes. Plotted against a late Holocene lake-level curve for Lake Michigan, these peaks are closely associated with many ~150-yr lake highstands previously inferred from beach ridge studies. Intervening periods of lower lake levels and relative sand starvation apparently permitted forestation and soil development at the sites we studied. While late Holocene lake-level change led to development and preservation of prominent foredunes along the southern and southwestern shores of Lake Michigan, the modern dune landscape of the eastern shore is dominated by perched dunes formed during ~150-yr lake highstands over the past 1500 yr.

Key Words: **Lake Michigan; lake-level; dunes; Holocene; paleosols.**

INTRODUCTION

Setting and History of Investigation

Along the eastern shore of Lake Michigan, a combination of strong southwesterly winds, high wave fetch, and abundant sand substrate has produced large coastal dunes on morainal headlands, outwash terraces, and lake plain deposits at various elevations (Dorr and Eschman, 1970; Hands, 1970; Farrand and Bell, 1982; Fig. 1). Because these dunes are now interspersed with major population centers and include valuable public lands and unique biological resources (Michigan Legislature, 1976; McEachern *et al.*, 1994), understanding of their geomorphic history is increasingly relevant to management and conservation.

During the early and mid-1900s, interdisciplinary research on Great Lakes dunes focused variously on geographic setting, history, and processes driving change (Cowles, 1899; Fuller, 1918; Stevenson, 1930; Dow, 1937; Calver, 1946; Olson, 1958b,c,d). Some of these studies qualitatively describe the origin of prominent foredunes (~5 m thick), formed by landward transport of sand from beaches over several decades (Olson, 1958d), but do not define the origin of larger (up to 50 m thick) dunes along the shore. Large perched dunes in the lee of high coastal bluffs are linked to sand nourishment from bluff faces (Dow, 1937), but the origin of other large dunes that mantle topographically lower lake plains is obscure.

During the mid-1970s and early 1980s, attention shifted away from dunes and toward the history of lake-level change, the dominant control on shoreline behavior (Hands, 1983). Through radiocarbon dating, a series of studies established that climatological control of lake level is superimposed upon control by isostatic rebound and erosion of outlets (Hough, 1963; Fraser *et al.*, 1975; Larsen, 1985; Fraser *et al.*, 1990). Studies of beach ridge sequences later combined analyses of coastal sediments with ^{14}C dating to quantify the magnitude and timing of past lake-level change (Thompson, 1992; Dott and Mickelson, 1995; Thompson and Baedke, 1995, 1997, 1999; Baedke and Thompson, 2000).

Beach Ridges and the Quantification of Lake-Level History

Beach ridges have formed along Lake Michigan as levels rise briefly and then fall (Thompson and Baedke, 1995). Sequences of beach ridges may be built and preserved in protected coastal indentations, in areas of positive net sediment supply, or both. Thompson and Baedke (1997) used vibracores from 256 beach ridges and radiocarbon dates from selected interridge swales within five multiridge sequences to construct

