Preliminary Report of Late Holocene Lake-Level Variation in Southern Lake Superior: Part 1

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ABSTRACT

The internal architecture and age of development of 60 beach ridges in the Grand Traverse Bay embayment, located along the southern shore of Lake Superior on the Upper Peninsula of Michigan, were studied to generate a late Holocene relative lake-level curve for Lake Superior. Basal foreshore elevations, collected from the lakeward sides of beach ridges, were used to determine the relative elevation of Lake Superior when each beach ridge formed. The break in slope between each ridge and the lakeward swale was cored to ensure that the foreshore was penetrated and a maximum basal foreshore elevation was obtained. Basal wetland sediments, collected from swales between beach ridges, were dated to determine the age of adjacent lakeward beach ridges. Basal wetland sediments were recovered from the deepest part of selected swales along the coring transect. Basal wetland sediments provided a minimum age for the lakeward adjacent beach ridge and a least squares regression was used to reduce variability in the data and to approximate the age of unsampled wetlands.

Beach ridges in the Grand Traverse Bay embayment formed between 900 and 3800 calendar years before 1950 (cal. yrs B.P.). The average timing for beach-ridge development of one ridge in the Grand Traverse Bay strandplain is 36 +/- 7.8 years. Groupings of four to six beach ridges indicate longer-term fluctuations in lake levels. Basal foreshore elevations indicate relative lake levels lowered about 4.5 m from 3800 to 1200 cal. yrs. B.P. and increased about 0.7 m from 1200 to 900 cal. yrs. B.P. A coarsening in foreshore mean grain-size per ridge also occurs at about 1200 cal. yrs. B.P. Foreshore thicknesses increase about 0.4 m from 2000 to 1200 cal. yrs. B.P. and remain fairly constant from about 1200 to 900 cal. yrs. B.P. Increased foreshore thicknesses indicate larger wave setup and may be related to a shift in the predominant wind direction that would produce greater wave setup in the Grand Traverse Bay embayment.

INTRODUCTION

Thompson and Baedke (1997) laid the foundation for the development of a Great Lakes-wide chronology of late Holocene changes in lake level and climate, and an understanding of shoreline behavior for sandy shorelines in response to lake-level fluctuations. Their study defined patterns of relative lake-level behavior for Lakes Michigan/Huron, but the applicability of their relative lake-level curves to other parts of the Great Lakes needs testing. Lake Superior contains several areas of sandy beach ridges that can be used to reconstruct past lake-levels using the same approach as Thompson (1992), and Thompson and Baedke (1997). Combining several overlapping data sets from Lake Superior permits a better understanding of past lake-level behavior and differences between data sets provides information on long-term patterns of isostatic adjustment throughout the lake. Because lake level may be considered a proxy for climate, changes in lake level may provide information on long-term and large-scale changes in climate in the upper Midwest of North America (Fraser and others, 1990).

This report summarizes the study of beach ridges in the Grand Traverse Bay embayment along the shores of Lake Superior in the Keweenaw Peninsula, Michigan. The objective of this study is to produce the first of at least four relative lake-level curves for Lake Superior. The relative lake-level curves are generated by systematically vibracoring the lakeward margins of beach ridges to determine the elevation of the foreshore sediments within the ridges and by radiocarbon dating basal-wetland sediments between ridges to date the time of beach-ridge formation. The methods used during the summers of 1998 and 1999 in Grand Traverse Bay, Michigan were consistent with the methods outlined by Thompson and others (1991), where foreshore elevations are interpreted as a close approximation of the elevation of the lake when each beach ridge formed and the radiocarbon dates indicate the age of lakeward adjacent beach ridges. The resulting curve is useful in determining the physical limits and timing of relative lake-level variation, and long-term patterns of shoreline behavior, isostatic adjustments, and paleoclimate change over the past several thousand years. Moreover, this study provides a geologic framework for hydrological and biological studies in the Lake Superior basin.

Study Site

The study area is located in northeast Houghton County, Michigan between 47°9'00" and 47°11'30" north latitude and 88°14'00" and 88°16'30" west longitude (fig. 1). This eastward-opening embayment is on the eastern side of the Keweenaw Peninsula, 25 km northeast of Hancock, 11 km southeast of Lake Linden, and 1.5 km south of Grand Traverse. Seventy beach ridges, separated by wetland-filled swales, arc across the Grand Traverse Bay embayment, capturing Rice Lake and Little Rice Lake from Lake Superior. An elevated surface of till and/or bedrock approximately 5.5 m above the elevation of Lake Superior forms the northern limit of the embayment. The southern limit forms an elevated bedrock surface extending up to 19 m above the lake, separating Grand Traverse Bay from Little Traverse Bay.

