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Notes

Palaeohydrographic reconstructions from strandplains of beach ridges in the Laurentian Great Lakes

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Abstract: The current temporal and spatial context of water-level change, drivers of change, and possible future scenarios of the Laurentian Great Lakes is controversial. Palaeohydrographs are being constructed from measured subsurface elevations of palaeo-swash zones and modelled ages in strandplains of beach ridges that are preserved in embayments along the lakes' edge. More than 800 elevations and 200 ages have been collected from 15 strandplains to construct site strandplain palaeohydrographs. Palaeo-beach elevations from whole strandplains or sets of correlative palaeo-beaches within strandplains are then used to establish an outlet palaeohydrograph for each lake. Adjusting strandplain palaeohydrograph elevations to account for glacial isostatic adjustment and refining age models help define the outlet palaeohydrograph. Common basin-wide water-level patterns and changes in outlet location or conveyance can then be interpreted. Systematic patterns of elevation and geomorphic/sedimentologic properties in individual, groups and sets of beach ridges in strandplains suggest that long-term patterns of water-level change and sediment supply occurred on decadal, centennial and millennial scales. Outlet palaeohydrograph construction for Lake Superior revealed discrepancies between geological and historical rates of glacial isostatic adjustment. These differences are currently being investigated using new data from Lake Huron.

Here, we introduce the Laurentian Great Lakes (LGL) and present more than two decades of research studying numerous, beach-ridge strandplains. Palaeohydrographic reconstruction from individual beach ridges, site strandplains and multiple sites around lake basins are discussed. This is followed by interpretation of changes in outlet location or conveyance, patterns in outlet palaeohydrographs, interpretation of the contemporary strandplain and summary of major advancements from strandplain records in the LGL.

The LGL are a set of freshwater lakes in north-central North America shared by two nations, Canada and the USA (Fig. 1). Five large lakes (Superior, Huron, Michigan, Erie and Ontario) comprise this system, which drains approximately 1200 km through the St Lawrence River to the North Atlantic Ocean. Although the volume of stored water is large (about 23 000 km^3), a relatively small amount (only about 1%) is replaced annually by precipitation and runoff, making the lake outflows and water levels susceptible to climatic shifts in water supply (US Environmental Protection Agency & Government of Canada 1995; Mortsch *et al.* 2000). Water levels have varied by nearly 2 m over the past 150 years of instrumental monitoring, and decadal to multidecadal oscillations in these records have been identified (Cohn & Robinson 1976; Thompson & Baedke 1997; Hanrahan *et al.* 2009; Watras *et al.* 2014). A relatively warmer climate and more fertile soil in the southern part of the LGL have contributed to population expansion (more than 30 million) and landscapes extensively altered by human activity (US Environmental Protection Agency & Government of Canada 1995). Although classified within a single climatic zone (Kottek *et al.* 2006), the LGL, having a latitudinal span of about 8° approximately half-way between the equator and North Pole and within an open corridor through eastern North America, experience recurrent alternation of frigid Arctic winds in winter and balmy subtropical air flows from the south during summer. During the Quaternary Period, moisture from the south and cold air from the north produced a centre of glaciation at mid-latitudes north of the LGL.

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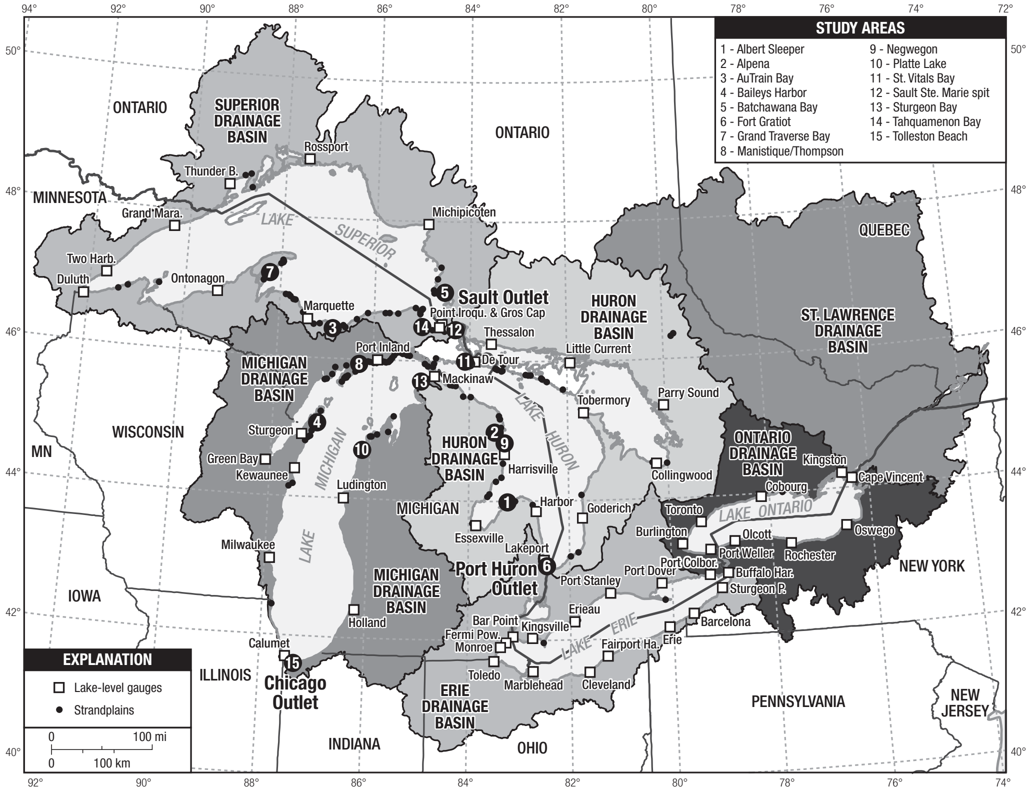