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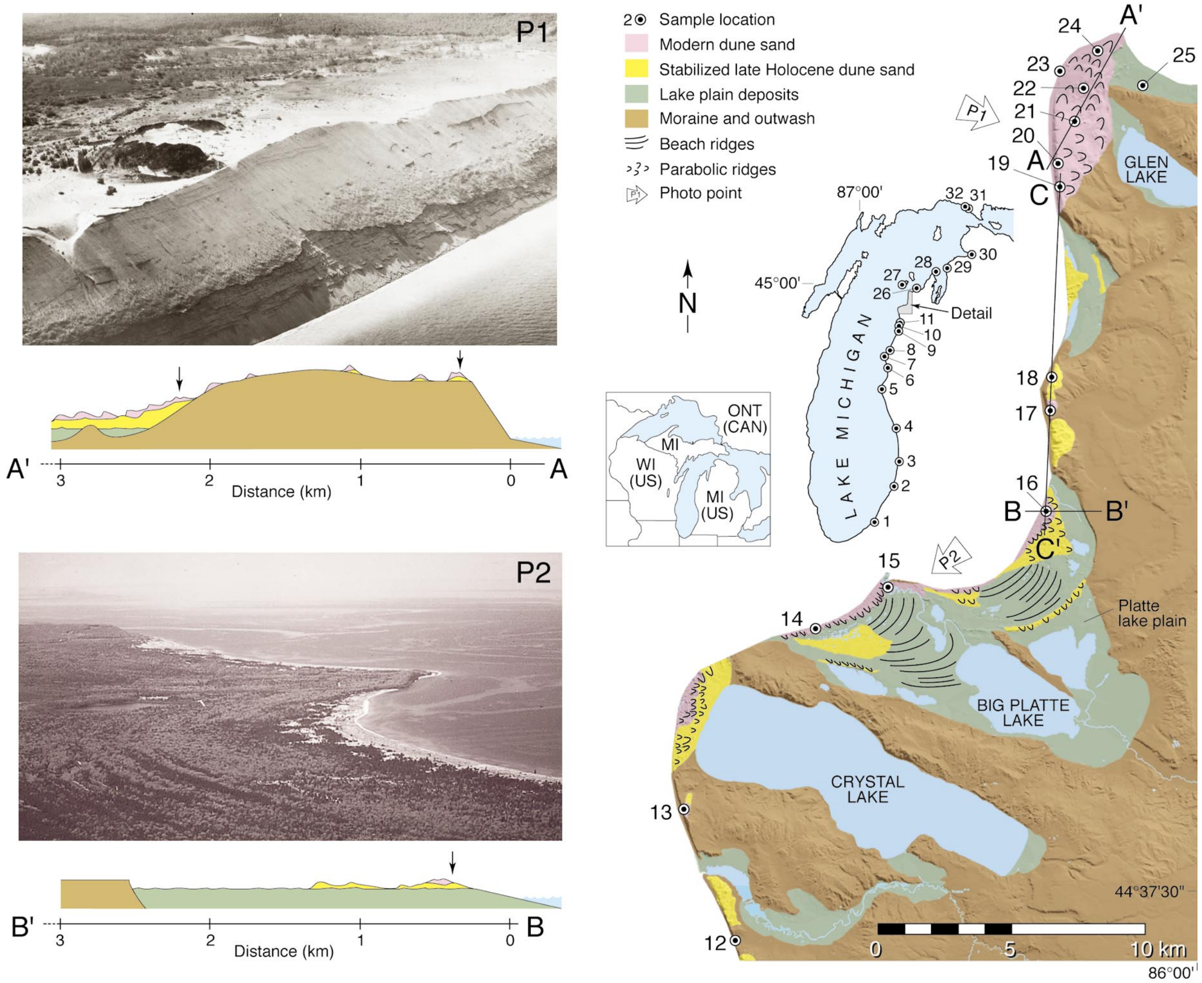

FIG. 1. Settings of 32 sampling localities along the eastern shore of Lake Michigan. Large-scale map shows settings of exhumed paleosols from sites 12–25. Photo P1 and section A–A′ typify settings of study sites on glacial headlands; photo P2 and section B–B′ typify settings of study sites on lake plain edges. Geology generalized from Farrand and Bell (1982), Snyder (1985), and Walbom (1999). MI, Michigan; ONT, Ontario; WI, Wisconsin.

four late Holocene hydrographs of Lake Michigan. These hydrographs imply late Holocene "quasi-periodic" lake level change with two distinct periods and magnitudes. Individual beach ridges form on ~30-yr return periods during lake level changes of ~0.5 m, and groupings of four to six ridges form on ~150-yr return periods during lake level changes of ~1.5 m. Using data from all five ridge sequences, Thompson and Baedke (1999), and Baedke and Thompson (2000), then produced rebound-adjusted composite hydrographs portraying levels of Lakes Michigan and Huron (observed at the Port Huron outlet) over the past 4750 cal yr.

Dune Behavior Revisited: Foredunes and Perched Dunes

How can recent work on lake-level history be used to clarify the relationships between lake-level change and dune-building? While the development of beach ridges is not directly associated with dune building, eolian caps (foredunes) often form on emergent beach ridges when water levels recede. Olson (1958b,c,d) observed foredune development along Lake Michigan's southern shore over several decades and showed that vegetation promotes foredune construction by altering surface roughness. Olson's (1958d) model linking foredune growth to low lake levels over decades has been validated in air-photo sequences along portions of Lake Michigan's eastern (Lichter, 1995) and southern shore (Hunter *et al.*, 1990) and applied to studies of beach ridges along the southwestern shore (Fraser *et al.*, 1975, 1990). Due to its elegance and the lack of an alternative of similar stature, Olson's model remains the dominant paradigm for coastal eolian activity. However, the model has been broadly applied, beyond its intended physiographic context, to imply explanation of all major changes in landward sand flux along Lake Michigan (e.g., Dorr and Eschman, 1970; Buckler, 1979).

