Preliminary Report of Late Holocene Lake-Level Variation in Southeastern Lake Superior Part II: Tahquamenon Bay, Michigan

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ABSTRACT

The internal architecture and age of development of 71 beach ridges in the Tahquamenon Bay embayment, located along the southeastern shore of Lake Superior on the Upper Peninsula of Michigan, were studied to generate a late Holocene relative lake-level curve for Lake Superior. The record from this embayment is important because Tahquamenon Bay is located near the outlet for Lake Superior and may have experienced similar vertical movement (isostatic uplift) rates as the outlet. The lakeward side of beach ridges were cored to obtain the elevation of basal foreshore deposits, which record the elevation of the lake when each beach ridge formed. Basal wetland sediments were collected from swales between ridges and radiocarbon dated to determine the age of the next lakeward adjacent beach ridge. Regression analysis of the calibrated dates was used to approximate the age of the beach ridges. Elevation data and age data were used to construct a relative lake-level curve for Tahquamenon Bay.

Beach ridges in the Tahquamenon Bay embayment formed between about 4,300 and 2,000 calendar years before 1950 (cal. yrs. B.P.). The average timing for beach-ridge development of one ridge in the Tahquamenon Bay strandplain is 31 ± 3.7 years. Groupings of four to six beach ridges indicate longer-term fluctuations in lake levels. Basal foreshore elevations indicate relative lake levels dropped rapidly (almost 5 m) from about 4,100 to 3,800 cal. yrs. B.P., lowered gradually (approximately 7 m) from about 3,800 to 2,300 cal. yrs. B.P., and remained fairly constant from about 2,300 to 2,000 cal. yrs. B.P. The rapid drop is associated with a drop in water level from the Nipissing II high water-level phase, and the change from a gradual fall to a fairly constant slope is associated with an outlet change from Port Huron, Michigan, to Sault Ste. Marie, Michigan. Grain-size and foreshore thickness trends may be attributed to variations in sediment source or littoral currents or wave climate or outlet location or outflow characteristics or vertical movement between the study area and the outlet or a combination of these.

INTRODUCTION

Thompson and Baedke (1997) laid the foundation for using strandplains of sandy beach ridges to interpret basinwide late Holocene lake-levels. Vibracoring beach ridges and dating wetland sediment between ridges in several strandplains of beach ridges in Lake Michigan were used to produce relative lake-level curves. Each curve is a high resolution record (approximately one data point every 30 years) of lake level and vertical movement. Combining several overlapping curves permits a better understanding of each of these variables and provides information on basinwide patterns. Because lake level may be considered a proxy for climate, changes in lake level can provide information on long-term and large-scale changes in climate in the upper Midwest of North America (Fraser and others, 1990). Lake Superior contains several strandplains of sandy beach ridges that can be used to reconstruct past lake-levels using the same approach as Thompson and others (1991), Thompson (1992), and

Thompson and Baedke (1997). Grand Traverse Bay, Michigan, was the first of four sites that will be studied in Lake Superior, and results are summarized in Johnston and others (2000). Tahquamenon Bay, Michigan, is the second study site. Future study sites include Au Train, Michigan, and Batchawana Bay, Ontario.

This report summarizes the study of beach ridges in the Tahquamenon Bay embayment along the southeastern coast of Lake Superior in the Upper Peninsula of Michigan. The purpose of this study is to produce a relative lake-level curve for the embayment. The relative lake-level curve was generated by systematically vibracoring the lakeward margin of beach ridges to determine the elevation of the lake when the beach ridge formed and by radiocarbon dating basal wetland sediments between ridges to determine the age of the beach ridge. The methods used during the summer of 1999 in Tahquamenon Bay, Michigan, were consistent with the methods outlined by Thompson and others (1991) and Thompson (1992), 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 lake-level variation, long-term patterns of shoreline behavior, vertical movement, and paleoclimate change over the past several thousand years. This study also provides a geologic framework for other research such as paleobotanical and hydrologic studies, in the Lake Superior basin.

Study Site

The study area is located in northwest Chippewa County, Michigan, between 46°27'30" and 46°29'30" north latitude and 84°57'30" and 85°02'30" west longitude (fig. 1a). It is approximately 35 km south of Whitefish Point, Michigan, 42 km northeast of Newberry, Michigan, and 50 km west of Sault Ste. Marie, Michigan. This northward-opening embayment extends approximately 6 km east-west and 2.5 km north-south (fig. 1b). The limit of the embayment is marked by an elevated bedrock headland to the east and an elevated bedrock or till surface or both to the south and west. The approximate edge of the embayment follows a 650-ft (198.1 m) contour (USGS, 1975a, b) and is about 14.6 m above the elevation of Lake Superior (183.5 m, 602 ft). A 10- to 15-m-high bluff forms the southeastern and eastern margin of the embayment and a 6-m-high bluff forms the western margin of the embayment. The southwestern margin of the basin extends approximately one kilometer further inland than the adjacent margins and forms an elevated platform that grades into the embayment.

The Tahquamenon Bay embayment opens up into Tahquamenon Bay (fig. 2a). Several offshore bars, paralleling the modern coastline occur on a platform that extends 300 m offshore and is under less than 2 m (6 ft) of water. Further offshore, the embayment is a part of a larger platform (<30 ft/< 9 m deep) that extends lakeward to a line from about Paradise, Michigan, to Salt Point, Michigan. This platform opens up into Whitefish Bay (<90 m deep). The outlet for Lake Superior is located approximately 35 km east of the study area at Sault Ste. Marie, Michigan. The Tahquamenon River flows into Lake Superior about 9 km north of the Tahquamenon Bay embayment. A submerged spit is located just south of the river and extends southward to about 3 km north of the study site (fig. 2a,b).

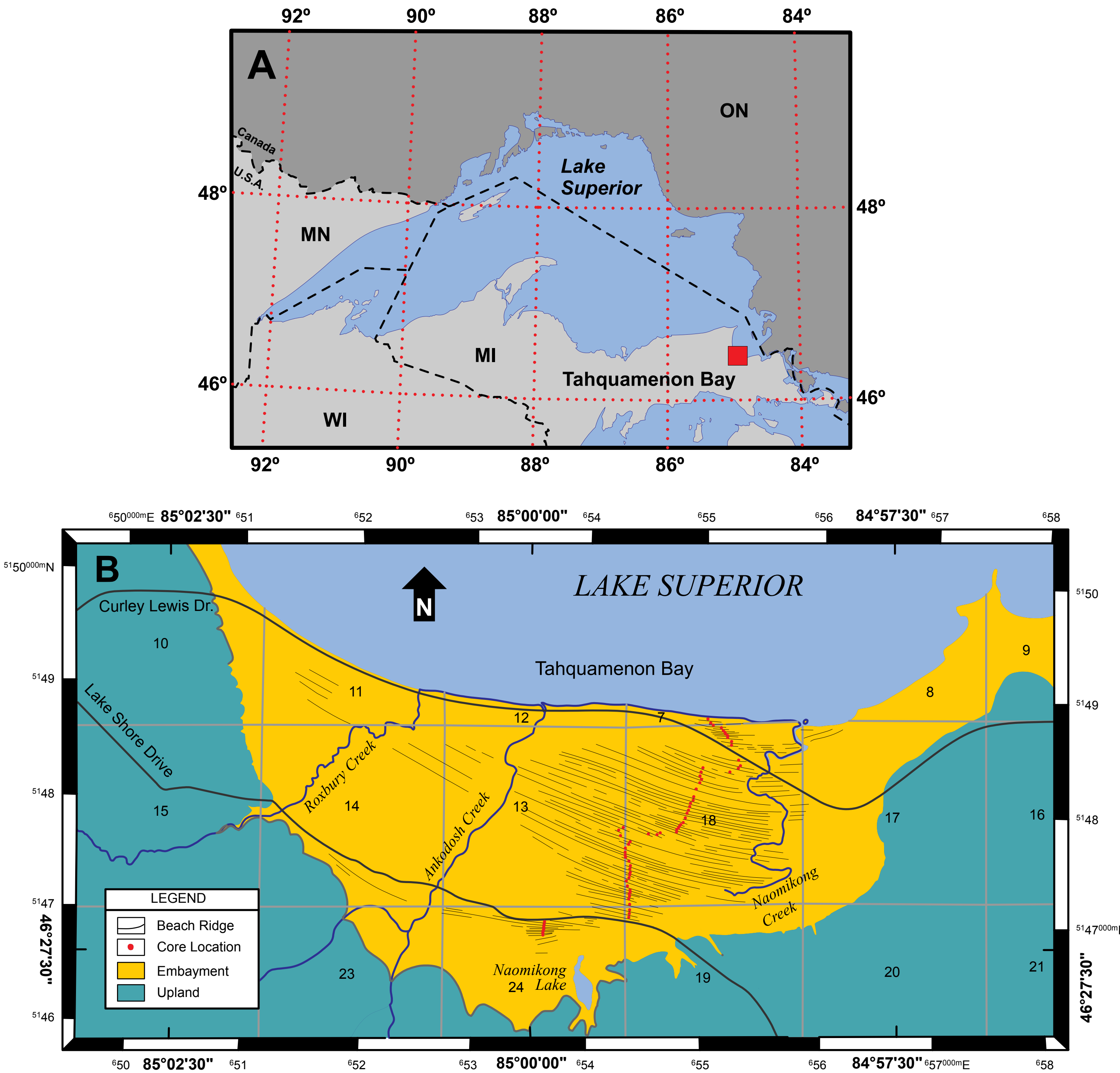

Figure 1. The Tahquamenon Bay field study area. (A) Tahquamenon Bay is located at the southeastern end of Lake Superior in Whitefish Bay, about 35 km south of Whitefish Point and 50 km west of Sault Ste. Marie in the Upper Peninsula of Michigan. (B) This northward-opening embayment contains 80 approximately shore-parallel beach ridges. The embayment is bordered by an elevated bedrock headland to the east and an elevated bedrock or till surface or both to the south and west. The lakeward side of 71 beach ridges were cored to determine the elevation of the lake when each beach ridge formed. Lines indicate beach ridge crests and dots indicate core locations.

