2014

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Fisher, Timothy G.; Krantz, David E.; Castaneda, Mario R.; Loope, Walter L.; Jol, Harry M.; Goble, Ronald J.; Higley, Melinda C.; DeWald, Samantha; and Hanson, Paul R., "Coastal geology and recent origins for Sand Point, Lake Superior" (2014). *Papers in the Earth and Atmospheric Sciences*. 418.

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ABSTRACT

Sand Point is a small cusate foreland located along the southeastern shore of Lake Superior within Pictured Rocks National Lakeshore near Munising, Michigan. Park managers' concerns for the integrity of historic buildings at the northern periphery of the point during the rising lake levels in the mid-1980s greatly elevated the priority of research into the geomorphic history and age of Sand Point. To pursue this priority, we recovered sediment cores from four ponds on Sand Point, assessed subsurface stratigraphy onshore and offshore using geophysical techniques, and interpreted the chronology of events using radiocarbon and luminescence dating. Sand Point formed at the southwest edge of a subaqueous platform whose base is probably constructed of glacial diamicton and outwash. During the post-glacial Nipissing Transgression,

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the base was mantled with sand derived from erosion of adjacent sandstone cliffs. An aerial photograph time sequence, 1939–present, shows that the periphery of the platform has evolved considerably during historical time, influenced by transport of sediment into adjacent South Bay. Shallow seismic reflections suggest slump blocks along the leading edge of the platform. Light detection and ranging (LiDAR) and shallow seismic reflections to the northwest of the platform reveal large sand waves within a deep (12 m) channel produced by currents flowing episodically to the northeast into Lake Superior. Ground-penetrating radar profiles show transport and deposition of sand across the upper surface of the platform. Basal radiocarbon dates from ponds between subaerial beach ridges range in age from 540 to 910 cal yr B.P., suggesting that Sand Point became emergent during the last ~1000 years, upon the separation of Lake Superior from Lakes Huron and Michigan. However, optically stimulated luminescence (OSL) ages from the beach ridges were two to three times as old as the radiocarbon ages, implying that emergence of Sand Point may have begun earlier, ~2000 years ago. The age discrepancy appears to be the result of incomplete bleaching of the quartz grains and an exceptionally low paleodose rate for the OSL samples. Given the available data, the younger ages from the radiocarbon analyses are preferred, but further work is necessary to test the two age models.

INTRODUCTION

The level of Lake Superior rose in the early 1980s to a record high (U.S. Army Corps of Engineers, 2012), threatening many man-made structures along the lake's southeastern shore. Threatened structures included a historic station of the U.S. Life Saving Service on the north edge of Sand Point, a small cusped foreland northeast of Munising, Michigan, within Pictured Rocks National Lakeshore (PRNL) (Fig. 1). As a unit of the National Park Service, PRNL is charged by law and policy with the protection of historic features, such as the life-saving station, while maintaining natural coastal processes to the extent possible.

Challenged by the tension between these competing management goals, and by rising lake levels, PRNL commissioned a study to assess the natural dynamics and geomorphic history of Sand Point (Farrell and Hughes, 1984). Farrell and Hughes used a time series of aerial photographs to show that continual change along the periphery of Sand Point predated the rise of lake level in the early 1980s. After storm surge during the fall of 1989 caused partial flooding of the historic station, PRNL emplaced an ~125 m rock revetment along the eroding northern shore of Sand Point. In subsequent years, water levels of Lake Superior receded and additional flooding events have not occurred. However, since 1991 small zones of continued erosion have developed along the western shore of Sand Point despite emplacement of the revetment and generally falling lake levels. Young (2004) suggested that the revetment may have perpetuated or driven erosion.

Models of late Holocene variations of water planes of the upper Great Lakes have been developed in the past 15 years that incorporate ages and stratigraphic analysis of beach-ridge sequences. These beach-ridge studies document century-scale periodicity of lake-level change of ~1–2 m for the past 4700 years (Thompson and Baedke, 1997; Baedke and Thompson, 2000).

Recent investigations elsewhere in the Lake Superior basin document the response of lake level to the emergence of a bedrock sill at Sault Ste. Marie by differential rebound (Johnston et al., 2007a, 2012). This event separated Lake Superior from Lakes Huron and Michigan, and started a slow transgression of the south shore of Lake Superior. This separation may have initiated development of Sand Point as a cusped foreland.

In the wake of the mixed success of shoreline protection efforts by PRNL and additional research, we here further test existing models of shoreline evolution at Sand Point. To that end, we recovered sediment cores from four ponds on Sand Point, assessed subsurface stratigraphy onshore and offshore using geophysical techniques, and interpreted the chronology of events using radiocarbon and luminescence dating. These data will be used directly to determine whether Sand Point emerged during the past ~1000 years during the Sub-Sault Phase of Lake Superior. The data also provide an opportunity to investigate the internal structure of a small cusped foreland in a non-tidal, freshwater lake environment.

Study Area

Sand Point is an emergent cusped foreland of ~50 ha lying within a protected embayment of Lake Superior (Fig. 1B). To the west is Grand Island, a bedrock high separated from the mainland by a broad, 2-km-wide trough cut into bedrock that trends northeast to southwest between the mainland and Grand Island. To the southwest, the trough leads into South Bay, a deep basin that fronts on the city of Munising. This trough and several other subparallel features in the area were likely formed as subglacial tunnel channels (Regis et al., 2003) with unknown depths of Holocene fill. Sand Point and its associated subaqueous platform extend 1.5 km into the bedrock trough.

Sand Point sits on the southern end of a subaqueous platform that is five times larger than the subaerial feature. The platform extends 3 km to the northeast as a narrowing wedge along the cliff shoreline of Pictured Rocks toward the promontory of Miners Castle Point (Figs. 1B, 2A). The friable sandstone exposed in the cliffs (Fig. 2) appears to be a source of sediment for both the platform and subaerial Sand Point. Presumably erosion of the cliffs has been ongoing during lake-level highstands for the past 10,700 years since deglaciation (Fisher and Whitman, 1999).

Bedrock within the study area consists of Lower Paleozoic sedimentary rocks along the northern flank of the Michigan Basin. Upward from the Precambrian basement is 300 m of the Lower and Middle Cambrian Jacobsville Formation, ~70 m of the Upper Cambrian Munising Formation, and the Ordovician Au Train Formation (Hamblin, 1958; Haddox, 1982). At the study site, the ~20-m-thick Chapel Rock Member of the Munising Formation is exposed at and below modern lake level. This unit is composed of relatively competent, cross-bedded sandstone with some thin mudstone beds. Overlying the Chapel Rock Member is the ~52-m-thick Miners Castle Member that forms the cliffs of that portion of the Pictured Rocks adjacent to the study area (Figs. 2B, 2D). The bulk of the Miners Castle Member consists of weakly competent sediments ranging from fine conglomerate to

shale. Resistant dolomitic sandstone of the Au Train Formation caps the sequence (Hamblin, 1958; Haddox, 1982).

While waves from major storms presently erode the cliffs of the Pictured Rocks, the historical rate of cliff retreat is slow. However, during the mid-Holocene Nipissing highstand Lake Superior stood ~12 m higher and the erodible, slope-forming units of the Miners Castle Member would have been exposed to direct wave attack. We assume that at this time, a significant volume of sand was mined from the Miners Castle Member and supplied to the littoral system. This sand apparently was deposited on the upper surface of the Sand Point platform.

Lake-Level History

While the general history of Holocene lake-level fluctuation in the Lake Superior basin has been established, the timing of many events is not well constrained. A maximum age of ~11.6 ka B.P. for recession of the Superior Lobe of the Laurentide Ice Sheet (LIS) has been established 80 km west of the study area (Lowell et al., 1999; Pregitzer et al., 2000). The position of the Munising Moraine, a few kilometers south of Sand Point (Fig. 1B) marks the analogous ice margin. A minimum radiocarbon age of 10.9 ka B.P. for ice retreat was derived from wood at

Figure 1. (A) Location of the study area on the southeastern shore of Lake Superior in eastern Upper Michigan. Label 1 shows Whitefish Point, and Label 2 shows the outlet of Lake Superior (Sault outlet) leading to the St. Marys River. (B) Hillshade digital elevation model of the topography surrounding the study area at Sand Point. P.R.N.L.—Pictured Rocks National Lakeshore.