Olson's foredune model does not describe dune behavior

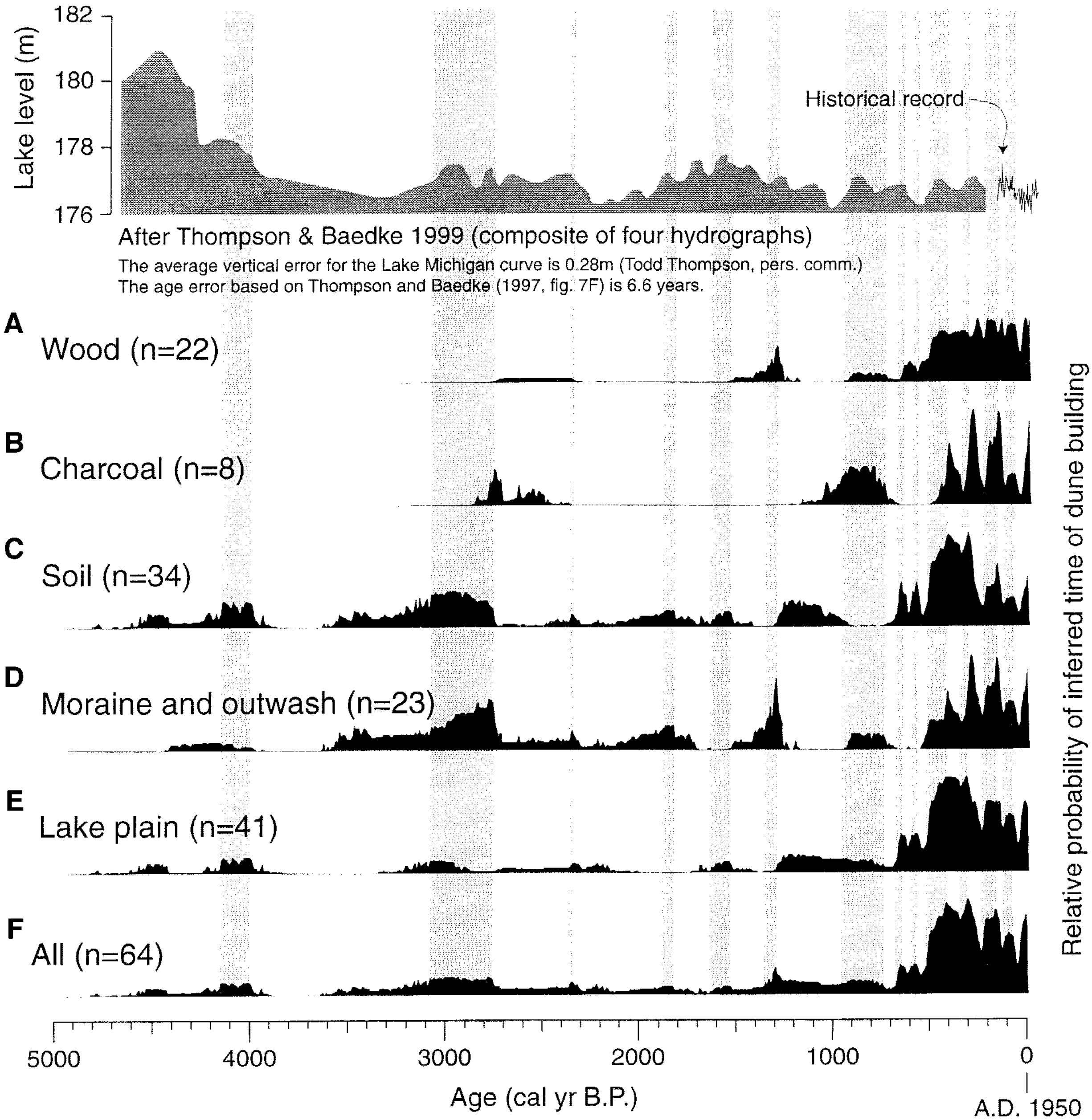

FIG. 2. Inferred late Holocene levels of Lake Michigan (Thompson and Baedke, 1999; Baedke and Thompson, 2000) compared with peaks in probability of inferred dune-building based on 64 calibrated radiocarbon ages from exhumed dune paleosols. Gray bars show how composite peaks in inferred dune building (graph F) compare with the inferred lake levels. Graphs A–E show ages grouped by material type (A–C) and geomorphic setting (D, E); graph F shows all these data combined.

