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Temporally constrained eolian sand signals and their relationship to climate, Oxbow Lake, Saugatuck, Michigan

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ABSTRACT

Interrelationships among late Holocene climate, the dynamics of coastal dunes and sedimentation in adjacent small lakes along coasts of the upper Great Lakes have been studied for over a decade. Nonetheless, many questions remain as to relationships between climate variability and dune activity. The study site is Oxbow Lake, near Saugatuck, Michigan, which formed as an artificial cutoff of the Kalamazoo River in 1906. Stratigraphic control of the infilled western end of the lake is from ground penetrating radar, and lake sediment from Livingstone and Glew cores with age control from $^{210}Pb/^{137}Cs/^{7}Be$ analysis. The climate data used included Lake Michigan water levels and temperature, precipitation, drought and evaporation data from a weather station 30 km to the south and wind data from buoys on Lake Michigan. Episodic peaks of eolian sand in the lake sediment are interpreted to be sourced from adjacent small parabolic dunes along the shoreline and from a foredune west of the lake. Linear regressions of the climate data and weight percent sand resulted in a variety of correlations, some conflicting, and with uncertain meanings. It was found through visual correlation that peaks in sand correspond with both peaks in water levels of Lake Michigan and the winter Palmer drought severity index. The implications of this research are that dune activity is linked to periods of wet conditions and storminess, contrary to typical eolian environments, but consistent with other studies in temperate coastal dunes along the Great Lakes. Results can be used as a modern analogue for coastal dune activity during times of high lake level.

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INTRODUCTION

Coastal sand dunes and adjacent lee-side lakes along the Lake Michigan coast are studied for their interrelated records of past climates. Coastal dune activity has been associated with both high and low stands of the upper Great Lakes (Anderton and Loope, 1995; Loope and Arbogast, 2000; Fisher and Loope, 2005; Fisher et al., 2007; Timmons et al., 2007; Hansen et al., 2010; Fisher et al., 2012, Argyilan et al., this volume; Kilibarda et al., this volume; Rawling and Hanson, this volume). One approach to inferring past climate is assessment of eolian sand within lake and bog sediments as a proxy record of airfall or saltation processes that occurred when dunes were active (e.g., Keen and Shane, 1990; Björck and Clemmensen, 2004; de Jong et al., 2006; Hansen et al., 2009; DeVries-Zimmerman et al., this volume; Hanes et al., this volume). One study has estimated the volume and extent of eolian sand present in snow and ice on a lake in contact with active dunes (Fisher et al., 2012), but we are unaware of any studies attempting to correlate climate data with eolian sand data from lake deposits. While the presence of eolian sand in lake sediments has been used to infer past dune activity, the initial conditions that trigger that activity remain uncertain. Time series analyses of eolian sand in cores from a variety of lakes appears to record quasiperiodic climate cycles analogous to those reported in beach ridge sediments and in other natural archives from the same environment (Fisher et al., 2012; Hanes et al., this volume). However, similar quasiperiodic cycles do not necessarily link increased eolian activity with low or high lake levels or their transitions. Some studies have proposed that high lake levels undermined coastal bluffs thereby disturbing coastal vegetation and liberating sand to nourish perched dunes (Anderton and Loope, 1995; Loope and Arbogast, 2000; Loope et al., 2004). However, a detailed analysis of eolian sand in lake sediment in the lee of a suite of coastal parabolic dunes produced equivocal results as to the linkage of dune activity with lake level (Timmons et al., 2007).

In this study, we examine a series of short sediment cores from a recently abandoned river mouth immediately in the lee of recently emplaced foredunes and adjacent, small parabolic dunes. Historical documentation of closure of the river mouth constrains the sedimentary record and lake sediment age. The purpose is to compare a young lake's sediment record with levels of Lake Michigan and with available meteorological data to test the hypothesis that eolian sand peaks in Oxbow Lake will correlate with trends in climate including individual measures (e.g., precipitation) and synthesizing measures (e.g., Lake Michigan water levels and a drought index). This study provides a modern analogue for comparison with similar work done on older lake sediments along this section of the Lake Michigan coast.

STUDY AREA

Oxbow Lake formed in the abandoned channel of the Kalamazoo River at Saugatuck, Michigan, when the river was artificially diverted~1 km to the north of its natural mouth (Fig. 1). Since 1906 Oxbow Lake has been infilling at both ends. At its western end, the focus of this study, the mouth of the abandoned channel was infilled by littoral sediment from Lake Michigan. Foredunes eventually formed atop the infill, between the west end of the Oxbow Lake and the modern beach (Fig. 2A). Early maps show that the Lake Michigan shoreline had prograded ~130 m since the early 1800s. Wooden jetties, constructed in 1895 are still in place along the Lake Michigan beach and within Oxbow Lake. Maps from 1867 and 1895 indicate small dunes were present along the northern shore of Oxbow Lake (Fig. 2C). The 1890 photograph (Fig. 2B) of the river mouth shows a flat plain from west of the lighthouse to the Lake Michigan

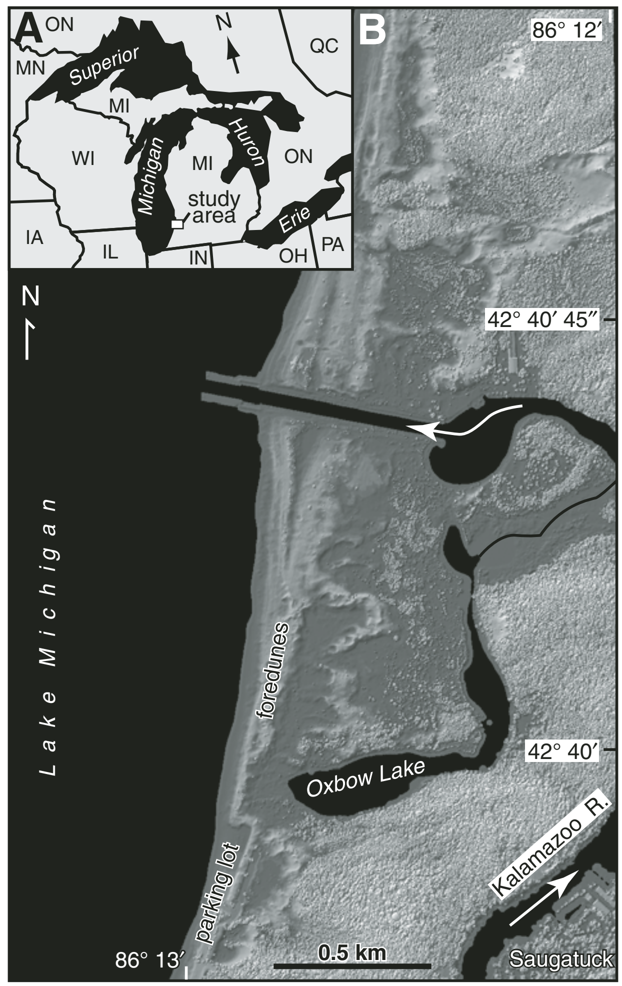


Figure 1. Study area at Saugatuk, Michigan (MI). (A) Study area is along the west coast of Michigan. (B) Digital elevation model based on LiDAR from USACE National coastal mapping program topobathy LiDAR. Rough texture is from trees, and lighter shades correspond to higher elevation in non-treed areas. IA—Iowa; IL—Illinois; IN—Indiana; MN—Minnesota; OH—Ohio; ON—Ontario; PA—Pennsylvania; QC—Quebec; WI—Wisconsin.