Figure 2. (A) Google Earth image of the study site at Sand Point and surrounding area northeast of Munising, Michigan. Zone of greater cliff recession between Miners Castle Point and White Rock is shown as dashed white line. Path of subsequent southwest littoral drift of sand is shown by thin white arrow. (B) Oblique aerial view of bluffs north of the inflection point. (C) 115 m of cliff retreat at the inflection point. Images B and C are from the Lake Superior Watershed Partnership. (D) Cross section a-a' (from A) showing elevation, topography, stratigraphy, peak Nipissing phase level and modern level of Lake Superior, modified from Handy and Twenter (1985). LL—lake level. (E) View of cliffs northeast of Miners Castle Point showing subaerial units portrayed in D.

the bottom of Beaver Lake 30 km northeast of Sand Point (Fisher and Whitman, 1999).

Proglacial Lake Minong formed between the receding LIS and the Upper Peninsula of Michigan. The highest water surface of Lake Minong was ~30 m higher than Lake Superior today along the eastern side of the Upper Peninsula (Loope et al., 2010). Water levels fell abruptly to the Houghton Low when the Nadoway Barrier in the southeast corner of the Lake Superior basin was breached at 9300 cal yr B.P. (Yu et al., 2010), and the early St. Marys River (Fig. 1A) became the outlet. The lake fell below the St. Marys River outlet into a hydrologically closed condition from 9100 to 8900 cal yr B.P. in the dry early Holocene climate (Boyd et al., 2012). After 8900 cal yr B.P., the higher glacioisostatic rebound rates at the North Bay outlet raised water level in the Superior basin to the mid-Holocene Nipissing highstand by 4500 cal yr B.P. (Thompson et al., 2011; Fisher et al., 2012; Thompson et al., this volume). At this time water levels were confluent in the Superior, Michigan and Huron basins. Glacioisostatic rebound rates were higher at the North Bay, Ontario outlet controlling lake level until the Port Huron outlet at the south end of Lake Huron was activated.

Following lake-level lowering in the Lakes Michigan and Huron basins at 4300 cal yr B.P. (Baedke and Thompson, 2000; Thompson et al., 2011; this volume), the Port Huron outlet remained the controlling outlet for Lake Superior since the St. Marys River lowland was submerged at this time. However, because the lowland lies on an isobase that has been rising faster than that at Port Huron, the St. Marys River eventually emerged at Sault Ste. Marie as the controlling outlet for Lake Superior (Sub-Sault phase of Farrand, 1960). Subsequently, areas northeast of the St. Marys River have been uplifted relative to the outlet, resulting in coastal emergence along the northeast shore of Lake Superior. Areas southwest of the isobase, including Sand Point, are experiencing submergence and coastal transgression (Johnston et al., 2004; 2007a, 2007b; 2012).

The transition from regression to transgression near the study site has been documented at the Au Train embayment 15 km to the west (Fig. 1B). At this site, Johnston et al. (2007b) collected a series of vibracores and ground-penetrating radar transects across a strandplain of beach ridges. Paleo lake levels were determined from sedimentological analysis of foreshore deposits recovered in the vibracores. The inflection point from decreasing to increasing elevation basinward of the foreshore gravels is mimicked by the beach ridges that rise in elevation basinward.

From a series of strandline chronosequences in the Lake Superior basin, Johnston et al. (2012) report an inflection point in the lake-level curve at 1100 ± 100 cal years ago to mark the start of the Sub-Sault Phase. Farrand (1960) estimated that the Sub-Sault phase began ~2200 cal years ago, a date supported by Larsen's (1994) data from Whitefish Point east of Grand Marais, Michigan (Fig. 1A). From strandplain sites along Grand Traverse Bay on the Keweenaw Peninsula and Tahquamenon Bay west of Sault Ste. Marie, Johnston et al. (2004) and Argyle et al. (2005) initially estimated that the Sub-Sault Phase

began 1200 years ago. This age has been revised, first to after ~2400 years ago and possibly ~1400 years ago (Johnston et al., 2007a), and subsequently to 1060 ± 100 years ago (Johnston et al., 2012). During the Sub-Sault Phase and according to the most recent analysis of lake-level gauge data between the Sault Ste. Marie outlet and Sand Point (Mainville and Craymer, 2005), lake level at Sand Point is rising ~10 cm/century. Thus, lake level during the Sub-Sault Phase has risen either 1.1 m using the Johnston et al. (2012) chronology or 2.2 m from earlier studies.

A primary purpose of this paper is to interpret the littoral processes and time scales of the evolution of Sand Point, and to evaluate those with regard to the younger estimate of 1060 ± 100 cal years ago for the initiation of the Sault outlet.

METHODS

Geomorphic Map

Prior to collection of cores or geophysical data from Sand Point, a generalized geomorphic map of the emergent feature was developed to show the primary beach ridges and ponds (Fig. 3A). The Point was subdivided into Regions 1 through 6 in order of decreasing relative age. These Regions typically are bounded by a prominent beach ridge or show a distinct change in the geometry of the ridges, and may truncate older ridge sets. Region 6, the youngest, is currently submerged, but appeared as an emergent but unvegetated part of Sand Point as recently as the 1980s. The geomorphic map of Sand Point was used to guide subsequent field work including locations of geophysical transects and samples for age dating.

Ground-Penetrating Radar

Ground-penetrating radar (GPR) surveys were conducted on the emergent parts of Sand Point and offshore from a raft towed by a zodiac boat. The on-land surveys used a Sensors and Software Pulse EKKO system with a 1000 V transmitter and 50 and 100 MHz antennas, with 0.5 m steps, 2-m antenna separation, and 32 stacks per shot. An elevation survey using a rotating laser leveler was used for topographic correction of the GPR profiles. The offshore surveys used the 100 MHz antennas mounted in a vinyl raft. Shots were collected using a 1-s automatic pulse and stacked 4 times. Position was recorded from a handheld GPS unit.

Marine Seismic Survey

An offshore seismic survey was conducted to record bathymetry and to observe sedimentary structures in deeper water in the channel and basin west and south of Sand Point. An Edge Tech SB-216S shallow-tow chirp seismic unit with an X-STAR topside acquisition system was used to collect 30 km of data. A handheld GPS unit mounted to the boat and connected to

Figure 3. (A) Traces of the most prominent beach ridges, and geomorphic regions of Sand Point mapped from aerial images. (B) Note that Region 6 is no longer subaerially exposed.

the seismic acquisition system was used to record position. The seismic towfish was lowered through a moonhole on the RV *Perforator* pontoon boat, and was suspended between the pontoons at ~1 m depth. Data was collected with a 10-ms swept-frequency pulse of 2.5–12.5 kHz. With this relatively high-frequency pulse, the penetration generally was limited in shallow water by hard surficial sediments compacted by wave and current action, and in areas with shallow subcrops of bedrock and diamicton. However, in deeper parts of the basin penetration was commonly 5–10 m with a maximum of ~15 m.

Sediment Cores

Sediment cores from each of the four perennial ponds on Sand Point (Fig. 3) were collected from ice platforms using a square-rod Livingstone corer. Ponds 1, 2, and 3 were sampled in January 2008, and Pond 4 in February 2010. Cores were extruded in the field onto plastic film, wrapped, and cased in 1-m PVC tubes split lengthwise. At the Glacial Lake and Sediment Science (GLASS) Lab at the University of Toledo, the cores were split, scraped, photographed, and sampled for terrestrial macrofossils by wet sieving on a 0.063 mm brass sieve.

Optically Stimulated Luminescence (OSL) Dating

Sand samples for OSL dating were collected from 1.2 m² soil pits dug to a depth of ~0.9 m into the crests of beach ridges and collected using the protocols established by Murray and Wintle (2000). A single modern beach sample was collected to evaluate bleaching. OSL ages were determined at the University of Nebraska–Lincoln using the single-aliquot regenerative-dose (SAR) protocol (Goble) and by single grain analysis (Hanson) to resolve equivocal age determinations of some initial multi-grain results.

All samples were prepared under amber light. Samples were wet sieved to extract the 150–250 μ m fraction, and treated with HCl to remove carbonates. Quartz and feldspar grains were extracted by flotation using a 2.7 g cm⁻³ sodium polytungstate solution, then treated for 75 min in 48% HF, followed by 30 min in 47% HCl. Each sample was resieved and the <90 μ m fraction discarded to remove any remaining feldspar grains. The etched quartz grains were mounted on the innermost 5 mm (initial run) or 2 mm (later runs) of 1-cm aluminum disks using Silkospray. Chemical analyses for estimating the environmental dose-rates were carried out by ACT Laboratories, Ancaster, Ontario, using a combination of inductively coupled plasma–mass spectrometry (ICP-MS) and inductively coupled plasma–atomic emission spectroscopy (ICP-AES). Dose-rates were calculated using the method of Aitken (1998) and Adamiec and Aitken (1998). The cosmic contribution to the dose-rate was determined using the techniques of Prescott and Hutton (1994).