along the entire shore, nor does it address sand supply fluctuations over hundreds of years. The presence of buried soils in dunefields widely spaced along Lake Michigan's eastern shore (Loope *et al.,* 1995; Arbogast and Loope, 1999) provides evidence that some periods of dune building have alternated with periods of stability sufficiently long (>100 yr) to permit forest development (Olson, 1958a), periods much longer than the multidecade intervals afforded by Olson's (1958d) foredune model. Radiocarbon dating of buried soils in perched dunes on lake-facing bluffs (Anderton and Loope, 1995) along Lake Superior also suggests periods of stability separated by a century or more.

Anderton and Loope (1995) proposed that perched dunes along the southeastern shore of Lake Superior are nourished episodically when adjacent lake-facing bluffs are undermined and collapse during rising lake levels, thereby providing sediment for landward eolian transport. This "perched-dune" mechanism of sand-supply change contrasts with Olson's suggestion that dunes are built by landward deflation of sand from low-relief beaches during low lake levels (Olson, 1958d). The perched-dune model has not been systematically tested elsewhere in the Great Lakes basin. How well do these two models explain variations in sand supply to the large dunes that occupy a variety of geomorphic surfaces along the eastern shore of Lake Michigan?

This paper has two closely related purposes. First, we test the hypothesis that ~150-yr highstands of Lake Michigan (Thompson and Baedke, 1997, 1999; Baedke and Thompson, 2000) caused soil burial events (i.e., dune building) on moraines, outwash plains, and lake plains along the Lake's eastern shore throughout the late Holocene. Second, we attempt to reconcile and integrate the foredune and perched-dune models of eolian sedimentation in the context of our data.

METHODS

We searched active dunefields (Hands, 1970; Buckler, 1979) on high-standing morainal headlands and outwash terraces and on truncated lake-plains closer to present lake level between the Mackinac Straits and Michigan's border with Indiana. We located 75 buried soils among 32 localities (Fig. 1). Individual soil profiles were described using standard techniques, noting field texture, color, thickness, and boundary characteristics (Schoeneberger *et al.*, 1998). The thickness of eolian sediment between soil horizons was measured using a hand level and meter tape. Samples of charcoal, wood, and soil organic matter were collected from the soils for ^{14}C dating (available as supplementary data).

To help compare these data with published lake-level hydrographs, we used the 1998 INTCAL data (Stuiver *et al.*, 1998) and the OxCal program (version 3.3; Bronk Ramsey, 1995, 1998) to convert ^{14}C ages to calibrated (approximately calendric) ages and to sum probability distribution of calibrated ages within the range of available lake-level data (Thompson and Baedke, 1997, 1999; Baedke and Thompson, 2000). The lake-level hydrographs contain errors from ^{14}C dating (e.g., Olsson, 1986), stratigraphic interpretation (e.g., Larsen, 1994), and calibration (Stuvier and Reimer, 1993). Our summation of ^{14}C ages from dune paleosols represents a proxy estimate of late Holocene dune building that contains uncertainty for similar reasons as do the lake-level data. However, because both entities are based on many data points gathered in a consistent manner at many sites (Pilcher, 1993), they probably have enough precision and accuracy to show how coastal dunes responded to past lake-level change.

Of 75 ^{14}C ages, 7 dated "modern" or less than 100 ^{14}C yr B.P. and 4 extended back in time beyond the range of the composite lake hydrographs (Thompson and Baedke, 1999; Baedke and Thompson, 2000). Sixty-four calibrated ages fell between 4750 and 110 cal yr B.P. and were included in the statistical analysis.

A key assumption of our approach is that ^{14}C ages from buried A horizons approximate the timing of vegetation death due to rapid sand accumulation. How valid is this assumption for materials that are typically associated with paleosols (wood, charcoal, soil organic matter)? Dating of in-place stems or soil wood fragments would be the most reliable because these fragments represent a direct link with a living forest (Birkeland, 1974). Charcoal is one step removed in time from the living forest; its durability also presents the problem of possible "recycling" of the same fragments across several episodes of vegetation death (i.e., forest fires) prior to burial. Finally, the dating of soil organic matter represents an unknown time lag between the death of twigs, leaves, and other litter on the soil surface, their incorporation into soils, and burial by advancing dunes.