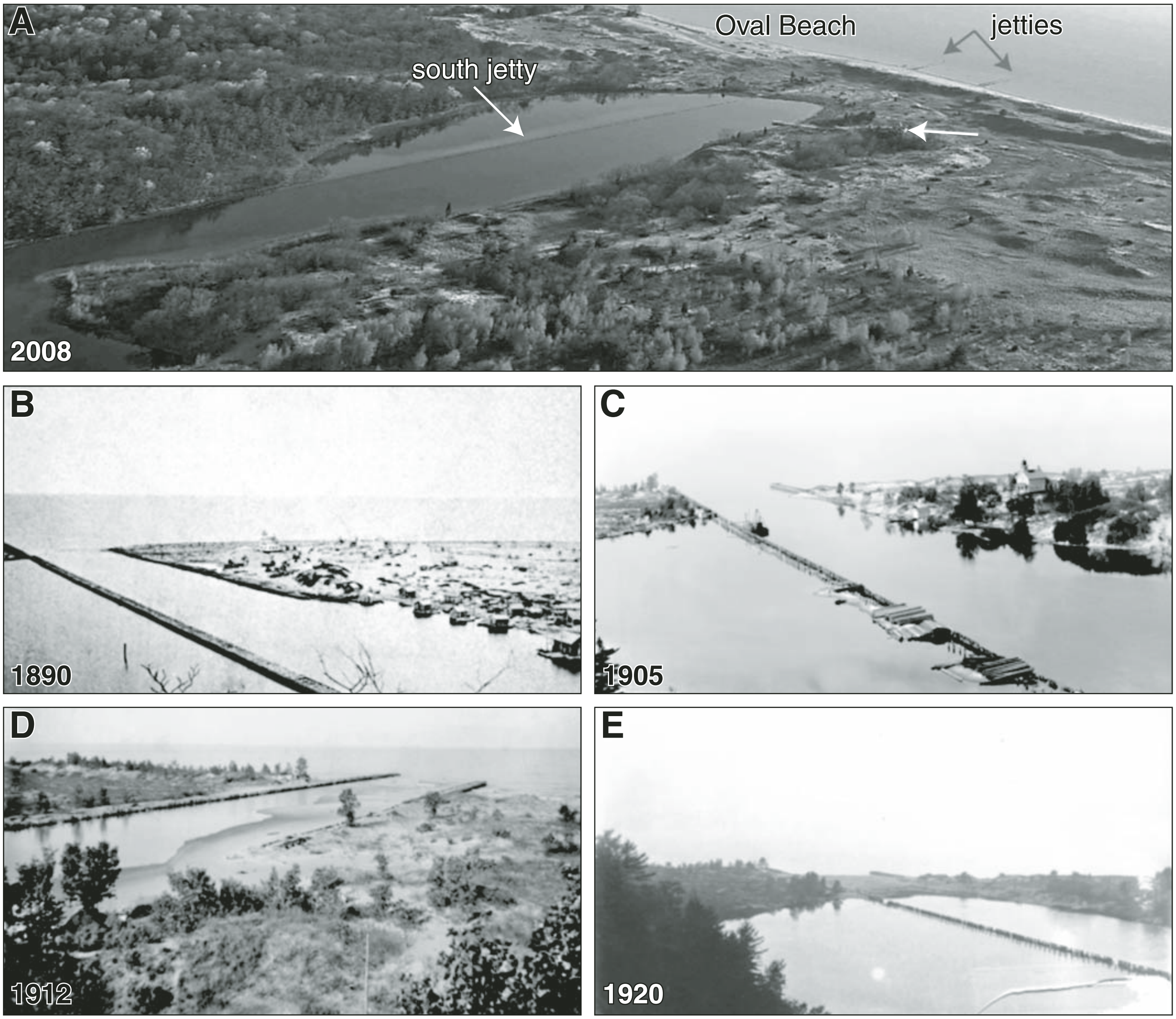


Figure 2. The study area revealed in a modern oblique aerial photograph and older (B–E) photographs courtesy of Norm Dean and the Saugatuck Douglas Historical Society.

shoreline, indicating that the 10-m-high foredunes have all formed since then. By 1906, the artificial channel was completed, and Oxbow Lake began to form. By 1912 (Fig. 2D), much of the river mouth had been filled by sand by littoral transport, primarily from the north. A 1920 photograph (Fig. 2E) shows the mouth of the former river channel plugged with sand and incipient foredunes developing further north. A 1938 aerial photograph showed initial foredune development atop the abandoned channel. Topographic maps, aerial photographs and satellite imagery of various vintages show that, during periods of flooding along the Kalamazoo River, water periodically entered Oxbow Lake and deposited sediment. Along the north and south sides of the modern Kalamazoo River jetties, large fillets of sand have formed (USACE, undated), protecting the foredunes from coastal erosion.

Stable and active dunes are distributed along the north side of the east–west trend of Oxbow Lake. The foredune ridge separating Oxbow Lake from Lake Michigan averages ~10 m high, and broadens northwards toward the artificial channel (Fig. 1). Both vegetated and non-vegetated (blow out) dunes exist in this area, as do swales in which water accumulates seasonally. During wintertime, eolian sand was observed interbedded with snowdrifts in the lee of the foredunes. The water level in Oxbow Lake is approximately the same as in Lake Michigan.

METHODOLOGY

Sediment Cores

One modified Livingstone core of two-inch diameter and a transect of six Glew cores at ~100 m intervals were collected in June 2011 along the southern arm of Oxbow Lake in water depths that varied between 2 and 3 m (Table 1). The coring transect was located in the former river channel between the wooden jetties (Fig. 3). Coring penetrated through lake sediment into coarser pebbly sand. A modified Glew corer (Glew, 1991) was used from a canoe raft to collect a series of short cores of lake sediment. After removal of the core from the water, all but 1 cm of water was siphoned from the core barrel. To preserve the sediment-water interface, 200 mg of Zorbitrol® (sodium polyacrylate) was added to the remaining water to create a gelatinous seal (Tomkins et al., 2008). Of the six Glew cores collected, only core G3 was sectioned into 1-cm-thick slabs in the field to be used for age dating, and the remainder returned to the lab for further analysis. Cores and samples were kept refrigerated at 4 °C for a few days before sectioning.

Age Model

An age model for sediment deposition was developed using the ^{210}Pb and ^{137}Cs age-dating protocol of Gottgens et al. (1999). After determining bulk density at 1 cm intervals, 2 cm^3 of dried ground sample was assessed for age. The activity of ^{210}Pb in each sediment layer declines with its age due to radioactive decay. Because of the short half-life (22.3 yr) of ^{210}Pb, this technique is restricted to sediments deposited within the past 120–150 years. The ^{210}Pb activity in sediments is both supported by continued decay of parent radionuclides contained in the sediments and augmented by fallout-^{210}Pb from emanation of ^{222}Rn, one of the daughters in the uranium-lead decay series. Subtracting the level of supported ^{210}Pb from the total ^{210}Pb activity, yields the fallout or "unsupported" activity upon which age-depth relationships are based. We used direct low-background gamma spectroscopy in a germanium well-detector to measure activities of supported and unsupported ^{210}Pb independently and simultaneously (Gottgens et al., 1999) and applied the results to the Constant Rate of Supply model (Appleby and Oldfield, 1978) to calculate sedimentary chronology. We used ^{137}Cs as an ancillary age-marker. This isotope, which does not occur naturally, may be correlated with historical levels of atmospheric nuclear weapons testing. It should not be present in sediments older than 1952 ± 2 years (McCall et al., 1984) and should peak around 1964. We also used ^{7}Be activity to ascertain whether we captured the most recent sediments. The impact of random error, caused by statistical fluctuations in the radiation emitted in nuclear decay, on ^{210}Pb-derived dates was estimated using Monte Carlo simulation (Gottgens et al., 1999).

TABLE 1. SEDIMENT CORE LOCATIONS

Core	Core type	Date	UTM coordinates	
OL-G1	Glew	6-30-11	16T 0564570m E	4723840m N
OL-G2	Glew	6-30-11	16T 0564580m E	4724041m N
OL-G3	Glew	6-30-11	16T 0564608m E	4724050m N
OL-G3-D	Glew	6-30-11	16T 0564608m E	4724050m N
OL-G4	Glew	6-30-11	16T 0564785m E	4724060m N
OL-G5	Glew	6-30-11	16T 0564925m E	4724096m N
OL-G6	Glew	6-30-11	16T 0565075m E	4724134m N
OL-L1-1	Livingstone	2-10-11	16T 0564576m E	4724040m N

Organic Matter and Particle Size Analyses

In order to estimate organic matter content, loss on ignition (LOI) was calculated at 1 cm intervals for the Glew cores following procedures outlined in Heiri et al. (2001). Organic matter was burned off at 550 °C for 4 h. Samples for particle size analysis were prepared in 50 ml plastic centrifuge tubes with 1–1.5 cc of sample. A 30% solution of hydrogen peroxide was added to remove organic material and the dispersant, sodium hexametaphosphate was added to the samples, stirred and left overnight before measurement using a Mastersizer 2000 diffraction unit.

Percent Sand by Weight

Percent sand by weight was determined by first using the LOI method after a sample was oven dried for 24 h at 100 °C and then further treatment. Once the organic matter was burned off, carbonate, including shells and shell fragments, were removed using 10% concentration hydrogen chloride (HCl) added slowly as needed until the reaction ceased. After drying and weighing, the sediment was wet sieved to remove sediment finer than 63 µm. Examination under a microscope after sieving did not reveal sand-size sediment agglomerates as a byproduct of heating. Percent sand was calculated using total dry sediment weight and final dry sediment weight.

Ground-Penetrating Radar (GPR)

GPR profiles across the former river mouth were collected with a Pulse Echo system using 1000 V transmitter and 100 MHz antennae at 1 m spacing. Antennae were aligned parallel to the

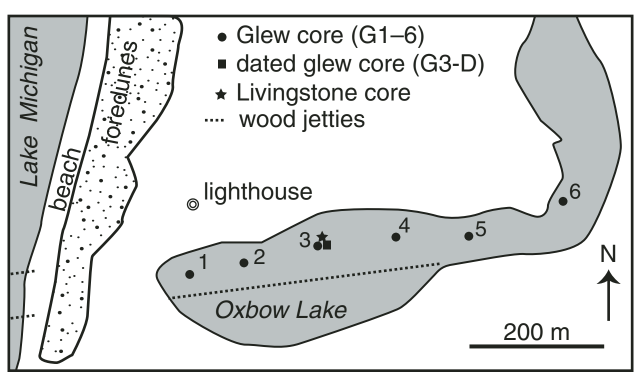


Figure 3. West arm of Oxbow Lake with core sample locations.

transect, moved in 0.25 m steps; data were collected every 2 seconds. A laser leveler was used to make topographic corrections. Elevations were determined relative to a lake level of 176.3 m asl for the day the GPR data were collected.