Rice Lake and Little Rice Lake are both 1.83 m above the elevation of Lake Superior and drain southward into Little Traverse Bay. Deer Lake is 3.05 m above the elevation of Lake Superior; it flows southeast for about 1.4 km and then northeast for about 1.3 km until it drains into Grand Traverse Bay. Deer Lake Creek cuts through several beach ridges in the northern part of the embayment and connects with a 1.4 km long slough which parallels the Lake Superior shoreline about 400 km inland. Ridge crest and swale elevations decrease from Lake Superior to the slough and increase from the slough to Rice Lake. Vegetation density and height increase inland from the slough except for a small timbered area just south of the Deer Lake Creek inflection point. Well-developed continuous ridges and swales occur near the landward (western) edge of the embayment and form groups of four to six ridges in each group. Ridges are farther apart near the center of the embayment and coalesce towards the northern and southern margins of the embayment. A few parabolic dunes,

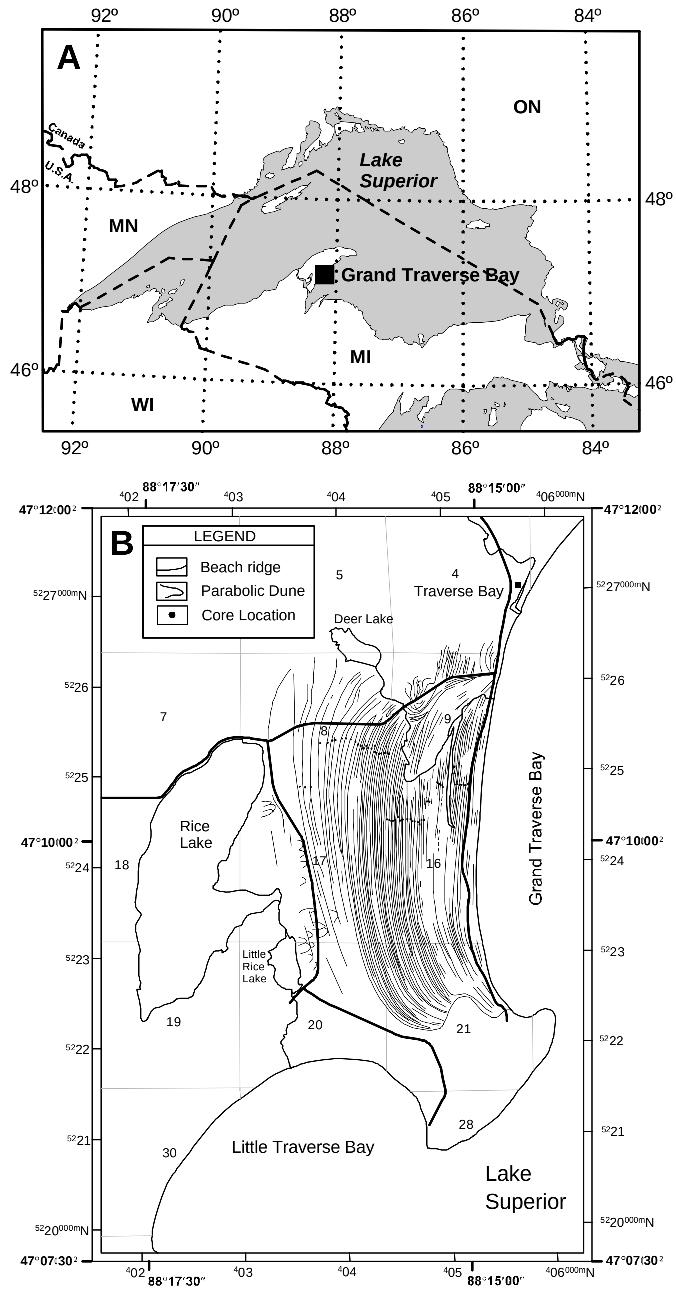

Figure 1. The Grand Traverse Bay field study area. A. Grand Traverse Bay is located on the eastern side of the Keweenaw peninsula, Michigan, and the southern shore of Lake Superior. B. This eastward-opening embayment contains 70 shore-parallel beach ridges capturing Rice Lake from Lake Superior. The northern limit of the embayment is bedrock/till upland, and the southern limit is a bedrock headland. The lakeward sides of 60 beach ridges were cored (black dots) to determine the elevation of the lake when each beach ridge formed.

identified from aerial photographs, occur in the most landward (western) edge of the embayment adjacent to Rice Lake and are oriented offshore.

The Grand Traverse Bay embayment is located along the eastern edge of the Keweenaw highlands of latest Precambrian or earliest Cambrian plutonic, volcanic, and sedimentary origin (Farrand, 1969). The Grand Traverse Bay embayment is underlain by late Precambrian or early Cambrian Jacobsville Sandstone (Martin, 1936). The coarse-grained nature of the sand in Grand Traverse Bay and the numerous outcrops of Jacobsville Sandstone along the eastern Keweenaw Peninsula suggest a Jacobsville Sandstone origin for Grand Traverse Bay sands. The distribution of recently deposited "stamp" sand and gravel, a byproduct of copper-ore processing, along the eastern side of the Keweenaw Peninsula north of Grand Traverse Bay, indicates the present littoral transport in the study area is from the north to the south.

Previous Work

Coastal features along the Lake Superior shoreline have been studied for 150 years (Agassiz, 1850). Most lake-level information in the Superior basin is primarily from morphological studies of Lawson (1893), Taylor (1894, 1895, 1897), Leverett (1929), Leverett and Taylor (1915), Stanley (1932), and Farrand (1960). Early investigators measured ancient shoreline elevations using hand-levels and/or aneroid barometers and related these chronologically according to distance from the existing shoreline. Lake-level elevations were interpreted as everything from the ground surface of the top of a shoreline feature to its base. The introduction of radiocarbon dating in the 1950s modified and strengthened shoreline chronologies in the Great Lakes and led to a comprehensive revision of Great Lakes history by Hough (1958). The subsequent development and limitations of dating methods and other methods, such as archeology, stratigraphy, and palynology, created the need for repeated revisions of Great Lakes history. Stratigraphical studies relating to the chronology of lake levels in the Superior basin are rare and the majority of dates are based on correlation with the Huron and Michigan basins (Saarnisto, 1975). Most of the studies in Lake Superior focus on major features created shortly after the retreat of the Wisconsin ice and lack detailed accounts of past lake levels.