In an effort to test the consistency of inferred signal from our samples, we compared probability peaks of calibrated ages among the three types of material collected (wood, charcoal, soil organic matter; Figs. 2A–2C). To test our dune-building hypothesis, we also compared peaks of probability of the timing of soil burial (i.e., dune building) on glacial headlands (Fig. 2D), on truncated lake plains (Fig. 2E), and on all surfaces (Fig. 2F) with a composite hydrograph derived from Holocene lake-level data (Fig. 2; Thompson and Baedke, 1999; Baedke and Thompson, 2000).

RESULTS AND DISCUSSION

Dune Building Events vs Late Holocene Lake Levels

The patterns of probability distribution of calibrated ages that we use as surrogates for the timing of dune-building appear to correlate well across types of material dated (Figs. 2A–2C), supporting the assumption that the various materials formed close to the time of vegetation death. The pattern of probability distribution also correlates well across differing geomorphic surfaces (Fig. 2D, 2E) supporting the hypothesis that the perched dune model (Marsh and Marsh, 1987; Anderton and Loope, 1995) can be applied to the entire eastern shore of Lake Michigan, above the beach. Most peaks of relative probability of inferred dune-building lie near hydrograph peaks separated by 100–200 cal yr (Thompson and Baedke, 1999; Baedke and Thompson, 2000; Fig. 2). The hypothesis that the building of perched dunes along the eastern shore of Lake Michigan is correlated with ~150-yr lake-level peaks is supported (Fig. 2F). The wide extent of the buried-soil signals of dune-building suggests that the dune landscape of the eastern shore of Lake Michigan is primarily a product of ~150-yr lake highstands.

Variability and Uncertainty in the Signal of Dune-Building

It is likely that much evidence of dune building corresponding with earlier lake-level history lies beneath heavily forested landscapes, was destroyed by bluff recession, or was buried deeply by later episodes of dune building. Thus, our sampling of surface outcrops may obscure the true distribution of burial events relative to time and geomorphic setting. Although a signal linking dune building with lake-level peaks separated by a century or longer seems apparent, synchrony of events along a given suite of surfaces is rare (Fig. 3). This variability suggests that dunes respond to lake-level change, storm events, and changes in littoral sediment supply in a complex manner.

Uncertainties of carbon residence time in soils has limited the utility of ^{14}C dates of soil organic matter to date episodes of sand movement in some studies (Gilet-Blein *et al.*, 1980; Geyh and Roeschmann, 1983; Matthews and Dresser, 1983). However, the late Holocene environment of the upper Great Lakes coast appears minimally vulnerable to these difficulties. The time required for forestation of a stable sand surface (~100–150 yr; Olson, 1958a) and return periods of soil burial appear to have a similar order of magnitude. Brief periods of soil development after forestation may thus explain the similarities in ^{14}C age among wood, charcoal, and soil organic matter (Figs. 2A–2C).

Testing Dune Paradigms

Our buried soil data show that the modern dune landscape along the eastern shore is young. While large coastal dunes along the upper Great Lakes are commonly interpreted as Nipissing in age (~5500–5000 cal yr B.P.; Dorr and Eschman, 1970; Buckler, 1979), the dune landscapes we sampled are primarily products of post-Nipissing events (see also Snyder, 1985; Arbogast and Loope, 1999). Seventy-five to 80% of the sand volume emplaced at sites 12–25 lies above buried soils dated at 1500 cal yr B.P. or younger.

Although the origin of parabolic "blowouts" along foredune ridges has been attributed to human disturbance and to wave runup during stochastic storm events, the ~150-yr timing of overlap of beach ridge sequences by parabolic dunes at sites 14–16 and 23–25 (Fig. 1) suggests that many blowout events are related to ~150-yr lake-level change. Dune-building events recorded at Aral Dunes (Fig. 3, site 16) may mirror formation of undated parabolic dunes recognized on strand plains by others (Stevenson, 1930; Olson, 1958d; Thompson, 1992; Lichter, 1995; Thompson and Baedke, 1997).

How much sand is moved during ~150-yr and ~30-yr cycles of lake-level change along the eastern shore of Lake Michigan? The thickness of dunes that cap beach ridges on the protected Platte lake plain (location of sites 14–16, Fig. 1), and which formed during ~30-yr return periods, is highly variable but probably much less than the average 0.5- to 2-m heights of the ridges (Thompson and Baedke, 1997). Average depths of soil burial for 26 paleosols from this area (Fig. 1, sites 12–25) provide a rough index of sand volume moved during ~150-yr dune-building episodes (10.1 m, n = 14, on glacial headlands and 8.5 m, n = 12, on truncated lake terraces).