Climate Data

The climate data spanned the time between 1929 and 2011, from South Haven, Michigan, 30 km south of Oxbow Lake. Data included annual and seasonal Palmer drought severity index (PDSI—sector 8 of Michigan), evaporation, average annual and seasonal temperatures and precipitation data. Annual and seasonal wind data were from offshore buoys (stations 94055, 94426) on Lake Michigan, 12 and 5.5 km, southwest and west of Oxbow Lake, respectively. Average annual lake levels between 1929 and 2011 was sourced from the Detroit Office Web site of the United States Army Corps of Engineers. Climate data was analyzed using scattergrams and correlations (r). Coefficients of determination (R^2) were calculated if the p value was <0.05. A 95% confidence interval was used to determine statistical significance and it was recognized that the choice of 95% is somewhat arbitrary. Some of the climate data were also analyzed by using a wiggle matching approach of plotted time series of climate data and weight percentage sand.

RESULTS

Ground-Penetrating Radar (GPR)

Radar reflections from two GPR transects are shown on Figure 4. Profile SAUG-01 shows a 245 m long south–north profile and SAUG-03 shows a 112 m long west–east profile. The profiles intersect at ~80 m distance on the west–east transect, and at 130 m on the south–north transect. In the SAUG-01 profile, the reflections become faint and disappear between 10 and 12 m depth. The penetration depth in SAUG-03 is less. In both transects there is a lower transparent facies, here referred to as older stratigraphy (facies 1). The top of facies 1 in the SAUG-01 transect has continuous to discontinuous wavy reflections. The top of the facies is marked by a strong reflection forming the base of facies 2. Facies 2 displays numerous inclined reflectors, dipping north and south as well as a lens-shaped facies between 120 and 170 m that lies within the former river channel. In the west–east profile, reflections of facies 2 are discontinuous and wavy. Many reflections dip to the east. Facies 3 is 2–3 m thick; continuous to semi-continuous, mostly flat-lying reflections, often parallel with the land surface.

Facies 1 is interpreted as an older stratigraphy into which the last position of the Kalamazoo River has incised. The strong radar signal indicates sandy material. Since the radar profile was collected close to the early 1800s shoreline, facies 1 is interpreted as a combination of littoral sediment and fluvial sediment derived from the migration of the Kalamazoo River along the coast. A county map of surficial geology interprets the study site as eolian sand overlying sandy glacial lake deposits (Gephart and Larson, 1982). These deposits lie on the south side of a buried valley wherein ~75 m of drift overlie bedrock (Forstat, 1982). Facies 2 is interpreted as a series of channel fill sands. The extent of facies 2 in the south–north transect represents the width of the former Kalamazoo River. The reflections dipping northwards between 0 and 110 m therefore likely represent packages of littoral sand infilling the channel from the south. The packages of sand within the channel bottom dipping southward are likely the sand bodies evident on the 1912 photograph (Fig. 2D) which appear to be infilling the channel with littoral transport and deposition from the north. The same sediments on the west–east transect indicate the sand packages were moving as large bedforms from west to east into Oxbow Lake. Uppermost facies 3 is interpreted as a composite of eolian deposits, supported by the eolian deposits on the surface (Fig. 4D).

Lake Stratigraphy

The general stratigraphy of all cores consists of sand overlain by organic-rich, silty sand. From the Livingstone and Glew cores (G1–G5), the stratigraphy is divided into six sedimentary lithofacies (Fig. 5). Glew core 6 is shown because the sand at the sediment water interface reveals that sand transport is ongoing along the shoreline. Particle size analysis, organic contents and weight percentage sand results are shown on Figure 6.

Lithofacies A is massive, light olive brown (2.5Y 5/3) pebbly sand found only at depth in the Livingstone core. The lithofacies consists of medium and coarse sand, and includes random clusters of very-fine pebbles. It contains more mafic sand grains than the other sandy lithofacies. Lithofacies A is the coarsest sedimentary lithofacies and its location at the greatest depth suggests deposition as either alluvium from the former Kalamazoo River, or as a littoral sand (GPR unit 2) deposited along Lake Michigan as the original river mouth closed after 1906. This lithofacies would be equivalent to GPR facies 1 if it is older sand, or equivalent to GPR facies 2 if it is littoral sediment deposited after 1906.

Lithofacies B is organic-rich, light olive brown (2.5Y 5/3) laminated sand, 7–13 cm thick, with an abrupt lower contact. Particle size analysis (15% coarse, 15% medium, 30% fine and 40% very-fine sand) reflects laminated coarse and finer sand interspersed with cm-thick laminated dark, grayish brown (2.5 Y 4/1) organic material composed mostly of wood chips and fragments. The sorted laminated sediment indicates an environment of varying energy, wherein pulses of mineral sedimentation in the lake may have alternated with deposition of less dense, organic material at the end of each depositional event.

Lithofacies C is greyish brown (2.5Y 5/2) silty sand found at the base of all Glew cores except G4 (Figs. 5, 6). It is also found as a thin lithofacies at 30 cm depth in the Livingstone core (Fig. 5). It is faintly laminated, and like lithofacies B, is interpreted as a record of sediment pulses entering the lake.

Lithofacies D and E are clean and muddy sand that, respectively sharply overlie lithofacies B and C. Lithofacies D is grayish brown (2.5 Y 5/2) while lithofacies E is very dark gray (2.5 Y 3/1)

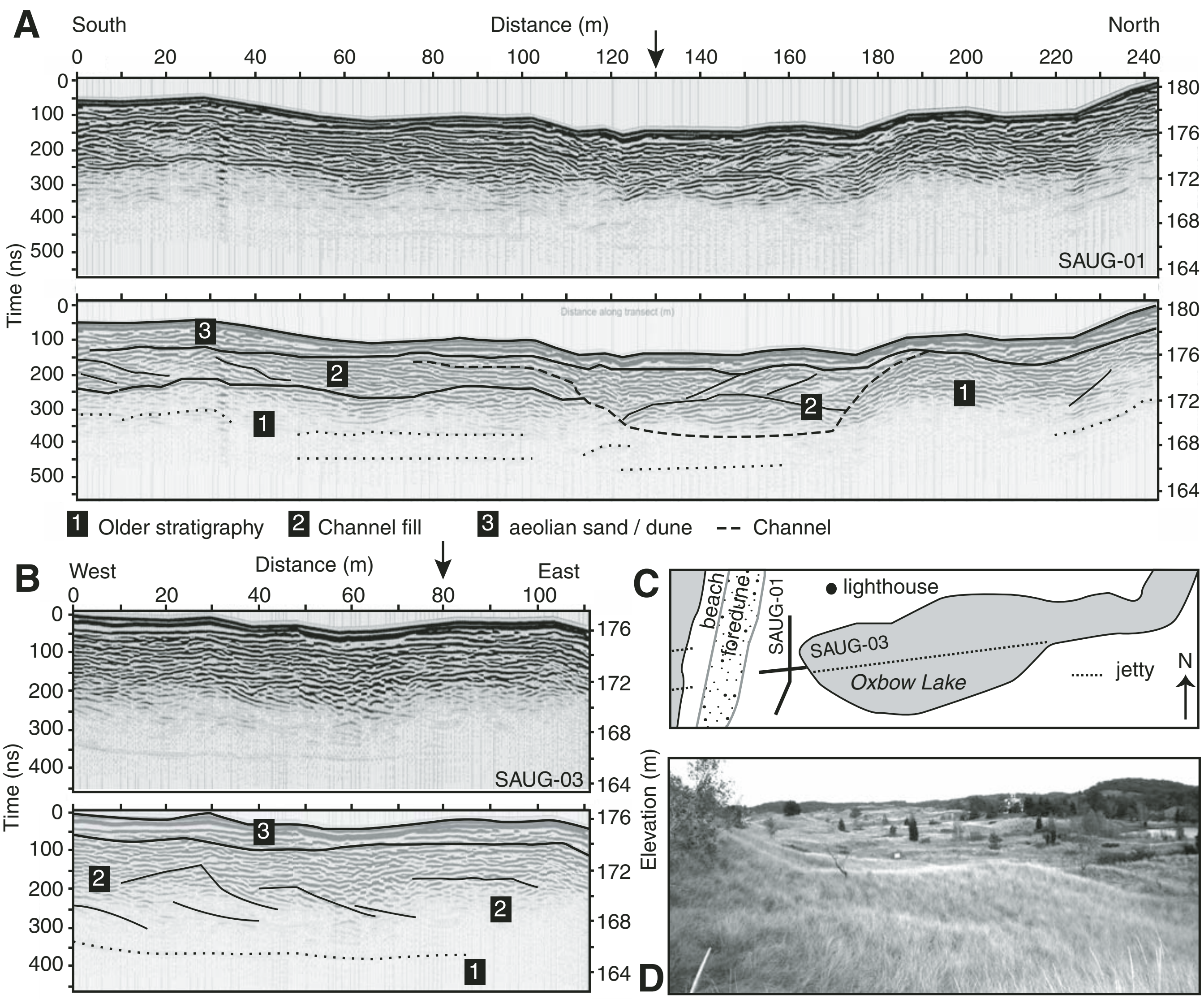


Figure 4. Ground penetrating radar (GPR) profiles (A, B) from two transects collected between the foredune and west end of Oxbow Lake (C). (D) View from the top of the foredunes looking to the northeast toward the lighthouse (arrow) across the area of the GPR transects. The lower panel in both radar transects A and B, has major reflections highlighted with black lines, and weak reflections in the deeper, and older stratigraphy are represented by a dotted line. See text for detailed interpretations of the different numbered GPR units.