Optically stimulated luminescence analyses were carried out on Riso Automated OSL Dating System Models TL/OSL-DA-15B/C and TL/OSL-DA-20, equipped with blue and infrared diodes, using the SAR technique (Murray and Wintle, 2000). Early background subtraction (Ballarini et al., 2007; Cunningham and Wallinga, 2010) was used. Preheat and cutheat temperatures were based upon preheat plateau tests between 180° and 280 °C. Dose-recovery and thermal transfer tests were conducted (Murray and Wintle, 2003). Growth curves were examined to determine whether the samples were below saturation ($D/D_0 < 2$; Wintle and Murray, 2006). OSL ages are based upon a minimum of 50 aliquots (Rodnight, 2008). Individual aliquots were monitored for insufficient count-rate, poor quality fits (i.e., large error in the equivalent dose, D_e), poor recycling ratio, strong medium versus fast component (Durcan and Duller, 2011), and detectable feldspar. Aliquots deemed unacceptable based upon these criteria were discarded from the data set prior to averaging. Calculation of sample

De values was carried out using the Central Age Model (Galbraith et al., 1999) unless the De distribution (asymmetric distribution; decision table of Bailey and Arnold, 2006) indicated that the Minimum Age Model (Galbraith et al., 1999) was more appropriate.

GEOLOGIC SETTING OF SAND POINT

As described above, emergent Sand Point sits on a subaqueous platform that extends more than half way across the trough carved into bedrock that separates Grand Island from the mainland (Fig. 1B). Sand Point is constructed of multiple sets of beach ridges and intervening swales that have been preserved differentially from previous episodes of constructive outbuilding of the foreland (Fig. 3). The oldest of these ridge sets, identified as Regions 1 and 2 in the geomorphic classification, are truncated on their northern edges. The truncation suggests that the cusped foreland has migrated alongshore to the southwest and extended westward during its evolution.

The depth of Holocene fill in the bedrock trough separating Grand Island from the mainland is unknown except from the driller's logs of two water wells from northwest Sand Point. These well logs record up to 65 m of sand overlying ~7 m of red clay (assumed to be glaciolacustrine) resting on a mixture of clay and gravel assumed to be glacial diamicton (till), above rock fragments interpreted here as bedrock (Fig. 2D). Bedrock is exposed in shallow water along the shoreline north of Sand Point, forming a ledge that varies from 35 to 75 m wide (Fig. 2C). Attempts to trace the bedrock into the subsurface with GPR were not successful because of limited penetration.

The subaqueous platform associated with Sand Point is broadly wedge shaped and ~1.5 km wide at the south end. The feature pinches down to an attachment point at the base of the Pictured Rocks cliffs ~3 km northeast of subaerial Sand Point (white circle on Fig. 4A). Two long linear shoals cap the platform. These shoals remain persistent features, although variable in form, in all historical aerial photographs of the area. The outer shoal appears in both the light detection and ranging digital elevation model (LiDAR DEM) (Fig. 5A) and on aerial photographs (Fig. 5B) as a sharp boundary with the active deep channel to the west that separates the platform from Grand Island. (Throughout the text, we refer to this informally as the "Grand Island channel.") The outer shoal receives wave attack directly by storm-driven waves approaching from the north and northeast and by refracted waves from the northwest that bend around Grand Island. The crest of the outer shoal lies 1.5–2 m below the lake surface, and has shoreface-attached ridges on the lakeward side (visible in Fig. 5) that migrate to the southwest. A linear channel trending southwest to northeast with water depths of 3–4 m separates the outer shoal from the inner shoal. The latter is shallower, less clearly defined, and more variable through time than the outer shoal. A second shallow channel lies between the inner shoal and the mainland, and curves westward along the northern edge of Sand Point.

At the southern end of the platform adjacent to subaerial Sand Point, sand bodies accumulate that may be very shallow shoals, emergent bars, or even ephemeral islands (Figs. 4A, 6B). These shallow shoals are at the distal end of the littoral transport system with dominant net flow from the northeast

Figure 4. (A) Littoral sand transport and deposition along the eastern shore of South Bay between the Town of Munising and Miners Castle Point. White arrows indicate net transport directions of sediment. Dashed white line marks the basinward edge of a bedrock abrasion platform. White star on land is the camera position for the image in panel B. White circle marks the up-drift start of the platform. (B) View from the cliff north of Sand Point looking to the southwest across the subaqueous platform, showing an emergent bar and part of the inner shoal. The distal edge of the platform is marked by the dashed line, where water depth increases rapidly. PRNL—Pictured Rocks National Lakeshore.

Figure 5. (A) LiDAR image of topography and bathymetry adjacent to Sand Point, with illumination from the northwest. White line marks the shoreline and dashed white line indicates outer edge of the platform. Gridded LiDAR data from the NOAA Coastal Services Center. (B) Aerial photomosaic from the FEMA-Fused Layer U.S. Geological Survey seamless database showing the shoals and large sand waves on the subaqueous platform associated with Sand Point.

toward Sand Point. The transported sand accumulates close to the southwestern edge of the platform, where water depths increase abruptly and dramatically into the deep basin of South Bay (Fig. 4). The southwestern shore of Sand Point has an extremely narrow shelf, generally less than 100 m wide, with prominent notches along the edge that we interpret as the heads of gullies that direct turbidity flows off the platform into the deep basin. The platform margin west of the tip of Sand Point is dissected by several sets of alternating short channels and shoals that extend up onto the platform (Fig. 6B). A dark mottled feature ~200 m by 100 m appears consistently in aerial photographs offshore of the strand plain in Region 5 (Fig. 6B). We tentatively interpret this as the top of a pillar of bedrock, and see evidence that it affects the dynamics of the southwestern shore of Sand Point.

Whereas the littoral system northeast of Sand Point indicates dominant net transport to the southwest, the shore of South Bay to the south of Sand Point shows a less vigorous transport to the northeast, also toward Sand Point, creating a zone of convergence. However, the shallow shelf along the eastern margin of South Bay is generally narrow, typically less than 200 m wide, and drops off steeply into the deep basin. From aerial photographs it appears that dominant sediment transport from this shelf is likely to be offshore, into the basin.

Shoreline Dynamics

A representative set of shoreline positions for Sand Point and the locations of the southwestern edge of the subaqueous platform are presented in Figure 6. The dates of each shoreline

Figure 6. (A) Changes in position of the shoreline of Sand Point and the western edge of the subaqueous platform between 1939 and 2008. (B) Aerial photograph of map area in panel A. (C) Recorded water levels in Lake Superior since 1930 (U.S. Army Corps of Engineers, 2012), with dates from panel A marked.

also are marked on the water-level record since 1930 for Lake Superior (Fig. 6C). One consistent trend that appears in this data set is the progradation of the subaqueous platform to the west, toward the deep basin, since 1939. The outer edge of the platform shows indentations that align with the channels running up onto the platform. Smaller crescentic cuts along the margin are likely head scarps of slump blocks that have broken off and moved

downslope; evidence for this process will be presented with the seismic data.

Although evaluating the response of Sand Point to late Holocene lake-level cycles was not a focus of the present study, there does not appear to be a simple relationship between lake level and configuration of the emergent foreland of Sand Point. For contrasting examples, the 1975 and 1982 shorelines (Fig. 6) are both extended basinward, but 1975 is just past the peak of a 10-year period of lake-level rise whereas 1982 is the end of a lowstand. Clearly, periods of basinward extension of Sand Point alternate with landward retreat and erosion, especially along the north shore. These shoreline changes do not appear to correlate with lake-level fluctuations, although the shoreline-position data are not sufficiently dense through time to make a confident interpretation. It is most likely that the configuration of the shoreline and the surrounding shoals on the platform are responding to a complex interaction among lake level, storms, and net sediment transport.

Interaction with the Deep Basin

The northern basin of South Bay, to the west and south of Sand Point, has maximum water depths of 65–70 m (215–230 ft) (Fig. 7). Seismic profiles across this basin show draped, mostly horizontally bedded sediments that likely were deposited from turbidity flows into the basin and settling of suspended particles during quiescent periods of ice cover and between storms. These sediments overlie a stratigraphic discontinuity that in different areas of the basin may be the top of till or bedrock.