Fig. 1. Map showing the Laurentian Great Lakes and their drainage basins. Location of lake-level gauges (white filled squares), sites with strandplains of beach ridges (black dots) and study sites (numbered sites in black filled circles) are also shown.

The LGL drainage basin area is about twice its surface area (approximately 244 000 km^2) and encompasses a glaciated landscape that straddles the Precambrian Canadian Shield to the NE and Palaeozoic rocks to the SW. The geological origins of the basin's bedrock composition and structure are rooted in a complex combination of tectonic events, including Precambrian midcontinental rifting with subsequent infilling of erodible sediments, which contributed to later erosion and formation of the Lake Superior basin (Larson & Schaetzl 2001). The tropical position and continental collision of North America and Africa during the Palaeozoic Era helped establish the setting for deposition of resistant carbonates and erodible siliciclastics that rim and underlie the Huron, Michigan, Erie and Ontario lake basins. Subsequent uplift, erosion and establishment of preglacial drainage systems on the varied bedrock, followed by the erosive Quaternary glaciations, contributed to the formation of the basins of the LGL (Larson & Schaetzl 2001). Extensive glacial erosion of relatively weak bedrock near the base of major bedrock valleys enlarged valleys into basins. However, Quaternary sediment thicknesses exceed 100 m near the base of lake basins, indicating that deposition during both glacial and postglacial times was an important factor in forming the LGL basin we see today.

The LGL are of both local and global significance. They comprise the largest system of fresh surface-water lakes on Earth and contain approximately 20% of the world's supply of fresh water (Beeton 2002; Petering & Klump 2003; Gronewold *et al.* 2013). This network of natural and engineered waterways is home to the longest deep draft navigation system in the world, which extends 3700 km into the North American heartland (Martin Associates 2011). The large size of the LGL, equivalent in area to the UK, and their unique shape, outlined by at least 16 000 km of coastline, make them one of the most recognizable features from space. Although the vast open-water area often dominates the discussion of this resource, the nearshore area is where biological productivity is greatest and where humans have maximum impact

(Environment Canada & US Environmental Protection Agency 2009). This has raised concern for the future of this important transition zone, one of the most diverse and expansive freshwater nearshore ecosystems in the world (Vadeboncoeur *et al.* 2011). A large set of water-level-gauge records (55 gauge sites, some going back to 1860) exists for the LGL (Fig. 1). Debate, however, continues about the current context of water-level change, drivers of that change, and possible future scenarios. Therefore, future studies should not only include models built on current data but should include also the past record of water-level changes, preserved in coastal sediments and landforms. Here, we present an iterative approach to reconstruct palaeohydrographs by studying individual relict beach ridges within strandplains between multiple sites and lake basins. Interpretations of results reflect the current status of knowledge during considerable compilation efforts in the upper Great Lakes (lakes Superior, Michigan and Huron). These data will help close the gap between the geological and historical records by providing the most detailed account of lake level, ranging from decades to five millennia.

Synthesis of history

The LGL developmental and water-level history has been studied and reviewed for more than 150 years. In 1915, Leverett and Taylor wrote the first major synthesis of LGL water-level history; more than 40 years later, Hough (1958) revised this synthesis, using additional relative and newly developed radiometric age controls. Recent compilations include those by Karrow & Calkin (1985), Teller (1987), Larson & Schaetzl (2001), Karrow & Lewis (2007), Kincare & Larson (2009), Clark *et al.* (2012) and Lewis & King (2012). These studies provide the general framework required to reconstruct the complex sequence of lake phases in the LGL basin.

Deglaciation of the Laurentide Ice Sheet produced glacial lakes bounded between upland areas and the ice front. Continued ice retreat uncovered valleys from the previous subglacial landscape and produced new outlets freed of ice; the water level in glacial lakes lowered. Re-advances of ice blocked lower outlets and forced lakes to rise and overflow at higher elevation outlets. By this process, an oscillating ice margin during final deglaciation produced many different lake phases, for example, in the Lake Huron basin from 14 000 to 10 000 uncalibrated radiocarbon years before 1950 (Fig. 2). Ice-lobe advances during the Port Bruce, Port Huron and Greatlakean stades contributed to lake-level highstands, whereas ice-lobe retreats during the Mackinaw and Twocreekan interstades contributed to lake-level lowstands (Fig. 2a).

