Measurement, Correlation, and Mapping of Glacial Lake Algonquin Shorelines in Northern Michigan

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Glacial Lake Algonquin, the most widespread proglacial lake in the Great Lakes basin, attained a high (Main) stage at about 11,000 B.P., at which time it developed a conspicuous shoreline. Several lower, less obvious Algonquin shorelines also exist. Previous research on this lake has involved three drawbacks: (1) imprecise methods of establishing the location and elevation of shoreline features, (2) misidentification of some offshore coastal landforms as beach ridges, and (3) tenuous and difficult correlation of named shorelines across wide distances. We believe that more than one name is used for some lake phases, making correlation difficult. Our study focused on these problems by surveying and mapping 160 Algonquin wave-cut bluffs throughout northern Michigan. We utilized global positioning system (GPS) technology to precisely record the three-dimensional positions of the bases of these bluffs and statistically fit trend surfaces to these positions. Classification of bluff data indicates that four strong Algonquin shorelines exist in the region, for which we recommend these names: Main, Ardtrea, Wyebridge, and Payette. Weak evidence for a possible fifth, lower shoreline was observed at five locations. Maps of the landscape during each lake phase were created, revealing islands not previously recognized. Rebound curves and maps of the lake during each phase, using the positional data set, indicate that isostatic rebound in the study area appears to be greatest in the northeast sector. *Key Words: field mapping, glacial lakes, GPS, isostatic rebound, Quaternary geology.*

The general shoreline chronologies of pro- and postglacial lakes occupying the Great Lakes basins had been fairly well established based on geomorphic evidence around the turn of the twentieth century (see, e.g., Spencer 1891; Coleman 1901; Goldthwait 1908; Leverett and Taylor 1915; Hansel et al. 1985). However, the actual elevations of former water planes, the nomenclature and correlation of these shorelines across the region, and their relationship to isostatic rebound mechanisms have yet to be fully resolved (e.g., Eschman and Karrow 1985; Larsen 1987; Colman et al. 1994). Previous attempts to determine elevations of former lake stands in the region relied primarily on evidence from relict lacustrine and fluvial landforms, including the crests of spits and offshore bars, delta plains, beach ridges, raised terraces, and wave-cut bluffs (e.g., Spencer 1891; Leverett and Taylor 1915; Deane 1950; Cowan 1985; Kaszycki 1985; Karrow 1986, 1988). However, some of these features are not accurate indicators of former lake stands and may thus have led to erroneous water-level estimates (Johnson 1933a; Thompson, Fraser, and Olyphant 1988). In addition, it is unclear from the pioneering studies of Spencer (1891) and Leverett and Taylor (1915) whether features identified as shorelines (aside from the highest Algonquin bluffs) are berms, beach faces, or bench faces, and at precisely what position on these landforms paleolake elevations were obtained. Moreover, because some of these features may form simultaneously during a single lake phase, we believe that multiple lake-planes may have been discussed for some locations (e.g., Coleman 1901; Leverett and Taylor 1915; Stanley 1945), when in fact only one existed.

Spencer (1891) was the first to recognize multiple bluff and strand features above the eastern rim of Lake Huron. He (12–13) named the most "conspicuous" of these features the "Algonquin Beach" after the indigenous people of southwestern Ontario. Subsequent work (e.g., Taylor 1892, 1895; Coleman 1901; Goldthwait 1908) culminated in the sequence of Lake Algonquin phases outlined by Leverett and Taylor (1915), much of which is still in use today. The durability of their work is astounding in light of the relatively crude maps and equipment they used for data collection. However, as improved maps and other technologies have become available, a reassessment of Algonquin landforms and chronologies seems appropriate. In this article, we focus on Main and post-Main Algonquin shorelines in the northern Lake Michigan and Huron basins and the southeastern Lake Superior basin (Figure 1). We limited our study area on the south to Traverse City (on the Lake

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Figure 1. The study area, showing the extent of Main Lake Algonquin (as determined in this study) and the location of GPS data points collected. Inset map shows the extent of the current Great Lakes, two interpretations of the extent of historical Main Lake Algonquin (Hough 1958; Larsen 1987), its major outlets, and the approximate ice-margin position at the Main Algonquin stage.

Michigan side) and Oscoda (on the Lake Huron side). South of these locations, Algonquin shorelines are upwarped less and hence become difficult to distinguish from those of other lakes of the Lake Michigan and Lake Huron basins.

The purpose of this article is to (1) produce accurate lake-level curves for Main Lake Algonquin and several post-Main lakes, (2) evaluate/correlate the post-Main lakes in light of new data on shoreline elevations, and (3) accurately map the areas inundated by the various lake levels. We use differential global positioning system (DGPS) technology to measure elevations of unquestionable Algonquin shorelines at wave-cut bluffs, which we think are the best geomorphic indicators of the former lake level (Johnson 1933a; Miller 1939). We then correlate our shoreline data to previous estimates of post-Main Algonquin features (e.g., Leverett and Taylor 1915; Futyma 1981; Farrand and Drexler 1985; Larsen 1987) in an attempt to clarify the sequence of post-Algonquin lakes.

Background

Lake-Level Changes in the Lake Michigan and Lake Huron Basins

Today, the Huron and Lake Michigan basins are connected through the Straits of Mackinac (Figure 1), but their histories were separate whenever the Straits were blocked by ice. Our knowledge of the these lake-level histories starts with Leverett and Taylor (1915), who produced the most detailed compilation of field data on glacial-lake stages in the Great Lakes region. Later, detailed chronologies using new and reinterpreted data were compiled by Hough (1958), Fullerton (1980), and Karrow and Calkin (1985), while treatments specific to Lake Algonquin include those by Karrow et al. (1975), Futyma (1981), Kaszycki (1985), Finamore (1985), and Larsen (1987). These chronologies identify up to eight pre-Main Algonquin lake phases at five separate elevations for Lake Michigan, with eleven named phases in Lake Huron at as many as twenty-two elevations. Obviously, there is much confusion associated with this complicated lake chronology.

Lake Algonquin's history essentially begins with the Port Huron readvance, around 13,000 B.P. (Blewett 1990; Blewett and Winters 1995), which completely covered Lake Huron with ice. Only the southwestern part of the Saginaw lowland was left ice-free (Eschman and Karrow 1985). Recession of the Port Huron ice led to a series of lakes in the Huron basin by around 12,400 B.P., each at a slightly lower level than its predecessor. These included Warren (210–204 m), Wayne (201 m), Grassmere (195 m), and Lundy (189 m) (Eschman and Karrow 1985, Larson and Schaetzl 2001).

Believing that ice still occupied the Straits during this time, Leverett and Taylor (1915) suggested that an Early Lake Algonquin stage at 184 m developed (only) in the Huron basin after Lake Lundy. Claiming it to be a short-lived event, they were unable to find any shorelines to prove the existence of this southward draining lake, using inference based on ice-front and outlet relationships instead (Eschman and Karrow 1985). A lower outlet was eventually opened by ice recession, east of Lake Simcoe, Ontario (Larson and Schaetzl 2001). This event caused a low lake to form, referred to as the Kirkfield phase, whose spillway was probably at Fenelon Falls (Deane 1950). Kirkfield was a midbasin outlet with regard to uplift. Hence, the outlet rose at a faster rate than did the basin to the south, causing the lake level in the south to rise over time relative to the outlet. The initial level of the Kirkfield stage "passed below the level of the Port Huron and Chicago outlets . . . falling at the north and rising at the south" (Leverett and Taylor, 413). By 11,600 B.P. (Fullerton 1980), either continued rebound (Finamore 1985) or a glacial advance (Deane 1950) caused the level of the Kirkfield phase to rise to the Main Algonquin level (184 m) in the Huron basin.

Next, a glacial readvance covered the Straits and Indian River outlets again during what is now known as the Greatlakean substage (Evenson et al. 1976). The glacial advance isolated the Lake Michigan and Huron basins, returning drainage to the Chicago outlet. The furthest advance of the Greatlakean ice occurred at about 11,800 years B.P. (Larson, Lowell, and Ostrom 1994). It was the last oscillation of ice into the Lower Peninsula of Michigan (Larson and Schaetzl 2001; Schaetzl 2001).

Retreat of the Greatlakean ice beyond the Straits of Mackinac connected Lake Chicago's Toleston stage with the Huron Algonquin phase at about 11,000 years B.P., forming Main Lake Algonquin (Hansel et al. 1985; Figure 1). Main Algonquin drained through both the Chicago and Port Huron outlets (Leverett and Taylor 1915; Hough 1958; Larson and Schaetzl 2001). Ice recession eventually allowed the lake to extend into the eastern half of the Upper Peninsula of Michigan (Bergquist 1936; Futyma 1981; Farrand and Drexler 1985). Main Lake Algonquin had many islands in northern lower Michigan and in the Upper Peninsula; geomorphic data from spits coming off these islands indicate that this was a period of strong winds and waves, coming from the east, driven by a glacial anticyclone (Krist and Schaetzl 2001). Further recession of the ice uncovered successively lower outlets in the Georgian Bay, Ontario region. Beach strands, wave-cut bluffs, and various shoreline features were formed when the lake level briefly stabilized at each successively lower outlet.