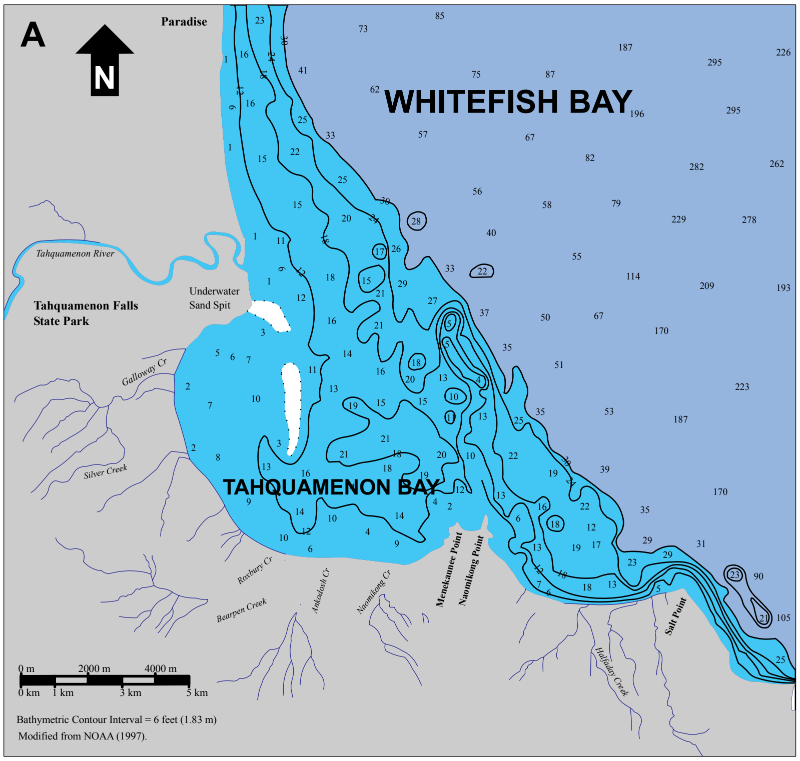

Figure 2. A regional perspective of the Tahquamenon Bay study area. (A) Land surface drainage into Tahquamenon Bay and bathymetry in Tahquamenon Bay. A shallow-water platform defines Tahquamenon Bay, which extends from a line between about Paradise and Salt Point landward. (Note: bathymetric depth are in feet.) The sand spit and the offshore bars are under at least 2 m (6 ft) of water. Surface drainage in the study area includes three creeks, the Roxbury, Ankodosh, and Naomikong. Modified from NOAA (1997). (B) A Landsat EMT+ image with bands 3, 2, and 1 displayed. A 5-km-long sand spit extends from the outlet of the Tahquamenon Bay River southward toward the study site. The white 300-m-wide band along the coastline is a narrow, shallow-water platform with several offshore bars.

Three drainages, Roxbury, Ankodosh, and Naomikong Creeks flow from the bedrock/till uplands, through the Tahquamenon Bay embayment and into Lake Superior. All these creeks cut through several beach ridges (fig. 1b). Large amounts of tannic acid in the modern nearshore suggests that these creeks are currently draining wetlands. The extension of a sand spit at the mouth of the Naomikong Creek from the 1975 topographic map (USGS, 1975a) to the 1997 Michigan Department of Natural Resources (MDNR) air photographs (scale 1:15,840) indicates littoral transport was toward the east along the coast. A small lake, Naomikong Lake, is located in the most landward, central part of the embayment on the elevated graded platform. It is approximately 10.4 m above the elevation of Lake Superior, doesn't appear to have any major surface tributary input, and flows into Naomikong Creek (fig. 1b).

The Tahquamenon Bay embayment contains 80 beach ridges separated by wetlands (fig. 1b). The best preserved ridges are in the eastern part of the embayment. Dense vegetation in the most landward part of the strandplain makes it difficult to define ridges and swales from air photos and makes accessibility to the field difficult. Ridge crest orientations lakeward of Curley Lewis Drive, the youngest ridges adjacent to Lake Superior, closely resemble the east-west orientation of the modern shoreline. Ridge crest orientations between Curley Lewis Drive and Lake Shore Drive are rotated 15° from the modern shoreline and follow a ESE to WNW direction. Ridge crest orientations landward of Lake Shore Drive, the oldest ridges and most landward, vary from east-west to WSW-ENE.

Previous Work

Previous investigations of the Tahquamenon Bay area have been few because of limited development and urbanization (poorly drained area, dense vegetation, few economic resources) and the lure of studying the Sault Ste. Marie area (DeVries, 1927). The only study with data collected directly from the Tahquamenon Bay embayment is the Soil Survey of Chippewa County (Whitney, 1992). All the other studies interpolate information from nearby sites through the Tahquamenon Bay embayment and deal with a more regional analysis. The following paragraphs describe previous works pertinent to the Tahquamenon Bay area starting with the oldest and deepest known sediments and ending with the most recent sediments, features, and biota at the ground surface.

Bedrock geology in the Tahquamenon Bay embayment is not well known owing to a lack of exposures, dense vegetation, and a lack of wells records. The closest exposure is southeast of Salt Point about 12 km southeast of the study site. This outcrop consists of sandstone over shale with fossils and is interpreted as part of the Miner's Castle Member of the Late Cambrian Munising Formation (Ver Wiebe, 1927; Hamblin, 1958). The next closest outcrop is located about 22 km northwest of the Tahquamenon Bay study site at the Tahquamenon Falls (Bergquist, 1936; Hamblin, 1958; Catacosinos and others, 2000). These outcrops consist of mainly sandstone with shale, siltstone, and sandy dolomite of the Chapel Rock Member (lower falls) and the Miner's Castle Member (lower and upper falls), both of the Late Cambrian Munising Formation (Hamblin, 1958). Isolated outcrops of sandy to argillaceous dolomite of the Early Ordovician Au Train Formation were found about 400 m above the upper falls following the Tahquamenon River (Hamblin, 1958). White sandstone described in several water well records from the next adjacent embayment about 4 to 8 km east of the Tahquamenon Bay embayment, at an approximate average depth of 10.5 m below the ground surface, may be related to the Au Train or Munising Formation(s) or both. A regional synthesis of these formations indicates that they dip gently toward the south and form the outermost preserved part of the Michigan structural basin. These formations were developed during the first advance of the Paleozoic seas into northern Michigan and were subjected to postdepositional subsidence, erosion, and glaciation. The hard dolomitic sandstone of the Au Train Formation forms a cuesta, a long, narrow hill with a steep slope (escarpment) on the north side and a gentle slope (dip-slope) on the south side underneath glacial drift and lacustrine deposits. The less resistant soft, friable sandstone of the Munising Formation forms the base of the escarpment (Hamblin, 1958).

Red sandstone described below white sandstone in several water well records around the Tahquamenon Bay area may be related to the characteristically red Precambrian Jacobsville formation. The Jacobsville formation presumably constitutes the bedrock of most of Whitefish Point and is in exposures at Ile Parisienne, Ontario (about 30 km northeast of the study site) (Hamblin, 1958). Regional analysis of the Jacobsville formation indicates it dips mainly to the north and northwest towards the Lake Superior Basin, is related to a highland extending eastward through northern Michigan connecting the Wisconsin Arch with the Precambrian highlands in Ontario, and probably constitutes the bedrock under most of Lake Superior (Martin, 1936; Hamblin, 1958; Dell, 1975).

Glacial and lacustrine deposits of Quaternary age cover the cuesta and the adjacent bedrock surfaces in the Tahquamenon Bay area. Major sedimentary units found in Lake Superior over bedrock include till, clay, and sand upward (Lineback and Dell, 1979; Farrand and Drexler, 1985). Till has not been studied in the immediate area of the Tahquamenon Bay embayment and water well descriptions are not useful since till is not distinguished from clay or sand. A basinwide analysis of cores from Lake Superior suggests the composition and color of the tills are associated with the underlying bedrock (Dell, 1975). Red tills are suggested to occur along most of the northwestern and southern part of the Lake Superior basin and are related to the Precambrian Jacobsville Sandstone as a source. Gray tills are suggested to occur along most of the eastern and northeastern part of the Lake Superior basin and are related to Archean granite and granite-gneiss (Dell, 1975). Regional analysis suggests red till may occur near the study site but granite and granite-gneiss rocks are relatively close to the study site and may suggest the occurrence of gray tills if the ice lobe advanced from the northeast. The direction of the advancing Superior lobe is difficult to determine in the Tahquamenon Bay area because of the lack of preserved or identified glacial features. This may be related to the elevated bedrock surface of the cuesta, which probably impeded or modified the ice lobe direction and only deposited a thin till cover (Drexler and others, 1983). Till in the Tahquamenon Bay area would be related most likely to the last advances of the Superior lobe, before about 10,000 B.P., since the ice during the Marquette advance (about 10,000 B.P.) did not reach the study area. This proposed limit of the ice for the Marquette advance is north of the Grand Marais moraine (moraine I) and a line connecting the moraine to Alona Bay, Ontario, which extends north of Whitefish Point (Drexler and others, 1983; Farrand and Drexler, 1985).