and dark grayish brown (2.5Y 4/2). Lithofacies E contains less than 20% mud. Medium sand is the most common particle size in both lithofacies, (30%–70%). Fine sand ranges between 20% and 30% and coarse sand, between 5% and 30%. The two cores that are farthest east have the most coarse sand (20%–30%). Structure in the Livingstone core is massive, and is assumed to be massive in the Glew cores, but because the Glew cores were sectioned at 1 cm intervals, structure could not be assessed. The muddy sand includes diffuse organic matter, thin beds of wood fragments, and gastropods (Fig. 5). The fragments of wood likely represent retransport of cut wood from former buildings or industrial areas from along Oxbow Lake shorelines and the Kalamazoo River that once hosted small towns including a sawmill. The presence of the mud within this lithofacies suggests the sand is being deposited in a lake environment with suspended sediment sourced from a flooded Kalamazoo River. The clean sand of lithofacies D, shown as a massive deposit in the Livingstone core, reflects a higher energy environment, however, because it overlies lithofacies B silty sand it may reflect a single depositional event in which the entire lithofacies was deposited at once in the lake. If this is the case, the source of the sand is expected to be from either the west end of the lake as a washover event from Lake Michigan equivalent to GPR facies 2, or as input of eolian sediment from around the lake, equivalent to GPR facies 3. The lithofacies E muddy sand is generally a thicker lithofacies and likely represents more time as recorded by the gastropods and organic matter.

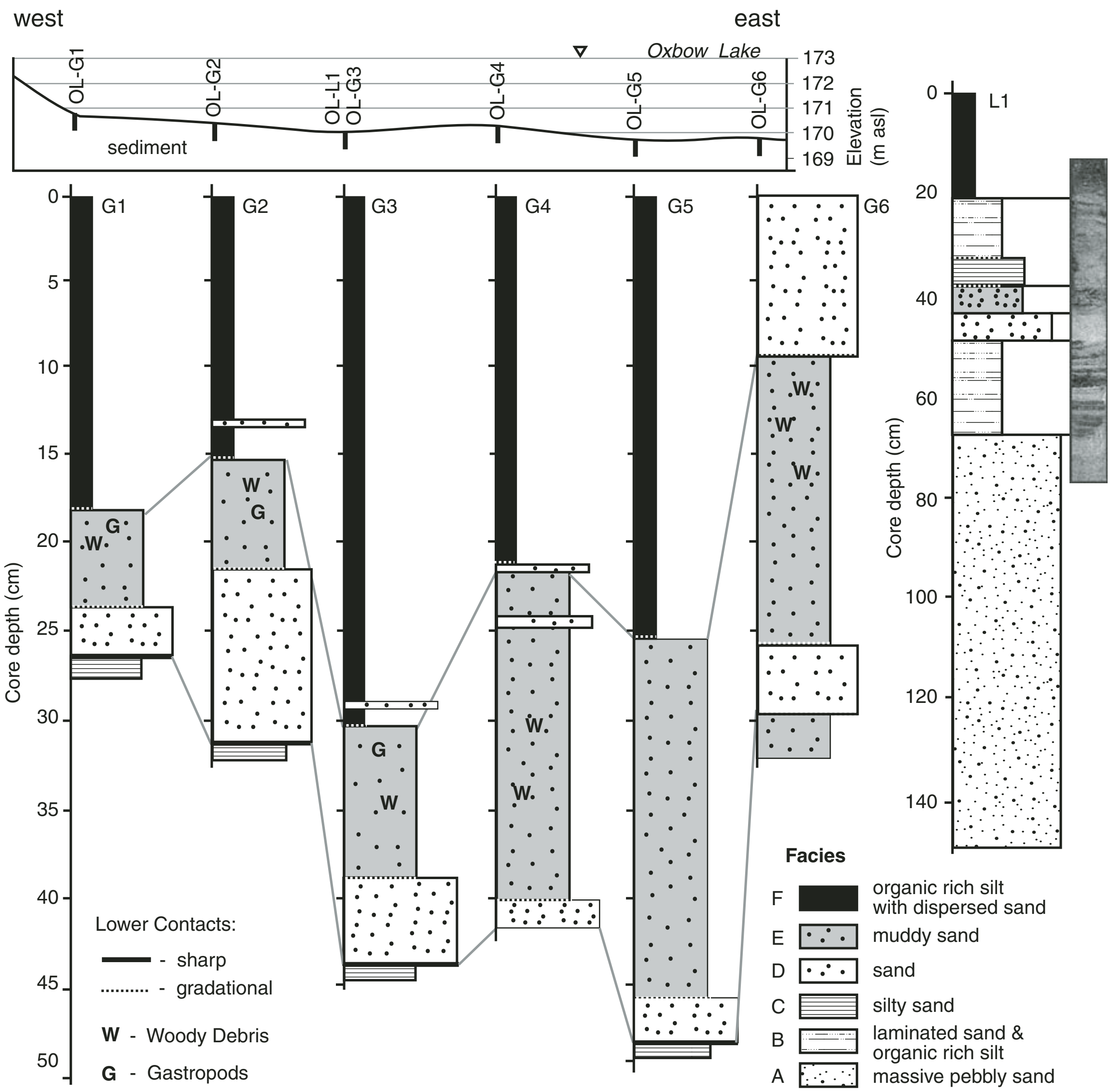


Figure 5. Lithostratigraphic logs of sediment lithofacies and Oxbow Lake water depths.

Lithofacies F is a black (10YR 2/1), organic-rich silt with dispersed sand; a sandy sapropel according to Schnurrenberger et al. (2003). This lithofacies is found at the top of cores G1–5. LOI values steadily increase up core (Fig. 6); the two westernmost cores contain 25%–30% organic matter and the remaining three cores contain less than10% organic matter, but which contain more silt. The clay composition is relatively constant at ~5% in all the cores. Silt content increases up core approximately doubling at the expense of the sand, which decreases up core (Fig. 6). In cores G1–5 the percentage of coarse and medium sand decreases up-core. In all cores but G3, the percentage of fine sand is uniform whereas in cores G1 and 2 the very-fine sand content increased, and remained constant in cores G3–5. In general the amount of sand decreased up-core and became finer. This lithofacies is interpreted as lacustrine sediment deposited after Oxbow Lake had become stable. The variability in sand (Fig. 6) records episodic input of finer sand into the system.