When Spencer (1891) mapped out these Algonquin and lower shorelines, he stated that they had been differentially isostatically uplifted such that successively lower beaches were uplifted at a slower rate and therefore diverged toward the northeast. Where the beaches came together in southwestern Ontario, Spencer believed, the Algonquin beach continued its general descent in altitude, eventually "diving" right under present lake level. Thus, Algonquin would be a low lake-level for the southern part of the Michigan and Huron basins while simultaneously, the northern portions would have maintained a high lake-level. This idea stems from Spencer's belief that the outlet to the lake was east of Georgian Bay, Ontario to the Trent Valley in the vicinity of Kirkfield (Figure 1). Therefore, the observed upwarping was differential—that is, tied to an outlet that had been raised at a lower rate than locations to its north and concomitantly faster than those to the south.

Goldthwait (1908) questioned Spencer's (1891) conclusion concerning the submergence of the Lake Algonquin shoreline in the southern part of the Michigan and Huron basins. He claimed that the shoreline was above and parallel to the present shore in the south, with the upwarping having ended at an east-west-trending hingeline. He presented his shoreline observations from the Lake Michigan basin on a figure showing distance north of Onekama, Michigan versus shoreline elevation. This figure showed the profile of the warped water-plane or rebound curve, demonstrating how each shoreline rose to the north and merged to a presumably horizontal plane toward the south. Discharge from Algonquin was shared between the Port Huron, Michigan and Kirkfield, Ontario outlets (Goldthwait). Each successively lower Algonquin beach resulted from uplift north of the hinge line (which shortly raised the Kirkfield outlet above the lake, causing all drainage to then go through Port Huron). An even lower outlet at North Bay, Ontario was eventually uncovered, culminating in an extremely low lake-level for the Lakes Superior, Huron and Michigan basins (Goldthwait) and essentially ending the Algonquin lake phases. Continued, post-Algonquin uplift resulted in rising lake-levels, eventual abandonment of the North Bay outlet, and a return to the single Port Huron outlet, culminating in the high level Nipissing phase. As rebound was still occurring, Nipissing shore features were also raised in the north.

After collecting and compiling data from a wider range of latitude, Goldthwait (1910b) constructed an isobase map showing lines of equal elevation of the raised Algonquin shore. The general trend is of an increase in the amount of rebound toward the northeast. He (239) also defined the term "hinge line" as the line separating "warping on one side and stability . . . on the other."

Spencer (1891, 14–15) alluded to shorelines lower than the Algonquin along the southern coast of Georgian Bay, giving elevations for several locations. Goldthwait (1910a), Taylor (Leverett and Taylor 1915), and later Stanley (1936) surveyed many of these shorelines in greater detail. Similarly, Mackinac Island became the focus of study for Algonquin shorelines due to an abundance of such features there (e.g., Taylor 1892; Leverett and Taylor 1915; Stanley 1945). Taylor (Leverett and Taylor, 415) noted that Mackinac Island shorelines "fell naturally into three groups" of closely spaced strands. He referred to these as the Upper (or Main) Group, Battlefield Group, and Fort Brady Group. The Upper Group included the highest Algonquin beach. About 13.5 m below the lowest Upper beach is the Battlefield Group, so named due to their distinct appearance on the Mackinac Island 1814 battlefield site. The lower Fort Brady Group was correlated from a type locality south of Sault Ste. Marie, Michigan (Leverett and Taylor) and is separated from the lowest Battlefield beach by a zone of about 7 m where no beach features were found. Leverett (1929, 66) traced Algonquin, Battlefield, and Fort Brady shorelines into the eastern Upper Peninsula of Michigan, remarking that islands, totaling "only a few square miles, . . . stood above . . . Lake Algonquin." Bergquist (1936) also noted Algonquin and lower shorelines in the Manistique drainage basin of northern Michigan, but he did not make any definite correlation to any shorelines except Main.

Leverett and Taylor (1915) shared Goldthwait's (1908) opinion that the outlet to the Algonquin lakes was to the south, though they included Chicago and Port Huron. They published three north-south profiles of distance versus shoreline elevation (Leverett and Taylor 1915, plates 23–25), all showing beaches converging toward the hinge line near Onekama. Though this is the largest compilation of data to date, Leverett and Taylor's (1915) profiles, like Goldthwait's (1910b) earlier version, are problematic in that many beaches in the north are merging into one beach in the south. It becomes increasingly difficult to determine which of the old shorelines is being observed and thence to resolve changes in slope.

Seeking to clarify inconsistent nomenclature and correlation, Stanley (1936, 1937) did detailed mapping in Georgian Bay. The importance of Stanley's work lies in his surveying of shorelines in an area large enough to accurately document isobase trends. Stanley (1936) mapped the main Algonquin shore and named four type-localities for Lower Group shorelines: Wyebridge, Penetang, Cedar

Point, and Payette (in descending order). Stanley's (1936, p. 1948) profile of these shorelines showed "unequivocally" that the water planes did not converge but were, in fact, parallel. He also found solid evidence of Payette shorelines below the Nipissing water plane. If the water planes do not merge towards a single outlet, then ice recession must have opened successively lower outlets, leaving the Port Huron outlet dry sometime during the Algonquin regression. Stanley (1936) went on to demonstrate that the Battlefield beach is probably the Wyebridge shoreline, while the Fort Brady Group encompasses the Penetang and Cedar Point shores. Incorrect correlation of Battlefield and Fort Brady away from their type localities led to low rebound estimates, causing Stanley (1936) to recommend that usage of the terms be suspended. Though not specifically proposed, it appears that Leverett and Taylor's (1915) three shoreline groups shrank to two at this time, the literature referring simply to the Upper Group and Lower Group.

Deane (1950) worked in the Lake Simcoe, Ontario (Figure 1) area in an effort to further quantify Algonquin shorelines and outlet relationships to the Trent River valley. He described type locations here for three post-Main Algonquin Upper Group shores: Ardtrea, Upper Orillia, and Lower Orillia. He also correlated Stanley's Lower Group beaches into the Lake Simcoe area. Deane believed that the Upper Group beaches, especially the Ardtrea, showed convergence and had, therefore, been subjected to uplift while the Port Huron outlet was still active. The Lower Group members showed "general parallelism," indicating "lowering of lake level by opening of other outlets" (Deane, 78). Hough (1958) criticized Deane's (1950) interpretation of Ardtrea convergence, claiming it was based on too few points.

After surveying on Manitoulin Island and Sault St. Marie, Ontario, Hough discovered two shore features below correlated Payette beaches, which he named Sheguiandah and Korah after their respective localities. He then correlated the Korah beach to the Fort Brady type location. If the Fort Brady adhered to the parallel slope of all other Lower Group phases, it would lie below present water level at Mackinac Island (Hough). On this basis, Hough (236) agreed with Stanley (1936) that the Fort Brady term should be "discarded." Hough (233) also stated that no shorelines from the Upper Group to Payette had yet "been recognized in the Michigan basin," though this does not seem in keeping with Leverett and Taylor's (1915) plate 23. Cowan (1985) resurveyed existing shoreline data from the Sault Ste. Marie, Ontario vicinity and found discrepancies with Hough's interpretations of Lower Group elevations. Though some of the problems probably stem from Hough's use of an altimeter, Cowan (37) concluded that "large data gaps" continue to hamper this type of research.