Several glacial lakes, namely Lake Algonquin and Lake Minong, occupied the eastern part of the Lake Superior basin before and after the Marquette advance and presumably deposited clay, silt, and fine sand in the

Tahquamenon Bay area (Farrand, 1960; Lineback and Dell, 1979; Drexler and others, 1983; Farrand and Drexler, 1985). Red and gray varved and nonvarved clays have been retrieved in several cores throughout the Lake Superior basin and have been related to bedrock and till distributions and inflow sources (Dell, 1975). The main source of the red clay was presumably from outwash from red till areas as the retreating ice margin was in the Superior basin and deposited during the stages of Lake Algonquin, before the Marquette advance. The main source of the gray clay was presumably from outwash from gray till areas as the ice retreated further north and was deposited during the stages of Lake Minong, before and after the Marquette advance (Dell, 1974; Lineback and others, 1979). Water well records in the next adjacent embayment east of the Tahquamenon Bay embayment describes 6- to 12- m-thick clay units only 3 to 6 m below the ground surface and may be related to Lakes Algonquin or Minong or both.

Shorelines formed from glacial and postglacial lakes around the study site have been described mainly by Leverett (1929), Farrand (1960), and Drexler (1981). Most of their work is focused on prominent shorelines such as those created by Lakes Algonquin and Minong. Several Lake Algonquin shorelines identified south and west of the Tahquamenon Bay study site suggest high water levels encircled elevated areas of the cuesta, which was covered by thin deposits of till and/or outwash sands and gravels in the eastern part of the Upper Peninsula of Michigan (Futyma, 1981; Drexler and others, 1983). Shoreline features related to Lake Minong have been identified along the east coast of Ontario between Sault Ste. Marie and Alona Bay (Farrand, 1960). The extent of Lake Minong during the Marquette advance was presumably about twice the size of Whitefish Bay and was restricted by the cuesta covered by till outwash to the south and a barrier of glacial drift between Nadoway Point, Michigan, and Gros Cap, Ontario, to the southeast (Drexler and Farrand, 1983; Cowan, 1985; Farrand and Drexler, 1985). The next lowermost prominent shoreline formed by Lake Nipissing has been identified throughout most of the Lake Superior basin and within the study area. Larsen (1994) studied many shoreline features younger than Lake Nipissing around Whitefish Point, Michigan, and used a geomorphic approach to improve estimates of past lake levels. Most of the shoreline studies in the study area used a geomorphic approach by relating topographic changes to lake level changes instead of a stratigraphic approach, which involves digging into the shoreline feature and correlating a specific sedimentary unit to lake level. Few shorelines created in the last several thousand years have been studied near the Tahquamenon Bay study area.

Three soil types occur in the Tahquamenon Bay beach ridge strandplain, the Markey, Kinross, and Au Gres (Whitney, 1992). Each soil was not mapped separately since they are all intricately mixed in the strandplain, but descriptions of the soils indicate Au Gres soils mostly occur on ridges and Markey and Kinross soils in swales between ridges. Markey and Kinross soils are both frequently ponded, have a higher percentage of organic material, and have 0 to 2 percent slopes. Markey soils contain a thicker organic layer over sand, are more poorly drained, and are found at slightly lower or similar positions than the Kinross soils. Au Gres soils are poorly drained, have a slope of 0 to 3 percent, and have a low percentage of organic material. Permeability is moderately slow to moderately rapid in the organic layers of the Markey and Kinross and rapid in the sandy substratum in all three soils. Water capacity is high in the Markey soils and low in the Au Gres and Kinross soils. The water table is seasonally high from 0.3 m (1 ft) above to 0.3 m (1 ft) below the surface from the fall to summer in the Markey and Kinross soils and is 0.15 to 0.46 meters (0.5 to 1.5 ft) below the surface from late fall to late spring in the Au Gres. The sandy substratum in the Markey and Kinross soils consists of sand (>85-90% sand, <15% silt, <10% clay) to loamy sand (>70-85% sand, <30% silt, <15% clay) and contains slightly more fines (silt and clay) than the sand at the base of the Au Gres soils. The different modes of grain transportation (water/air) or availability of grains or percolation of fines or a combination of these from the overlying organics may contribute to the grain size variations.

The Tahquamenon Bay embayment is classified as a woodland habitat and currently is owned by logging companies and private land owners. The primary woodland habitat is dominated by eastern hemlock on the ridges and northern white cedar mainly in the swales. Other common species include red maple, yellow birch, and aspen on the ridges, and white and black spruce, balsam fir, and tamarack mainly in the swales. High levels of wetness, shallow rooting, and instability of the organics allows trees to be blown easily over during high winds and causes severe seedling mortality rates and windthrow hazards. Dominant ground flora include sphagnum, gold thread, bunch berry dogwoods, sedge, Canada mayflower, American starflower, and wood sorrel (Whitney, 1992).

METHODS

Sediment cores were collected using a land-based vibracorer (Thompson and others, 1991) to collect foreshore sediments. The lakeward side of beach ridges were cored to minimize collecting dune sand and to ensure that penetration was deep enough to include basal foreshore sediments. Sediment cores were retrieved following transects roughly perpendicular to the modern shoreline. Sediment-core elevations were determined using a transit and calibrated to the International Great Lakes Datum 1985 (IGLD85) using data from the closest gauging station, Point Iroquois, which is about 25 km east of the Tahquamenon Bay embayment. Sediment-core locations were determined using a Global Positioning System (GPS) and aerial photographs. Peat/organic cores were collected by hand-augering aluminum tubes into wetlands between beach ridges to obtain organic sediments at the deepest point in the swale. An onshore/offshore profile was surveyed and sediment samples were retrieved from each recorded elevation across the modern Tahquamenon Bay shoreline to investigate modern sedimentary relationships to lake level. 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. Core samples were sieved using a ½ phi interval and statistical parameters (mean, skewness, standard deviation, coarsest one-percentile, and kurtosis) were calculated for each sample by the mathematical method of moments. Statistical parameters were plotted per core to identify sedimentary variations at depth. Latex strips are physical records of the cores and were used to enhance the visibility of sedimentary structures that were not identified or well defined in the raw core. Visual descriptions, grain-size statistical results, photographs, and latex strips were compared to distinguish nearshore and onshore facies, specifically the upper and lower contacts of foreshore sediment. The elevation of the basal foreshore contact is interpreted as a record of lake level when the beach ridge began to form at Tahquamenon Bay. The upper contact is used in conjunction with the lower contact to calculate a foreshore thickness and is interpreted as an indicator of wave setup when the beach ridge formed in the Tahquamenon Bay embayment. Several clay samples found in the bottom of the sediment cores were analyzed for grain size and mineral content.

Wetland cores were split in half, described, photographed, and sampled. One basal, approximately 3-cm-thick organic sample was removed from each wetland core, dried, and sent to Geochron Laboratories, Cambridge, Massachusetts, for radiocarbon dating. The dates were calibrated to calendar years before 1950 using methods of Stuiver and Reimer (1993) to correct for variations in atmospheric ^{14}C through time. The age of the basal wetland sample is interpreted to approximate the age of the next lakeward adjacent beach ridge.

DETERMINATION OF LATE HOLOCENE LAKE-LEVEL VARIATION

Data

General

Fieldwork was conducted in Tahquamenon Bay between 7 July and 29 July 1999. Seventy-one sediment cores (vibracores) were retrieved from the lakeward side of beach ridges following three transects. Several vibracore holes needed to be revisited a second time and vibracored deeper to penetrate the clay underneath the foreshore sediment. The clay acts as a plug in the end of the aluminum tube to ensure the base of the foreshore was penetrated and retrieved. Sediment-core elevations were determined using a David White 300LT transit and calibrated to IGLD85 using the National Oceanic and Atmospheric Administration (NOAA) Point Iroquois, Michigan, gauging station, hour average of 6-minute water level height readings. Sediment-core locations were determined using a differential GPS and 1997 Michigan Department of Natural Resources (MDNR) air photographs (scale 1:15,840). Twenty-two peat/organic cores were retrieved from laterally continuous and well-developed wetlands along the same two landward transects as the sediment cores were obtained. One onshore/offshore transect of the modern shoreline was surveyed and 27 sediment samples were collected from the modern nearshore and onshore.

Onshore/Offshore Transects

One onshore/offshore topographic profile was surveyed and 27 sediment samples were collected from most of the recorded elevations on 29 July 1999 to determine the characteristics of modern dune, foreshore, and upper shoreface sediment in the Tahquamenon Bay study area. The 871-m-long transect extended from the top of the first dune ridge landward from the modern shoreline, into Lake Superior and across one offshore bar and two troughs. An hour average of 6-minute water level elevation readings from the Point Iroquois gauging station indicates the water level was 602.17 m (IGLD85) at the time of the survey. The crest of the first dune ridge landward from the modern shoreline was 1.2 m higher and 10 m landward of the current water/land intersect. The most lakeward part of the transect extended into an offshore trough, which extended 0.83 m below the water level and about 800 m offshore from the water/land intersect. Only the most landward part of the transect is plotted (65 m) to focus on topographic and grain-size trends near the modern shoreline (fig. 3).

The Tahquamenon Bay onshore/offshore profile decreases lakeward and contains a relatively steep profile from the first dune ridge to the water line, decreasing about 1.2 m over about 10 m with several steps forming scarps.