Dating

The results of the gamma counts of ^{210}Pb, ^{137}Cs and ^{7}Be at centimeter intervals in core G3 are shown in Figure 7. From these data, a curve of sedimentation rate was developed to assign ages to core G3 using known gamma markers (e.g., the 1964 peak from atmospheric nuclear weapon testing recorded by ^{137}Cs at 25-cm depth). The strong ^{7}Be signal primarily restricted to the top 5 cm (or 3 years) of the core indicates that the sediment/water interface was adequately recovered. The weak ^{7}Be signal at 19 cm depth is best explained as contamination from younger sediment. Sediments dated to 10 years of age had an error with

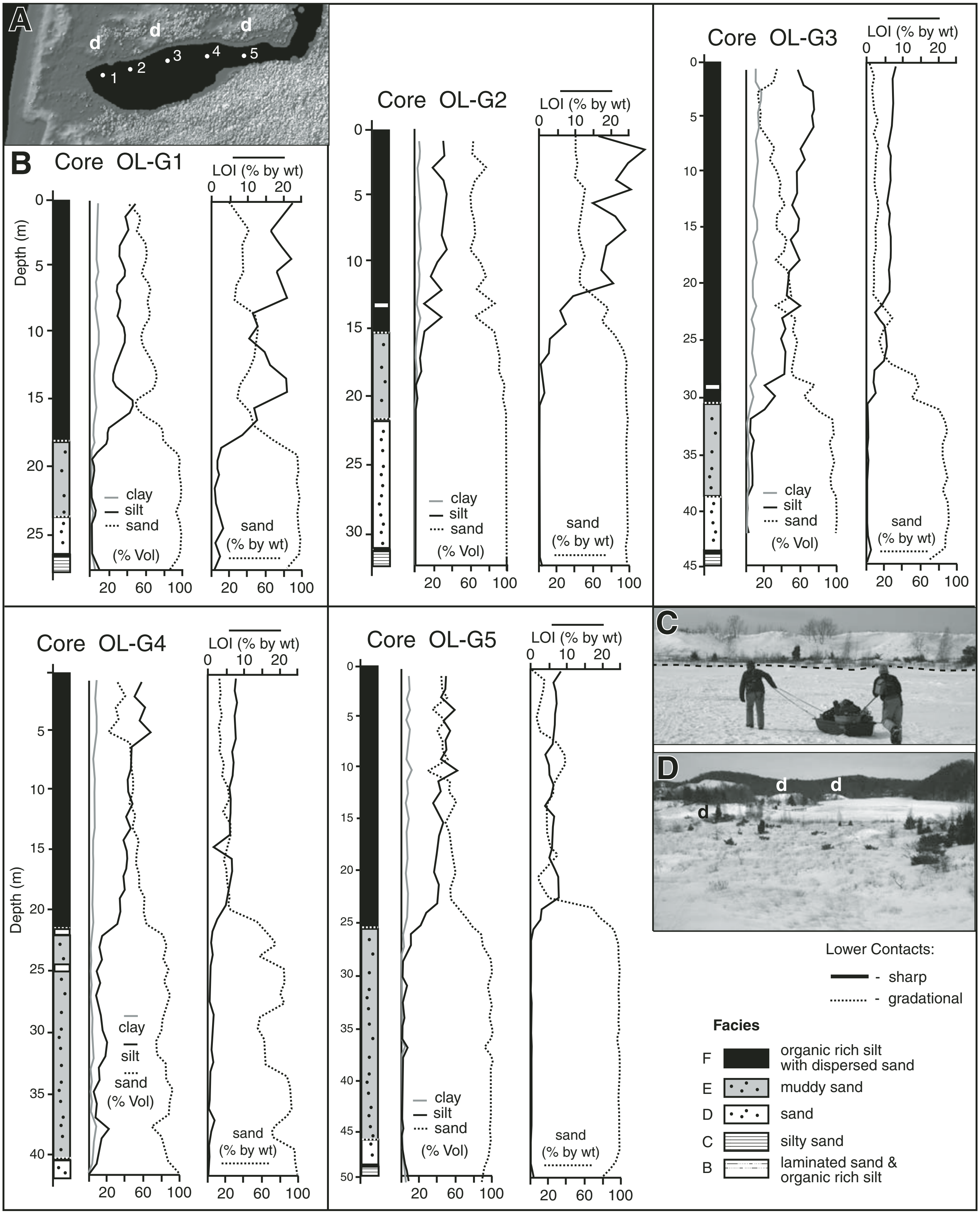


Figure 6. (A) Coring sites for core data shown in (B). Lowercase d indicates locations of small active dunes along the north side of the lake. (B) Analytical data from the five Glew cores. The first column of particle size data was determined using a Mastersizer 2000 particle size analyzer, and the second column shows sand percent as determined by the loss on ignition (LOI) method. (C) View from west end of Oxbow Lake looking west toward the 10-m-high foredunes on the horizon. (D) View from the top of the foredune looking east toward Oxbow Lake. Note lighthouse in upper left of photograph; lowercase d identifies the active dunes also shown on (A).

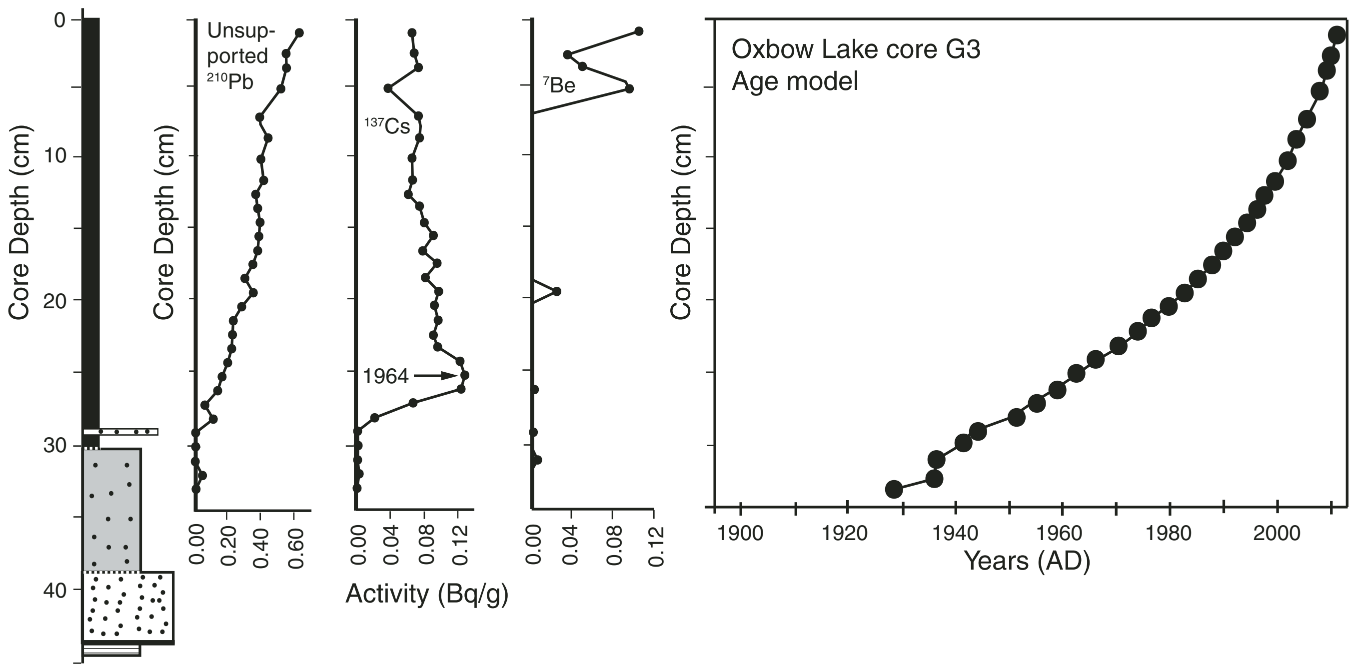


Figure 7. Age dating results and age model for core G3.

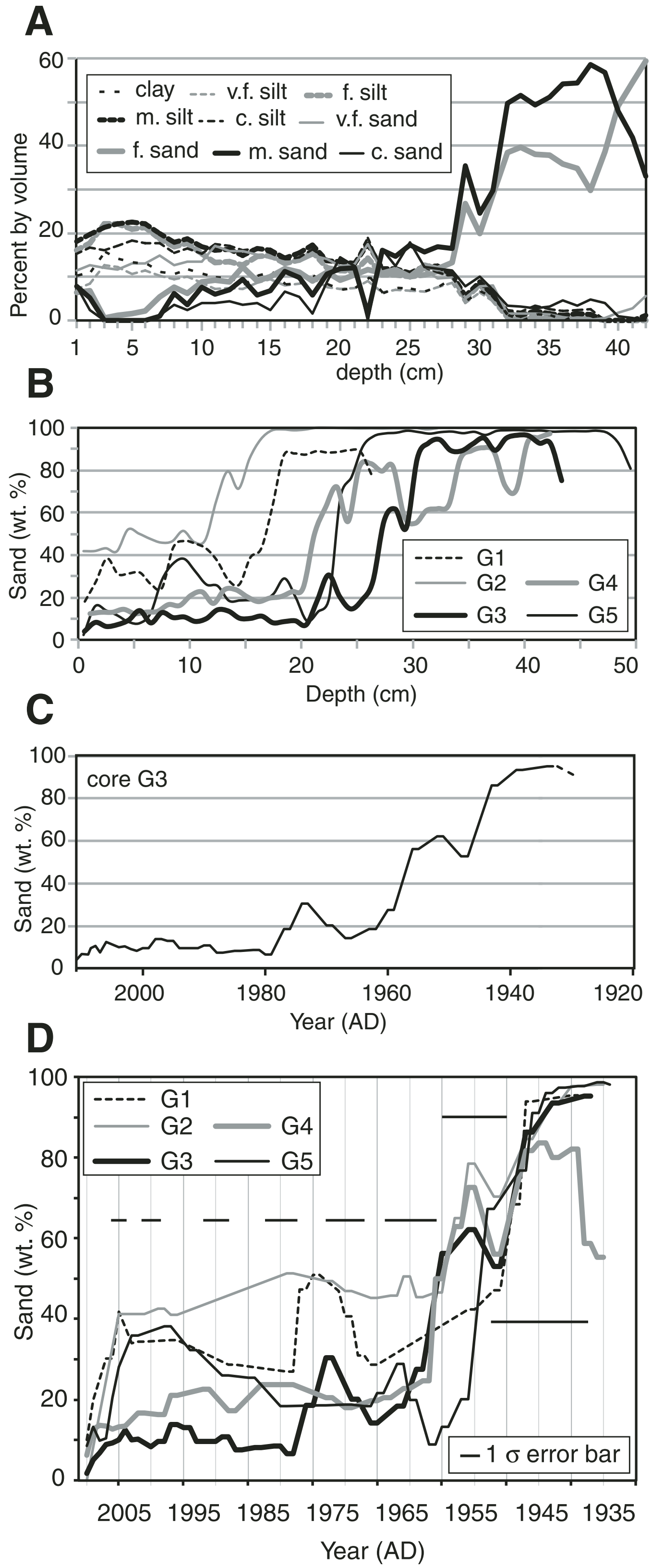
an approximate 95% confidence interval of ± 1.5 years, 30-year-old sediments ± 2.5 years, 60-year-old sediments ± 5 years and sediments older than 100 years ± 20 years.