Later, Farrand and Drexler (1985) investigated evidence for the extent of Algonquin shorelines into the Lake Superior basin. They traced lower Algonquin features as far as seventy miles north of Sault Ste. Marie and correlated two strong wave-cut bluffs above a Minong shore in the Dollar Settlement area of northern Michigan to the Wyebridge and Payette phases. They also concluded that Lake Minong probably existed at least by the time of the lower Algonquin Sheguiandah level, giving credence to Stanley's (1936) concerns about usage of the Fort Brady term. Neglecting the problem Stanley (1936) identified with the Battlefield phase, Futyma (1981) opted to retain the term for his shoreline correlations in the Upper Peninsula of Michigan. Table 1 lists the pre-

Table 1. Selected Summary Information about Various Phases of Glacial Lake Algonquin and Post-Algonquin Lakes

Lake Name or Algonquin Lake Phase	Original Classification[a]	Pre-rebound Elevation (masl)[b]	Original and Other Important Sources
Main Algonquin	Main	184	Spencer (1891); Leverett and Taylor (1915)
Ardtrea	Upper group	180	Deane (1950)
Upper Orillia	Upper group	174	Deane (1950)
Lower Orillia	Upper group	168	Deane (1950)
Wyebridge (Battlefield)	Lower group	164	Stanley (1936); Leverett and Taylor (1915)
Penetang	Lower group	155	Stanley (1936)
Cedar Point	Lower group	151–150	Stanley (1936)
Payette	Lower group	142	Stanley (1936)
Shegiuandah	Lower group	131	Hough (1958)
Korah (Fort Brady)	Lower group	122–119	Hough (1958); Leverett and Taylor (1915)
Chippewa, Stanley, and Hough	Post-Algonquin low lakes	70 and 33(?)	Stanley (1936); Hough (1958); Eschman and Karrow (1985)

Source: After Fullerton (1980).
[a] Leverett and Taylor (1915).
[b] Meters above mean sea level.

rebound elevations of the lake phases as compiled by Fullerton (1980). By the 1980s, the scientific community had come to recognize three upper (excluding Main) and six lower shorelines, whose correlations across the Great Lakes basin were difficult.

Lake Algonquin: Issues of Isostatic Rebound

Main Lake Algonquin has long been considered the most areally extensive lake level in the Great Lakes basin, marking "the culmination of the waters controlled by the retreating ice sheet" (Leverett and Taylor 1915, 409). Its size was due not only to the northerly position of the ice front, but also to isostatic depression of large land areas. Studying Algonquin shorelines, which would facilitate an understanding of the extent of the lake, is made difficult by several factors. Lake levels of equal, lower, and higher elevation existed within the same basin as Main Algonquin (Karrow and Calkin 1985). Isostatic rebound has raised the elevation of lakeshore features progressively to the north, while differential uplift has shifted shorelines as though they were "swung . . . on a fulcrum" around the outlet (Leverett and Taylor, 413).

Tracing shore features over broad regions is also difficult because they are seldom continuous or morphologically uniform from place to place (Karrow 1986). In fact, this is a persistent problem with shoreline correlation. Evidence of ancient shorelines is not a simple matter of tracing features across the countryside. Strength of the shoreline's development depends on how the dominant wave-action impinged on the shore and how long the water level remained at a particular elevation, as well as the type of material at the shore (e.g., bedrock versus sand). Strands (shorelines) may be separated by many miles due to erosion, may be represented by a bluff at one location and a beach face elsewhere, and can appear at different elevations due to isostatic rebound. Hence, correlation of widely separated strands depends on accurate construction of isobase maps to know where shorelines should occur at any particular latitude and longitude. Fortunately, because Main Algonquin was the highest lake in northern Michigan, its rebounded shoreline is, in many places, readily identifiable and hence mappable.

Leverett and Taylor's (1915, plate 23) lake-level rebound curves depict both their lake-level correlations and the elevation of the shoreline(s) at particular geographic points. However, due to technological advances in the past century, greater measurement accuracy now available can be used to refine their rebound curves. Their shoreline graphs also show rebound ending towards the south, where lake levels of equal original elevation merge into coincident beaches. This phenomenon led Leverett and Taylor (1915) to adopt the hingeline concept of Goldthwait (1908), which favored crustal deformation rather than isostatic adjustment. Larsen (1987) argued that the Main Algonquin level may have been well below the present lake surface in the southern part of the basin due to the downwarped northern part of the basin. He contended that, rather than merging, Algonquin shorelines continue to descend below the present lake surface. As Eschman and Karrow (1985, 89) state, "[T]he question of parallelism or convergence of the shorelines will not be fully resolved until better data are available from a much wider spread of latitude."

Water-Plane Estimation

The Great Lakes region contains abundant features of Lake Algonquin and its successive lower levels (e.g., wave-cut bluffs, beach ridges, off-shore bars and spits, and terraces of rivers graded to the lake). These features, by their very nature and mode of formation, are variable in their ability to delimit the actual paleowater plane; many, such as spits, bars, and deltas, present problems when used to estimate former water planes (Johnson 1933a). For instance, the crest of an offshore bar may be about 2 m below the water plane (Reineck and Singh 1973), whereas a spit crest may be over 4 m above it (Ollerhead and Davidson-Arnott 1995). Likewise, a beach ridge may be very near the mean water plane (Thompson 1992). Thompson, Fraser, and Olyphant (1988) argued that *depositional* landform proxies such as spits or bars might permit as much as ± 5 m of variation in estimates of water level. Additionally, identification of multiple lake planes where only one existed is possible when water-plane elevations are taken from the base of a wave-cut bluff *and* the crest or footslope of an offshore bar that was incorrectly interpreted as a lower bluff. Using this logic, Leverett and Taylor (1915) cast doubt on the identification by Coleman (1901) of several Algonquin beaches in Ontario, and Johnson (1933a) and Miller (1939) concluded that wave-cut bluffs are the best proxy indicators of former water-plane elevations.

Well-defined, wave-cut bluffs are common throughout the study area (Leverett and Taylor 1915; Farrand and Drexler 1985) and are generally composed of either till, glaciofluvial sediments, or limestone bedrock; today, all are vegetated and stable. A bouldery/gravelly lag is often located on the surface of the bench just below the base of the bluff (Figure 2A). While several bluffs have accumulated up to 2+ m of detritus (i.e., slopewash and colluvium) at their bases, many remain essentially free of debris. Where the bench is covered with detritus, the lag can often be found by coring. Although previous studies

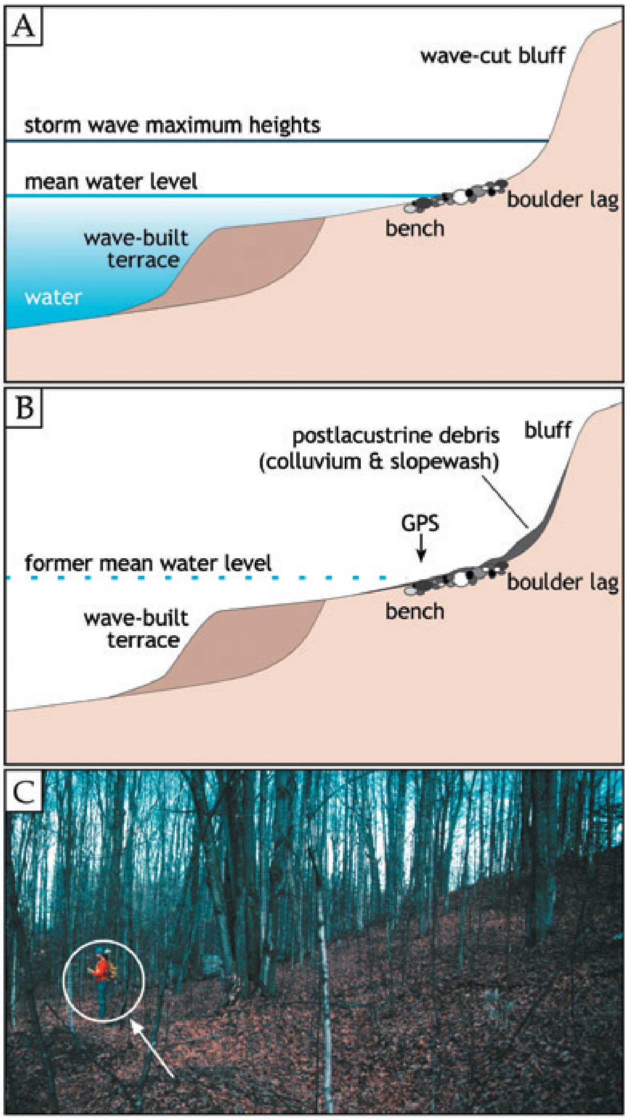


Figure 2. (A) Diagram of a modern wave-cut bluff during formation, showing mean water-level and boulder lag. (B) Diagram of wave-cut bluff after lake recession, showing former mean water-level and position of GPS point-collection. (C) GPS data-collection at the base of a Lake Algonquin wave-cut bluff.

have placed the mean water level at or well above the base of the bluff (e.g., Johnson 1919; Dietz and Menard 1951; Bradley 1958; Rovey and Borucki 1994), we suggest that the bouldery lag at the bluff base provides the most credible estimation of mean water level (Johnson 1933b; Miller 1939; Zenkovich 1967; Steers 1969). Our observations of modern Great Lakes shorelines also support the use of this position as a surrogate for previous water planes.

In previous mapping research, surveyors used level (e.g., Spencer 1891; Gilbert 1898; Goldthwait 1908) and barometer (e.g., Leverett and Taylor 1915; Kaszycki 1985) technologies and topographic maps (Futyma 1981) to measure past water plane elevations. This method has been used successfully on small spits or stretches of beach front (e.g., Firth et al. 1995), but was inappropriate for the large area we studied. Nonetheless, the durability of such research provides support for continued use of these traditional tools in current mapping exercises when more advanced technologies cannot be used. However, GPS technology, used in this study, is capable of producing horizontal and vertical position measurements with submeter accuracy and is more accurate and cost-efficient when used over a large study area.