A concurrent process that also induced changes in lake level was removal of the ice load during deglaciation and recovery of the formerly depressed Earth crust. The upward crustal movement, termed 'glacial isostatic adjustment' (GIA), was faster in northern areas where ice was thicker and longer-lasting, resulting in differential uplift and tilting of the lake basins towards the south and SW. Early high-level lakes in the LGL were connected and drained southwards to the Mississippi valley through the Chicago outlet because the lower St Lawrence valley to the east was blocked by ice (Fig. 2b). During further ice retreat, the isostatically depressed Kirkfield outlet along the eastern shore of the Lake Huron basin opened, providing a pathway to the St Lawrence valley, which contributed to a lowering lake level (recession) along the southern shores and the lowstand of the Kirkfield lake phase (Fig. 2a). Upon further glacier retreat, rapid upward isostatic rebound of this northern outlet tilted the water southwards (transgression), contributing to a lake-level highstand in the Lake Huron basin (the Main Algonquin phase; Fig. 2a, c). Simply put, the LGL basin originally tilted northwards because of the weight of the glacial ice depressing the Earth's crust; when the ice began to exit the region, the tilt gradually rectified. During the late Wisconsinan, this tilt, in combination with the outlets opening and closing as ice margins fluctuated, caused the glacial lake phases and the formation of multiple regressive and transgressive sequences.

Postglacial lake phases are also driven by changes in outlets related to GIA, but outlet conveyance (overflow) and climate are emerging as possible important drivers of change in lake level and, hence, shoreline behaviour of the LGL. Early Holocene low water levels in the Lake Huron basin were caused by outflow through the northernmost, still-depressed North Bay outlet (Fig. 2d) and glacial meltwater supplies ceasing or bypassing the LGL basins (Lewis *et al.* 2008). An early Holocene drought in the LGL caused hydrological closure, reducing water levels below the outlet sill during the Stanley lowstand (McCarthy & McAndrews 2012). This lowstand phase was interrupted by episodes of meltwater overflow from upstream glacial lakes NW of the Lake Huron basin. These overflows filled the Lake Huron basin to relatively high levels for short periods, known as the 'Mattawa highstands' (Lewis *et al.* 2005, 2007; Lewis & Anderson 2012). After the Stanley lowstands and Mattawa highstands, wetter conditions increased basin water supply and raised the lake level to overflow the isostatically rising North Bay outlet in the northeastern corner of the Lake Huron basin.

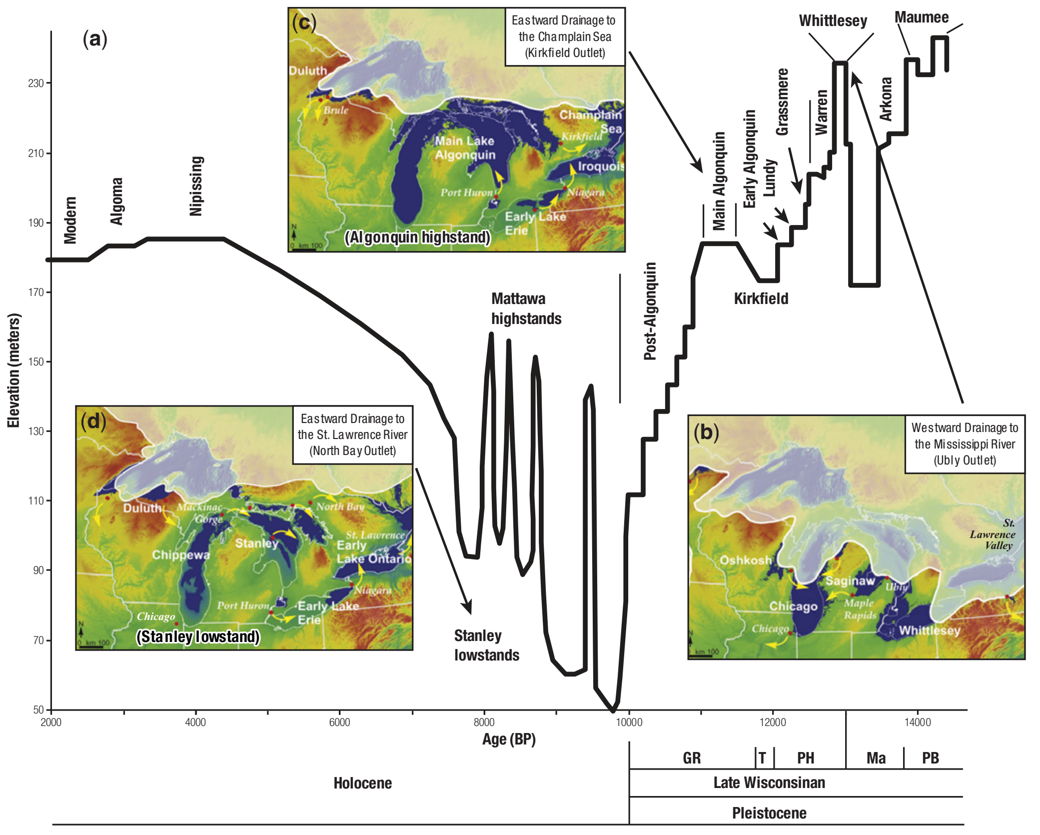

Fig. 2. Lake phases, elevations, and ages in the Huron basin (**a**) (modified from Eschman & Karrow 1985; Lewis & Anderson 2012; Gr, Greatlakean Stade; Ma, Mackinaw Interstade; PB, Port Bruce Stade; PH, Port Huron Stade; T, Twocreekan Interstade). Ages are in uncalibrated radiocarbon years before 1950. Glacial ice and lake extent, including active outlets in the Laurentian Great Lakes during the Whittlesey (**b**), Main Algonquin (**c**) and Stanley (**d**) lake phases (modified from Clark *et al.* 2012).