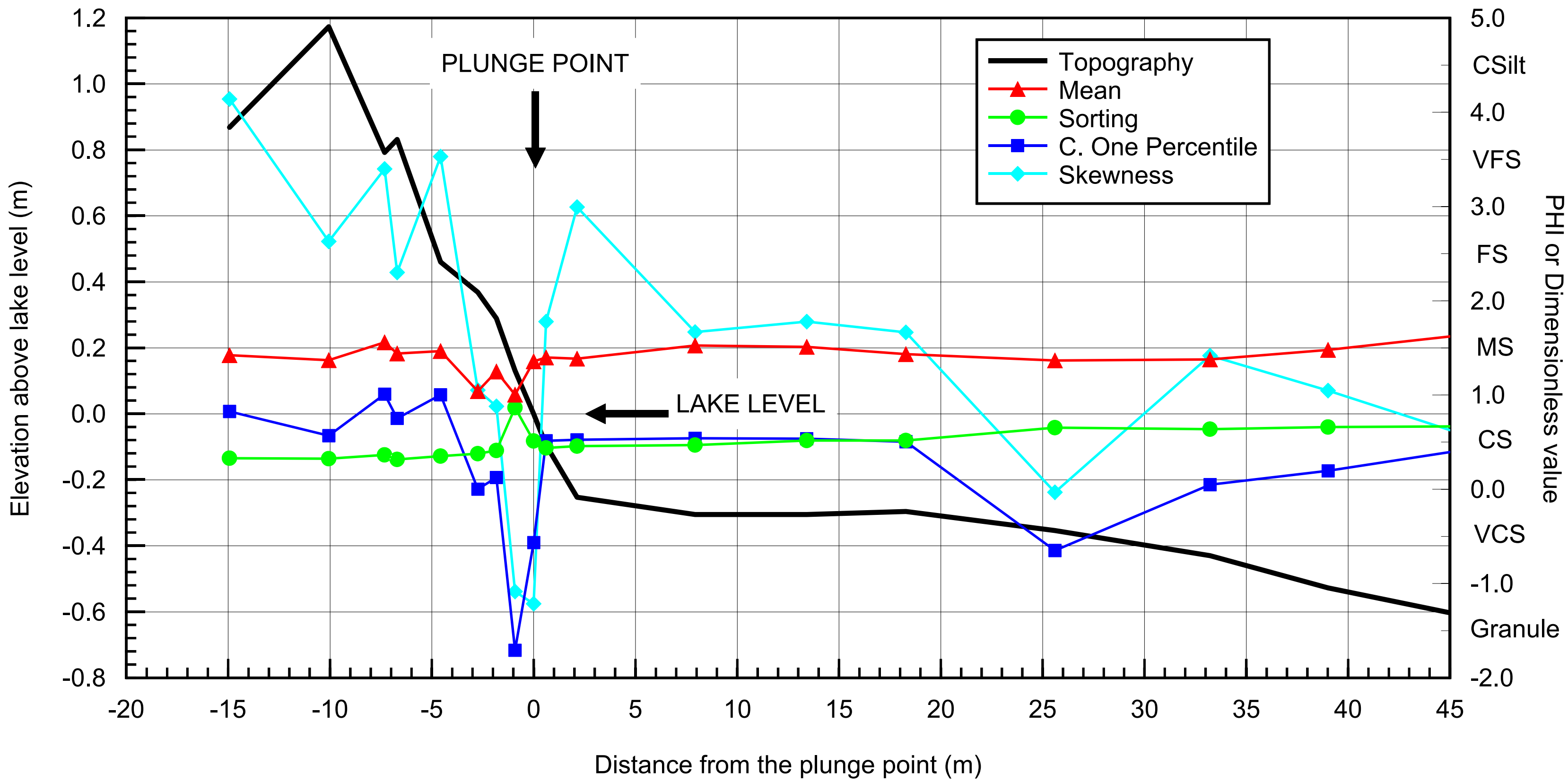

Figure 3. Onshore/offshore topography and grain-size trends perpendicular to the modern shoreline at Tahquamenon Bay, Michigan. The transect extends across the modern beach, over the plunge point (land/water interface) and into the nearshore. A steep topographic profile on the landward part of the transect suggests the modern shoreline is eroding. Sharp changes in grain-size trends at the plunge point indicates the base of the foreshore, which is a good approximation of the water level. Foreshore sediment is coarser-grained, more poorly sorted, and has a coarser C1% than adjacent sediment lakeward (upper shoreface) and landward (dune).

These scarps are related to decreased accommodation space, filling of the Tahquamenon Bay embayment or decreased sediment supply, littoral sediment captured by Whitefish Point or long-term rising lake level due to greater vertical movement (isostatic uplift) at the lake's outlet or a combination of these. Ample sediment supply from the Tahquamenon River about 10 km to the north of Tahquamenon Bay, some regional accommodation space in an indented shoreline between Emerson (Tahquamenon River outlet to Lake Superior) and Menekaunee Point (peninsula bordering eastern margin of Tahquamenon Bay embayment), and several offshore bars suggest a long-term rise in lake level has produced a long-term inundation of the shoreline.

Statistical grain-size trends across the shore-perpendicular transect at Tahquamenon Bay are typical of Great Lakes shorelines. Dune, foreshore, and upper shoreface sediments all show certain characteristics that distinguish them from each other.

Mean grain-size trends for dune, foreshore, and upper shoreface sediments vary within the medium sand grain-size fraction (fig. 3). The small grain size range may reflect few or a single source of sand. The coarsest sand is located where the waves break and wash up the beach face. Coarse-grained sediment is driven onshore by shoaling waves and accumulates at or slightly landward of the plunge point. A fining-offshore trend indicates fine-grained sediment is carried offshore by return flows. Therefore, foreshore sediment is slightly coarser than dune and upper shoreface sediment and is much coarser at the plunge point or plunge step, at the water line.

Coarsest one-percentile (C1%) trends change from coarse sand in the dune, medium sand to granules in the foreshore, and coarse to very coarse sand in the upper shoreface (fig. 3). The coarsest C1% occurs at the plunge step as in the mean grain-size trend and also represents coarse-grained sediment being driven onshore. A general fining offshore also indicates offshore transportation of fines. Because the C1% represents the fraction of sand carried as bed load, it is a good parameter to distinguish water-lain from wind-lain sediment. Upper shoreface sediment is transported by water, which is much more efficient at transporting bed load (coarser sediment) than wind, which is responsible for dune sediment transport.

Sorting trends change from very well sorted in the dune, well-sorted in the foreshore (moderately sorted at the plunge step), and well-sorted to moderately sorted in the upper shoreface (fig. 3). Dune sediment is better sorted than foreshore and upper shoreface sediment since wind is efficient at transporting only a small range of fine grains. Foreshore sediment is relatively well sorted since wind winnows out many of the fines and transports them into the dune. Plunge step sediment is more poorly sorted than upper shoreface sediment because coarse and fine-grained sediment is driven onshore but only a small range of fine-grained sediment returns offshore. Within the upper shoreface, C1% and mean grain size fine and become more poorly sorted with increasing distance offshore.

Skewness trends change from more strongly fine skewed in the dune, strongly fine skewed to strongly coarse skewed in the foreshore to less strongly fine skewed in the upper shoreface (fig. 3). Dune sediment consists of more fine grains due to wind transportation, foreshore sediment consists of more coarse sediment due to processes driving theses grains on shore and return flows winnowing out fines, and upper shoreface sediment consists of fine grains due to offshore transport of fines.

Vibracores

Seventy-one sediment cores from the lakeward margin of beach ridges in Tahquamenon Bay were split, described, photographed, sampled, and preserved on Masonite strips using Rub-R-Mold latex. A total of 1,281 grain-size samples were sieved using a ½ phi interval. Statistical parameters (mean, standard deviation, C1%, skewness, and kurtosis) were calculated for each sample to distinguish three sedimentary facies (dune, foreshore, and upper shoreface). The most useful statistical parameters in distinguishing the three facies from the onshore/offshore topographic profile are mean, sorting and C1% (fig. 3). These statistical parameters were also used to distinguish the three facies in core (fig. 4). Foreshore sediments are coarser-grained, more poorly sorted, and have coarser C1% than dune and upper shoreface sediments. Dune sediment is coarser-grained, has a coarser C1%, and is more poorly sorted than upper shoreface sediment and is finer-grained, has a finer C1%, and is better sorted than foreshore sediment. Upper shoreface sediment is finer-grained, more poorly sorted, and has a finer C1% than foreshore and upper shoreface. Several coarse grain horizons within the upper shoreface are related to storm deposits or offshore troughs created from longshore currents or both.

Statistical parameters were compared with visual descriptions, core photographs, and latex peels to determine the upper and lower boundary of the foreshore (fig. 5). The upper line represents the contact between dune and foreshore deposits. The next lower line represents the contact between foreshore and upper shoreface deposits, which represents the relative water-level elevation during beach ridge formation. The difference between the upper and lower foreshore contacts or thickness of foreshore deposits represent variations in wave setup during ridge formation. The lowest line represents a sand/clay contact. This contact defines a surface, consisting of clay, where shoreline sediment is deposited on top. All contact elevations across the strandplain generally decrease lakeward except for foreshore contacts lakeward of about 250 m.

Basal foreshore elevations decrease almost 12 m from the most landward to lakeward part of the strandplain with the largest decrease occurring in the most landward part, dropping almost 5 m from 2.1 to 1.8 km lakeward (fig. 5). Basal foreshore elevations indicate that relative lake levels, which include vertical movement and water level fluctuations, ranged from a maximum elevation of 195.91 m to a minimum elevation of 182.86 m above sea level (IGLD85) in the Tahquamenon Bay area.

Groups of three to six ridges separated by wider than normal wetlands and rising and falling elevations occur throughout the strandplain. Such groupings are more readily apparent when vertical movement is removed from the relative lake-level data. These groups are also apparent when viewing air photos of the embayment focusing on the coalescing ridges within a group near the edge of the embayment. Similar groupings in Lake Michigan strandplains were interpreted as 160-year quasi-periodic fluctuations (Baedke and Thompson, 2000).