Sand through Time

The particle size distribution of sand is shown for core G3 (Fig. 8A) to illustrate the changes in particle size in the core. A plot of the sand in each of the five Glew cores is shown in Figure 8B. The basal section of each core is characterized by high sand percentages. Sand percentage drops to lower values in lithofacies F. There are episodic peaks in sand throughout the core. Of particular interest is the sand in lithofacies F. Using the age model in Figure 7, ages can be assigned to the core G3 sand data (Fig. 8C). In core G3 the drop in sand percent occurred over a period of 40 years; two periods of greater sand deposition occur during the overall decline. While the age model cannot be used to directly date the sand in the other cores, three approaches were used to estimate the sand ages to assess the timing of sand delivery during formation of lithofacies F across the southern end of Oxbow Lake. The first approach was to assume a constant sedimentation rate for the individual cores. Sporadic influx of sand cannot be accounted for in this technique, and a graphical plot of this data did not result in any alignment of sand peaks. Next, a wiggle-matching approach was taken to align sand peaks, and while it resulted in good alignment of sand peaks it is considered too subjective, and renders the resulting data unusable to assess random distribution of the sand in lithofacies F through time. Instead we chose to assume that deposition of organic matter in the cores was constant through time and used the variability in the LOI data (Fig. 6) to assign ages from core G3 to the other cores. This method has the advantage of using a separate proxy to correlate the sand data, has the simplest and most reasonable assumption, and the longest reliable time span. A possible problem is that cores G1 and G2 have approximately three times the organic content as the other cores. The resulting age assignments are shown in Figure 8D along with the error bars. All the cores show a decrease in sand from 1940 to 1945; cores G2–4 show an increase that peaked in 1951 and then dropped to relatively constant levels by 1956. Sand percent in all cores drops off beginning in 2005. Closer examination of the sand peaks in lithofacies F shows aligned peaks (stippled gray columns in Fig. 8D). After 1979, sand peaks are less obvious, perhaps a reflection of decreasing compaction up core. There is a general rise in sand percentage in cores G1, G2, and G5 between 1999 and 2005; sand percentages in G3 and G4 stay relatively low with minor fluctuations. Peaks in sand are not aligned across all cores. This indicates spatial variability across the basins, as well as episodic deposition at individual locations within the basin.

Climate Variables and Weight Percentage Sand

Summaries of significant (p = <0.05), and nearly significant (p = 0.051–0.099) results are listed in Table 2 and some of the results presented graphically (Fig. 9). Beyond individual climate variables, synthesizing indexes such as PDSI and Lake Michigan lake level were also used to test hypotheses reached by others that increased storminess and higher lake levels correspond with increased transport of sand as represented by coastal dune activity. Significant correlations were not observed between the



temperature data and weight percentage sand. From the evaporation data, only a marginal negative correlation was found between winter average evaporation in core G3 ($r = -0.39$, $p = 0.05$).

In two of the five cores annual average precipitation negatively correlates with weight percentage sand (G2: $r = -0.51$, $p = 0.022$; G3: $r = -0.54$, $p = 0.002$). There was no statistically significant correlation for the other three cores (Fig. 9A). When seasonal precipitation was examined, a correlation was observed between weight percentage sand and summer average precipitation in core G5 ($r = 0.51$, $p = 0.006$) and fall average precipitation in core G3 ($r = -0.37$, $p = 0.041$).

Only the wind data from buoy 94055 resulted in statistically significant correlations with weight percentage sand. Cumulative annual hours wind >7m/sec^{-1} in core G5 correlated with weight percentage sand ($r = 0.61$, $p = 0.048$), but in core G3, there is a negative correlation ($r = -0.56$, $p = 0.029$) (Fig. 8B). A negative correlation in which more sand is associated with less wind was not expected. Similarly for core G4, the cumulative annual hours wind >10m/sec^{-1} correlation was also negative ($r = -0.65$, $p = 0.024$) (Fig. 8C). A statistically significant correlation was not found when the ratio of cumulative fall and winter hours wind >7m/sec^{-1} were plotted against weight percentage sand (Table 2), although the resulting p values were similar to other wind data results. The ratio of cumulative fall and winter hours to cumulative annual hours >7m/sec^{-1} correlated with weight percentage sand in two cores (Fig. 8D), but one is positive (G3: $r = 0.61$, $p = 0.016$) and the other negative (G5: $r = -0.66$, $p = 0.027$). It should also be noted that the overlap wind data recorded at two adjacent buoys is quite different (Figs. 10B, 10C) which calls into question the validity of the wind data used in this study. A much stronger positive correlation would be expected between wind strength and weight percent sand from anemometer measurements at the field site.

A statistically significant correlation was not observed between annual average lake level of Lake Michigan and weight percentage sand. The highest correlation observed was from core G3 ($p = 0.43$) (Fig. 8A, Table 2). Annual offsets of the lake-level data by up to three years only resulted in negative and weaker results. Annual average PDSI correlated with weight percentage sand in core G5 ($r = -0.38$, $p = 0.042$) (Fig. 8F), but not in the other cores.

A graphic comparison of the sand signal with winter PDSI, average annual lake level, and wind data is shown in Figure 10.

Figure 8. Figure 8. (A) Particle size data for core G3. Note that the decrease in coarse and medium sand is reflected by increase in finer sediment (clay and silt) to indicate a relatively constant supply of mud to the lake through time, but with episodic variations in sand sizes in the upper 28 cm. (B) Weight percent sand from Glew cores 1–5. Note all cores show a similar trend of high values followed by a drop to 50% or less. (C) Age model assigned to sand percent data from core G3. (D) Plot of sand from all five cores with error bars. Ages assigned to the other cores assuming a constant accumulation of organic material in all cores through time.

TABLE 2. LIST OF CLIMATE VARIABLES THAT SIGNIFICANTLY (95% CI) OR VERY NEARLY SIGNIFICANTLY CORRELATE TO WEIGHT PERCENTAGE SAND THROUGH TIME IN LITHOFACIES F

Climate variable	Core*	r	R^2	p value	Buoy
Annual average precipitation	**G2**	–0.51	0.26	0.022	N.A.
	G3	–0.54	0.29	0.002	N.A.
	G4	–0.35		0.059	N.A.
	G5	–0.34		0.079	N.A.
Summer average precipitation	G5	–0.51	0.26	0.006	N.A.
Fall average precipitation	G2	–0.40		0.077	N.A.
	G3	–0.37	0.14	0.041	N.A.
Annual average evaporation	G3	–0.34		0.092	N.A.
Summer average evaporation	G3	–0.36		0.069	N.A.
Winter average evaporation	G3	–0.39	0.15	0.050	N.A.
Annual average PDSI	**G5**	–0.38	0.14	0.042	N.A.
Cumulative annual hours >7m/s	**G3**	–0.56	0.32	0.029	94405
	G5	0.61	0.37	0.048	94405
Cumulative annual hours >10m/s	G3	–0.51		0.052	94405
	G4	–0.65	0.42	0.024	94405
Cumulative annual hours >15m/s	G3	–0.49		0.067	94405
	G4	–0.51		0.091	94405
Fall/winter ratio	G3	–0.45		0.094	94405
	G4	–0.56		0.056	94405
Ratio	**G3**	0.61	0.37	0.016	94405
	G5	–0.66	0.44	0.027	94405

Note: PDSI—Palmer drought severity index.
*Bold signifies data plotted in Figure 9.