Tilting of abandoned shorelines from isostatic rebound have been studied for more than 100 years (Taylor, 1895, 1897). Original concepts involving increasing shoreline elevations to the north, vertical shoreline divergence to the north, and the "hinge line" have been continuously questioned by workers using dating methods, recorded lake-level gauge data, and alternative shoreline correlations. Disagreement still exists between geologists attempting to understand the chronology of lake-level events, geophysicists studying the cause of tilting, and glaciologists attempting to reconstruct ice sheet thickness along the ice margins (Clark and others, 1994). Apparent rates of vertical movement were calculated by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1977) from lake-level gauge data. June to September monthly mean water levels (1931 to 1974) from five gauging stations around Lake Superior were used to create 0.1 ft/century (3.0 cm/century) contours across Lake Superior. This data suggests that the area around the Point Iroquois gauging station, which is at the head of the St. Mary's River (Lake Superior outlet) is currently uplifting about 6.0 cm/century more than Grand Traverse Bay. Farrand (1962) used shoreline elevation data from Leverett and Taylor (1915), and Hough (1958) and age data from Crane and Griffin (1960) and Dreimanis (1958) and Hough (1958) to create an uplift curve for the Sault outlet at Sault Ste Marie, Michigan. This was plotted against a linear curve representing downcutting at the Port Huron outlet since the Algoma phase to predict the approximate age of separation of Lakes Superior and Michigan/Huron. The intersection of these two curves suggest the separation occurred about 2177 calendar years before 1950 and lake level was about 180.14 m at the time of separation (Farrand, 1962).

The only study focusing on shoreline features similar in age and morphology to the features examined in this study is Larsen's (1994) at Whitefish Point, Michigan. Larsen's (1994) study is based on a geomorphic analysis instead of the sedimentological analysis used in this study. Elevation data for shoreline features at Whitefish Point were obtained from topographic maps and ages were obtained by correlating the elevation curve to a curve created by Thompson and others (1991) and Thompson (1992) near Gary, Indiana. The method used in this study improves upon previous estimates of lake level interpreted from the geomorphic approach.

METHODS

We used the same techniques as Thompson and others (1991) during the 1998 field season in Grand Traverse Bay. Vibracores were retrieved from the lakeward margin of beach ridges to collect foreshore sediments. Fairly dry annual conditions and a low ground-water table contributed to shallow vibracore penetration. Following the same transect, peat/organic cores were obtained by hand-augering wetlands between the ridges to collect basal organic sediments at the deepest point of the swale. Sediment-core elevations were determined using a transit and calibrated to IGLD85 (International Great Lakes Datum 1985) using the NOAA (National Oceanic and Atmospheric Administration) Marquette, Michigan, gauging station, hour average of six-minute water level height readings. Onshore/offshore profiles were surveyed and sediment samples were retrieved from each recorded elevation. All sediment cores, peat/organic cores, and profile samples were returned to the Indiana Geological Survey, Bloomington, Indiana, for further analysis.

Sediment cores were split in half, described, sampled, photographed, and preserved on strips of Masonite using Rub-R-Mold latex. Latex peels were used to enhance the visibility of sedimentary structures that were not identified and/or well defined in the core description. Samples were sieved using a ½ ϕ interval and input into a statistical analysis package created by Todd A. Thompson (Sieve 4.0.8). Statistical parameters were calculated by the mathematical method of moments for each sample, and graphs of various statistical parameters (i.e., mean, skewness, kurtosis, standard deviation, and coarsest one-percentile) were generated per core and transect. Core photographs, latex peels, visual descriptions, and grain-size statistical results were used to distinguish nearshore and onshore facies, specifically the upper and lower contact of foreshore sediments. The basal foreshore elevations are interpreted to approximate the actual elevation of the lake level at Grand Traverse Bay when each beach ridge formed, and foreshore thicknesses are interpreted to indicate the wave setup.

Wetland cores were split in half, described, photographed, and sampled. One basal, 3-cm thick, organic sample in each of the wetland cores were removed from the split cores, dried, and sent to Geochron Laboratories, Cambridge, Massachusetts for radiocarbon dating. In addition to the delta-^{13}C correction performed at the radiocarbon laboratory, the dates were corrected for variations in atmospheric ^{14}C through time using the methods of Stuiver and Reimer (1993). The age of the basal wetland sediments is interpreted to approximate age of beach ridge development for adjacent lakeward beach ridges.

DETERMINATION OF LATE HOLOCENE LAKE-LEVEL VARIATION

Data

General

Fieldwork was conducted in Grand Traverse Bay between 7 July and 25 July 1998 and on 28 July 1999. Vibracores were collected from all accessible beach ridges and hand augers were collected from all continuous and well-developed wetlands. Vibracore elevations were established using a transit and stadia rod using the IGLD85 datum. A roughly shore-perpendicular transect was topographically profiled, and samples were retrieved along the transect. Beach-ridge crests were traced from black and white 1997 Michigan Department of Natural Resources air photographs (scale 1:15,840) onto a 7.5-minute series Rice Lake, Michigan, quadrangle map using a Bausch and Lomb stereo zoom transfer scope. Vibracore locations were plotted on the topographic map and digitized with the beach-ridge crests (fig. 1).