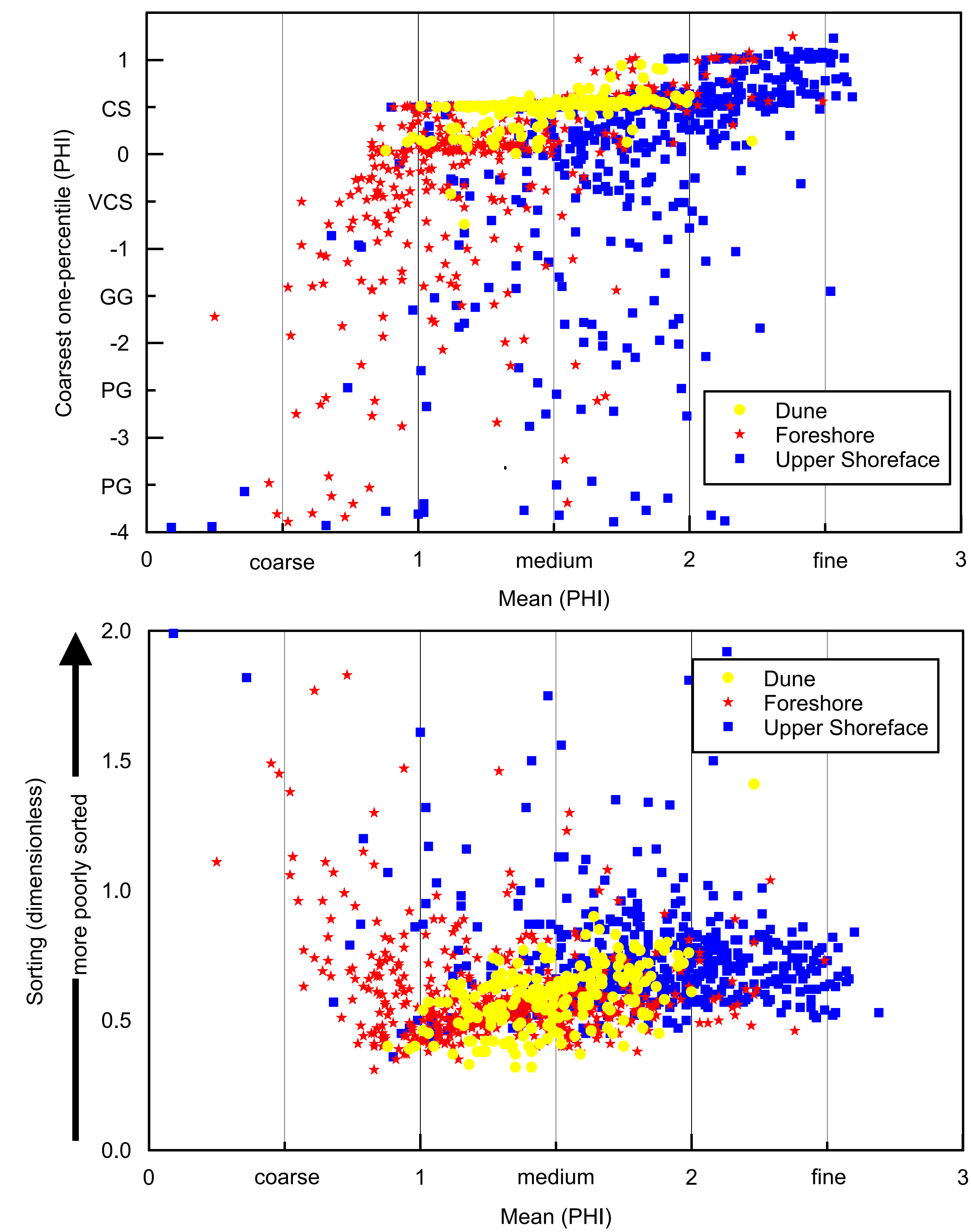

Figure 4. Statistical results of 1,281 sand samples collected from 71 beach-ridge cores in the Tahquamenon Bay embayment. Three sedimentary facies, dune, foreshore, and upper shoreface, form distinct overlapping zones. The most useful plots for distinguishing these three zones are mean versus C1% and mean versus sorting. Foreshore sediment is generally more poorly sorted, coarser-grained, and has a coarser C1% than dune and upper shoreface sediment. Coarse and poorly sorted outliers of upper shoreface sediment represent storm deposits.

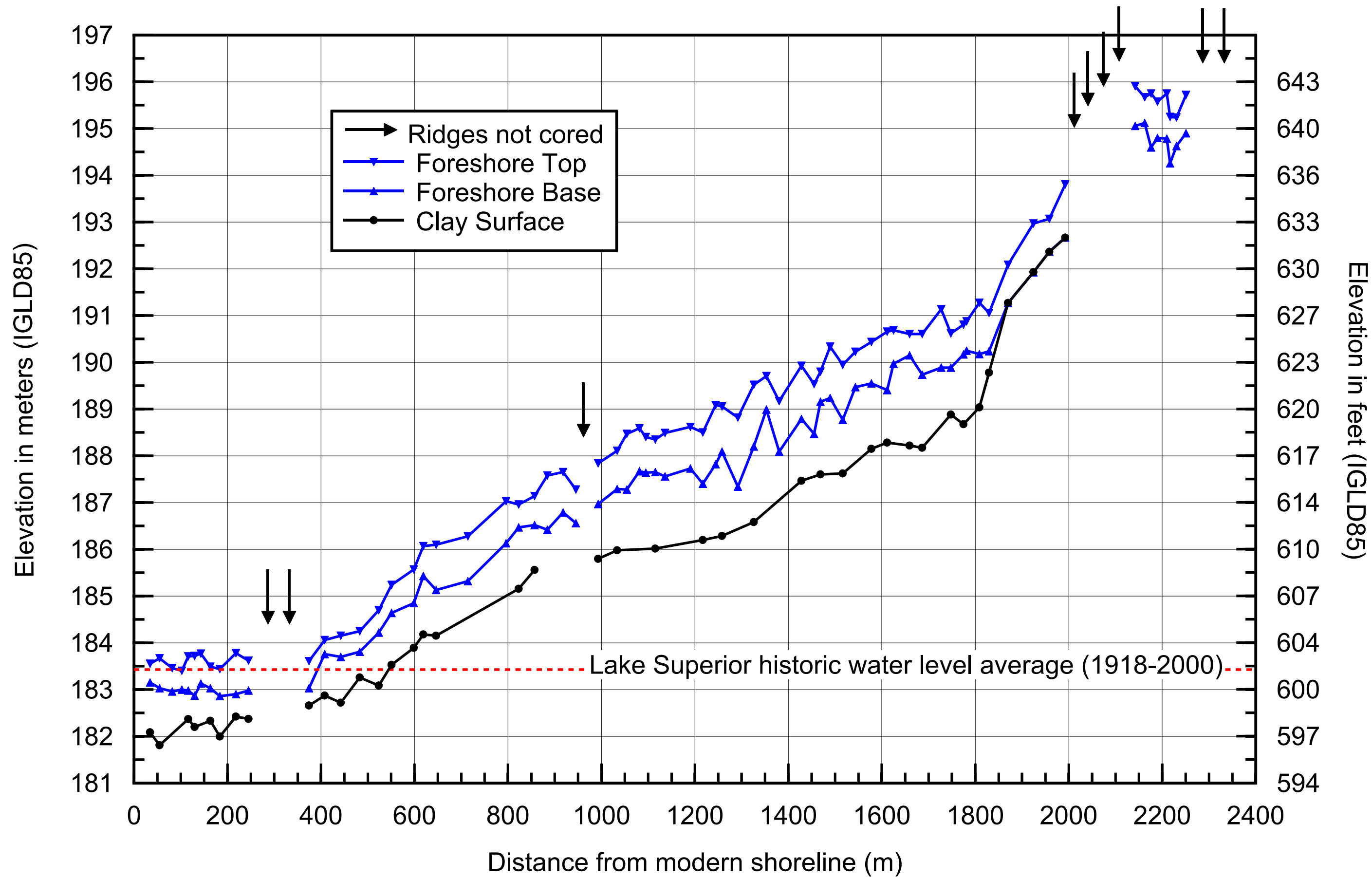

Figure 5. The elevation of upper and lower limits of foreshore sediment versus distance from the modern shoreline. The middle line represents the boundary between foreshore and upper shoreface sediment and approximates the elevation of the lake during beach-ridge formation. These measured elevations are unique only to the Tahquamenon Bay study site, since they record localized differential vertical movement from the time the beach ridge formed to present, as well as the elevation of the lake when the beach ridge formed. The uppermost line represents the boundary between dune and foreshore sediment and is used in conjunction with the middle boundary to calculate foreshore thickness, which approximates wave setup during beach-ridge formation. The lowermost line represents the contact between upper shoreface sediment and clay. This contact or upper surface of the clay is important since it reveals the predepositional surface on which the beach ridges formed.

The sand/clay contact or upper surface of the clay forms an important pre-depositional surface underneath the beach ridge strandplain. The slope of the clay surface decreases lakeward but is almost five times steeper between 2000 m and 1800 m than the slope lakeward (fig. 5). The clay surface also forms a slightly lakeward-dipping platform between 900 m and 1300 m. Deposits between the basal foreshore contact and the clay surface represent upper shoreface sediment, which was deposited subaqueously (down to average fairweather wave base). Upper shoreface thicknesses range from 0 (eroded after deposited) along the steeply sloping clay surface up to 1.94 m. Variations in clay surface elevations and upper shoreface thicknesses are due to fluctuations in water level and sediment supply. Clay surface trends are roughly similar to basal foreshore trends except in the most lakeward part of the curve where they diverge and in the most landward part of the curve where they converge. The clay surface slightly diverges from basal foreshore trends, increasing upper shoreface thicknesses lakeward. Projection of the clay surface into Lake Superior corresponds to bathymetric elevations lakeward of submerged bars, which extend up to about 300 m offshore (NOAA, 1997). Projection of basal foreshore elevations into Lake Superior are similar to bathymetric elevations calculated in the onshore/offshore profile. This suggests that a wedge of upper shoreface sand extends from underneath beach ridges on land to about 300 m offshore forming submerged bars in the nearshore. There is no evidence from reviewing data from upper shoreface deposits from the first 11 sediment cores to suggest there are multiple stacked foreshores in the lakeward wedge. Therefore, evidence for submerged beach ridges in the nearshore is lacking because there are no foreshore deposits and the current morphology is shaped by longshore currents.