Stippled gray columns indicate where sand peaks are aligned and, or some cores record an increase in sand. All of the aligned sand peaks correspond with both positive (wetter) winter PDSI values and rising or higher lake levels. This alignment suggests a possible causal relationship that is episodic and corresponds to periods of stormier conditions. In Figures 10E and 10F, wind data from two Lake Michigan buoys southwest and west of the study area record wind velocities at different threshold values. Note that during the overlap period for the two buoys the wind data differed in timing of peaks and cumulative hours for given velocity bins even though they are only 6 km apart. Considering the possible error in the ages of the sand peaks there appears to be an offset of a few years in Figure 10B that is within the error bars on Figure 10A. If the sand peaks between 1960 and 1980 are a few years older they align well with peaks in wind velocity >15 ms^{-1}. This shift in the age of the sand peaks would place them at either peak water levels in Lake Michigan, or on the rising limb of lake levels, consistent with the hypothesis of higher lake levels being synchronous with increased eolian activity.

DISCUSSION

Sedimentation within Oxbow Lake

Within the modern Oxbow Lake basin, the vertical transition, and the west to east lateral transition of sedimentary lithofacies records a transition from higher- to lower-energy environments. The GPR data reveal that the western end of the Kalamazoo River channel is plugged with 7 m of sand. Ten meters of sand above the plug comprise a capping foredune. The basal 7 m of sand must have been deposited by littoral and eolian processes since the channel was cut off in 1906. Sand deposition into the lake from littoral processes is not likely to have traveled far within Oxbow Lake. Above the interpreted fluvial sand (lithofacies A, core G3) is 0.5 m of sand, silt and organic matter of lithofacies B–E (Fig. 5) deposited between 1906 to early 1940s after the river channel was abandoned and before the foredune developed (Fig. 5). Considering that the lake is surrounded by sand, the mud is considered to be allochthonous, sourced from the Kalamazoo River during flood stage and/or as loess from dunes to the west. The organic matter is interpreted to be both allochthonous from the Kalamazoo River and autochthonous. The infilling and thinning of the north–south section of Oxbow Lake indicates that littoral processes have been active in the lake, possibly explaining some sand deposition (core G6, Fig. 5). The transition from the sand and muddy sand lithofacies (lithofacies D, E) to the organic-rich sediment of lithofacies F represents a decrease in energy as recorded by the decrease in sand and by the decrease in sand particle size (Fig. 8A).

Eolian Sand of Lithofacies F

The decrease in sand and increase in organic matter of lithofacies F is coeval with the establishment of the foredunes.

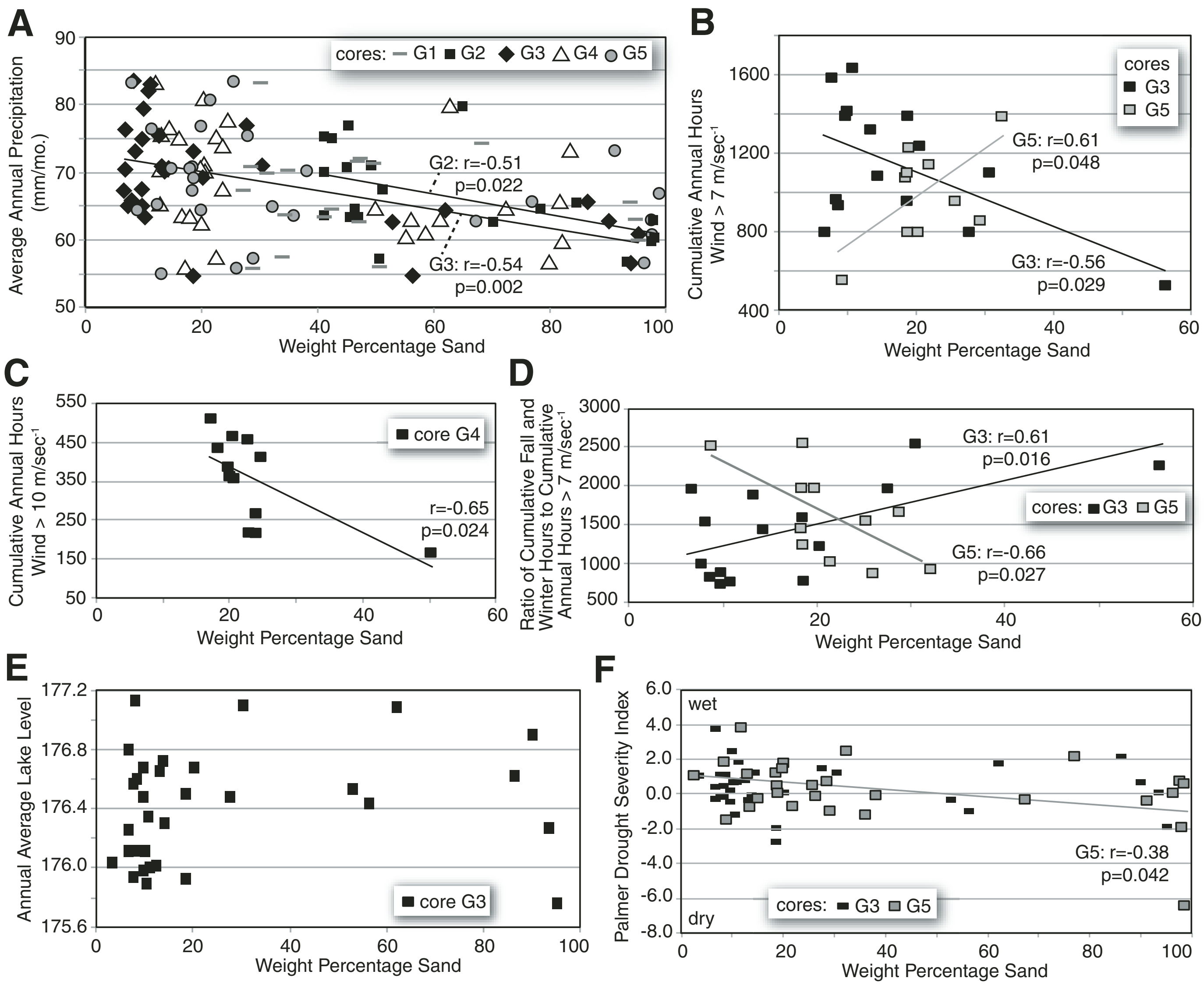


Figure 9. Scattergram plots of different climate variables plotted against weight percentage sand from lithofacies F. (A) Average annual precipitation, (B) cumulative annual hours of wind >7 m/sec^{-1}, (C) cumulative annual hours of wind >10 m/sec^{-1}, (D) ratio of cumulative fall and winter hours of cumulative annual hours of wind >7 m/sec^{-1}, (E) annual average lake level of Lake Michigan, and (F) annual average Palmer drought severity index. Trendlines and statistics indicated where a 95% confidence interval was calculated.

In Figure 6C, the modern foredune to the west of the lake is evident in the background and sand interbedded with the snow in the lee of the foredune records wintertime transport of sand inland. The dunes along the north shore of Oxbow Lake (Figs. 6A, 6D) are another, and closer source of sand to the coring sites. The sand in lithofacies F is interpreted as eolian in origin since: (1) The decrease in sand particle size of lithofacies F is synchronous with establishment of the foredune preventing additional littoral transport of sand into the lake from Lake Michigan. (2) The input of fine and very-fine sand within lithofacies F is episodic in nature. Sand could also be sourced from the channel linking Oxbow Lake with the Kalamazoo River at the lakes northern end (Fig. 1), but the transport of sand from any deltaic position to the southern basin by suspension is not expected. (3) While sediment gravity flows from the inflowing channel, or channel walls from slumping might be expected to transport sand to the coring sites, only fine and very-fine sand varies within lithofacies F and a broader spectrum of particle sizes would be expected. Sand may be transported in Oxbow Lake along the shallow littoral zone during high wind events, with some sand moving downslope to the lake bottom, but transport to the middle of the lake would require currents. Currents strong enough to transport sand would also erode, transport and redeposit lake bottom sediment. Such a process is testable using the unsupported ^{210}Pb profile in Figure 7. More structure would be expected in the profile from older sediment being redeposited. The slight decrease in ^{210}Pb activity at 7