Seismic profile SP-08.07 (Fig. 8) runs west to east across the northernmost part of the South Bay basin from a submerged bedrock outcrop by Wick Point to the edge of the Sand Point platform (Fig. 7). Maximum depths along this transect are only 62 m, but the profile shows the steepness of the slope coming off the platform. This particular transect runs obliquely up the slope and has inclination approaching 6°; typical observed inclinations in slope-perpendicular transects range between 6.5° and 7.5°, with a maximum of 18.5° where the platform drops into the Grand Island channel. The deepest section of profile SP-08.07 also aligns with the channel presented in Figure 9. Visible on the eastern flank of profile SP-08.07 between 35 and 45 m depth is a surficial unit bounded by a distinct underlying surface that likely represents a deposit from downslope transport. Profile SP-08.11 (upper panel, Fig. 8) shows a similar, but more obvious, example of a slump block between 23 and 32 m depth, and the sheer edge of the platform. Equivalent displaced sediments appear in the profiles in Figure 9, and in most of the other seismic profiles from this basin margin.

The head of South Bay shallows dramatically from 70 m in the basin, to a platform ~45 m deep, to a ramp up into the constricted channel between the western boundary of the Sand Point platform and Grand Island (Fig. 5). This channel is less than 0.5 km wide at its narrowest and as shallow as 13.5–15 m (45–50 ft). The seismic lines presented in Figure 9 show profiles

Figure 7. Map of selected tracklines from the marine seismic survey in the deeper-water areas of the channel and basin to the west and southwest of Sand Point. Seismic lines presented in Figures 8, 9, and 10 are highlighted and labeled. Base chart is NOAA NOS Chart 14969; water depths in feet.

across the channel south of the narrowest and shallowest section. Profile SP-08.04 in particular shows the abrupt drop-off of the outer edge of the platform adjacent to the channel. The undulating bathymetric features on the eastern side of profile SP-08.03 between 15 and 20 m depth are gullies or small canyons tracking down the slope into the basin.

Seismic profile SP-08.05 (Fig. 10) runs down the axis of the channel, and shows large sand waves in the shallowest section. These sand waves are as much as 1.5 m high, with wavelengths on the order of 25–35 m, and are asymmetrical indicating a dominant flow direction to the northeast. The wave forms are slightly rounded, implying sub-dominant flows in the opposite direction. Based on the predominant grain size (400–600 μm) and water depth, flow velocities in the range of 0.75–1 m/sec would be required to produce these bedforms (Rubin and McCulloch, 1980).

The geometry of the constricted channel and the field of large bedforms are shown on the LiDAR DEM (Fig. 5A). The overall feature is analogous to the ramp of a flood-tidal delta of an ocean-coast inlet (FitzGerald et al., 2012). Two relatively deeper channels bifurcate around a central ramp with climbing sand waves that get larger as the ramp shallows to the northeast.

Undulations on the lake floor seen in water as deep as 24 m on profile SP-08.05 (Fig. 10) indicate a continuous field of smaller sand waves leading up the slope from South Bay into the constricted channel. The LiDAR DEM (Fig. 5A) also shows the possible exit path of a coastal current flowing out of the Grand Island channel to the northeast, parallel to shore. Along this section of the shelf, a series of low-relief transverse dunes with wavelengths of 250–300 m occupy a track ~4 km long, from 0.5 to 1.2 km offshore in water 9–18 m deep. All the bathymetric and stratigraphic evidence suggest strong currents flowing episodically out of South Bay, to the northeast through the Grand Island channel, toward open Lake Superior.

The Sand Point Platform

The subaqueous platform is a key to understanding the evolution of Sand Point. Water depths on the platform range from 0.5 m or shallower on the shoals to an average of 3 m in the deeper channels. As a sedimentary body, the platform is composed of sand, with minor thin interbeds of mud, down to ~65 m below modern lake level (based on unpublished logs from two water wells at the northwest point on Sand Point [Fig. 3B] provided by

Figure 8. Lower panel: West to east seismic transect across the deep basin in northern South Bay from the bedrock outcrop of Grand Island to the outer edge of the Sand Point platform. Location of tracklines shown in Figure 7. Upper panel: Seismic section perpendicular to the platform edge and subparallel to SP-08.07, showing the abrupt drop-off into the basin and a slump block that has moved downslope. Label LF identifies the lake floor, and label M the lake-floor multiple. Label A marks the underlying surface of bedrock or till. Depth assumes seismic velocity of 1500 m/sec.

the Michigan Department of Environmental Quality). The sand is underlain by ~10 m of red silt-clay, interpreted as glaciolacustrine, which in turn overlies a diamicton down to bedrock at 80 m. By contrast in elevation, the beach ridges on the emergent Sand Point are generally less than 2 m above lake level, and the bases of the swales and ponds are near or below lake level.

What processes constructed the Sand Point platform? The platform is the shallowest part of a larger sedimentary feature that fills the bedrock trough between Grand Island and the Pictured Rocks cliffs (Figs. 2B, 11). By inference from the geometry of the trough and the well logs from Sand Point (Fig. 2C), this deposit extends ~4 km from the head of South Bay to the

northeastern tip of Grand Island. Assuming that the deep basins of South Bay and Lake Superior north of Miners Castle Point represent the depth of the trough plus the thickness of the till, the sand filling the 2-km-wide trough is on average ~52 m thick; the base of the sand is 65 m below modern lake level and the average water depth between Grand Island and the mainland is 13 m, except for the Sand Point platform, which has an average water depth of ~2 m and covers roughly one-third of this area.

Although it is clear that erosion of the friable sandstone in the cliffs currently supplies sand to this system, and presumably has in the past during high lake levels, it is unlikely that the entire volume of sediment filling the trough was derived from

Figure 9. Seismic profiles across the deeper channel between the subaqueous platform of Sand Point and Grand Island to the northwest. Locations of these sections are shown in Figure 7.

the cliffs. The less-indurated, slope-forming unit of the Miners Castle Member is ~45 m thick on average; erosion of the indurated lower and uppermost units in the cliff generally produces boulders and cobbles, but relatively less sand.

Based on the simplifying assumptions stated above, the total volume of sand deposited into the bedrock trough is on the order of $400\text{--}415 \times 10^6 \text{ m}^3$. Assuming that the 6.5 km length of cliff between Sand Point and Miners Castle Point contributed most of the sand, and that the 45-m-thick Miners Castle Member was the only source, shoreline erosional retreat of 1.4 km is required; even with the entire 15 km of shoreline up to Sail Rock contributing sand, 600 m of retreat is required. As mentioned previously, a wave-eroded ledge of more-indurated sandstone is visible along much of the Pictured Rocks shoreline (Fig. 2C), but this is narrower than ~100 m except in a few locations.

An alternative source for the sand filling the trough is redistributed ice-marginal sediment deposited from the Superior Lobe as it receded. We hypothesize an initial deposition of a large volume of outwash sand within the trough, possibly during a short-term pause during ice recession. Large outwash fans and sheets are prominent features of the land surface south of the Munising Moraine (Blewett and Rieck, 1987; marked on Fig. 1B). An equivalent deposit may fill the 2-km-wide gap between the western and eastern bedrock highs that make up Grand Island (Fig. 11). At that location, a composite coastal feature 0.7 km wide (southwest to northeast) that is similar in shape to a tombolo connects the two bedrock islands. The adjacent embayment to the south is 32 m deep, and the northern opening to Lake Superior is 40 m deep; water deeper than 60 m occurs farther away in both directions. The connecting feature itself is composed of two

Figure 10. Axial seismic profile within the constricted section of the channel between the Sand Point platform and Grand Island, showing large sandwaves in the channel. Location of trackline shown in Figure 7; crossing points of seismic lines in Figure 9 are indicated. Label A marks draped sediments filling a depression on the slope, which is the typical mode of deposition in the deeper basin.

Figure 11. Map depicting the two bed-rock troughs on either side of Grand Island east that are interpreted to have been produced by glacial erosion. Schematic representation of the bathymetry, with contours of 3 m, 15 m, and 60 m, shows deep basins to the northeast in Lake Superior and to the southwest in South Bay. Thick sedimentary deposits partially fill these two troughs. Labels A and B mark a cusate foreland (A) and a strandplain (B) that close the gap between the west and east bedrock islands that comprise Grand Island.

parts: a cusped foreland similar in size and shape to Sand Point (label A, Fig. 11), but attached to the western bank, and a strandplain of beach ridges (label B, Fig. 11) similar to those in Au Train Bay, that close the gap between the two bedrock islands. In this setting as with the Sand Point platform, the volume of sand eroded from the bedrock cliffs of the islands is sufficient to create the cusped foreland and strandplain, but is unlikely to be enough to fill the entire depth of the trough between the islands.