With the lake controlled at this northern outlet, water levels rose, transgressing southward until overflow occurred through the southern outlets at Chicago and Port Huron. Later, a post-Algonquin high was reached, and it lasted as a near-stillstand known as the Nipissing lake phase in the Superior, Michigan and Huron lake basins. Following the Nipissing highstand phase, the continuing isostatic rebound uplifted the shores of the Lake Huron basin, and the water level was controlled by the outflow at the southern Port Huron outlet. Sudden increased rates of relative lake-level drops to the Algoma and Modern levels (Fig. 2a) were associated with rapid erosion at the outlet of less resistant Palaeozoic rock-substrate layers. The lake surface regressed from uplands and series of beach ridges (strandplains) formed at successively lower elevations (Fig. 3).

A considerable amount of data has been collected in these beach-ridge strandplains recording past variation in relative water level of the lakes. This is valuable knowledge that could be useful for current and future water resource management. However, these data are often not incorporated into management decisions or cited in management documents (IUGLSB 2012). Whether this is related to a lack of awareness or a lack of understanding, the geological data are often difficult to reconcile with current conditions. Difficulties comparing instrumental and geological records arise from past glacial conditions that are very different from those of the present, long gaps in time and large differences in data resolution. Stochastic modelling of 100–150 years of instrumental data is used primarily to provide the long-term perspective of lake level in the upper Great Lakes (International Upper Great Lakes Study Board, 2009, 2012) and in Lake Ontario (International Lake Ontario–St Lawrence River Study Board 2006). Although this statistical method is helpful, the water-level data are limited by their relatively short length of record. This limitation could be lessened by the use of high-resolution geological records of palaeo-water levels. The focus of the remainder of this manuscript is relict shorelines, specifically, strandplains of beach ridges deposited after the Nipissing phase in lakes Superior, Michigan and Huron (Fig. 1); these strandplains have had a direct and relatively high-resolution relationship with changing water levels in the lake basin for the past several millennia.

Ancient shorelines: beach ridges

The most recent prominent palaeoshoreline preserved around the Great Lakes today is associated with the Nipissing phase of approximately 4500 calendar years BP, which, at the Port Huron outlet, had a water-level elevation of 183.3 m (Lewis 1969; Karrow 1980; Larsen 1985*a*; Thompson *et al.* 2014). This shore, now located approximately 1.5 km inland from the modern shoreline, is approximately 7 m higher than the historical average for Lake Michigan/Huron. It is also expressed either erosionally as a prominent cliff or bluff, or depositionally as a single barrier, several beach ridges in a strandplain or a spit. Greater detail about the Nipissing phase was extracted from the study of a transgressive sequence overlain by a regressive sequence at Alpena, Michigan (Thompson *et al.* 2011). Both sequences were developed during a rise to the peak Nipissing water-level elevation, but a change in shoreline behaviour occurred in response to a slowing rate of water-level rise and a possible increased rate of sediment supply. As the shoreline translated landward, it experienced erosional transgression that formed a ravinement surface, then aggradation that formed a barrier beach and adjacent lagoonal deposits during a brief lake-level stillstand. This was followed by depositional transgression that buried lagoonal deposits with washover sequences as the shoreline translated an additional 135 m inland. This entire sequence was then buried as the shoreline translated lakeward, experiencing depositional regression that formed a lakeward-thickening sandy nearshore sequence of beach ridges. Systematic patterns within this nearshore sequence indicate that many shoreline behaviours can occur during the formation of each individual beach ridge (Johnston *et al.* 2007*b*). Although 20 beach ridges in a wedge of sediment that thickens lakeward define the lake-level rise up to the Nipissing peak, it is the subsequent lakeward deposits that have attracted the attention of many researchers for over a century.