Eleven clay samples retrieved from the bottom of the first two sediment cores landward of the modern Lake Superior shoreline were analyzed for grain size and mineralogy (fig. 6). Eight samples from core number 901 (lakeward) were retrieved from depths of 2.1 to 4.9 m (6.8 to 16.0 ft) below the ground surface and three samples from core number 902 (landward) were retrieved from depths of 2.5 to 3.1 m (8.1 to 10.2 ft) below the ground surface. Grain-size distributions and mineralogy between the samples from different cores at depth were nearly identical. Grain-size distributions above 3.1 m (10.2 ft) below the ground surface range from 1 to 6 percent sand, 35 to 53 percent silt, and 45 to 58 percent clay. Mineralogy of two samples, one from 2.1 m (6.9 ft) below the ground surface in core 901 and one from 2.5 m (8.2 ft) below the ground surface in core 902 include clay minerals such as chlorite, illite, and kaolinite, and nonclay minerals such as quartz and feldspar (plagioclase). Grain-size distributions below 3.1 m (10.2 ft) slightly increase in silt and decrease in clay and sand. The largest grain-size change occurs between 4.5 and 4.6 m (14.6 and 15.2 ft) below the ground surface in core number 902. The percent clay increases to 82 and 83 percent, the percent silt decreases to 12 and 13 percent, and the percent sand increases to 5 percent. Grain-size changes in core number 902 correlate to slight color changes identified in visual descriptions. The upper unit had few pockets of red clay in brown/deep red clay, the middle unit consisted of grey mixed in with deep red and brown clay, and the lower unit was characteristically more red than the upper two units. Clay units seemed to be massive having little mottling but the vibration of the vibracorer may have disturbed possible varved sequences Further mineralogical analysis is needed to better define the observed changes in core 902 and maybe relate each unit to different sediment sources or older lake stages or both.

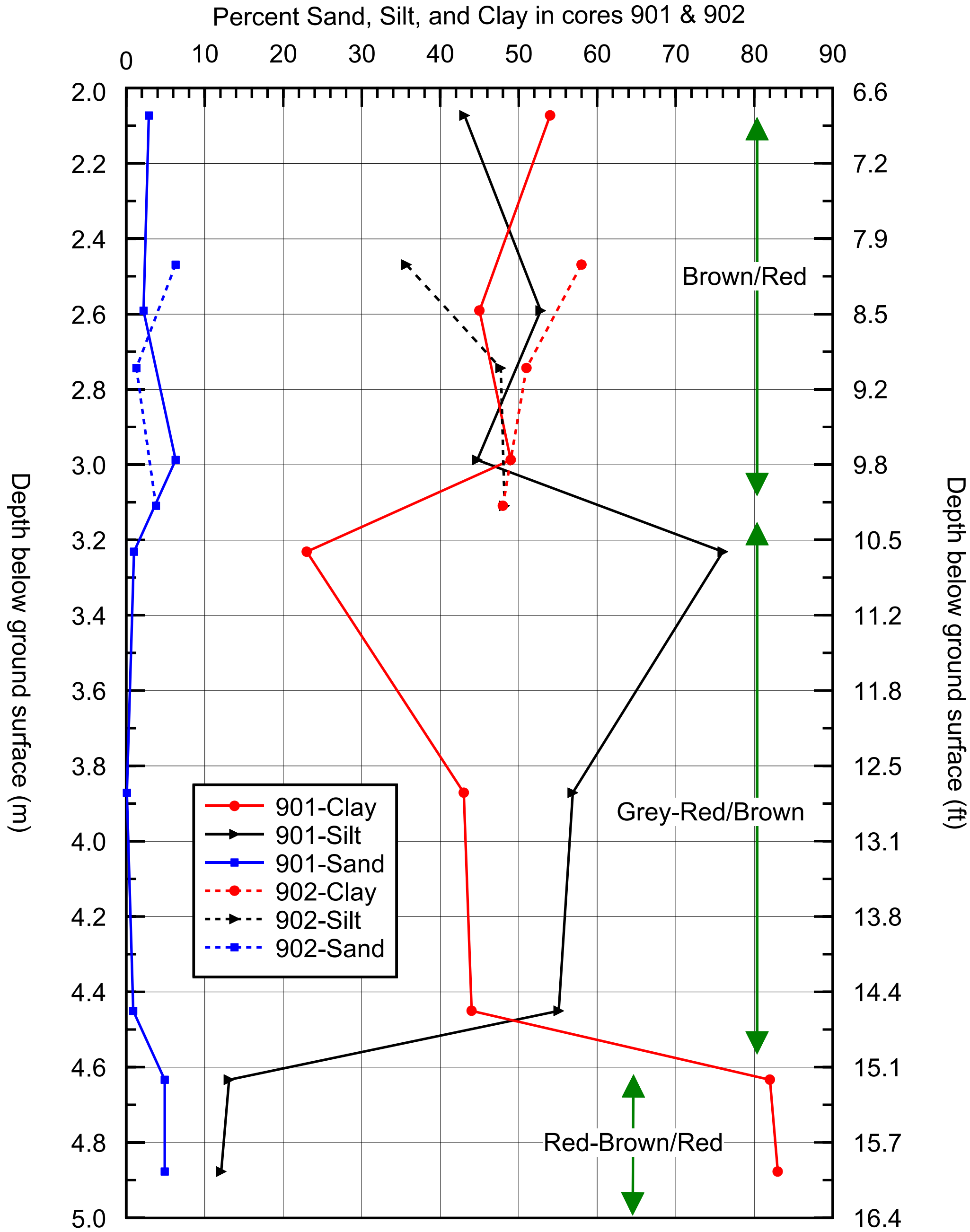

Figure 6. Grain-size analysis of 11 clay samples from beneath two beach ridges adjacent to the modern Tahquamenon Bay shoreline. Although the depth of penetration varies between cores, grain-size variations are similar at depth. Three different grain-size units have been identified. The upper unit consists of almost equal percentages of silt and clay, the middle unit consists of more silt than clay, and the lower unit consists almost entirely of clay. These units may represent different sources or are related to different older lake stages or both. Further mineralogical analysis must be completed to investigate ideas.

Peat Cores

A total of 35 dates were used to estimate the age of beach ridges in the Tahquamenon Bay embayment. Twenty-two peat and organic samples and eight macrofossils from basal wetland sediments between beach ridges and five organic samples from basal foreshore sediments were radiocarbon dated. All radiocarbon dates were corrected 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 then used to estimate the age of beach ridges by plotting distance from the modern shoreline versus age (fig. 7). A best-fit line was used to estimate the age of each beach ridge since less than half of the ridges had corresponding dates and there was considerable variability between dates ($r^2 = 0.70$). The regression line intersects the modern shoreline (0 m) at about 1960 cal. yrs. B.P., which indicates that beach ridges did not form or were not preserved for about the last 2,000 years in the Tahquamenon Bay embayment. The erosional scarp identified in the onshore/offshore transect indicates recent erosion along the modern shoreline. The inverse of the slope of the regression line in the distance versus age plot indicates the progradation rate was about 0.98 m/yr in the Tahquamenon Bay embayment. The slope of the regression line in the ridge number versus age plot indicates each beach ridge was created approximately every 31 ± 3.7 years in the Tahquamenon Bay embayment. This rate of beach ridge formation in the Tahquamenon Bay embayment is similar to rates calculated from strandplains in Lake Michigan with a range of 29 to 38 years per ridge (Thompson and Baedke, 1997).

Discussion

Regression analysis of distance versus age was used to estimate an age for each beach ridge in the Tahquamenon Bay embayment. Upper and lower foreshore elevations from sediment core analysis were combined with age estimates to create a relative lake-level curve for Tahquamenon Bay (fig. 8). Beach ridges at Tahquamenon Bay record relative lake-level fluctuations from about 4,300 to 2,000 cal. yrs. B.P. Basal foreshore elevations indicate relative lake-levels ranged from about 195.91 m to 182.86 m above sea level (IGLD85). A rapid relative lake-level drop of at least 4 m between about 4,100 and 3,800 cal. yrs. B.P. was recorded in the most landward part of the strandplain. Baedke and Thompson (2000) observed a rapid decline approximately 4.1 m from about 4,400 to 4,000 cal. yrs. B.P. in the Manistique strandplain on the northern shore of Lake Michigan. This rapid drop was associated with a fall from the Nipissing II high water level phase. Basal foreshore elevations in the 11 most lakeward-cored beach ridges remain fairly constant and vary below the historic mean lake-level elevation for Lake Superior. Johnston and others (2000) observed a long-term relative lake-level fall followed by a short-term relative lake-level rise at about 1,200 years B.P. at Grand Traverse Bay, Michigan, and attributed it to the outlet at Sault Ste. Marie regulating Lake Superior lake levels. Since Tahquamenon Bay has experienced similar uplift rates as the Sault Ste. Marie outlet (based on historical gauge data; CCBHD, 1977) relative lake levels should be similar to those seen at the outlet and there should be a constant or slight rise in relative lake level. However, dates at Tahquamenon Bay suggest the outlet at Sault Ste. Marie may have begun regulating Lake Superior lake levels around 2,300 cal. yrs. B.P., if the strandplain represents a continuous sequence.