To determine the stratigraphy of the Sand Point platform, geophysical surveys were conducted on both the emergent fore-

land and the surrounding platform. Reconnaissance seismic transects across the platform did not produce any meaningful profiles because of prominent multiples and no penetration of the signal through the hard-packed sand. However, GPR transects across major features of the platform (Fig. 12) document characteristic bedding geometries and facies. Representative facies from the platform are presented in Figure 13.

GPR line SP-W-10 (Fig. 13A) shows the outer 160 m of the platform past the tip of Sand Point. The shallow and relatively flat floor of the platform drops off rapidly at 20 m along the transect

Figure 12. Map of GPR transects collected on the emergent part of Sand Point and offshore across the shallow subaqueous platform surrounding the subaerial feature. Sections of transects presented in Figures 13, 14, and 15 are highlighted with bold lines.

Figure 13. Representative depositional features and facies of the subaqueous platform illustrated by GPR profiles. Locations of these sections are shown in Figure 12. Label LF marks the lake floor; labels M₁ and M₂ identify the first and second lake-floor multiples, respectively. (A) Steeply dipping beds at the outer edge of the subaqueous platform (labels X, Y, Z). (B) Channel cut and maintained by storm-generated currents flowing generally southwest-northeast across the platform. (C) Section across one of the shallow shoals on the platform immediately north of the emergent Sand Point.

(label X, Fig. 13A). This edge is equivalent to the shallowest parts of seismic profiles SP-08.07 (Fig. 8) and SP-08.04 (Fig. 9) that cross the same break in slope at nearby locations. Steeply dipping reflections in the GPR profile above the strong lake-floor multiple show successive edges of the platform as it has prograded to the west-southwest toward the deep basin (labels Y and Z, Fig. 13A).

GPR line SP-W-07 (Fig. 13B) crosses the main channel on the platform that lies between the outer and inner shoals (Fig. 12). The sand bodies of both shoals each overlie a prominent sub-horizontal reflection (label X, Fig. 13B) that is at an elevation equivalent to the active channel floor. Subsurface reflections below the channel show an apparent dip to the west (labels Y and Z, Fig. 13B), and are associated with what appear to be offlapping sediment packets that are not as steep as those in Figure 13A. It is possible that these dipping surfaces are the eastern margin of a previous channel that was equivalent to the active Grand Island channel, which is only 300 m west of this site.

GPR line SP-W-08 that runs subparallel to the northern shore of Sand Point (Fig. 13C) crosses a relatively small shoal that formed in the second channel on the platform between the inner shoal and mainland. This shoal is representative of a number of small shoals that appear in the historical aerial photographs. These shoals migrate fairly rapidly over a period of a few years, and typically weld onto the north shore of Sand Point where the sand is redistributed along the beachface. The dominant facies on either side of the shoal has thinly layered, mostly horizontal reflections. A prominent flat-lying reflection (label X, Fig. 13C) extends under the entire body of the shoal and is contiguous with the lake floor in the channel. A migrating body of sand, the shoal, was deposited on top of that shallow ravinement surface. This geometry is consistent with a surficial sand 1–2 m thick that is moved about on the platform by waves and currents.

The Emergent Foreland

As presented above, the land surface of the emergent Sand Point is subdivided into five geomorphic regions (Fig. 3A), with a sixth region to the west that is presently submerged. Regions 1 through 4 are constructed of multiple beach ridges and intervening swales that have roughly the same gross shape as the entire emergent Sand Point. Each of Regions 1 through 4 represents a reconfiguration of the emergent Sand Point, with erosional truncation of the preexisting feature followed by migration along-shore to the southwest, and progradation basinward, generally to the west toward the edge of the platform. Successive beach ridges arc out away from the existing beachface, extend alongshore, and enclose the low area between to form a swale. This process is expressed in the modern system by a small lobe of sand on the north shore (visible in Fig. 6B) that extends slightly offshore and downdrift as seen in the LiDAR DEM (Fig. 5).

Region 5 is distinctly different from the other Regions in that it is composed of arcuate ridge sets that trend north-

northwest, parallel to the southwestern shore of Sand Point. Region 5 developed immediately inshore from the persistent feature in the aerial photographs that we tentatively interpret as a bedrock pinnacle. The small-scale strandplain of Region 5 has minimal vegetation, and the aerial photographs show that it formed within the past few decades. Notably, photos from 1998 to 2006 show the strandplain extending as a tombolo to attach to the bedrock knob.

In a sequence-stratigraphic sense, each Region would be expected to have been produced during an extended period of similar external conditions of lake level and sediment supply. Further, each Region should be bounded in the subsurface by major ravinement or downlap surfaces. Two sets of parallel GPR transects were collected in Region 4 and part of Region 5 (Fig. 12) that represent approximate dip (SP-01, -02) and strike (SP-11, -12) lines relative to the beach ridges of Region 4.

The dip GPR line, SP-01 (Fig. 14A), has coherent reflections down to 20–22 m, and shows several prominent surfaces that can be traced over 100 m. These major surfaces bound packets of sediment with consistent internal bedding, and usually have a significant break in slope (surface B, Fig. 14A), equivalent to that seen on the outer edge of the platform (Fig. 13A). The upper bounding surface of these packets is typically a flat reflection that is overlain by the thinly bedded, horizontal reflections (surfaces A₁ and A₂, Fig. 14A) equivalent to those from the shallow part of the platform (Fig. 13C). These two predominant facies are interpreted as the prograding outer edge of the platform and the shallow shoreface, respectively. Along this transect, all the units are offlapping with an apparent dip to the northwest. The subsurface packets bounded by major surfaces correspond with the transition on the land surface to Region 5 at 30 m along the transect, and with prominent ridges within Region 4 at 170 m (associated with surface B, Fig. 14A) and 300 m (associated with surface C, Fig. 14A). The deepest continuous reflection (surface E, Fig. 14A) has an entirely different character than the overlying surfaces, and correlates with the deep surface in GPR profile SP-12 (surface E, Fig. 14B).

The strike line, SP-12 (Fig. 14B), shows a series of oblique to sigmoidal sedimentary packets with an apparent dip to the southwest. These dipping packets are separated by high-amplitude, continuous reflections that can be traced 200 m in some cases (surface C*, Fig. 14B), and are truncated and bounded above by a horizontal erosional surface (surface A₂, Fig. 14B), above which the depositional units between the primary reflections are thin and flat-lying. The packets converge at the base onto an undulating surface (surface E, Fig. 14B) between 20 and 23 m. A unique packet on the northeast end of the transect, from 190 to 280 m, is bounded by the lower surface E and an overlying high-amplitude dipping reflection (surface D, Fig. 14B). This depositional unit is interpreted as the down-drift leading edge (the southwestern edge) of the developing platform for an earlier Sand Point foreland (models discussed next, Figs. 15 and 16). The stratigraphic significance for the evolution of Sand Point of these primary surfaces and sediment packets

Figure 14. (A) GPR profile running generally shore perpendicular (approximate dip) northwest to southeast across Regions 4 and 5 of the emergent Sand Point. Location of transect shown in Figure 12; geomorphic regions shown in Figure 3. Interpretation of prominent surfaces and primary depositional packets presented in lower panel. (B) GPR profile running approximately along strike (southwest-northeast) across Region 4 of the emergent Sand Point. Interpretation of major surfaces and units in the lower panel. Surfaces labeled with letters are correlated among the four GPR transects in this area (SP-01, -02, -11, -12). The exceptions are surfaces B* and C*, which are within the same sedimentary packets but are not the same surfaces as B and C, respectively. Surface E appears on all transects between 20 and 23 m, and is interpreted as the top of the underlying deposit, presumably glacial outwash, that is the base for the Sand Point platform.

will be explained in the next section in the context of a depositional model for this system.

Model of Sediment Transport

The following conceptual model of the transport of water and sediment in the Sand Point–South Bay system is based on a process interpretation of the observed bathymetric features and stratigraphy, and limited observations of wave fields and currents around the Sand Point platform and in the Grand Island channel. No actual measurements of direction or magnitude of currents are presently available.

The most significant observation is the field of sand waves within the constricted deeper channel between Grand Island and the Sand Point platform. These bedforms clearly indicate strong episodic currents that flow dominantly to the northeast, out of South Bay. Other important observations relate to the flow-indicative structures of the shoals and channels on the platform.