The beach-ridge strandplains were first described more than a century ago as a regular series of crests and swales that give a washboard appearance to the topography (Goldthwait 1908; Leverett & Taylor 1915). Decades later, geomorphic studies of LGL by Lewis (1969, 1970) and sedimentologic studies by Hester & Fraser (1973) and Fraser & Hester (1974, 1977) initiated a combination of geomorphic and sedimentologic investigations of beach ridges to reconstruct past lake levels and climate (Larsen 1985*a*, *b*, 1994; Thompson 1989, 1992; Fraser *et al.* 1990; Thompson *et al.* 1991; Dott & Mickelson 1995). However, it was not until Thompson's (1992) study that a field method was developed to interpret the elevation of past lake levels using a modern beach analogue, in which coarse sediments concentrated in the wave swash zone are interpreted to correlate with the water level. Thompson's (1992) subsurface method involves vibracoring each beach ridge to recover basal foreshore (swash zone) deposits (Fig. 3a). A direct relationship between these basal foreshore sediments and lake level on the modem coastline supports a lake-level interpretation for this ancient subsurface sedimentary contact (contact between basal foreshore and upper shoreface deposits) which has been investigated at 15 different sites in the upper Great Lakes (Baedke *et al.* 2004; Fig. 1). The most consistently useful properties to differentiate foreshore and upper shoreface deposits in core and on the modern beach were sedimentary structures and grain size parameters. Foreshore sediments commonly contain parallel, horizontal to low-angle lakeward-dipping laminae, consist of abundant coarse grains and are relatively well-sorted to poorly-sorted. Upper shoreface sediments commonly contain ripples and micro-trough cross-stratification, organics and fine grains, and are relatively well-sorted. This subsurface approach avoids less direct lake-level estimations by measuring, for example, the topography of dunes of variable thickness over beach ridges or the foreshore-dune contact (Thompson 1992; Thompson & Baedke 1997; Johnston *et al.* 2007*b*; Tamura 2012). Directly measuring the elevation of this subsurface contact (basal foreshore and upper shoreface) in cores also avoids velocity–depth calibration requirements when using ground penetrating radar (GPR). Indirect methods, such as common midpoint surveys, are often used to estimate average subsurface velocities when using GPR, but cores or trenches are required to calibrate these velocities to produce the most accurate elevations. However, GPR is integral in defining the internal architecture of beach ridges. When combined with a conceptual model of beach ridge formation (Thompson & Baedke 1995), GPR surveys provide an essential context for the basal foreshore contact collected in cores (Johnston *et al.* 2007*a*). Work by Searle & Woods (1986), Tamura *et al.* (2008), Nielsen & Clemmensen (2009) and Hede *et al.* (2013) support lake-level determinations