Onshore/Offshore Transects

Two onshore/offshore transects were surveyed across the modern beach and 34 sediment samples were retrieved from most of the recorded elevations to determine the characteristics of dune, foreshore, and upper shoreface sediments in the Grand Traverse Bay study area (fig. 2). Both transects extended from the first dune ridge inland from the modern shoreline and extended lakeward. Fourteen samples were collected along a 49-m-long transect (A) and 20 samples were collected along a 73-m-long transect (B). All 34 samples were sieved and statistical grain-size parameters of the dune, foreshore, and upper shoreface were calculated.

Both transects contain a steep and scarped foreshore and dune profile, suggesting that the summer 1998 shore is undergoing erosion. This erosion may be related to sediment trapping updrift (north) of the Traverse Bay harbor and to long-term rising lake level because of isostatic rebound of the lake's outlet. Offshore topographic profiles in both transects generally decrease in elevation lakeward. Similar mean, coarsest one-percentile (C1%), and sorting trends occur in both transects. Mean grain-size trends change from coarse sand in the dune and foreshore, to very coarse sand at the plunge point (also known as a plunge step), to medium sand further offshore in the upper shoreface in both transects. This pattern of mean grain size is typical of most Great Lakes shorelines because coarse-grained sediment is generally driven onshore by shoaling waves, accumulating at the plunge point, whereas fine-grained sediment is carried offshore with return bottom flows. Upper shoreface sediment close to shore is normally similar in mean grain size to dune sediment. At Grand Traverse Bay, however, dune sand is coarser than upper shoreface sand, probably because of the very coarse-grained nature of the foreshore that supplies the dune with sand.

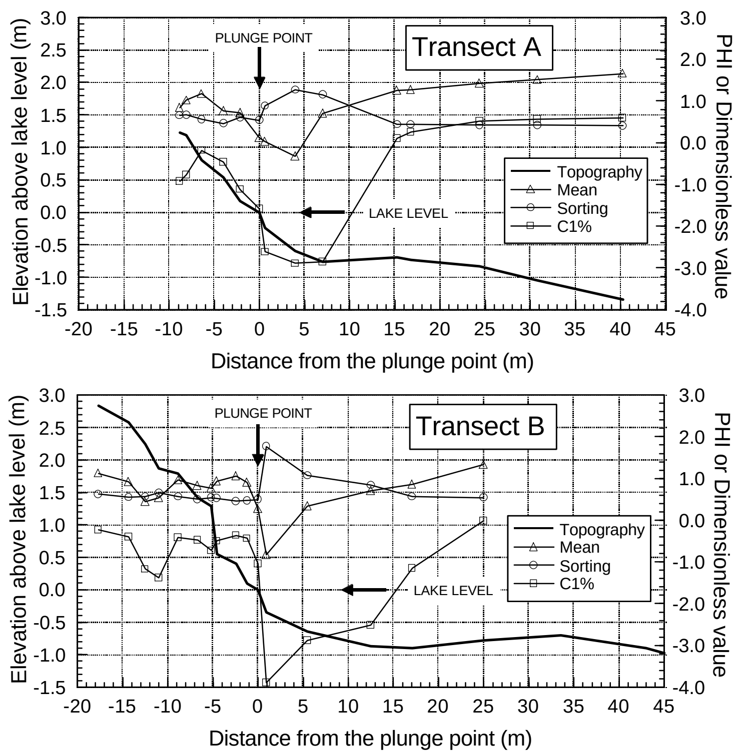

Figure 2. Onshore/offshore topography and grain-size trends perpendicular to the modern shoreline at Grand Traverse Bay, Michigan. Both transects extend from the plunge point (water/land interface) landward across the modern beach and lakeward into the nearshore. Steep topographic changes landward of the plunge point suggest the modern shoreline is eroding. Sharp changes in grain-size trends at the plunge point indicate the base of the foreshore. Coarser mean and coarsest one-percentile trends and poor sorting lakeward of the plunge point is from influx of "stamp sand" from the north. Sediment becomes finer and better sorted lakeward from the "stamp sand" into the upper shoreface and landward from the foreshore into dune sand.

Coarsest one-percentile trends in both transects change from very coarse sand in the dune and foreshore, to granules and pebbles at the plunge point, to very coarse to coarse sand further offshore in the upper shoreface. The C1% represents the traction carpet, which is carried as bed load during sediment transport; and for the nearshore, it should mirror mean grain-size trends. Coarser C1% of the upper shoreface compared with the dune reflects the inability of wind to transport such coarse material up the beach face and into the dune. Consequently, C1% is a good parameter for distinguishing dune and upper shoreface sediments from each other.

Sorting trends in both transects change from poorly sorted near the plunge point in the foreshore to well sorted in the dune and upper shoreface. Air (wind) is efficient in transporting relatively small grain sizes but only within a small range. Relatively coarse and fine-grained sediment is driven onshore but only a small range of relatively fine-grained sediment is transported offshore in weak return flows.