Winds blowing from the northwest across Lake Superior have a fetch approaching 300 km. The strongest winds on Lake Superior occur in May and October, as recorded by NOAA Data Buoy 45004 (NOAA NDBC, 2013), near the center of the eastern basin ($47^{\circ}35'3''$ N $86^{\circ}35'12''$ W) and 125 km north of Sand Point. Northwestern winds are either dominant or subdominant during spring and fall, accounting for 20%–22% of the average wind direction; 35% of the winds above 20 knots (10.3 m/sec) blow from the northwest. Significant wave heights in open Lake Superior during storms are typically 4–5 m with a maximum of ~7 m; these waves have periods of 6–8 s up to 11 s, respectively. Although these waves shoal rapidly before impacting the Pictured Rocks shore, they still expend tremendous energy to erode

the cliffs and drive longshore transport. Wave base for typical storm waves is 30–50 m, which would move sand on most of the shelf north of the Sand Point platform. Wave base for maximum storm waves is 75–90 m.

In the proposed model of sediment transport for the Sand Point platform, northwesterly winds sustained over several days may generate water-level set-up along the south shore of Lake Superior of a meter or more. Coauthor Loope, a resident of Munising, has observed water-level set-up during storms as high as ~3 m; storm surge during the 1989 storm that flooded the National Park Service building was >2 m. Locally on the west side of Grand Island, set-up will be amplified in height as the water is forced into the funnel-shaped embayment between the headland east of Au Train Bay and Grand Island (Fig. 1B). Under these conditions, the water level along the Pictured Rocks shoreline northeast of Sand Point should be elevated, but not as dramatically as west of Grand Island. The resulting pressure gradient will induce strong flow through the narrow channel that is the western entrance to South Bay, between the southwestern tip of Grand Island and the mainland (Fig. 15A). This storm flow would elevate the water level in South Bay and exit to the northeast through the eastern Grand Island channel. Although the strongest current will flow through the deeper channel, branched flow will impact the southwestern margin of the Sand Point platform, and flow predominantly into the outer channel of the platform. This flow will rework the sand bodies on the platform at the south ends of the outer and inner shoals. Some of the flow onto the platform will follow a relatively small channel that courses along the tip of South Point, near the revetment (visible in Figs. 3A and 6B).

For storm winds from the north to northeast sector, the pressure gradient is effectively reversed, and flow through the deeper

Figure 15. Conceptual model of water flow and littoral transport around Sand Point with storm winds from different directions. (A) Storm winds from the northwest quadrant generate a strong current flowing from the southwest through the deep channel between Sand Point and Grand Island. The gray arrow marks the location of the subaqueous dunes shown in Figure 10. (B) Winds blowing from a narrow sector from the northeast produce flow toward the southwest through the channel.

channel will be from the northeast into South Bay (Fig. 15B). Under these conditions, and also for refracted waves from the north-northwest, waves break across the outer shoal of the platform, setting up littoral transport to the southwest that probably drives the migration of the shoreface-attached ridges. The unexpended momentum of the waves breaking across the outer shoal will transport water onto the platform, which exits by flowing southwest through the outer and inner channels on the platform. At the southern end of the inner channel on the platform, the flow bends sharply to the west and follows the north shore of Sand Point, and interacts with the sand bodies at the southern tip of the inner shoal. It seems unlikely that the hardened shoreline of the revetment is by itself causing erosion of Sand Point. Rather, active erosion of the shoreline occurs where the channel meanders toward the shore, including the section protected by the revetment. An engineered solution to erosion of the north shore of Sand Point should consider the storm-generated currents flowing both directions through this narrow but moderately deep (3–4 m) channel that lies immediately offshore.

Water-level set-up and wave attack from the northwest to north-northeast sector also will impact the Pictured Rocks cliffs, eroding the sandstone and transporting sand toward the Sand Point platform. The entire coastal compartment that may supply sand to Sand Point extends 15 km northeast to Sail Rock, however several submerged bedrock promontories including Miners Castle Point are likely to interrupt longshore transport and divert sand offshore. For the shore segment south of Miners Castle Point, waves that are energetic, but less vigorous than storm waves, will efficiently sweep sand up the slope of the shelf and feed the littoral system and the outer shoal of the Sand Point platform. This process of up-slope transport on the inner shelf has been observed along ocean coasts, as summarized by Schwab et al. (2013). It is possible that sand transported northeast through the eastern Grand Island channel will be deposited on this moderate-slope shelf only to be swept up onto the outer shoal of the platform, forming a partially closed loop. This process of up-slope and landward transport suggests another potential sand source to build up the Sand Point platform, that is, the glacial outwash sediment that was initially deposited down to about what is now the 20 m isobath. Some evidence of this proposed process

Figure 16. Conceptual model for the evolution of Sand Point, reconstructed from the preserved geomorphic regions of the modern foreland (outlined by light gray dashed lines). (A) Initial phase of cusate foreland developing updrift to the northeast to create the remnant of Region 1 (dark gray with bold outline). Arrows show migration alongshore to the SSW and outbuilding to the WSW. (B) Creation of Region 2 and erosional truncation (dashed line) of initial foreland 1 (medium gray). (C) Creation of Region 3 and erosion of foreland 2. The prograding foreland has reached the southwest edge of the deeper sedimentary foundation; alongshore migration slows and outbuilding shifts toward the West. (D) Final stage of development to produce the modern emergent Sand Point. Alongshore migration is minimal, and outbuilding progradation shifts to the WNW.

appears in the bedforms on this section of the shelf in the LiDAR DEM (Fig. 5A).

The observed stratigraphy of Sand Point can be summarized in the context of the proposed model of sediment transport. The emergent foreland of Sand Point has migrated alongshore to the southwest and built out across the shallow subaqueous platform (Fig. 16). The timescales of this evolution will be discussed in the next section as the radiocarbon and OSL ages are presented.

By geomorphic interpretation, Sand Point has had at least four prior episodes of outbuilding and accretion, as evidenced by the preserved succession of beach ridges (Figs. 2A, 16). During each phase of this evolution, the northeastern part of the previous foreland was eroded and the sand reworked to produce the next set of beach ridges (Fig. 16). However, in the subsurface, the growth of the subaqueous platform dominates the stratigraphy. Major packets of sediment are bounded by high-amplitude reflective surfaces, and show net progradation to the southwest and west. Before the most recent extension that produced Regions 5 and 6, these sediment packets were deposited into water between ~15 and 20 m deep, and they lap down onto an undulating surface between 20 and 23 m. In the most recent phase, the platform and Sand Point itself have migrated to the edge of the steep drop-off into the 70-m-deep basin of South Bay. The deepest unit imaged beneath Sand Point, below surface E in Figures 14A and 14B, is interpreted to be a preexisting foundation onto which the Sand Point platform was built; this older, deeper unit could be a thick deposit of glacial outwash that partially fills the bedrock trough.

AGE MODEL AND EVOLUTION OF SAND POINT

To evaluate the age of Sand Point we use common dating methods for determining the age of strandline complexes. First, assuming an inverse relationship of beach ridge Region number with age, and if each beach ridge represents $\sim 25 \pm 5$ years—the rate assumed by Johnston et al. (2012) for the Au Train beach ridge chronosequence—then the 38 beach ridges mapped by Castaneda (2009) and shown in Figure 3A correspond to a total growth duration of 760–1140 years. Such a result can be considered only an approximation for the age of Sand Point. Of the four ponds cored, Core 4 from pond 4 in Region 2 is geomorphically older than Cores 1, 2 and 3 from Region 2. Results from basal radiocarbon ages from the ponds are presented next; followed by OSL ages from near the crest of beach ridges across Sand Point (Fig. 17A).

Radiocarbon Ages

The four sediment cores from the Sand Point ponds (Table 1, Fig. 17A) record a similar stratigraphy of peat over sand (Fig. 18). Transitional units of peaty sand were identified in cores SP1 and SP3, and thin peat units between sand in cores SP3 and SP4. In all cores the sand is medium-to-fine grained, with either horizontal or inclined laminations, and scattered organic fragments throughout. At the coring sites the elevation of the sand/peat contact is between 0.3 and 1.7 m below the level of Lake Superior (183.1 m

Figure 17. Dates from radiocarbon and optically stimulated luminescence (OSL) analyses related to the primary beach ridges of Sand Point. (A) Sample sites. (B) Age results, note radiocarbon ages are consistent with the relative ages from the geomorphology, but the OSL ages are generally much older and considered unreliable due to incomplete bleaching. Refer to text for details. (C) Age results plotted on a smoothed LiDAR derived topographic profile. Profile is a composite of three different cross sections.

TABLE 1. CORING LOCATIONS*

Core	Latitude (N)	Longitude (W)
SP1	46.44927°	86.60505°
SP2	46.44948°	86.60288°
SP3	46.45112°	86.60214°
SP4	46.45006°	86.59977°

*Geographic Coordinate System WGS_1984.