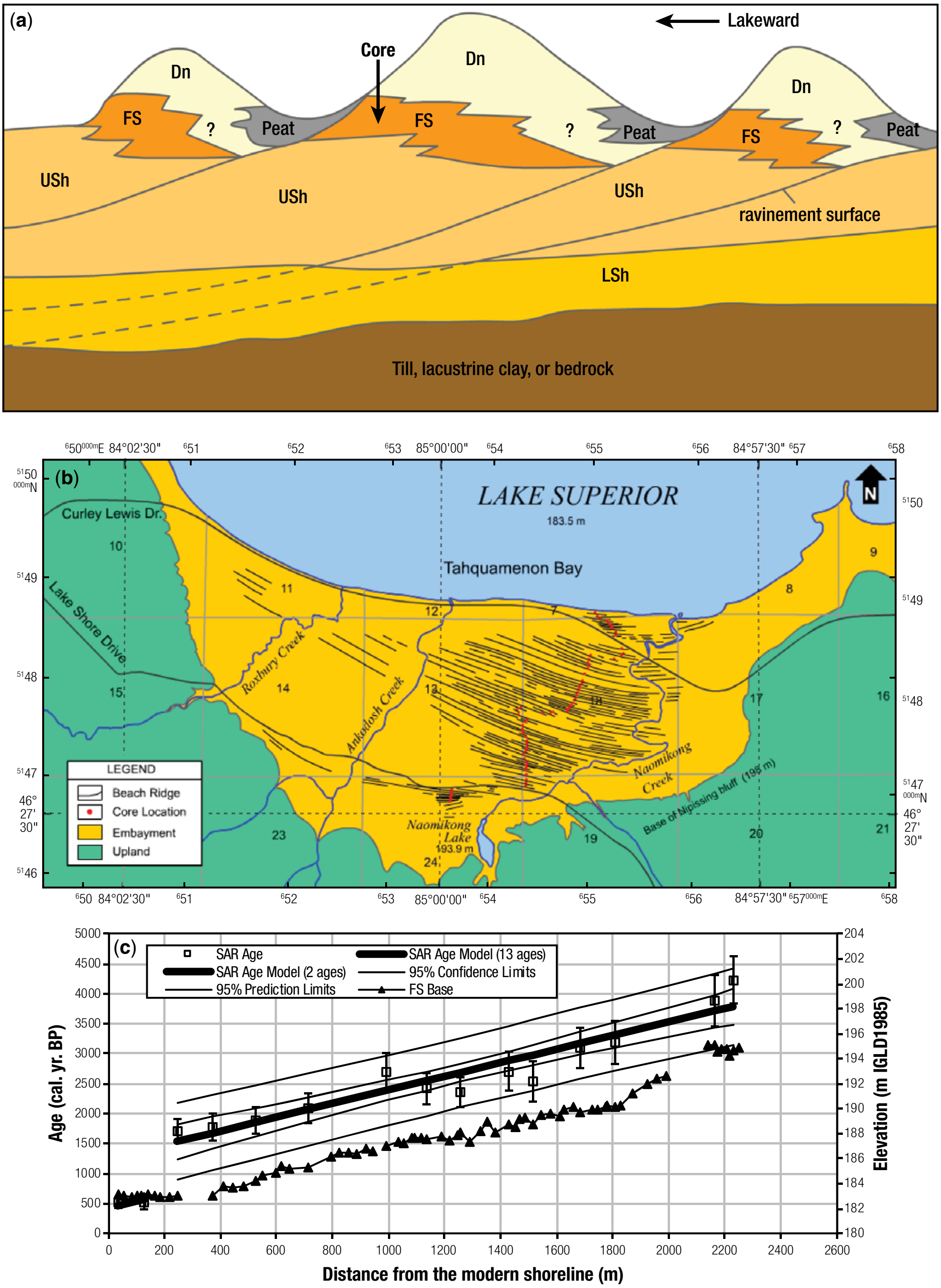

Fig. 3. Internal architecture of a typical beach ridge in the Laurentian Great Lakes. (**a**) Coring location denoted for one beach ridge used to determine water-level elevation during ridge formation. The highest basal foreshore or contact between the foreshore and upper shoreface elevation is collected to interpret water-level elevation for individual ridges (Dn, Dune; FS, Foreshore; USh, upper shoreface; LSh, lower shoreface). (**b**) Map of the Tahquamenon Bay embayment, Lake Superior, containing a beach-ridge strandplain. Core locations are also shown. (**c**) Plot of age and

from basal foreshore elevations by demonstrating that the upper shoreface-to-beach face transition in a marine microtidal regime can be used to reconstruct local sea-level during the Holocene. In the atidal setting of the LGL, Thompson & Baedke (1995) and Johnston *et al.* (2007*a*) indicate that this subsurface contact (basal foreshore and upper shoreface) records the final stages of a multidecadal water-level rise, where the rate of rise is decreasing (approaching a high and stable water-level elevation) and the shoreline is experiencing aggradation or, possibly, depositional regression. A methodology is presented here to establish an accurate estimate of past lake-level elevations from detailed analysis of raised beach ridges.

Strandplain palaeohydrograph

A palaeohydrograph, showing the change in lake level over time, requires two types of data: the elevation of the water and the duration of that elevation. Preserved within individual beach ridges is a sedimentary contact that can be interpreted as representing a lake-level elevation (Thompson 1992). Each beach ridge, therefore, provides a specific lake-level elevation. A combination of multiple beach-ridge data of known age from one strandplain offers a lateral chronosequence that can be used to create a palaeohydrograph (Figs 4 & 5). Beach ridges are differentiated by changes in elevation and vegetation. Often, vertical relief is attained by wind-blown dunes capping the waterlain cores and, therefore, vibracores to sample the former swash zone deposits are taken on the lakeward side of the beach ridge; this minimizes poor recovery that is often associated with thick and dry aeolian deposits (Fig. 3a). Coring at the lakeward break in slope between the beach-ridge crest and adjacent landward swale allows some dune recovery while obtaining the maximum elevation of the basal foreshore contact.

To date, more than 800 beach ridges have been cored (core recovery from 1 to 6 m but on average 2.5 m) at 15 sites in the upper Great Lakes (Figs 1 & 3b). After determining ages of the beach ridges (Fig. 3c), these data are combined to construct palaeohydrographs for each site. The method for determining the age of each individual beach ridge has evolved. Initially, radiocarbon-dated peat retrieved from the base of wetland sediments between beach ridges was used to date the next lakeward-adjacent beach ridge (Thompson & Baedke 1997; Johnston *et al.* 2004). However, this assumes that there is no significant gap in time between beach-ridge formation, the establishment of hydrophilic plants and accumulation of sufficient organic material for radiocarbon dating. To avoid this possible disparity and the lack of preserved peats in wetlands in northern parts of the Great Lakes Basin (such as in Lake Superior), alternative dating methods were sought (Argyilan *et al.* 2005). Optically stimulated luminescence (OSL) dating of quartz fine-sand grains provides an opportunity to date the actual sediment of the ancient shore zone and should determine the age of the associated lake-level elevation more accurately (Murray-Wallace *et al.* 2002; Argyilan *et al.* 2005; Tamura 2012). Because of limited time and funding, only about one-fifth to one-third of the beach ridges were dated (radiocarbon and OSL) in 15 strandplains of the upper Great Lakes. Using the dated ridges, age models for the strandplains were generated to assign an appropriate age to every cored beach ridge. This process involves many steps and includes analyses of both age and elevation data at one study site and between study sites within one lake basin (Figs 3c & 4a). A linear model was applied consistently to all sites to reflect the dispersion in data and to avoid violating the basic tenet that beach ridges increase in age with distance from the modern shoreline (Johnston *et al.* 2012). The number of age models per site was established by investigating multiple sequential outliers that corresponded with abrupt changes in cross-strandplain geomorphic and sedimentologic characteristics (Johnston *et al.* 2007*b*). Common trends and patterns in basal foreshore elevation peaks and troughs among sites were used in conjunction with cross-strandplain geomorphic and sedimentological trends, described in Johnston *et al.* (2007*b*), to formulate age models (Johnston *et al.* 2012). Abrupt cross-strandplain changes and poor age-model fits helped identify possible discontinuities and indicated that models should be developed and applied to sets of beach ridges within one strandplain. Comparing multiple strandplain palaeohydrographs within one basin enhances the evaluation of modelled ages and measured elevations. Once this comparative approach is completed, data are combined to create a composite palaeohydrograph representative of that lake basin (Fig. 4b, c).