The influx of "stamp" sand and gravel (granules to pebbles) carried southward from Gay, Michigan caused unusual changes in sedimentary characteristics in the beach profile that are generally not observed in other natural shorelines throughout the Great Lakes. The coarse-grained "stamp" sand and gravel accumulates lakeward of the plunge point and extends the coarser-grained and more poorly sorted zone, characteristic of the foreshore, lakeward from the plunge point into the nearshore zone. We did not expect nor did we find these trends vertically distributed in the cores.

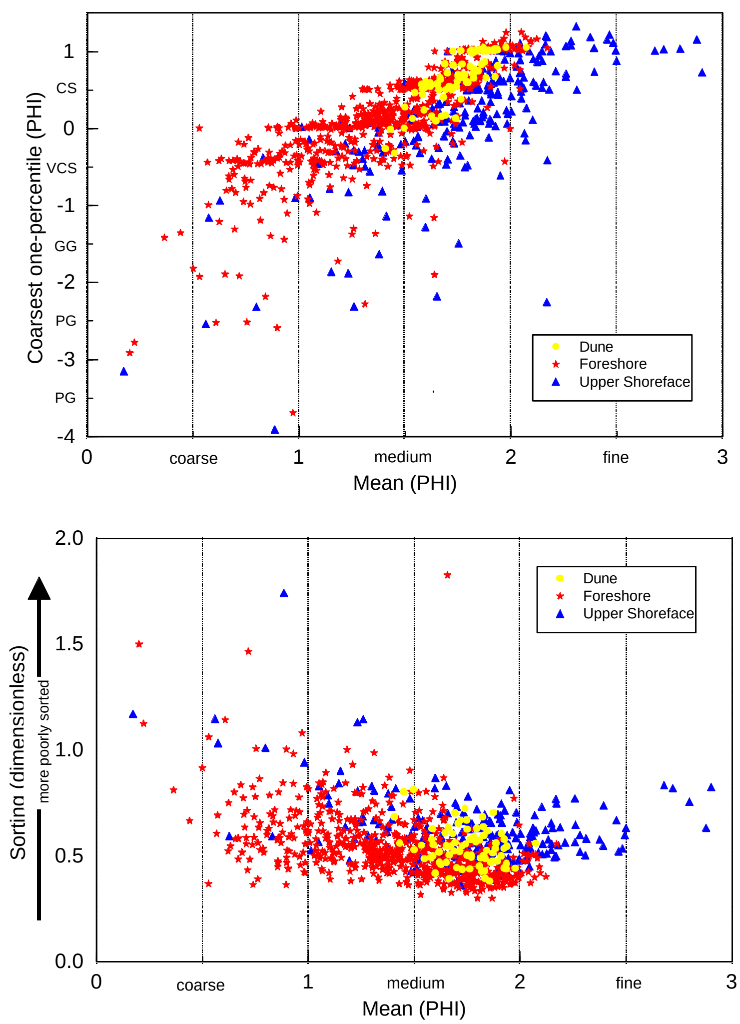

Figure 3. Statistical results of 966 sand samples collected from 60 beach-ridge cores at Grand Traverse Bay. Three sedimentary facies (dune, foreshore, and upper shoreface) form distinct overlapping zones. The most useful plots for distinguishing these zones are mean versus C1% and mean versus sorting. Foreshore sediment is generally coarser grained, has a coarser C1%, and is more poorly sorted than dune and upper shoreface sediment. Dune sediment is better sorted and has a coarser C1% than upper shoreface sediment.

Vibracores

Sixty vibracores collected from the lakeward sides of beach ridges in Grand Traverse Bay were split, described, photographed, sampled, and preserved on Masonite strips using latex. We extracted 966 sand samples from the 60 cores, sieved them, and calculated statistical parameters (mean, skewness, standard deviation, kurtosis, and coarsest one-percentile) for each sample to distinguish three sedimentary facies (dune, foreshore, and upper shoreface). The most helpful plots of statistical parameters are mean vs. C1% and mean vs. sorting (fig. 3). Foreshore sediments are coarser-grained, have a coarser C1%, and are more poorly sorted than dune and upper shoreface sediment. Air (wind) transports grains mainly by saltation and has a relatively lower competence than water, which transports grains mainly by traction. Foreshore sediments differ from upper shoreface sediments because of differing current velocities. Relatively higher current velocities towards the shoreline are more competent and have higher capacities than currents moving offshore. Dune sediment is generally more poorly sorted and slightly coarser than upper shoreface sediment because dune sediment is primarily sourced from the coarse-grained, poorly sorted foreshore. Coarser than average and more poorly sorted upper shoreface sediment may be related to storm deposits.

Integrated information from core photographs, latex peels, visual descriptions, and grain-size statistical results were used to determine and graph the upper and lower limits of the foreshore deposits (fig. 4). The uppermost line represents the boundary between dune and foreshore sediment and the lower line represents the boundary between foreshore and upper shoreface sediment. The lower contact indicates the relative water-level elevation during ridge formation. The upper contact is used in conjunction with the lower contact to calculate foreshore thickness, which represents wave setup during ridge formation. Variations in elevations in this plot helps interpret morphological changes across the entire Grand Traverse Bay strandplain (i.e., spacing and grouping of beach ridges). Groupings of four to six ridges separated by wider than average wetlands occur landward from a position 800 m from the modern shoreline. Similar groupings were interpreted in Lake Michigan strandplains as 150-year quasi-periodic fluctuations with 30-year quasi-periodic fluctuations producing individual beach ridges (Thompson and Baedke, 1997). A similar pattern of longer-duration fluctuation with a shorter-duration fluctuation superimposed appears to be present in the preserved record at Grand Traverse Bay. Basal foreshore elevations along the transect indicate relative lake levels ranged from a minimum of 182.1 m to a maximum of 186.7 m above sea level (IGLD85) in the Grand Traverse Bay area. An obvious kink in foreshore elevations at 400 m landward (location of the slough) indicates the time when there was a change from a long-term lowering in relative lake-level followed by a short-term rise. Foreshore thickness is greater between 165 m and 920 m lakeward than 920 m to 2175 m lakeward.