Methods

Point Sampling with GPS

Collection of Position Data (Field). We chose an initial set of possible Algonquin wave-cut bluff sites by examining 7.5-minute USGS topographic maps, guided by detailed, interpretive descriptions of the study area (Leverett and Taylor 1915; Stanley 1945; Futyma 1981; Schaetzl et al. 2000; Krist and Schaetzl 2001). We collected field measurements during the leaf-off season (October, November, and again in April). Leaf-off conditions provide clearer sight lines between forested sites and satellites in orbit above the horizon. Prior to each field exercise, we recorded an almanac using a Trimble ProXL GPS unit (Trimble Navigation Limited 1998) and analyzed the data it contained using GPS Pathfinder® Office software. We queried the almanac data to identify and select satellite constellation configurations that would allow us to make the most accurate vertical (Z axis) measurements. Because such constellations exist only during short time frames (10- to 15-minute intervals are typical), we planned data collection activities around these windows.

In the field, we visited an initial set of predetermined sites and selected only those with clearly identifiable, wave-cut bluffs. We made position measurements using GPS at locations near the bluff inflection point in order to approximate the mean water level of the former water plane (Figure 2). At bluffs with obvious colluvial fill, we measured a few meters downslope of the bluff inflection point and made notes on the thickness of the colluvium over beach gravel (if present), so that we could later adjust the measured elevation downward by that amount. While the location of such an observation may not be as accurate as one from a fresh wave-cut bluff or one that lacked colluvium, we felt that the error associated with each estimate of colluvial fill would not be more than ±2 meters. At most wave-cut bluff locations, we collected 120–250 position readings at one-second intervals while standing at each designated location. OmniSTAR™

Worldwide DGPS (OmniSTAR, Inc. 1999) and United States Coast Guard DGPS services made real-time differential corrections to position data. In all, we collected more than 15,000 measurements (x,y,z triplets) at 160 locations.

We made every effort to minimize error in our position data. First, we limited selection errors by choosing only those locations at clearly identifiable wave-cut bluffs. Second, we attempted to minimize measurement errors as follows: (a) by collecting data only when optimal satellite constellation configurations occurred; (b) by taking measurements in relatively less densely forested locations so fewer multipath errors would occur; and (c) by discarding position data that did not exceed an acceptable level of precision.

Processing of Position Data. We processed position data for each of the 160 field locations using Pathfinder® Office software and screened them for indications of poor positional accuracy. We discarded individual positions if they had a dilution of vertical or positional precision that exceeded our predetermined limits (VDOP > 4.0; PDOP > 6.0), and those with obvious multipath errors. For each field location, we combined remaining position coordinates to produce a point with average northing, easting, and elevation values. Out of 160 field locations surveyed, 138 sets of position readings were deemed accurate and combined into points. This set of 138 points is the set of data we analyzed.

Accuracy Assessment of Point Data. In addition to shoreline data, we collected and processed position data for eight different benchmarks in order to assess the accuracy of our methods. We compared calculated benchmark elevation values to those published by the National Geodetic Survey (NGS Information Services Branch 1999), yielding a root mean squared error (RMSE) of 1.34 m between calculated and published elevation values (Table 2). Because the methods used to gather and process shoreline data were the same methods used to gather and process benchmark data, we concluded that the mean vertical error in the shoreline data is <1.5 m.

Table 2. Differences between Benchmark Elevations Measured for This Study and Published Elevations for Same Benchmarks

Benchmark	Elevation Calculated by the GPS (masl)[a]	Elevation Published by the National Geodetic Survey (1999) (masl)[a]	Difference (m)
1	193.89	194.28	−0.39
2[b]	234.76	234.77	−0.01
2[b]	236.82	234.77	2.05
3	198.87	196.51	2.36
4	185.97	184.00	1.97
5	267.55	266.70	0.85
6	191.35	192.37	−1.02
7	267.06	266.70	0.36
8	247.71	248.41	−0.70
		Mean error:	0.61
		Root mean squared error (RMSE):	1.34

[a] Meters above mean sea level.
[b] This benchmark elevation was measured on two different dates.

Correlation of Shoreline Elevations

Assignment of Data Points to Shorelines. Assignment of each GPS data point to its appropriate Algonquin shoreline, and correlation of these shorelines to each other and to ones previously recognized in the literature, were critical to this research. Various shoreline and lake categorization schemes have been proposed (e.g., Leverett and Taylor 1915; Spencer 1936; Deane 1950; Hough 1958), and in some instances, multiple names have been applied to the same shoreline.

We began shoreline categorization near Douglas Lake, Cheboygan County, in the northern lower peninsula, because only two highly distinct shorelines exist in this region: Main Algonquin, at approximately 225 m, and a lower shoreline at about 210 m (Leverett and Taylor 1915; Futyma 1981). We classified all GPS points within this area (i.e., within that particular topographic quadrangle) that were 225 ± 3 m as "Main" (the plus/minus is included to account for the presence or absence of colluvial fill, and measurement error). We designated all our shoreline GPS points in this quadrangle that were at 210 ± 3 m as "BIO," for the nearby University of Michigan Biological Station, deliberately avoiding correlating it to a previously named shoreline at this early point in the analysis. Then, assuming that the rebound isobases in this region are generally east-west in orientation (Futyma 1981), we examined the quadrangle to the immediate west and labeled GPS points at 225 ± 3 m as "Main" and points at 210 ± 3 m as "BIO." We continued this practice until we reached the Lake Michigan coast, where we encountered an additional (third) shoreline near Good Hart. This distinct shoreline was 3 to 4 m below the Main Algonquin shoreline. We designated it "Main Lower" (again, avoiding a correlation to a previously recognized shoreline) and continued plotting these three shorelines. This procedure was then continued for all GPS points due *east* of the Douglas Lake area to the Lake Huron coast.

Next, we repeated the procedure on the subsequent tier of quadrangles to the south. We assumed that the elevations of the three shorelines would be 3 to 6 m lower on these quadrangles, based on rebound curves (Leverett and Taylor 1915; Spencer 1936; Deane 1950; Futyma 1981) and our own preliminary field data. Our assumption proved reliable, and mapping/correlation continued as before. We eventually correlated all our GPS points in the lower peninsula to five shorelines, adjusting our expected elevations upward or downward based on rebound curves and distance north or south of Douglas Lake.

We located Farrand and Drexler's (1985) correlated Payette and Wyebridge shorelines and assumed that the GPS points we collected at the same wave-cut bluffs represented good elevation control for them. We then located all shorelines in the vicinity, including some lower, Lake Minong (Farrand and Drexler 1985) shorelines, and correlated them within a four-quadrangle area, using our GPS data as a first elevation approximation. Correlation among the three Algonquin shorelines we found in the Upper Peninsula (Main, Wyebridge, Payette) and the five shorelines we found in the Lower Peninsula was straightforward based on previously mentioned rebound curves; it also helped to have shoreline data for Mackinac Island, which lies between the two peninsulas and has distinct shorelines. Our Upper-to-Lower-Peninsula shoreline correlations allowed us to drop the names initially assigned to shorelines in the lower peninsula and assign/correlate them to known shorelines from the literature.

A shoreline not identified by Farrand and Drexler (1985), but which lies between the elevation of Main Algonquin and one we identified as Wyebridge, was correlated to Ardtrea based on relationships described in Futyma (1981) and Deane (1950). The directions of maximum uplift based on their isobase maps are N15E and N21E, respectively. This correlates the center of Deane's study area (1950) to the vicinity of Mackinac Island, thus matching most closely the 4-m difference between his Main Algonquin and Ardtrea with our 6-m difference between the same.

Describing Shorelines and Isobases in Three Dimensions. We produced five scatterplots of bluff base elevation versus northing, one for each of the major shorelines we believed to be in the area. After carefully inspecting each scatterplot, we reexamined several outliers to determine if they had been misclassified. We eventually reclassified nine (of 138) points. In most cases, the original classifications/correlations for these points had been flagged as questionable during the first iteration—that is, we had not been confident as to which shoreline these points belonged to, and therefore we reevaluated them again as our trend-surface equations became more refined and our confidence in them grew.