Fig. 3. (*Continued*) elevation data from the Tahquamenon Bay strandplain used to reconstruct a strandplain palaeohydrograph (modified from Johnston *et al.* 2012). Ages were derived using single aliquot regeneration methods of optically stimulated luminescence dating of sand grains, and linear model of these ages are plotted. Basal foreshore elevations relative to the International Great Lakes Datum 1995 (Coordinating Committee on Great Lakes Basic Hydraulic & Hydrologic Data 1995) derived from cores through individual beach ridges are also plotted.

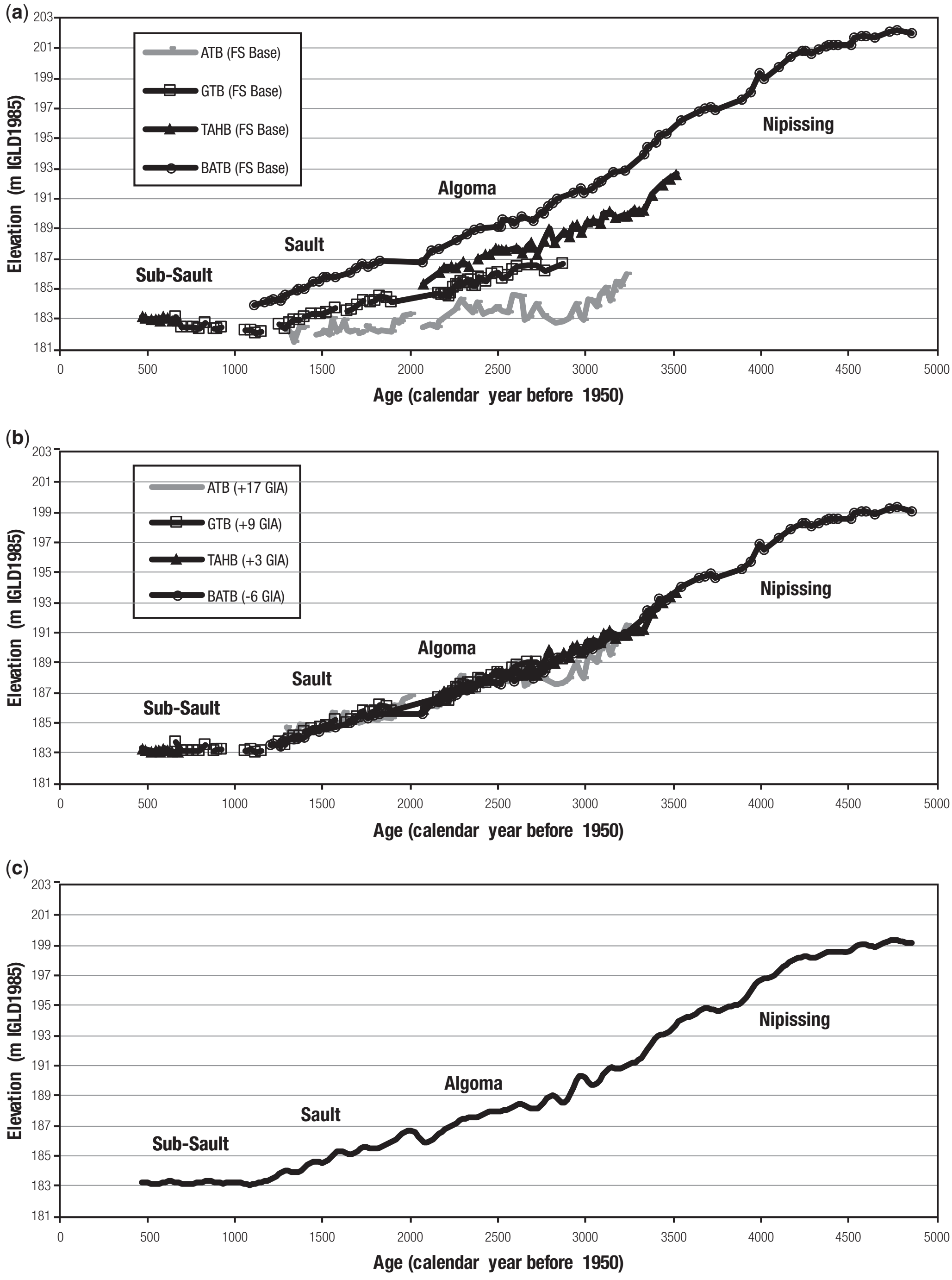

Fig. 4. Strandplain palaeohydrographs. (**a**) Plots of four strandplain palaeohydrographs from Lake Superior used to create an outlet palaeohydrograph. Symbols represent basal foreshore elevations derived from cores through individual beach ridges from each strandplain study site (ATB, Au Train Bay; GTB, Grand Traverse Bay; TAHB, Tahquamenon Bay; BATB, Batchawana Bay). (**b**) Plot of the Sault palaeohydrograph after glacial isostatic adjustment (GIA) was taken into account and applied individually to each strandplain. Rates of GIA per strandplain are shown. (**c**) Plot of the Sault palaeohydrograph after a Fourier transform was applied. (Modified from Johnston *et al.* 2012.)