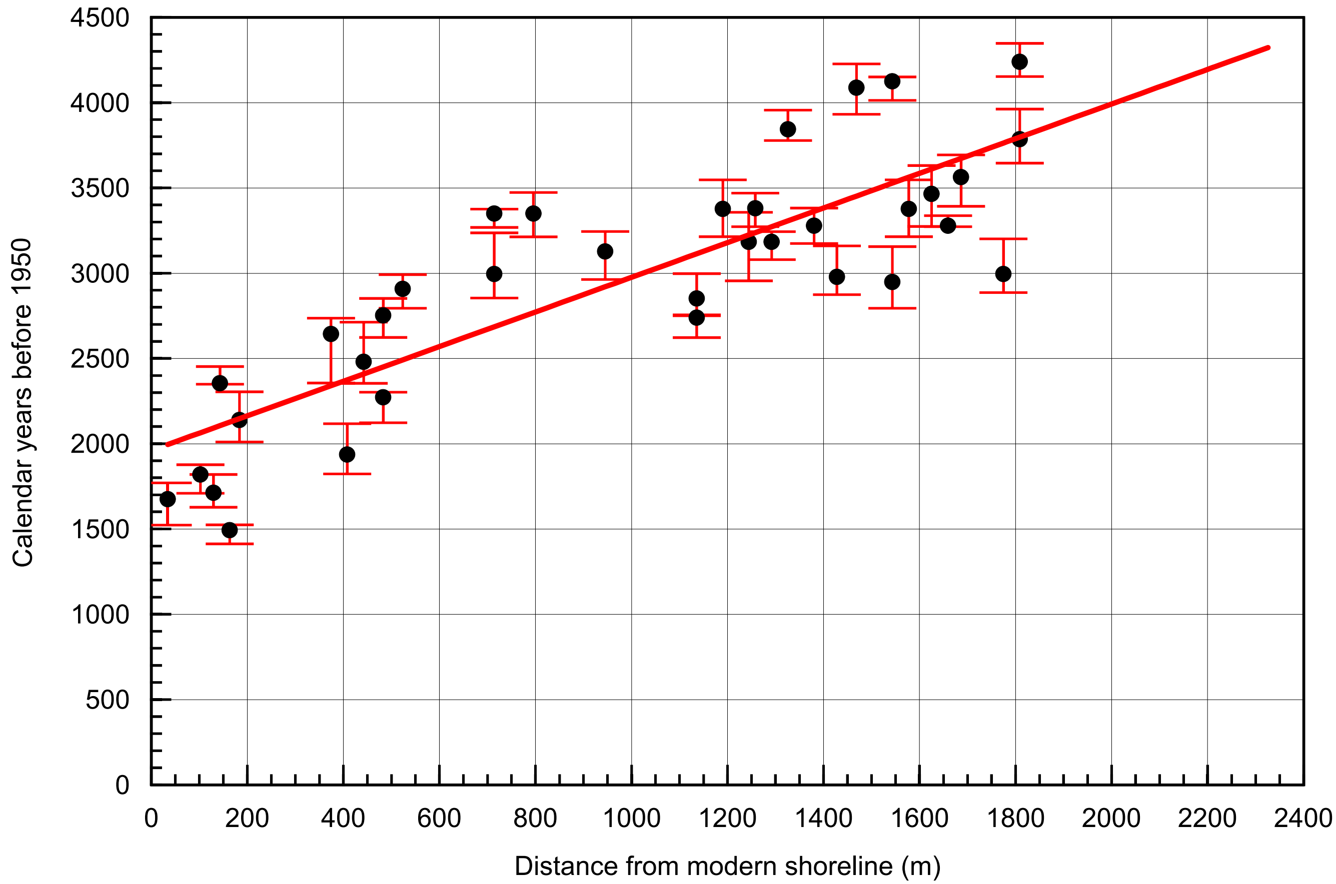

Figure 7. Calibrated age versus distance from the modern shoreline. Twenty-two peat/organic dates (bulk) and eight macrofossil dates (AMS) from the base of wetlands between ridges and five peat/organic dates (bulk) from basal foreshore sediments from sediment cores were used. A line of best fit was used to calculate approximate ages for each beach ridge in the Tahquamenon Bay embayment. Age generally increases further inland starting at about 2,000 years before 1950. The inverse slope of the best-fit line indicates the approximate progradation rate of the strandplain was 0.98 m/yr.

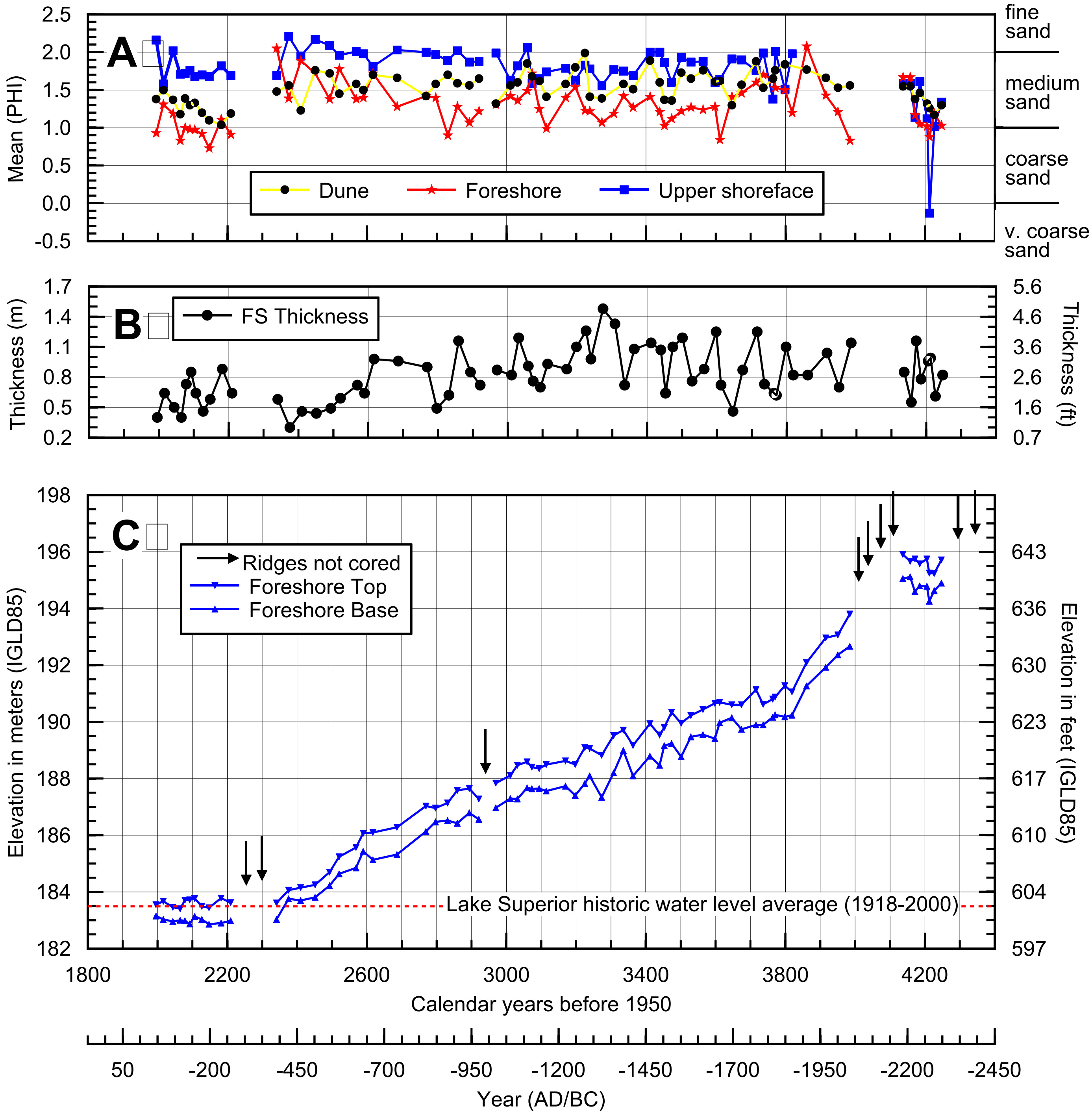

Figure 8. Mean grain size of nearshore and onshore facies per core (A), foreshore thickness (B), and foreshore (top and base) elevation trends (C) versus calendar years before 1950 across the entire Tahquamenon Bay strandplain. Dune and foreshore mean grain size coarsens at about 2,300 cal. yrs. B.P., whereas upper shoreface remains fairly constant. Foreshore thickness decreases from about 3,300 to 2,300 cal. yrs. B.P. and remains fairly constant from about 4,200 to 3,400 cal. yrs. B.P. Basal foreshore elevations indicate relative lake levels lowered rapidly between about 4,100 and 3,800 cal. yrs. B.P., lowered gradually from about 3,800 to 2,300 cal. yrs. B.P., and remained fairly constant from about 2,200 to 2,000 cal. yrs. B.P. (Note: Basal foreshore elevations in (C) are relative lake-level elevations with respect to only Tahquamenon Bay because vertical movement has not been removed.)

Mean grain-size and foreshore thickness trends are plotted across the entire beach ridge strandplain above the relative lake-level curve in figure 8. Foreshore thickness ranges from 0.3 to 1.5 m, having an average of 0.8 m. Foreshore thickness remains fairly constant from about 4,200 to 3,300 cal. yrs. B.P., decreases approximately 1 m from about 3,300 to 2,300 cal. yrs. B.P., and decreases approximately 0.3 m from about 2,200 to 2,000 cal. yrs. B.P. Decreasing foreshore thicknesses indicate a smaller wave setup during beach ridge formation and may be related to a shift in the predominant wind directions and decreased wave setup. Mean grain size ranges from 0.7 phi (coarse sand) to 2.2 phi (fine sand) in the Tahquamenon Bay strandplain. Foreshore sediment is generally coarser-grained than dune sediment and dune sediment is coarser-grained than upper shoreface sediment. The only major mean grain-size changes occur between 2,900 and 2,300 cal. yrs. B.P., where the foreshore fines gradually while the dune and upper shoreface remain relatively constant, and at about 2,300 cal. yrs. B.P. where the dune and foreshore coarsens abruptly while the dune and upper shoreface remain fairly constant.