The observed correlation of dune-building events on glacial headlands (Fig. 1, sites 17–20, photo P1, section A^1-A) with ~150-yr lake highstands (Fig. 4A) might be expected given the timing of similar events along other portions of the upper Great Lakes shore (Anderton and Loope, 1995; Loope *et al.*, 1995; Arbogast and Loope, 1999). Unexpected, however, is the ~150-yr period for soil-burial events on the truncated edges of the low-lying Platte lake plain (Fig. 1, sites 14–16, photo P2, section B^1-B). How can similar periodicities of forestation and forest burial (i.e., dune-building) on glacial headlands (Fig. 4A) and on truncated lake plains (Fig. 4C) be explained? Buried soils data from sites 14–20 (Fig. 1), in concert with data from a beach-ridge study within the Platte lake plain (Thompson and Baedke, 1997), can be used to answer this question and to develop a general hypothesis on the late Holocene interaction of the foredune and perched dune models along the eastern shore of Lake Michigan.

Perched Dunes and Foredunes on and Adjacent to the Platte Lake Plain

Between 3500 and 1100 cal yr B.P., lake-level change drove the construction of a large sequence of beach ridges within Platte Bay—a deep, sheltered indentation of the Lake Michigan shoreline (Fig. 1, detail; Fig. 4B). Foredunes of varying thickness capped many of these ridges during low lake phases (Fig. 4B, scenes 3 and 5; Thompson and Baedke, 1997). Positive net sediment-supply and the absence of eroding wave action within the indentation permitted the preservation of the signals of both multidecade lake-level change (of ~0.5 m, forming individual beach ridges; Fig. 4B) and multicentury lake-level change (of ~1.5 m; forming groups of 3–6 beach ridges; Thompson and Baedke, 1997). The lakeward building of the beach ridge sequence ultimately filled the sheltered indentation of Platte Bay (Fig. 1, photo P2, section B^1-B—lake plain deposits) about 1100 cal yr. B.P., when the beach ridge sequence ceased to form. Our data from sites 14–16 (Fig. 1) show that, during subsequent ~150 lake-level peaks, the lakeward edge of the beach-ridge sequence was truncated (Fig. 1, section B^1–B; Fig. 3, site 16; Fig. 4C, scene 1), a lake-facing bluff was formed, and perched dunes developed in the lee of the bluff, burying forests that had invaded the landward portion of the sequence. Deposits associated with ~30-yr lake-level change were routinely removed or rearranged by wave action after 1100 cal yr B.P. because the site no longer afforded protection from direct wave action (Thompson and Baedke, 1997); thus, regular beach ridges and foredune caps were no longer preserved. Each time Lake Michigan rises to a ~150-yr high (Fig. 4C, scenes 3 and 5), any beach-edge sand deposits are destroyed, perched