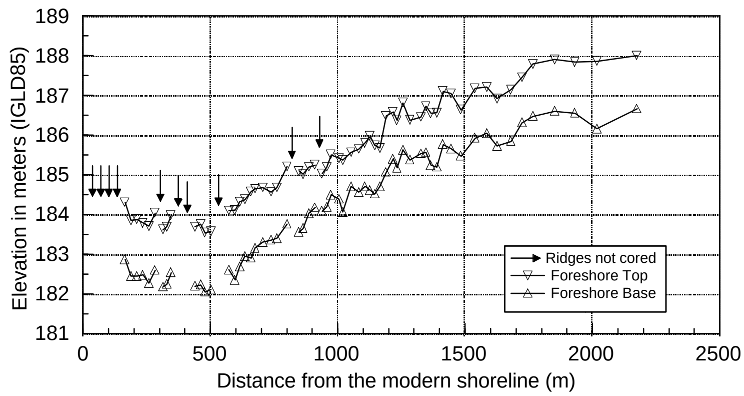

Figure 4. Upper and lower limits of foreshore sediment versus distance from the modern shoreline. The lowermost line represents the boundary between foreshore and upper shoreface sediment and approximates the elevation of the lake during beach ridge formation. The uppermost line represents the boundary between dune and foreshore sediment and is used in conjunction with the lower boundary to determine wave setup (foreshore thickness).

Peat Cores

Twenty-three basal peat samples and 11 basal macrofossil and charcoal samples from wetlands between beach ridges were radiocarbon dated. These samples were calibrated to correct for variations in atmospheric ^{14}C through time using the University of Washington's Quaternary Isotope Lab Radiocarbon Calibration Program 1999, revision 4.1.2 (Stuiver and Reimer, 1993). Calibrated ages were plotted against distance from the modern shoreline and a best-fit line was calculated (fig. 5). The distribution of the data points and the best-fit line represent a progradational system where ages decrease lakeward. Because only about a third of wetlands in the Grand Traverse Bay embayment were dated, and because the data shows considerable variability, a line of best fit of age versus distance landward was used to estimate the age of each beach ridge (fig. 5). The regression does not pass through zero calendar years before 1950 indicating that all lake level events may not be preserved near the most recent end of Grand Traverse Bay. This is reflected by the erosion that is occurring on the modern beach. The inverse of the

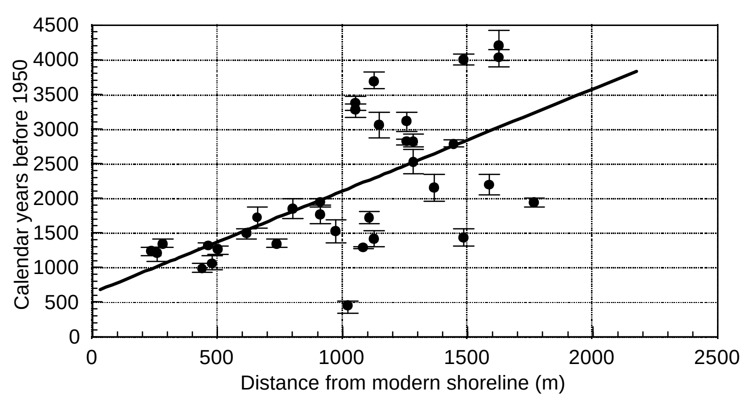

Figure 5. Calibrated basal wetland sediments versus distance from the modern shoreline. A line of best fit was used to calculate approximate ages for each beach ridge in the Grand Traverse Bay strandplain. Age generally increases further inland and variability between calibrated ages increases inland. The slope of the best-fit line indicates the progradation rate of the strandplain was approximately 0.21 +/- 0.1 m/yr.

slope of the best-fit line indicates the approximate progradation rate of the Grand Traverse Bay strandplain was 0.68 +/- 0.1 m/yr. Regression analyses of ridge number versus calibrated ages indicate each beach ridge formed approximately every 36 +/- 7.8 years at Grand Traverse Bay. Thompson and Baedke (1997) observed a 33-year per ridge average of beach ridge development for all of their study areas in Lake Michigan, with a range of 29 to 38 years per ridge.

Discussion

Measured foreshore elevations (fig. 4) and ages for each beach ridge calculated from the best-fit line (fig. 5) were combined to create a relative lake-level curve for Grand Traverse Bay (fig. 6). Beach ridges at Grand Traverse Bay record relative lake-level elevations from about 3800 to 900 calendar years before 1950. During this time period, basal foreshore elevations indicate that the upper limit of relative lake level ranged from a maximum of 186.7 m at approximately 3800 cal. yrs. B.P. to a minimum of 182.1 m between about 1400 and 1200 cal. yrs. B.P. The curve shows a relative lake level lowering from about 3800 to 1200 cal. yrs. B.P. followed by a relative lake-level rise from about 1200 to 900 cal. yrs. B.P.