International Great Lakes Datum of 1985 [IGLD85 datum]). The stratigraphy is interpreted to record the transition from a foreshore (sand) to paludal (peat) environment. When a new sand ridge forms, a wetland may become trapped behind it, in which organics can begin to accumulate (cf. Thompson, 1992). The interbedding of sand and organics in some of the cores may record final construction of the enclosing sand ridge and/or storm events.

Only woody organic material was chosen for radiocarbon dating from the four cores, which is supported by the $\delta^{13}\text{C}$ values in Table 2. The peat was dominated by fibrous organic matter and aquatic seeds. Samples were chosen from the base of the peat as well as from the uppermost sand to constrain the age of the contact. Two samples from peat (SP1 and SP3) provided the same age of 550–670 cal yr B.P. and are considered minimum ages for establishment of the respective wetlands. The more limiting maximum age of 540–650 cal yr B.P. of the two samples from sand in SP1 is virtually identical to the age in the peat; thus pond 1 is interpreted to have formed between 550 and 670 cal yr

B.P. Geomorphically, pond 2 is older than pond 1 and the three maximum ages from sand just below the contact in core SP2 all overlap at the two sigma error range providing a combined range of 670–910 cal yr B.P. The most limiting maximum age is the youngest age, meaning that the pond formed sometime after 670–780 cal yr B.P. The single date in core SP3 is a minimum date from just above the interbedded sand indicating that the pond had formed by 550–660 cal yr B.P. The age for pond 4 also is based on one date. Woody organic material was concentrated from the interbedded sand assumed to be reworked from the underlying peat. The presence of two older peat units in this core indicate that the age of 740–910 cal yr B.P. can only be considered a minimum age; however, the thinness of the older peat units probably does not represent more than ~100 years. Based on the available radiocarbon data, the ponds increase in age inland, which is consistent with the relative ages from the geomorphology.

OSL Ages

Nine samples were collected for OSL dating across Sand Point to determine its age and rate at which the cusped foreland grew. One modern beach sample and eight beach ridge samples were collected (Table 3, Fig. 17A). Age results are shown on Figure 17B and in Table 4. The sample pits at each beach ridge site revealed either an A or O soil horizon above either massive or laminated sand. While samples were collected as deeply as possible, the depth was limited by the water table. Other than sample

Figure 18. Lithostratigraphic logs of cores recovered from four ponds on Sand Point. Numbers below the column label indicate the calibrated radiocarbon age of the pond. Vertical column beside SP-3 is a greyscale photomosaic of the core.

TABLE 2. RADIOCARBON AGES

Lab	¹⁴ C age raw	δ ¹³ C	Material	¹⁴ C age corrected	Calibrated 2σ mean	2σ range	Prob.
AA79701	618 ± 34	-25.3	Wood	613	605	660–550	1
AA79702	829 ± 34	-26.5	Wood	805	730	780–680	1
AA79703	874 ± 34	-25	Wood	874	775	830–720	0.73
					875	910–840	0.25
AA79704	827 ± 34	-24.5	Wood	835	740	800–680	0.98
AA79705	644 ± 34	-28.5	Wood	588	615	650–580	0.7
					555	570–540	0.3
AA79706	713 ± 34	-29.9	Wood	635	580	610–550	0.58
					645	670–620	0.42
AA79707	739 ± 33	-26.7	Wood	712	670	700–640	0.86
Beta-295066	980 ± 30	-29.6	Wood	900	790	840–740	0.55
					875	910–840	0.45

number 2 (1.6 ka), the ages increase inland consistent with the relative age dating recorded by beach ridge geomorphology (Fig. 17B). Beach ridge OSL ages across Sand Point ranged from 0.62 ± 0.13 ka to 4.92 ± 0.71 ka using the minimum age model (Table 4), and are significantly older than the radiocarbon dates from intervening ponds.

Although the OSL ages other than sample #2 show the expected decrease in age westward as required by the geomorphology, the ages are 2–3 times greater than the radiocarbon derived ages for the ponds. For example, Pond 1 is assigned an age between 540 and 670 cal yr B.P. and OSL age #8 from the damming beach ridge is 1.5 ± 0.23 ka. Similarly, Pond 2 is assigned an age of <970–780 cal yr B.P. and OSL age #4 from the damming beach ridge is 1.95 ± 0.31 ka. The geomorphically oldest pond has a minimum age of 740–910 cal yr B.P., and the proximal beach ridge was dated at 1.61 ± 0.26 ka. There is a discrepancy in results between the two dating methods.

The discrepancy in age between the OSL and radiocarbon dating methods requires some discussion. The sediment geochemistry (Table 4) reveals very low concentrations of radioactive elements that provide a paleodose. Argyilan et al. (2005) working to the east of PRNL had similar low concentrations of U (average of 0.41 ± 0.1 ppm, $n = 17$ versus 0.38 ± 0.1 ppm, $n = 8$), 50% more Th (average 1.31 ± 0.1 ppm, $n = 17$ versus 0.86 ± 0.1 ppm, $n = 8$), and 1400% more K (average $1.3 \pm 0.01\%$ versus $0.09 \pm 0.01\%$, $n = 8$) for similarly aged sediment (chemical

analyses in both studies were carried out by ACT Labs, Ancaster, Ontario). However, the low dose rate based on the geochemistry is at odds with the OSL ages presumed to be too old. Older ages can be explained by incomplete bleaching. The sand is derived from Cambrian rocks sourced within only ~250 m to ~3 km from where it was deposited. Thus the quartz sediment may not have experienced multiple episodes of bleaching and signal storage, and, presumably, the sediment is incompletely bleached after being buried for ~500 million years. To test whether the sand was completely bleached, a modern beach sample was collected in January 2013. The result is an age of 0.69 ± 0.31 ka using the central age model or 0.26 ± 0.02 ka with the minimum age model (Table 4). These results indicate sand is incompletely bleached. Similar results have been reported from beaches ridges at Tahquamenon Bay from the same bedrock formation (Argyilan et al., 2005; Johnston et al., 2007a).

To further assess the SAR-derived OSL ages, the single-grain method was used from sand in OSL samples 1 and 5 (UNL2094 and UNL2098, respectively; Table 4), which span the distance between the radiocarbon-dated ponds (Fig. 17). A total of 2500 grains were analyzed from each site and only a few grains from each site produced meaningful luminescence signals. The purpose of the single-grain method was to determine if the grains were poorly bleached, but because of the low signals it was not possible. Alternatively, there may be some other systematic problem with OSL dating in this setting. It is redeeming to note that OSL has been used successfully elsewhere across the Upper Peninsula of Michigan (e.g., Arbogast et al., 2002; Loope et al., 2004; Argyilan et al., 2005; Loope et al., 2010; Johnston et al., 2012; Loope et al., 2012) with sand assumed to have been derived from the same or similarly aged bedrock units, but with longer surface exposure to bleach the sand completely before burial.

Using radiocarbon ages from basal organics in wetlands between successive beach ridges as a method to date beach-ridge sequences (Thompson, 1992) has been criticized because organic accumulation in the wetland may not be coeval with ridge emplacement (Larsen, 1994; Lichter, 1997; Thompson and Baedke, 1997; Johnston, 2004; Argyilan et al., 2005; Johnston

TABLE 3. OPTICALLY STIMULATED LUMINESCENCE
SAMPLE SITES

No.	Sample ID	Latitude (N)	Longitude (W)	Depth (cm)
1	SPOSL-1	46.45169	86.5984	89
2	SPOSL-2	46.45151	86.59886	78
3	SPOSL-3	46.45129	86.60103	83
4	SPOSL-4	46.4062	86.60321	43
5	SPOSL-5	46.45085	86.60386	62
6	SPOSL-6	46.45228	86.60811	48
7	SPOSL-7	46.45252	86.6054	59
8	SPOSL-8	46.44705	86.60564	57
9	modern	46.45363	86.60536	60