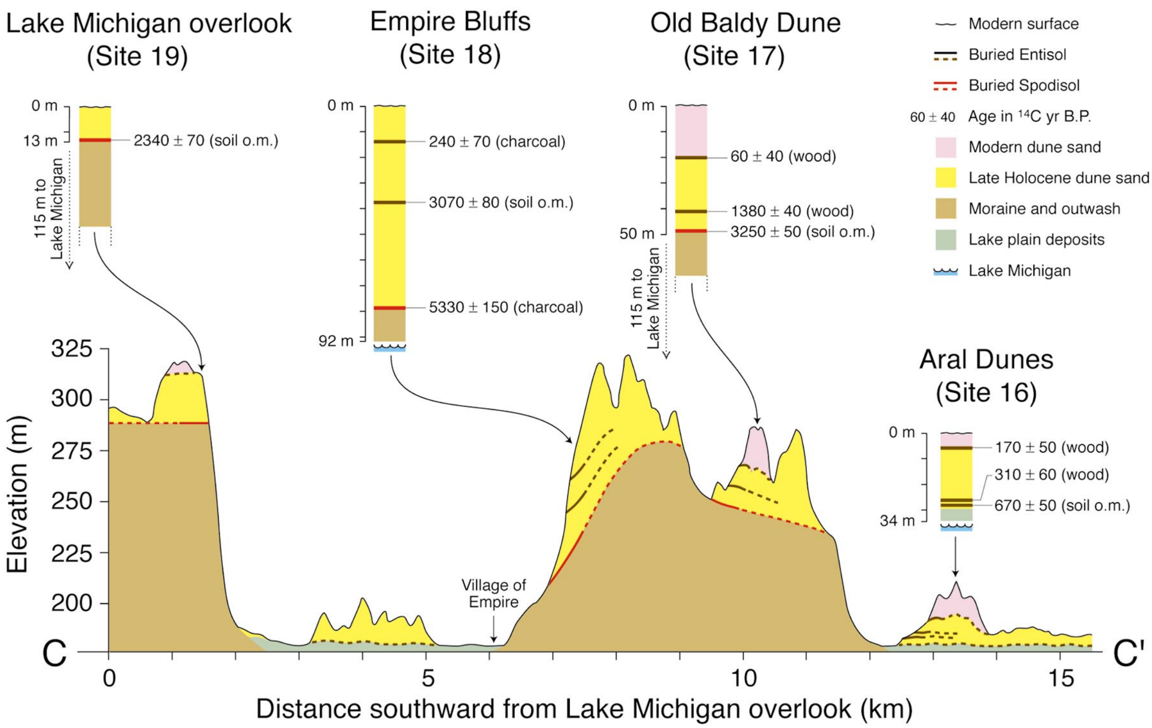

FIG. 3. Stratigraphic sections showing relationships among paleosol outcrops along a topographic profile between sites 16 and 19 (Fig. 1). Geology generalized from Farrand and Bell (1982), Snyder (1985), and Walbom (1999). o.m., organic matter.

dunes are activated along bluff crests and forests are again buried. A decline of lake levels from ~150 yr peaks starves perched dunes, which then become forested (Fig. 4C, scene 2). The record of three iterations ofthis or a similar process is present in stacked buried soils at Aral (Fig. 3, site 16); no beach-ridge sequences are present.

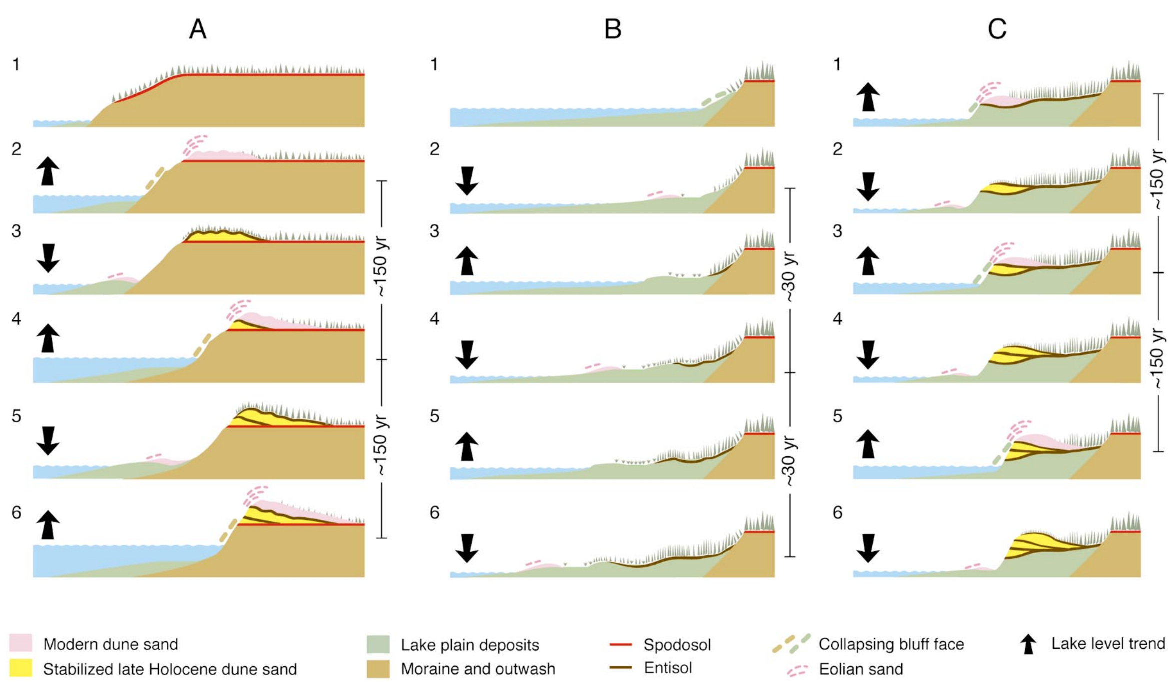

FIG. 4. Mechanisms of sand supply change for various geomorphic surfaces, magnitudes of lake level change, and return periods. (A) Glacial headlands (after Anderton and Loope, 1995). (B) Late Holocene lake plains (~30-yr return period). (C) Truncated late Holocene lake plains (~150-yr return period).