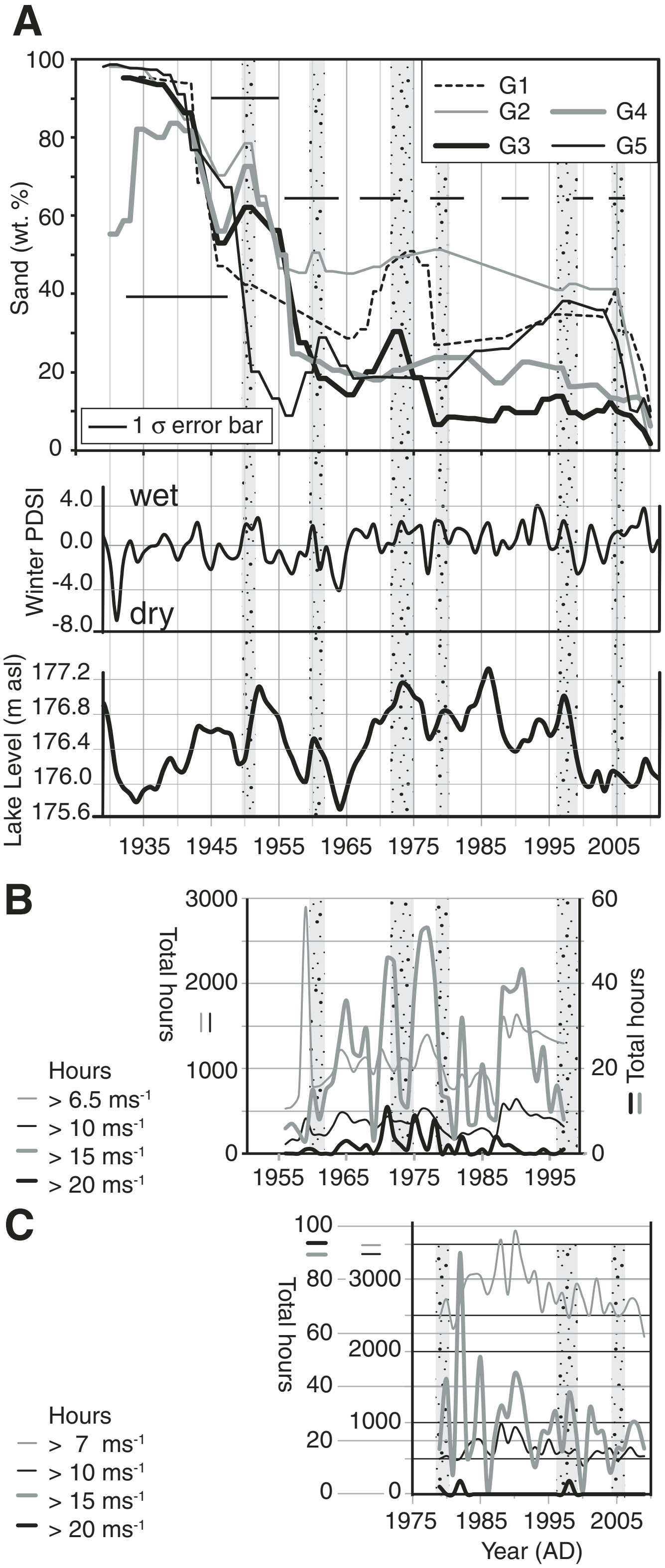


Figure 10. (A) Plot of sand from all five cores with error bars. Ages assigned to the other cores assume a constant accumulation of organic material in all cores through time. Many sand peaks from different cores are aligned. Sand peaks align with wintertime Palmer drought severity index (PDSI) peaks in wetness, and with peak annual lake level in Lake Michigan. (B) Annual cumulative wind velocities from buoy 94426 in Lake Michigan. (C) Annual cumulative wind velocities from buoy 94055 in Lake Michigan. Note that near alignment of stippled gray columns (the aligned sand peaks in Fig. 8A) in B and C with peaks in >15 m/s^{-1} wind velocity are well within the age dating error bars.

cm depth corresponds with a sand signal in 2005, but nowhere else is there a peaked decrease in ^{210}Pb activity in the core. At 19 and 28 cm depth there is a slight increase in ^{210}Pb activity and a corresponding peak in ^{10}Be at 19 cm depth most likely caused by contamination with surface sediment, but sand peaks were not associated with these depths.

The physical mechanism for eolian sand deposition in the lake is from direct airfall onto the water surface or lake ice if deposition occurred during wintertime. During wintertime saltation or sliding across the ice surface can move sand elsewhere across the ice surface until ice melting releases sand into the lake (Fisher and Loope, 2005). For comparison, a 25-cm-thick eolian sand lithofacies, interbedded with organic-rich lacustrine sediment, was recently deposited adjacent to dunes in dune-contact Silver Lake (Fisher and Loope, 2005; Fisher et al., 2007), and the mechanisms for transporting sand from dunes into adjacent lakes is discussed elsewhere in this volume (DeVries-Zimmerman et al., this volume; Hanes et al., this volume).

Correlation of Sand and Climate Data

While there are some interesting correlations between the sand signals and the nearby climate data from South Haven and offshore buoys, the explanatory value of the statistics (R^2 values) with dated core G3 and the other proxy-dated cores is low (Table 2). Of the data listed in Table 2, 10 of the 21 results are from directly-dated core G3, and these are considered the most reliable. Core G3 results suggest that more sand is deposited in Oxbow Lake when there is less annual and fall precipitation, less evaporation, and less wind. Increased sand was only associated with winds >7m/s^{-1} during the fall and winter as a ratio of annual wind, with other results indicating more sand with less wind. Considering high wind events along the Great Lakes are associated with cyclonic activity the results are not what was expected. One error that may be associated with this approach is the two data sets have varying age precisions. The more precise meteorological data is at odds with the sand signal data reported as annual totals with age error bars ranging from ±1.5 to ±5 years for lithofacies F. One conclusion from these analyses is the distant climatological data do not reflect local conditions at the study site. Future work should use sediment traps with concomitant, on-site meteorological measurements to further test the hypothesis.

The other approach of plotting time series of sand signals against lake level and winter PDSI (Fig. 10) resulted in an interesting discovery that all sand signals are associated with peaks in lake level and winter PDSI, but not all lake-level peaks or winter PDSI peaks are associated with sand signals. Perhaps these data can best be understood if the conditions permitting eolian deposition in the lake are episodic and require strong winds at times when other, poorly quantified conditions are favorable for entrainment and subsequent transport of sand. Because strong winds in this location stem from passage of extratropical cyclones (Angel, 1996; Angel and Isard, 1998), and their frequency controls precipitation, a relationship is expected between lake levels, PDSI and eolian activity. In this local environment, a physical casual mechanism (bluff undercutting) is not necessary to initiate eolian activity, it is reasonable to use the sand signals as a proxy for storminess. The lack of correlation between lake level and sand signal in Figure 9E is not unsurprising because lake level alone does not appear to drive eolian deposition in Oxbow Lake. Instead, it is likely that a variety of conditions need to be met, two of which are increased cyclonic activity and a wetter PDSI index. Other conditions would be site specific, controlling availability of sand for transport under specific wind fields. The association of sand signal with wetter wintertime PDSI values (Fig. 10A) supports results from other studies for wintertime transport of sand in Great Lake dune environments (e.g., Marsh and Marsh, 1987; van Dijk, this volume).

The decrease in sand percent in Oxbow Lake beginning in the late 1930s is assumed to reflect a stabilization of the landscape at the west end of the lake coincident with development of foredunes and establishment of vegetation where the lake was infilled by littoral transport of sediment from Lake Michigan. Episodic increases in sand percent within lithofacies F since that time is interpreted as episodic input of eolian sand into the lake during storm events associated with a rising or high Lake Michigan and wet PDSI conditions. Thus the hypothesis that the sand signals can be correlated with climate data is partially accepted—there is a relationship between the eolian sand signal and wiggle matched lake-level and wintertime PDSI data, but a more rigorous approach involving sediment traps and on-site meteorological measurements is necessary for further hypothesis testing. These findings are consistent with previous work by Fisher and Loope (2005); Fisher et al. (2007, 2012), Timmons et al. (2007); Hanes et al. (this volume); and DeVries-Zimmerman et al. (this volume) who described eolian sand deposited in lakes in the lee of dunes along the Lake Michigan coastline as recording storminess.

CONCLUSIONS

Sediment within Oxbow Lake records past episodes of sand transport in a littoral and eolian environment. Historical maps and photographs used with GPR data reveal infilling of the river mouth with sediment, first along the north side of the channel. Inclined reflections within the radar data record sequences of sediment accumulation that culminate with the deposition of 7 m of sand between 1906 and 1920. Beginning in the 1920s through early 1940s and until present, a 10 m high foredune became established above the former river mouth. Between 1906 and the early 1940s, ~0.5 m of sand, mud and organic material accumulated under present day Oxbow Lake. The sand is interpreted as mostly eolian in origin. As realized by Timmons et al. (2007), a series of cores rather than a single core, is best for detecting signals of eolian sand. After establishment of the foredune, sedimentation within the lake changed from mostly sand to an organic-rich mud with sand decreasing in particle size and volume. Analysis of individual climate data with sand data resulted in variety of statistically significant correlations ($p = <0.05$), but with different cores providing conflicting significant positive and negative correlations with the same climate variables, in general a coherent relationship was not found. Peaks in weight-percent sand correspond in time with wet peaks as measured by the Palmer drought severity index and with peaks, or near-peak rising limbs of lake level. From this we conclude that the deposition of eolian sand into Oxbow Lake is not random through time, but related to periods of storminess associated with wet conditions that correspond with rising lake levels. These results suggest that, in southeastern Lake Michigan, onshore eolian transport is greatest at higher lake levels.

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