Mean grain-size and foreshore thickness trends are plotted across the entire beach ridge strandplain above the relative lake-level curve in figure 6. Foreshore thicknesses range from 0.9 m to 1.8 m, having an average of 1.3 m. An obvious sharp increase to greater foreshore thickness occurs at about 2000 B.P., which is at a different time than the inflection in the foreshore elevation curve. Thicker foreshores from about 2000 to 900 cal. yrs. B.P. indicate a larger wave setup during beach-ridge formation and may be related to a shift in the predominant wind direction and increased wave setup. The only sharp increase in the mean grain-size occurs at about 1200 B.P. Dune and foreshore trends are fairly consistent laterally, whereas upper shoreface mean grain-size slightly coarsens toward Lake Superior.

SUMMARY

A relative lake-level curve for Grand Traverse Bay, Michigan was created by a systematic technique of vibracoring beach ridges to obtain lake-level information and augering and radiocarbon dating basal wetland sediments between beach ridges to obtain beach ridge age information. The curve indicates that the Grand Traverse Bay embayment recorded lake levels from about 3800 to 900 cal. yrs. B.P. Currently, the shoreline appears to be undergoing erosion. During the recorded period relative lake levels decreased 4.5 m from about 3800 to 1200 cal. yrs. B.P. and increased 0.7 m from about 1200 to 900 cal. yrs. B.P. This kink, thicker than average foreshore thicknesses after about 2000 cal. yrs. B.P., and mean grain-size coarsening trends after 1200 cal. yrs may be attributed to variations in isostatic uplift between the study area and the Sault Ste. Marie outlet and/or the Lake Superior water budget and outflow restrictions.

A short-term quasi-periodic lake-level fluctuation with a period of about 36 years was instrumental in the creation of beach ridges in the Grand Traverse Bay embayment. Foreshore elevations rise and fall in groups of four to six beach ridges and are interpreted to form from longer-duration quasi-periodic fluctuations. Superimposed on these shorter-duration fluctuations are isostatic rebound, outflow restrictions, and Lake Superior hydrodynamics.

ACKNOWLEDGMENTS

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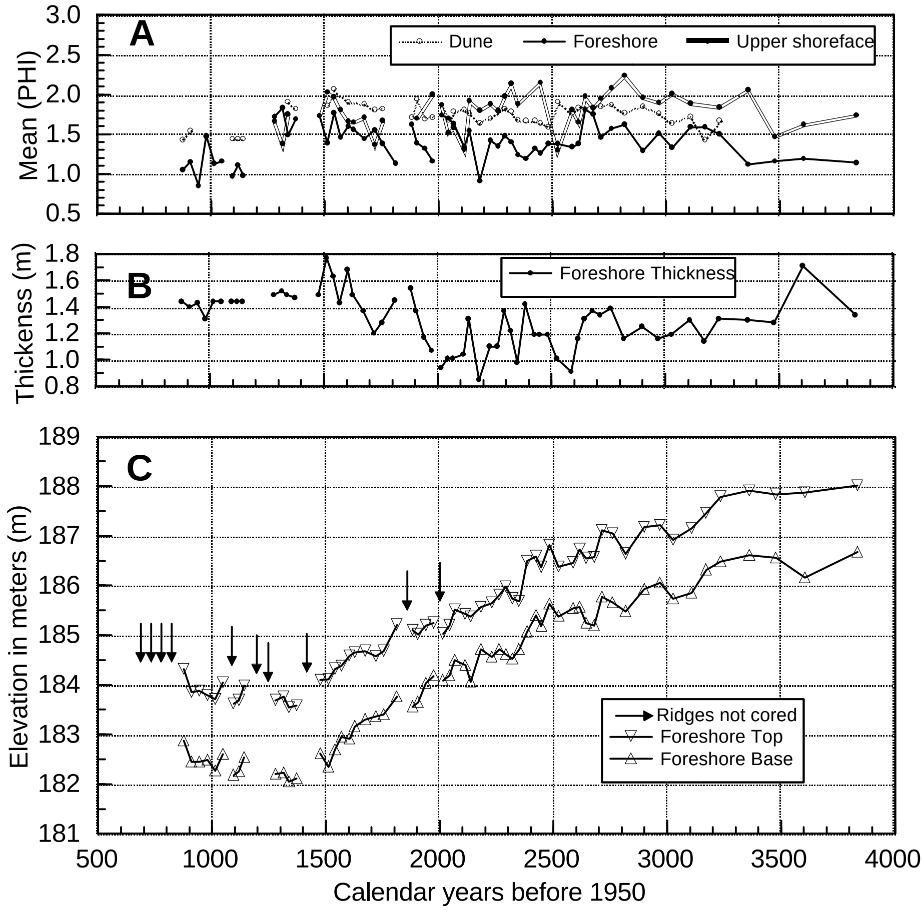

Figure 6. Mean grain-size of nearshore and onshore facies per core (A), foreshore thickness (B), and foreshore (top and base) elevation trends (C) versus calendar years before 1950 across the entire Grand Traverse Bay strandplain. Foreshore mean grain-size per core coarsens at about 1200 B.P., whereas dune and upper shoreface remain fairly constant. Foreshore thicknesses increase from about 2000 to 1200 B.P. and remain fairly constant from about 1200 to 900 B.P. Basal foreshore elevations indicate relative lake levels lowered from about 3800 to 1200 B.P. and increased from about 1200 to 900 B.P. (Note: Basal foreshore elevations in C are relative lake-level elevations with respect to only Grand Traverse Bay because isostatic rebound has not been removed.).