TABLE 1

A Comparison of Processes and Products Implied by the Foredune (Olson, 1958d) and Perched-Dune (Marsh and Marsh, 1987; Anderton and Loope, 1995) Models for Dune Behavior as Observed along the Shore of Lake Michigan

Model:	Foredune	Perched dune
Location, setting of prominent dunes	Southern, southwestern shore; massive accumulation of littoral sand drift during late Holocene	Eastern shore, exposed to wave action in lee of strong effective winds and high fetch; sand starved
Types of dunes produced	Thick foredunes in broad, roughly linear belts	Large perched dunes; blowout dunes, parabolic dunes
Sand source	Beaches	Upper portions of lake-facing bluffs cut into glacial headlands, lake plains, established dunes
Dune building relative to lake level	Dunes build as lake levels fall	Dunes build as lake levels rise
Attitude; orientation of sand source	Near horizontal; parallel to shore	High-angle to near-vertical; variable, irregular
Landscape position	Lakeward of bluff of winter beach[a]	Above, in lee of, bluff of winter beach of truncated lake plains, glacial headlands
Periodicity of dune building	~30 Yr	~150 Yr
Elevation above lake	A few meters	Many meters

[a] Wide beach formed after late fall storms and before development of coastal ice.

Signals of Dune-Building along the Southern and Southwestern vs Eastern Shores of Lake Michigan

How can dominance of a ~150-yr signal in the building of perched dunes along Lake Michigan's eastern shore be reconciled with the apparent dominance of foredune development and the relative rarity of buried soils in dunefields along the Lake's southern and southwestern shores (Olson, 1958d; Fraser *et al.*, 1975, 1990)? For most of the late Holocene, the eastern shore has been continually attacked by wave action driven by consistent southwesterly winds and long fetch and has received insufficient littoral sand drift to protect beach ridges and foredunes formed during low lake phases. Beach-ridge sequences (with attendant thin foredunes) preserve signals of both ~30- and ~150-yr lake-level fluctuation only in protected indentations (e.g., Platte lake plain, Sturgeon Bay embayment; Thompson and Baedke, 1997). The southern and southwestern shores of Lake Michigan, in contrast, have received massive sand drift from both coasts during thousands of years of late Holocene lake-level change (Chrzastowski and Thompson, 1992). These deposits resulted in shore progradation and in the preservation of a beach-ridge record of ~30-yr as well as ~150-yr lake-level change, even along the open lake (Thompson, 1992; Thompson and Baedke, 1997). Large accumulations of sediment along the southern and southwestern shores also probably led to formation of very broad beaches during low lake phases (e.g., the 1940s and 1950s, Bishop, 1994). These broad beaches led to increased landward sand flux and the impressive foredunes observed by Olson (1958d).

CONCLUSIONS

Episodes of late Holocene dune building along Lake Michigan's eastern shore have occurred primarily during high lake stands, separated by one to several centuries. The history of dune-building can be directly related to lake level histories as revealed in beach ridge studies (Thompson and Baedke, 1997, 1999; Baedke and Thompson, 2000; Fig. 2). Processes mediating change in sand supply on ~150-yr return periods are similar across lake-facing bluffs of varying origin but are distinct from those operating on enlarged beaches, during low lake phases. While landward sand flux is influenced by both high and low lake phases (Table 1), landforms produced by low lake phases lie near lake level and are quickly destroyed along the eastern shore. Dunes built during ~150-yr lake-level peaks atop lake-facing bluffs are remote from direct wave action and thus are not readily destroyed. They dominate the modern dune landscape. Despite the commonly held notion that most dunes along Michigan's east coast formed during the postglacial peak in lake level ~5500–5000 cal yr B.P. (the Nipissing transgression; Hough, 1963), our data suggest that most of the modern dune landscape originated later. The apparent contrast in dune-building processes relative to lake level along different portions of Lake Michigan's shore is probably due to differences in each factors as littoral sand supply, winds, and waves (Table 1).

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