The sediment source for the Tahquamenon Bay embayment currently seems to be from the north. The orientation of a sand spit south of the Tahquamenon River and a wedge of sediment along the coastline north of the Tahquamenon River suggest littoral transportation is toward the Tahquamenon Bay embayment (south). This suggests the Tahquamenon River is supplying sediment by reworking coastal sediment to the north and is supplying sediment to the Tahquamenon Bay embayment. The large supply of sand and the shallow-water platform, defining the Tahquamenon Bay, seems ideal for beach ridge development and preservation. Since the Tahquamenon Bay embayment, defined in this study, is lacking in accommodation space, it is likely that future beach ridges would form along the shore of Tahquamenon Bay.

The original source of sand, a certain rock formation, is difficult to ascertain because specific bedrock geologic information is lacking in the study area (namely, bedrock boundaries). Three formations could be the source of sand--the Au Train, Munising, and/or Jacobsville formations. The Au Train and Munising Formations form the outermost concentric bands of bedrock associated with the Michigan structural basin and surface in areas close to the Tahquamenon Bay study site. The Jacobsville formation is located underneath the Au Train and Munising Formations near the study area but presumably forms the bedrock surface under Whitefish Point, which is just north of the study area. Since the Au Train Formation consists predominantly of hard sandy dolomite and the Munising Formation consists predominantly of soft, friable sandstone, the Munising Formation seems a more likely source for sand. The sand spit at the mouth of the Tahquamenon River and exposures of the Munising Formation at Tahquamenon Falls suggest that the Munising Formation is probably a dominant source of sediment for the study site area transported to the Tahquamenon River. Further analysis is essential for a clear correlation (namely, mineralogy) however, sediment sources may have changed throughout time.

SUMMARY

A relative lake-level curve for Tahquamenon Bay, Michigan, was created by a systematic technique of vibracoring the lakeward margin of beach ridges to obtain lake-level information, and radiocarbon dating basal foreshore sediment and hand augering and radiocarbon dating basal wetland sediments between beach ridges to obtain beach ridge age information. The curve indicates that beach ridges in the Tahquamenon Bay embayment recorded lake levels from about 4,300 to 2,000 cal. yrs. B.P. During the recorded period, relative lake levels dropped rapidly (almost 5 m) from about 4,100 to 3,800 cal. yrs. B.P., lowered gradually (approximately 7 m) from about 3,800 to 2,300 cal. yrs. B.P., and remained fairly constant from about 2,300 to 2,000 cal. yrs. B.P. The rapid drop is associated with a drop in water level from the Nipissing II high water level phase and the change from a gradual fall to a fairly constant slope is associated with an outlet change from Port Huron to Sault Ste. Marie, regulating lake levels in Lake Superior. Grain-size and foreshore thickness trends may be attributed to variations in sediment source, littoral currents, wave climate, outlet location and outflow characteristics, and vertical movement between the study area and the outlet.

A short-term quasi-periodic lake-level fluctuation with a period of about 31 years was instrumental in the formation of beach ridges in the Tahquamenon Bay embayment. Foreshore elevations rise and fall in groups of four to six beach ridges in each set and are interpreted to represent quasi-periodic fluctuations of longer duration. Superimposed on these shorter-duration fluctuations are differential vertical movement, outflow location changes or restrictions, and Lake Superior hydrodynamics.

ACKNOWLEDGMENTS

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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.)
901	34.00	184.13	1995.58	183.55	183.15	1.38	0.93	2.16
902	54.40	184.25	2016.31	183.67	183.03	1.50	1.31	1.58
903	81.60	184.38	2043.93	183.46	182.96	1.37	1.19	2.02
904	102.00	184.37	2064.65	183.40	183.00	1.18	0.83	1.71
905	115.60	184.32	2078.47	183.71	182.98	1.39	1.00	1.72
906	129.20	184.27	2092.28	183.72	182.87	1.30	0.98	1.76
907	142.80	184.53	2106.10	183.77	183.13	1.33	0.97	1.68
908	163.20	184.31	2126.82	183.49	183.03	1.20	0.92	1.70
909	183.60	184.25	2147.54	183.44	182.86	1.10	0.73	1.68
910	217.60	184.48	2182.08	183.78	182.90	1.04	1.11	1.82
911	244.80	184.23	2209.70	183.62	182.98	1.19	0.91	1.69
912	374.00	184.22	2340.94	183.61	183.03	1.48	2.05	1.69
913	408.00	184.46	2375.47	184.06	183.76	1.56	1.39	2.21
914	442.00	184.52	2410.01	184.15	183.70	1.23	1.89	1.95
915	482.80	184.77	2451.45	184.25	183.81	1.76	1.72	2.17
916	523.60	185.16	2492.89	184.70	184.22	1.72	1.38	2.09
917	550.80	185.66	2520.52	185.24	184.64	1.45	1.78	1.96
918	598.40	186.07	2568.87	185.57	184.85	1.58	1.38	2.01
919	618.80	186.77	2589.59	186.07	185.43	1.50	1.40	1.98
920	646.00	186.71	2617.22	186.10	185.13	1.70	1.72	1.81
921	714.00	186.92	2686.29	186.28	185.32	1.66	1.28	2.03
922	795.60	187.39	2769.18	187.03	186.13	1.42	1.42	2.00
923	822.80	187.72	2796.81	186.96	186.47	1.58	1.40	1.97
924	856.80	187.85	2831.34	187.14	186.52	1.70	0.90	1.89
925	884.00	188.13	2858.97	187.58	186.42	1.59	1.28	2.02
926	918.00	188.21	2893.51	187.65	186.79	1.56	1.07	1.87
927	945.20	188.19	2921.13	187.28	186.56	1.65	1.22	1.88
928	992.80	188.39	2969.48	187.84	186.97	1.32	1.31	1.99
929	1033.60	188.69	3010.93	188.11	187.29	1.56	1.42	1.63
930	1054.00	189.11	3031.65	188.47	187.28	1.60	1.36	1.82
931	1081.20	188.92	3059.28	188.59	187.67	1.85	1.49	2.06
932	1094.80	189.16	3073.09	188.40	187.64	1.68	1.72	1.59
933	1115.20	188.81	3093.81	188.35	187.65	1.62	1.25	1.65
934	1135.60	188.92	3114.53	188.49	187.56	1.41	0.99	1.74
935	1190.00	189.26	3169.79	188.62	187.73	1.58	1.40	1.79
936	1217.20	189.29	3197.42	188.50	187.40	1.80	1.54	1.63
937	1244.40	189.39	3225.05	189.09	187.82	1.99	1.23	1.83
938	1258.00	189.40	3238.86	189.06	188.09	1.41	1.22	1.78
939	1292.00	189.52	3273.40	188.82	187.34	1.39	1.07	1.56
940	1326.00	189.52	3307.93	189.52	188.20		1.19	1.77
941	1353.20	190.20	3335.56	189.71	188.99	1.58	1.42	1.75
942	1380.40	189.84	3363.19	189.17	188.09	1.51	1.27	1.69
943	1428.00	190.28	3411.54	189.93	188.79	1.89	1.41	2.00
944	1455.20	190.18	3439.17	189.54	188.47	1.60	1.21	2.00
945	1468.80	190.44	3452.98	189.80	189.16	1.37	1.03	1.86
946	1489.20	191.07	3473.70	190.34	189.24	1.36	1.12	1.60
947	1516.40	190.72	3501.33	189.95	188.77	1.73	1.22	1.93
948	1543.60	191.09	3528.96	190.23	189.47	1.65	1.27	1.87
949	1577.60	191.08	3563.49	190.44	189.55	1.76	1.24	1.88
950	1611.60	191.02	3598.03	190.66	189.41	1.61	1.28	1.60
951	1625.20	191.08	3611.84	190.69	189.97	1.62	0.84	1.64
952	1659.20	191.19	3646.38	190.61	190.15	1.30	1.41	1.91
953	1686.40	191.16	3674.01	190.61	189.74	1.57	1.46	1.90
954	1727.20	191.57	3715.45	191.14	189.89	1.88	1.60	1.76
955	1747.60	191.47	3736.17	190.62	189.89	1.53	1.70	1.99
956	1774.80	191.45	3763.80	190.81	190.17	1.65	1.64	1.38
957	1781.60	191.59	3770.71	190.88	190.25	1.76	1.53	2.01
958	1808.80	191.74	3798.34	191.28	190.18	1.84	1.50	1.51
959	1829.20	191.61	3819.06	191.06	190.24		1.20	1.98
960	1870.00	192.58	3860.50	192.09	191.27	1.77	2.08	
961	1924.40	193.43	3915.76	192.97	191.93	1.66	1.43	
962	1958.40	193.87	3950.29	193.07	192.37	1.53	1.21	
963	1992.40	194.43	3984.83	193.81	192.67	1.56	0.83	
964	2142.00	196.40	4136.78	195.91	195.06	1.55	1.67	1.59
965	2162.40	196.43	4157.50	195.67	195.12	1.55	1.67	1.59
966	2176.00	196.21	4171.32	195.75	194.60	1.38	1.17	1.14
967	2189.60	196.25	4185.13	195.58	194.80	1.46	1.05	1.61
968	2210.00	196.45	4205.85	195.75	194.79	1.32	1.02	1.12
969	2216.80	196.21	4212.76	195.25	194.26	1.26	0.88	-0.13
970	2230.40	196.30	4226.57	195.24	194.63	1.17	1.19	1.02
971	2250.80	196.51	4247.30	195.72	194.90	1.30	1.03	1.34