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APPENDIX A

Core #	Distance (m)	Ground Elev. (IGLD85)	Calculated Age (BP)	Foreshore Top (IGLD85)	Foreshore Base (IGLD85)	Mean (Dune)	Mean (Foreshore)	Mean (Upper Sh.)
801	164.86	184.50	875	184.31	182.87	1.43	1.05	
802	188.41	184.19	909	183.85	182.45	1.54	1.15	
803	211.96	184.06	944	183.88	182.45		0.85	
804	235.51	184.09	979	183.79	182.48		1.48	1.47
805	259.07	184.02	1014	183.71	182.27		1.13	
806	282.62	184.04	1048	184.04	182.60		1.16	
807	314.02	183.97	1094	183.62	182.18	1.59	0.97	
808	329.72	184.03	1118	183.69	182.25		1.11	
809	345.42	183.98	1141	183.98	182.54		0.98	
810	439.63	184.00	1279	183.69	182.20		1.72	1.66
811	463.18	184.06	1314	183.76	182.23		1.83	1.38
812	478.88	184.12	1337	183.54	182.05	1.91	1.49	1.75
813	502.43	184.11	1372	183.58	182.11	1.82	1.69	
814	573.08	184.56	1476	184.10	182.61		1.73	1.73
815	596.63	184.51	1511	184.11	182.35	1.86	1.39	2.03
816	616.26	184.80	1540	184.32	182.69	2.07	1.77	1.97
817	635.89	184.81	1569	184.38	182.95		1.46	1.81
818	659.44	184.98	1603	184.58	182.91	1.91	1.60	1.66
819	675.14	185.02	1626	184.65	183.16		1.56	1.65
820	706.54	185.22	1673	184.68	183.30	1.88	1.44	1.71
821	737.94	185.19	1719	184.57	183.36	1.81	1.55	1.37
822	761.49	185.29	1754	184.68	183.40	1.82	1.38	1.67
823	800.75	185.50	1811	185.21	183.76		1.13	
824	847.85	185.55	1881	185.10	183.56	1.71	1.62	
825	863.55	185.63	1904	185.02	183.65	1.94	1.39	1.70
826	887.10	185.75	1939	185.20	184.03	1.69	1.32	
827	910.65	185.77	1973	185.25	184.18	1.71	1.16	2.00
828	938.13	185.70	2014	185.03	184.09	1.87	1.74	1.87
829	957.76	185.81	2043	185.20	184.19	1.68	1.70	1.52
830	973.46	186.00	2066	185.51	184.50	1.79	1.63	1.58
831	1004.86	186.03	2112	185.42	184.39	1.81	1.34	1.31
832	1020.56	185.95	2135	185.37	184.06	1.76	1.54	1.92
833	1051.96	186.17	2181	185.57	184.71	1.64	0.91	1.80
834	1083.36	186.17	2228	185.65	184.56	1.70	1.42	1.88
835	1106.91	186.39	2262	185.81	184.71	1.79	1.35	1.80
836	1126.54	186.44	2291	185.98	184.61	1.82	1.48	1.98
837	1146.17	186.44	2320	185.74	184.52	1.79	1.40	2.14
838	1165.79	186.48	2349	185.68	184.71	1.68	1.24	1.88
839	1189.34	186.88	2384	186.49	185.07	1.67	1.19	
840	1216.82	187.02	2424	186.59	185.40	1.67	1.32	
841	1232.52	186.70	2447	186.37	185.18	1.64	1.26	2.15
842	1256.07	187.28	2482	186.82	185.63	1.59	1.38	
843	1283.55	186.87	2523	186.38	185.38	1.91	1.38	1.30
844	1326.73	187.03	2586	186.46	185.54	1.77	1.34	1.81
845	1346.35	187.13	2615	186.73	185.57	1.83	1.38	1.65
846	1365.98	187.31	2644	186.55	185.24		1.81	1.98
847	1389.53	187.03	2679	186.57	185.20		1.75	1.83
848	1413.08	187.56	2713	187.11	185.77	1.85	1.46	1.95
849	1444.48	187.53	2760	187.05	185.66	1.87	1.57	2.08
850	1483.74	187.24	2817	186.64	185.48	1.77	1.62	2.24
851	1538.69	187.55	2898	187.18	185.93	1.85	1.29	1.96
852	1585.79	187.67	2968	187.21	186.05	1.76	1.51	1.90
853	1625.04	187.59	3026	186.92	185.73	1.64	1.33	2.01
854	1680.00	187.74	3107	187.15	185.85	1.72	1.59	1.89
855	1723.18	187.92	3170	187.46	186.32	1.43	1.59	
856	1766.35	188.31	3234	187.79	186.48	1.67	1.50	1.84
857	1852.71	187.91	3361	187.91	186.61		1.12	2.06
858	1931.21	187.84	3477	187.84	186.56		1.16	1.47
859	2017.57	187.87	3604	187.87	186.16		1.19	1.62
860	2174.58	188.01	3835	188.01	186.67		1.14	1.74