Based on this classification, we applied a best-fit linear trend-surface solution to each set of elevations using optically stimulated luminescence (OLS) and polynomial algorithms in Matlab. Trend-surface analysis has been successfully used to determine patterns of uplift from shoreline data (Smith, Sissons, and Cullingford 1969; Gray 1974; Firth 1989). In addition, we followed Davis's (1986) methods and applied second-order trend-surface solutions to shoreline data sets having more than 15 points (i.e., Main, Ardtrea, and Wyebridge). Third-order and higher surfaces, which have been used elsewhere on more complicated landscapes (e.g., Firth, Smith, and Cullingford 1993), were not useful. Calculated root mean squared error (RMSE) values associated with all second-order surfaces were lower than those calculated for corresponding first-order surfaces, indicating that the second-order solutions better fit our data. Once the five trend surfaces had been calculated, we examined outliers a second time. Points with elevations that deviated greatly from each respective trend surface and for which there was good geomorphic and mathematical evidence for misclassification (6 points) were reclassified. After a third and final iteration, final trend surfaces were calculated in the manner described above (Davis). Again, calculated RMSE values associated with all second-order surfaces were lower than those calculated for corresponding first-order surfaces, indicating that the second-order solutions better fit our data (Table 3). The paucity of data points (11 and 5, respectively) for the Payette and the possible lower shoreline constrained our analysis to only a basic first-order (planar) surface solution.

The general equation for the planar surface is given by

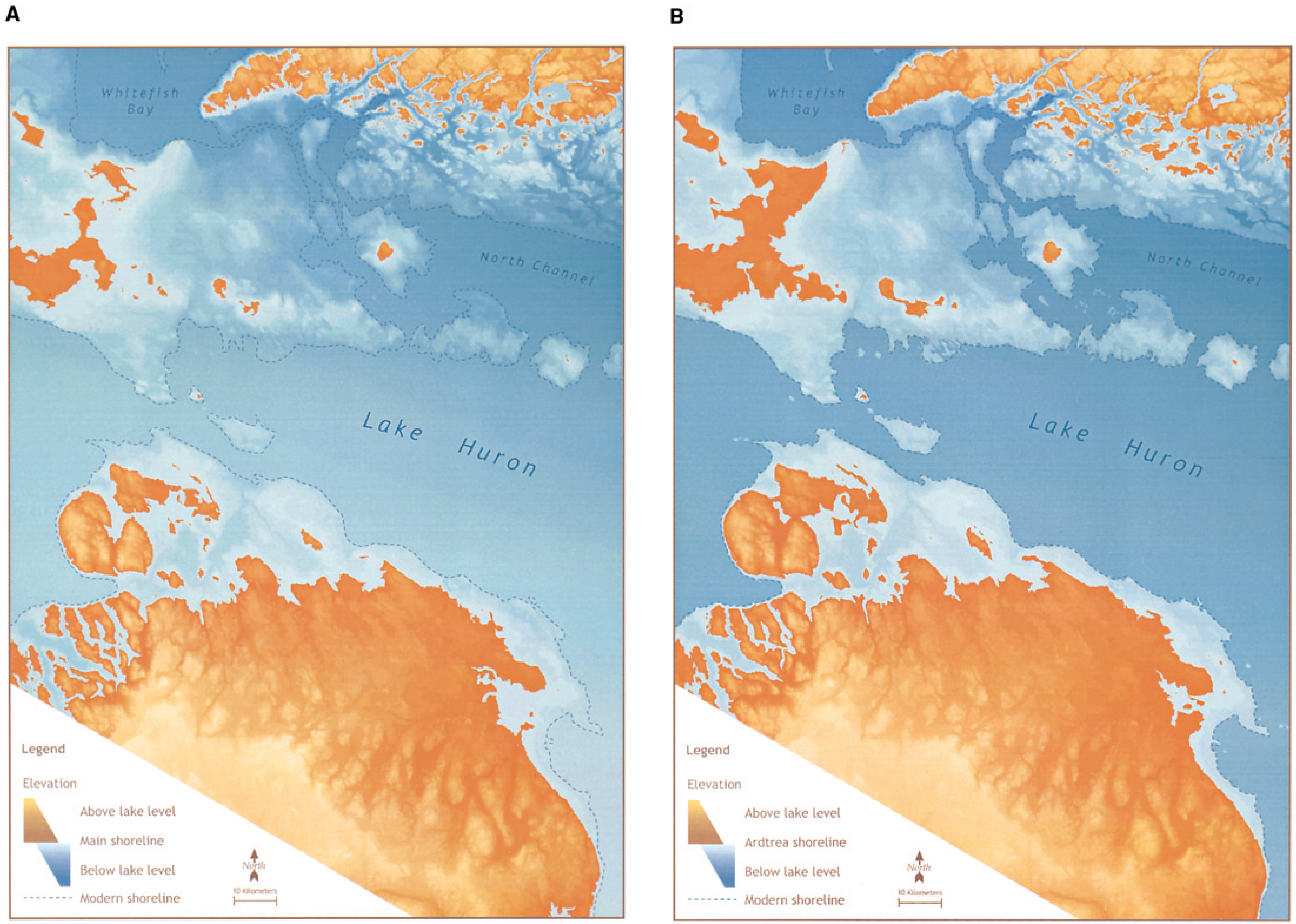
$$Z_i = b_0 + b_1(easting_i) + b_2(northing_i) + e_i \qquad (1)$$

where Z_i is the value (elevation in meters above sea level [masl]) of the surface at the point i, b_0 is the constant (base) of the surface, b_1 and b_2 are coefficients of the surface, representing slope with respect to easting and northing axes, and e_i is the error term.

For the larger datasets associated with the Main, Ardtrea, and Wyebridge shorelines, we were able to fit more robust, second-order trend-surface solutions. For a second-order trend surface, the general form of the equation (quadratic) of the surface is given by

$$Z_i = b_0 + b_1(easting_i) + b_2(northing_i) + b_3(easting_i)^2 + b_4(easting_i)(northing_i) + b_5(northing_i)^2 + e_i \qquad (2)$$

Four of the five final trend-surface equations (we excluded the lowest shoreline surface generated from only five data points and having a relatively high RMSE) were then used to construct isobase maps of shoreline elevations within the study area.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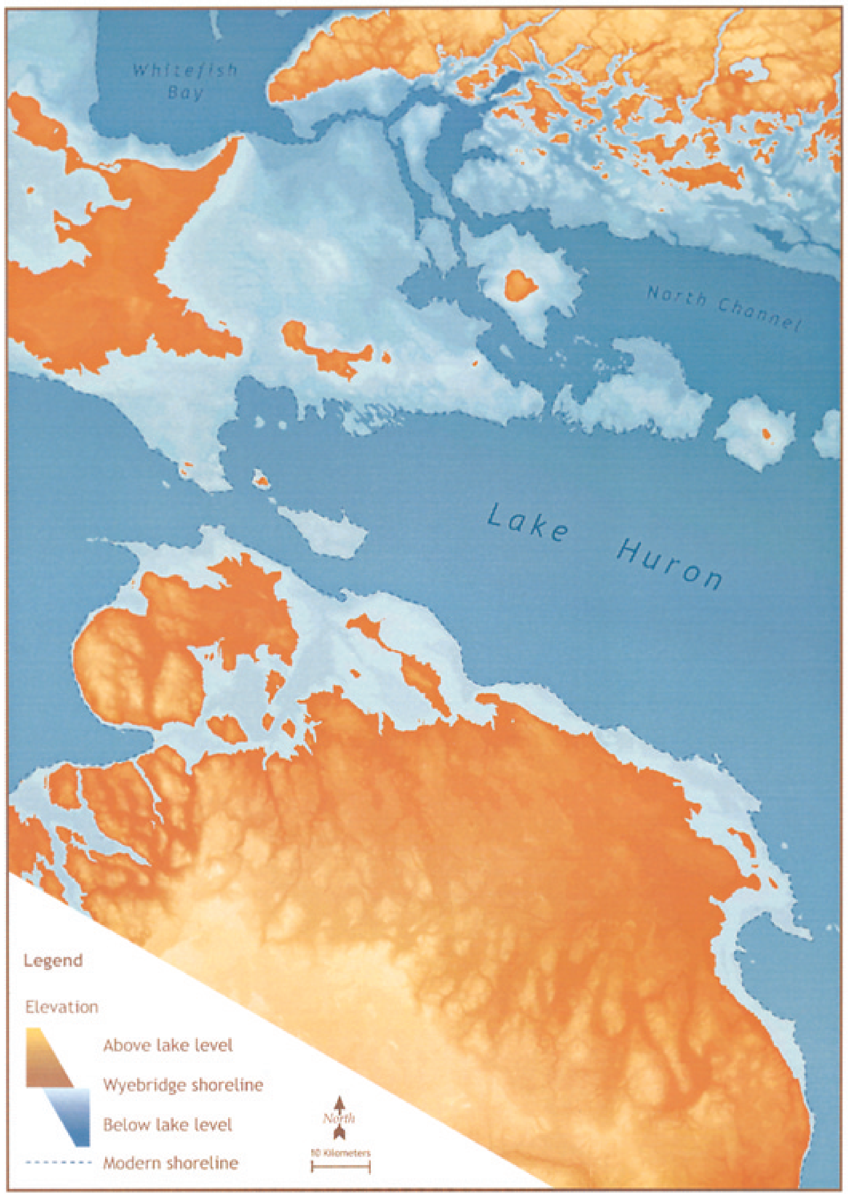

Figure 3. Maps of the central portion of Lake Algonquin during its (A) Main, (B) Ardtrea, and (C) Wyebridge phases, made by calculating and then flooding a rebound-adjusted digital elevation model.