TABLE 4. SINGLE-ALIQUOT REGENERATIVE-DOSE OPTICALLY STIMULATED LUMINESCENCE AGE DATA

Site #	UNL #	Burial depth	H ₂ O (%) [*]	K ₂ O (%)	U (ppm)	Th (ppm)	Cosmic (Gy)	Dose rate (Gy/ka)	De (Gy) [†]	No. of aliquot	Age (ka) [§]
1	2094	0.9	17.4	0.04	0.26	0.62	0.19	0.27 ± 0.03	1.39 ± 0.57	54	4.03 ± 0.4
					Minimum Age Model (Galbraith et al., 1999) =				1.35 ± 0.20		4.92 ± 0.71
2	2095	0.8	8.3	0.03	0.73	1.05	0.20	0.38 ± 0.03	0.64 ± 0.58	50	1.20 ± 0.30
					Minimum Age Model (Galbraith et al., 1999) =				1.62 ± 0.08		1.61 ± 0.26
3	2096	0.8	5.1	0.03	0.36	0.82	0.19	0.34 ± 0.03	0.74 ± 0.57	53	2.60 ± 0.37
					Minimum Age Model (Galbraith et al., 1999) =				0.65 ± 0.08		1.91 ± 0.32
4	2097	0.4	17.0	0.03	0.29	0.69	0.20	0.29 ± 0.03	0.56 ± 0.06	50	1.95 ± 0.31
5	2098	0.6	3.8	0.22	0.37	0.95	0.20	0.51 ± 0.04	0.52 ± 0.06	51	1.02 ± 0.15
6	2099	0.5	2.2	0.19	0.30	0.89	0.20	0.48 ± 0.04	0.30 ± 0.06	50	0.62 ± 0.13
7	2100	0.6	4.6	0.12	0.30	0.83	0.20	0.41 ± 0.03	0.36 ± 0.16	50	0.9 ± 0.40
8	2101	0.6	17.2	0.05	0.43	0.99	0.20	0.34 ± 0.03	0.52 ± 0.06	54	1.5 ± 0.23
9	3670	0.6	25.9	0.03	0.44	1.35	0.20	0.33 ± 0.02	0.23 ± 0.10	55	0.69 ± 0.31
					Minimum Age Model (Galbraith et al., 1999) =				0.086 ± 0.001		0.26 ± 0.02

*In-situ moisture content.

†Error on De is 1 standard error.

§Error on age includes random and systematic errors calculated in quadrature.

et al., 2012). This has been especially true in the Lake Superior basin, which explains why the OSL method has become the preferred method (Argyilan et al., 2005; Johnston et al., 2012). However, here we have determined that OSL is not the preferred method for dating the beach ridges at Sand Point, forcing us to rely on radiocarbon dating of swales behind beach ridges. Before accepting the radiocarbon dates as accurate age control on the beach ridges, the effects of climate change during the Medieval Climate Anomaly (MCA) on lake levels must be addressed.

Recently, Laird et al. (2012) described ~1.5 m lower water levels in six small (<80 ha) lakes in northwest Ontario in response to drought during the MCA (800–1400 AD or 1200–600 years ago [Seager et al., 2007]). Their data demonstrate a widespread effect of the MCA. The timing of the MCA is similar to the radiocarbon ages from the Sand Point ponds, which prompts the hypothesis of whether the beach ridges are older than the pond dates because the pond dates record refilling of the ponds after the MCA. We reject this hypothesis for three reasons. First, there are numerous OSL ages on beach ridges that record lake-level high-stands elsewhere around the Lake Superior basin (Johnston et al., 2012) during the MCA. Second, while the ages for the ponds (540–910 cal yr B.P.) do overlap with the MCA, sedimentological evidence such as oxidation or pedogenesis in the sand beneath the peat was not observed. Third, while a lower water level in the Lake Superior basin can draw down groundwater tables, the ponds on Sand Point are fed by a stream that has eroded a gully and built an alluvial fan over time, suggesting that the Sand Point ponds may not be particularly sensitive to lake-level fluctuations. Thus, while MCA and other Late Holocene droughts have been described in the Great Lakes region (e.g., Booth et al., 2006), the effect on water levels in the Lake Superior basin remain to be identified.

A final analysis is to compare the Sand Point data with the Au Train Bay strandline complex (Johnston et al., 2012). A smoothed LiDAR derived topographic profile in Figure 17C can

be used to extrapolate foreshore elevation deposits by subtracting 2 m from the ground surface for a first approximation (cf. Johnston et al., 2012). The profile most closely matches the Au Train beach ridge topography and foreshore elevations between 300 and 900 m distance from the modern shoreline (fig. 5 of Johnston et al., 2012). The Au Train OSL ages have much higher element concentrations providing a higher paleodose, with ages between 1590 ± 160 and 2260 ± 210 for ridges between 300 and 900 m distance. The youngest beach ridge data set from Au Train Bay where the foreshore elevation and topography of the beach ridges rise toward the modern shoreline were not used in the final construction of the Sub-Sault Phase of the Lake Superior hydrograph by Johnston et al. (2012) because they were quite different from their three other study sites in the Lake Superior basin. At Au Train Bay a total of 19 peat and macrofossil radiocarbon dates from swales did not result in a satisfactory relationship and is explained as a complex paleohydrological response to rising lake levels from the past ~1000 years promoting wetland development. A direct comparison with Sand Point is not simple because the ponds on Sand Point are larger and fed by a stream, and it is uncertain if ridge topography and foreshore elevations from a small cusped foreland sheltered behind Grand Island can be directly compared to similar landforms in an embayment open to Lake Superior.

Response to Late Holocene Lake Level

Lake level has risen ~1.1 m at Sand Point during the Sub-Sault Phase, which is equivalent in amplitude to the range of lake-level fluctuations during historical time. From OSL dating of beach ridges along the southeastern shore of Lake Superior, Johnston et al. (2012) determined that the rise started 1060 ± 100 years ago. The radiocarbon ages of the ponds and enclosing beach ridges in Regions 2 and 3 are of Sub-Sault Phase age (Fig. 19). Since Regions 4–6 are younger than Region 3, nearly

Figure 19. Pond ages from Sand Point plotted on the Lake Superior paleohydrograph modified from Johnston et al. (2012). The Sand Point radiocarbon ages date to the Sub-Sault Phase during which lake level rose ~1 m at Sand Point suggesting that most of Sand Point developed within the past ~1000 years.

all of subaerial Sand Point is interpreted to be of Sub-Sault Phase age. This interpretation requires that the OSL ages are all too old, here explained by incomplete bleaching of the sand and low paleodose rates, and agrees quite well with the earlier estimate for the age of Sand Point based on the number of beach ridges making up Sand Point, and the rate at which the adjacent Au Train beach ridges form. There remains some uncertainty whether much of Sand Point could be associated with the Sault Phase based on elevation comparisons with beach ridges in the Au Train embayment.

SUMMARY

Sand Point is a small cusplate foreland constructed of sets of beach ridges and swales that built out across the distal end of a dynamic subaqueous platform. Sand Point is divided into five emergent geomorphic Regions consisting of arcuate, mostly parallel sets of beach ridges and swales. The platform contains shoals with intervening channels extending from Miners Castle Point, fed by sand from the cliffs of PRNL. Sand bodies on the platform accumulate as shallow shoals, emergent bars, ephemeral islands, and sand bodies welded onto Sand Point. Geophysical data indicates that the subaqueous platform and subaerial Sand Point have migrated to the southwest, and rest on a foundation ~23 m below lake level that we interpret as glacial outwash partially filling a trough carved into bedrock. The present edge of the Sand Point platform coincides with the steep drop-off into the 70-m-deep basin of South Bay. During historical time, the southwestern edge of the platform west of Sand Point has migrated fairly consistently to the west. However, the geometry and position of the emergent Sand Point has been much more variable through time, and cannot be associated directly with changes in lake level. Concave gulley heads that are cut into the platform edge and slump blocks down the slope seen in the seismic profiles are evidence of down-slope transport of sediment into the deep basin. The strongest currents of this dynamic system flow episodically out of South Bay to the northeast through the chan-

nel between Grand Island and the Sand Point platform where large sand waves were observed.

Radiocarbon ages on terrestrial plant macrofossils from the base of four ponds on Sand Point range in age between 540 and 910 cal yr B.P. These data are interpreted to record when the individual ponds and enclosing beach ridges on Sand Point began forming as lake level was rising slowly during the Sub-Sault Phase. The older OSL ages with very low paleodoses are explained by incomplete bleaching of sand sourced from the adjacent ~500-million-year-old sandstone, or some other systematic error. The age results suggest that Sand Point began forming ~1000 years ago, which is consistent with the start of the Sub-Sault Phase at 1060 ± 100 years ago.

ACKNOWLEDGMENTS

The AMS laboratory at the University of Arizona provided an internship opportunity for Castaneda to process the radiocarbon samples. John Johnston is thanked for comments on an earlier draft. Anthony Foyle and Michael Lewis are thanked for their detailed and thoughtful reviews. This paper is contribution 1820 of the U.S. Geological Survey, Great Lakes Science Center. The project received partial funding through USGS Assistance Award #07HQAGD150 to Fisher, and from The University of Toledo, Department of Environmental Sciences Ruedisili Fund.

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MANUSCRIPT ACCEPTED BY THE SOCIETY 2 MARCH 2014