Table 3. Equations and Descriptive Data for the Major Shorelines of Glacial Lake Algonquin

Shoreline	Best-Fit Equation[a]	RMSE (m)	Maximum Absolute Error (m)	n
Main	$Z = 2066.3172 - 0.0026(\mathit{easting}) - 0.0042(\mathit{northing}) + 0.0000(\mathit{easting})^2 + 0.0000(\mathit{easting})(\mathit{northing}) + 0.0000(\mathit{northing})^2$	3.4	9.3	68
Ardtrea	$Z = 1342.4820 - 0.0022(\mathit{easting}) - 0.0021(\mathit{northing}) + 0.0000(\mathit{easting})^2 + 0.0000(\mathit{easting})(\mathit{northing}) + 0.0000(\mathit{northing})^2$	3.1	6.4	28
Wyebridge	$Z = 1806.4519 - 0.0024(\mathit{easting}) - 0.0035(\mathit{northing}) + 0.0000(\mathit{easting})^2 + 0.0000(\mathit{easting})(\mathit{northing}) + 0.0000(\mathit{northing})^2$	2.1	4.9	26
Payette	$Z = -65.4359 + 0.0001(\mathit{easting}) + 0.0004(\mathit{northing})$	5.2	10.5	11
"lowermost" (?)	$Z = -39.7983 + 0.0002(\mathit{easting}) + 0.0002(\mathit{northing})$	5.9	9.1	5

[a] Units are in meters above sea level and are based on the State of Michigan GeoRef coordinate system. The equations apply only to locations within the extent of the GPS data. The second-order surfaces have large b_0 coefficients (elevation intercepts). Obviously, these magnitudes of elevation did not exist in this region. Such magnitudes are artifacts of the least-squares process. The minimum bounding rectangle for the GPS data is described by the following coordinates:

GeoRef easting minimum: 558790
GeoRef easting maximum: 714440
GeoRef northing minimum: 436080
GeoRef northing maximum: 661270

Coefficients with zero values represent actual and significant non-zero rates of change; all coefficient values were rounded (0.0001 m) for this display.

Results and Discussion

Our analyses of Lake Algonquin shoreline elevations in upper Michigan indicate that only four widespread, definitive shorelines are evident in the study area. These shorelines correspond to, from highest to lowest: Main, Ardtrea, Wyebridge, and Payette phases (Hough 1958). A fifth, lower shoreline was observed at five locations. We felt that we had insufficient data on this shoreline to attempt correlation. We produced maps of each of the four major phases of Lake Algonquin by projecting the shoreline elevations onto a rebound-adjusted digital elevation model (DEM; three are shown in Figure 3).

We often found that a shoreline had been given multiple names by different researchers, or was correlated to different shorelines in disparate areas. As a result, we renamed/reclassified some shorelines named in Futyma (1981) and Leverett and Taylor (1915) (Table 3). For example, the shoreline associated with the Battlefield phase of Lake Algonquin, as proposed by Leverett and Taylor, correlates to the Wyebridge shoreline as used by Stanley (1936). In the Upper Peninsula, our Wyebridge shoreline correlates to a similarly named shoreline in Farrand and Drexler (1985), and to the "Upper Group Strong Strands" observed by Futyma (1981). On Mackinac Island and in the northern Lower Peninsula, our Wyebridge shoreline correlated to the Lowest Beach of Leverett and Taylor's "Upper Group."

Assuming that the relative positioning between successive shorelines remained constant through time as the lake level fell, we made classifications attributing certain shorelines to distinct elevations. Continually identifying shorelines that occur at the same elevation and along the same isobase with the same name should make correlation among parts of study areas straightforward. For example, in the northern lower peninsula of Michigan, shorelines at an elevation of about 225 m occurring along the same isobase were attributed to Main Algonquin. Subsequent lower shorelines were classified similarly. Leverett and Taylor (1915) identified six Algonquin beaches on Mackinac Island. We analyzed these beaches and concluded that several appeared to be offshore bars and should not have been interpreted as distinct shorelines. Until such time as trenching these beaches is possible, our contention in this regard remains conjectural. We have data from only three distinct shorelines on Mackinac Island: Main, Ardtrea, and Wyebridge. A fourth, lower shoreline—probably Payette—was observed on the island, but the GPS data contained errors in vertical and horizontal displacement due to poorly positioned satellites and were therefore abandoned.

Scatterplots of GPS data points showed that a second-order polynomial regression best fit the data for Main, Ardtrea, and Wyebridge, with goodness-of-fit values ranging from 0.97 to 0.99. All four shorelines in this study increase in elevation, trending southwest to northeast; isostatic rebound has been greatest in the northeast sector (Figure 4). We used these surfaces to construct elevation isobases (Figure 4), similar to those of Deane (1950), Futyma (1981), and Larsen (1994). An absolute

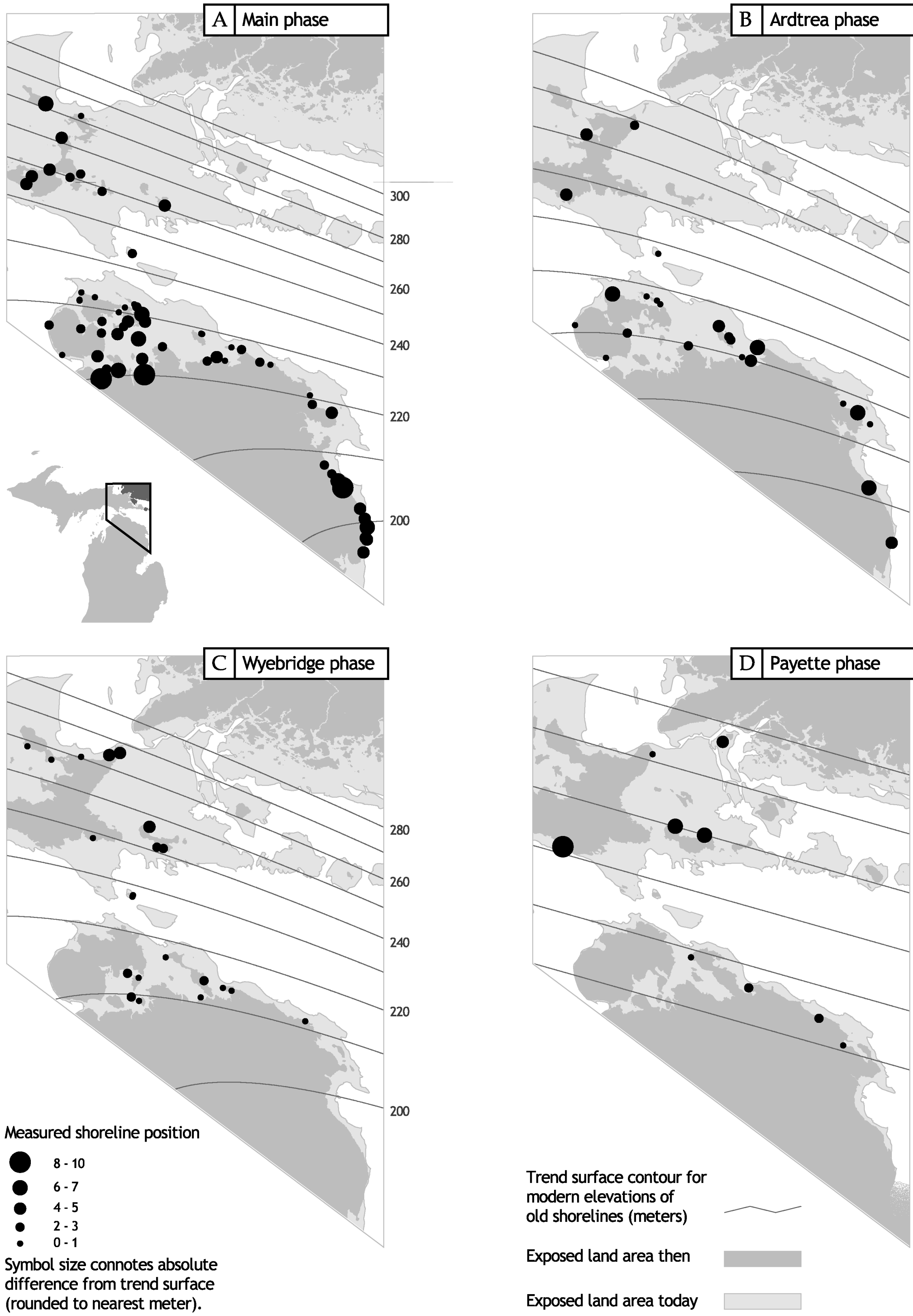

Figure 4. Isoline maps of bluff elevations for the (A) Main, (B) Ardtrea, (C) Wyebridge, and (D) Payette shorelines of Glacial Lake Algonquin, also showing the land area exposed (and hence, the shoreline) during each lake phase. Locations of GPS sampling-points are shown, along with the difference ("error") between the elevation at the site and the predicted elevation from the trend surface equation. Larger circles imply larger errors.

inclination for each isobase could not be made because of the curvilinear nature of the upper three surfaces. However, the linear Payette surface has an inclination (slope) of 0.39 m km^{-1}. The isobases (Figure 4) suggest an approximate rebound trend (*declination*) for all surfaces of between N7E and N23E, similar to the N15E inclination proposed by Futyma (1981), and the N21E azimuth established by Deane (1950) and Goldthwait (1908).

The Main Algonquin shoreline rises from an elevation of <200 m in the southeast to >310 m in the far north (Figure 4; Table 4). We feel very confident about our uppermost shoreline curve (Main), in that elevations predicted by the trend surface were often extremely close to elevations reported in the literature. For example, Taylor (1895) reported an elevation for the "highest beach" on Munuscong Island of 261 m, which is within 4 m of our predicted elevation (Table 4).

In Michigan, the Ardtrea and Wyebridge shorelines increase in elevation, northwardly, to approximately 280 m, again trending toward the northeast (Figure 4). Our calculated rebound elevations in the northeast are less than that proposed by Leverett and Taylor (1915), and at their northern extremities are approximately 10 m lower than the rebound estimated by Futyma (1981) (Figure 4). Examination of the elevation differences between shorelines suggests that the time interval between Ardtrea and Wyebridge was shorter than any of the other four intervals (Table 4). Projected shoreline elevations show that convergence of the Main and Ardtrea shorelines occurs at about 44.6°N latitude, which agrees with Deane's (1950) observations. Deane attributed the convergence to differential uplift coinciding with the use of the same outlet between the Main and Ardtrea phases; our data support this hypothesis. Our data cannot be used, however, to help resolve the question of where Lake Algonquin stood in the southern part of the Lake Michigan-Huron basin (Figure 1), because our study area did not extend that far south. This difficult question, which has perplexed researchers for years (Goldthwait 1908; Larsen 1987; Clark et al. 1994; Colman et al. 1994), remains unanswered.

Our data also indirectly corroborate work done by Krist and Schaetzl (2001). Using geomorphic and sedimentologic data from large, sandy spits that extend to the northwest from several Algonquin islands, they suggested that strong east and southeasterly winds at this time battered the islands of Main Algonquin. Many of the Algonquin islands studied by Krist and Schaetzl have spits trailing off to the northwest, while high wave-cut bluffs with offshore gravel bars are found on the south and southeast sides. During our fieldwork, we noted high, clear bluffs on islands in the Upper Peninsula, as well as on the northeastern side of the Lower Peninsula. We initially assumed that the high bluffs were cut during Main Algonquin. Later, we learned that the elevations of many of these bluffs were lower than would have been expected for that phase. The reason for the elevation discrepancy lies in the fact that these windward bluffs were initially cut during Main Algonquin, but continued to retreat during later phases, especially Ardtrea. As a result, several bluff faces on the southeast sides of Algonquin islands are at Ardtrea level, even though they are the highest bluff on the island. These observations strongly support Krist and Schaetzl's model for strong east and southeasterly winds during Lake Algonquin time.

Table 4. Three-Dimensional Aspects of the Rebounded Lake Algonquin Shoreline at Key Locations within the Study Area

	Alpena	Douglas Lake	Munuscong Island	Sault Ste. Marie
Main				
Elevation[a]	212	228	265	305
Gradient[b]	1.07	0.79	0.40	0.42
Aspect[c]	9	8	19	22
Ardtrea				
Elevation	210	223	255	285
Gradient	0.78	0.62	0.41	0.48
Aspect	20	9	19	23
Wyebridge				
Elevation	202	214	245	279
Gradient	0.90	0.66	0.34	0.36
Aspect	14	7	19	22
Payette[d]				
Elevation	195	205	229	246
Gradient	0.39	0.39	0.39	0.39
Aspect	16	16	16	16
x coordinate[e]	701090	600630	613270	626780
y coordinate[e]	504120	559600	620630	662070

[a] Elevation: height of rebounded water plane at the location noted. This value should not be used to indicate presence of a shoreline in that area. Rather, it indicates what the shoreline would be *if* one exists in the area. Elevations are rounded to the nearest meter.
[b] Gradient: inclination of the rebounded water plane surface at the location noted, or the maximum instantaneous rate of change. Units are in m km^{-1}.
[c] Aspect: declination of the rebounded water plane surface at the location noted, or direction or maximum rate of change. Units are in degrees azimuth.
[d] Based on first-order trend surface (all others are second-order surfaces).
[e] x and y coordinates in the Michigan GeoRef projection, rounded to nearest 10 m.

Conclusion

This study has shown that effective identification, reconstruction, and correlation of pro- and postglacial lake levels can best be achieved through examination of elevation data from wave-cut bluffs. Such bluffs are found throughout the upper Great Lakes basin and are arguably the best indicators of past water levels, yielding more reliable elevation data than do spits and offshore bars. Further geomorphologic and stratigraphic research is still needed, however, to accurately identify the location of paleowater planes from additional wave-cut bluffs within and beyond our study area.

Shoreline data suggest that four distinct Algonquin shorelines exist in the study area, along with a fifth, weak, lower shoreline. Other, more ephemeral shorelines represented by beach faces, bars, and so on may be present but were not within our research design. We suggest that the four major shorelines be named Main, Ardtrea, Wyebridge, and Payette, to facilitate nomenclatural uniformity. Our generated rebound curves provide quantitative data on isostatic uplift in the region, which in this area increases from southwest to northeast. We feel that our rebound curves and isobase maps are more accurate than those reported previously.

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References

Bergquist, S. G. 1936. *The Pleistocene history of the Tahquamenon and Manistique drainage region of the northern peninsula of Michigan*. Michigan Geological Survey Publication 40. Lansing: Michigan Geological Survey.

Blewett, W. L. 1990. The glacial geomorphology of the Port Huron complex in northwestern Southern Michigan. Ph.D. diss., Michigan State University.

Blewett, W. L., and H. A. Winters. 1995. The importance of glaciofluvial features within Michigan's Port Huron moraine. *Annals of the Association of American Geographers* 85:306–19.

Bradley, W. C. 1958. Submarine abrasion and wave-cut platforms. *Bulletin of the Geological Society of America* 69:967–74.

Clark, J. A., M. Hendriks, T. J. Timmermans, C. Struck, and K. J. Hilverda. 1994. Glacial isostatic deformation of the Great Lakes region. *Geological Society of America Bulletin* 106:19–31.

Coleman, A. P. 1901. Marine and freshwater beaches of Ontario. *Bulletin of the Geological Society of America* 12:129–46.

Colman, S. M., J. A. Clark, L. Clayton, A. K. Hansel, and C. E. Larsen. 1994. Deglaciation, lake levels, and meltwater discharge in the Lake Michigan basin. *Quaternary Science Reviews* 13:879–90.

Cowan, W. R. 1985. Deglacial Great Lakes shorelines at Sault Ste. Marie, Ontario. In *Quaternary evolution of the Great Lakes*, ed. P. F. Karrow and P. E. Calkin, 33–37. Geological Association of Canada Special Paper 30. St. John's, Newfoundland: Geological Association of Canada.

Davis, J. C. 1986. *Statistics and data analysis in geology*. New York: John Wiley & Sons.

Deane, R. E. 1950. *Pleistocene geology of the Lake Simcoe district, Ontario*. Geological Survey of Canada Memoir 256. Ottawa: Canada Department of Mines and Technical Surveys.

Dietz, R. S., and H. W. Menard. 1951. Origin of abrupt change in slope at continental shelf margin. *Bulletin of the American Association of Petroleum Geologists* 35:1994–2016.

Eschman, D. F., and P. F. Karrow. 1985. Huron basin glacial lakes: A review. In Quaternary evolution of the Great Lakes, ed. P. F. Karrow and P. E. Calkin. *Geological Association of Canada Special Paper* 30:79–93.

Evenson, E. B., W. R. Farrand, D. F. Eschman, D. M. Mickelson, and L. J. Maher. 1976. Greatlakean substage: A replacement for the Valderan substage in the Lake Michigan basin. *Quaternary Research* 6:411–24.

Farrand, W. R., and C. W. Drexler. 1985. Late Wisconsinan and Holocene history of the Lake Superior basin. In Quaternary evolution of the Great Lakes, ed. P. F. Karrow and P. E. Calkin. *Geological Association of Canada Special Paper* 30:17–32.

Finamore, P. F. 1985. Glacial Lake Algonquin and the Fenelon Falls outlet. In Quaternary evolution of the Great Lakes, ed. P. F. Karrow and P. E. Calkin. *Geological Association of Canada Special Paper* 30:125–32.

Firth, C. R. 1989. Late Devensian raised shorelines and ice limits in the inner Moray Firth, northern Scotland. *Boreas* 18:5–21.

Firth, C. R., D. E. Smith, and R. A. Cullingford. 1993. Late Devensian and Holocene glacio-isostatic uplift patterns in Scotland. In *Neotectonics: Recent advances*, ed. L.A. Owen, I. Stewart, and C. Vita-Finzi, 1–14. Proc. no. 3. Cambridge, U.K.: Quaternary Research Association.

Firth, C. R., D. E. Smith, J. D. Hansom, and S. G. Pearson. 1995. Holocene spit development on a regressive shoreline, Dornoch Firth, Scotland. *Marine Geology* 124:203–14.

Fullerton, D. S. 1980. Preliminary correlation of post-Erie interstadial events (16,000–10,000 radiocarbon years before present), central and eastern Great Lakes region, and Hudson, Champlain and St. Lawrence lowlands, United States and Canada. U.S. Geological Survey Professional Paper 1089. Washington, DC: USGS.

Futyma, R. P. 1981. The northern limits of glacial Lake Algonquin in upper Michigan. *Quaternary Research* 15:291–310.

Gilbert, G. K. 1898. Recent earth movements in the Great Lakes region. U.S. Geological Survey 18th Annual Report, part 2. Washington, DC: USGS.

Goldthwait, J. W. 1908. A reconstruction of water planes of the extinct glacial lakes in the Lake Michigan basin. *Journal of Geology* 16:459–76.

———. 1910a. An instrumental survey of the shore-lines of the extinct lakes Algonquin and Nipissing in southwestern Ontario. *Canada Geological Survey Memoir* 10:1–57.

———. 1910b. Isobases of the Algonquin and Iroquois beaches and their significance. *Geological Society of America Bulletin* 21:227–48.

Gray, J. M. 1974. The main rock platform of the Firth of Lorn, western Scotland. *Transactions of the Institute of British Geographers* 61:81–99.

Hansel, A. K., D. M. Mickelson, A. F. Schneider, and C. E. Larsen. 1985. Late Wisconsinan and Holocene history of the Lake Michigan basin. In Quaternary evolution of the Great Lakes, ed. P. F. Karrow and P. E. Calkin. *Geological Association of Canada Special Paper* 30:39–53.

Hough, J. L. 1958. *Geology of the Great Lakes*. Urbana: University of Illinois Press.

Johnson, D. W. 1919. *Shore processes and shoreline development*. New York: John Wiley and Sons.

———. 1933a. The correlation of ancient marine levels. *Comptes Rendus du Congres International de Geographie Paris* 2:42–54.

———. 1933b. Supposed two-metre eustatic bench of the Pacific shores. *Comptes Rendus du Congres International de Geographie Paris* 2:158–63.

Karrow, P. F. 1986. Valley terraces and Lake Algonquin shoreline position, southeast shore of Lake Huron, Canada. *Journal of Great Lakes Research* 12:132–35.

———. 1988. The Lake Algonquin shoreline, Kincardine–Port Elgin, Ontario. *Canadian Journal of the Earth Sciences* 25:157–62.

Karrow, P. F., T. W. Anderson, A. H. Clarke, L. D. Delorme, and M. R. Sreenivasa. 1975. Stratigraphy, paleontology, and the age of Lake Algonquin sediments in southwestern Ontario, Canada. *Quaternary Research* 5:49–87.

Karrow, P. F., and P. E. Calkin, eds. 1985. Quaternary evolution of the Great Lakes. *Geological Association of Canada Special Paper* 30.

Kaszycki, C. A. 1985. History of Glacial Lake Algonquin in the Haliburton Region, South Central Ontario. In Quaternary evolution of the Great Lakes, ed. P. F. Karrow and P. E. Calkin. *Geological Association of Canada Special Paper* 30:109–23.

Krist, F., and R. J. Schaetzl. 2001. Paleowind (11,000 BP) directions derived from lake spits in northern Michigan. *Geomorphology* 31:1–18.

Larsen, C. E. 1987. *Geological history of Glacial Lake Algonquin and the Upper Great Lakes*. United States Geological Survey Bulletin 1801. Washington, DC: USGS.

———. 1994. Beach ridges as monitors of isostatic uplift. *Journal of Great Lakes Research* 20:108–34.

Larson, G. J., T. V. Lowell, and N. E. Ostrom. 1994. Evidence for the Two Creeks interstade in the Lake Huron basin. *Canadian Journal of Earth Sciences* 31:793–97.

Larson, G. J., and R. J. Schaetzl. 2001. Origin and evolution of the Great Lakes. *Journal of Great Lakes Research* 27:518–46.

Leverett, F. 1929. *Moraines and shore lines of the Lake Superior Region*. U.S. Geological Survey Professional Paper 154A. Washington, DC: USGS.

Leverett, F., and F. B. Taylor. 1915. *The Pleistocene of Indiana and Michigan and the history of the Great Lakes*. U.S. Geological Survey Monograph 53. Washington, DC: USGS.

Matlab. 1999. Version 5.3. The Mathworks Inc., Natick, MA.

Miller, A. A. 1939. Attainable standards of accuracy in the determination of preglacial sea levels by physiographic methods. *Journal of Geomorphology* 2:95–115.

National Geodetic Survey (NGS) Information Services Branch. 1999. NGS datasheets. http://www.ngs.noaa.gov/datasheet.html (last accessed 13 May 2002).

Ollerhead, J., and R. G. D. Davidson-Arnott. 1995. Buctouche Spit, New Brunswick, Canada. Canadian Landform Examples-30. *Canadian Geographer* 39:274–82.

OmniSTAR, Inc. 1999. OmniSTAR Satellite Differential subscription for Trimble Pathfinder™ Pro XRS Product™. OmniSTAR, Inc., Houston, TX.

Pathfinder Office. 1998. V. 2.02. Trimble Navigation Limited, Sunnyvale, CA.

Reineck, H. E., and I. B. Singh. 1973. Depositional sedimentary environments. Berlin: Springer-Verlag.

Rovey, C. W. II, and M. K. Borucki. 1994. Bluff evolution and long-term recession rates, southwestern Lake Michigan. *Environmental Geology* 23:256–63.

Schaetzl, R. J. 2001. Late Pleistocene ice flow directions and the age of glacial landscapes in northern Lower Michigan. *Physical Geography* 22:28–41.

Schaetzl, R. J., F. Krist, P. Rindfleisch, J. Liebens, and T. Williams. 2000. Postglacial landscape evolution of northeastern lower Michigan, interpreted from soils and sediments. *Annals of the Association of American Geographers* 90:443–66.

Smith, D. E., J. B. Sissons, and R. A. Cullingford. 1969. Isobases for the Main Perth Raised Shoreline in southeast Scotland as determined by trend-surface analysis. *Transactions of the Institute of British Geographers* 46:45–52.

Spencer, J. W. 1891. Deformation of the Algonquin beach, and birth of Lake Huron. *American Journal of Science* 41: 12–21.

Stanley, G. M. 1936. Lower Algonquin beaches of Penetanguishene Peninsula. *Geological Society of America Bulletin* 47:1933–60.

———. 1937. Lower Algonquin beaches of Cape Rich, Georgian Bay. *Geological Society of America Bulletin* 48:1665–86.

———. 1945. *Prehistoric Mackinac Island*. Michigan Geological Survey Publication 43.

Steers, J. A. 1969. *The sea coast*. London: Collins.

Taylor, F. B. 1892. The highest old shore line on Mackinac Island. *American Journal of Science* 63:210–18.

———. 1895. The Munuscong Islands. *American Geologist* 15:24–33.

Thompson, T. A. 1992. Beach-ridge development and lake-level variation in southern Lake Michigan. *Sedimentary Geology* 80:305–18.

Thompson, T. A., G. S. Fraser, and G. Olyphant. 1988. Establishing the altitude and age of past lake levels in the Great Lakes. *Geological Society of America Abstracts with Programs* 20:392.

Zenkovich, V. P. 1967. *Processes of coastal development*. Edited by J. A. Steers and C. A. M. King. London: Oliver and Boyd.

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