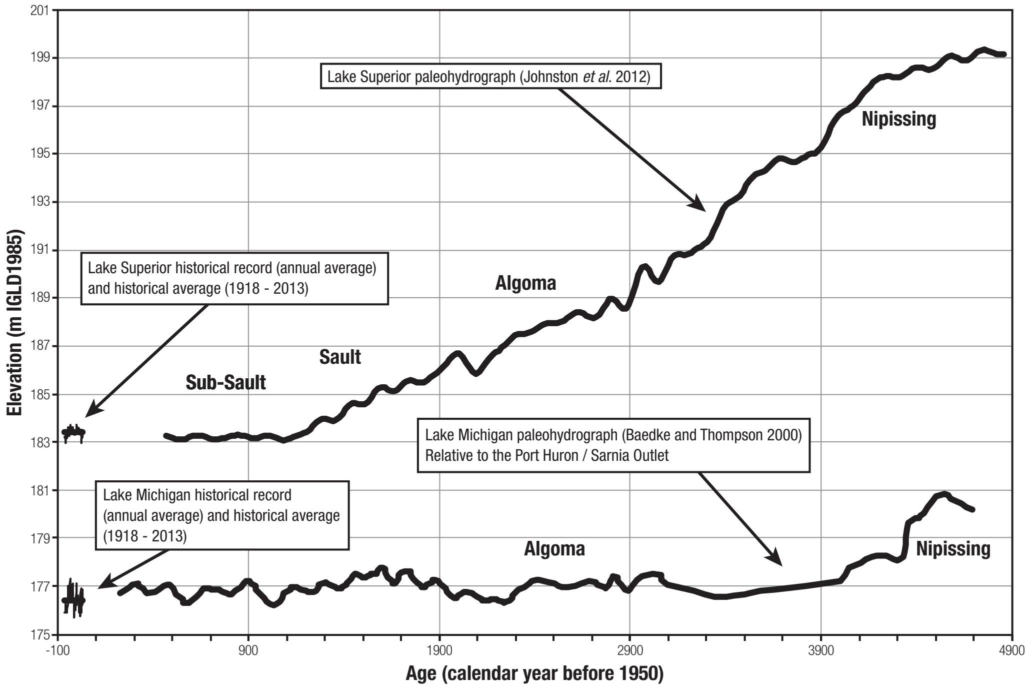

Fig. 5. Smoothed palaeohydrograph of Lake Superior (Johnston *et al.* 2012) and inferred palaeohydrographs for the Port Huron–Sarnia outlet derived by compiling data from five strandplains along Lake Michigan (Baedke & Thompson 2000). Historical gauge data (1918–2013) for lakes Superior and Michigan are also shown.

Basin or outlet palaeohydrograph

One palaeohydrograph is usually created for a site near a lake outlet because of the importance of an outlet in regulating basin-wide lake levels (Fig. 4c). To properly combine data from all strandplain palaeohydrographs, appropriate values of GIA for each study site (embayment) are required. GIA in this paper is defined as the vertical movement of the ground surface following its loading and depression by the former ice sheet. Movement is generally upward throughout the LGL, with faster rates occurring in the northern regions where ice was thicker (heavier) and longer lasting. Site GIA is the rate of uplift of a specific strandplain site relative to the lake outlet. When elevation adjustments in strandplain palaeohydrographs are completed by removing GIA effects, in various strandplains peaks and troughs of similar age should align in a common plot of their elevation v. age. Disparity in elevations requires re-evaluating adjustments in the GIA model or correcting potential errors in survey records, whereas disparity in ages requires re-evaluation of sampling methods, age models or individual ages. This comparative and iterative approach ultimately provides an independent evaluation of GIA that can be compared with modern GIA calculated from water-level gauge stations (Mainville & Craymer 2005). However, it is difficult to determine differences between unequally spaced palaeohydrographic data. Two methods have been used to determine GIA for the 15 strandplain palaeohydrographs in the upper Great Lakes: the 'residual' approach of Baedke & Thompson (2000) and the 'interval' or 'lake phase' approach of Johnson *et al.* (2012). In the Baedke & Thompson (2000) method, entire palaeohydrographs (plots of beach elevation v. age called 'relative lake-level curves') are modelled by least squares fitted lines, which include an intercept value, a measure of the present lake level. The line slopes (metres/year) are the inferred GIAs for individual strandplain sites. At each site, subtraction of the GIA value for the age of each palaeo-beach (GIA line slope in metres/year × beach age in years) resulted in a site-specific residual lake-level curve. Baedke & Thompson (2000) used the residual approach to adjust five strandplain palaeohydrographs in Lake Michigan to produce one palaeohydrograph representative of the lake's outlet at Port Huron, Michigan (Fig. 5). They set the intercept (present outlet lake level) as the average elevation of the last 33-year quasi-periodic lake-level fluctuation interpreted from water-level gauge records in Lake Michigan, a measure that is considered equivalent to the swash zone sediment in beach-ridge cores.

In the Johnston *et al.* (2012) interval (lake-phase) approach, only a selected set of beach ridges in a strandplain are fitted. The elevation v. beach age data are also modelled linearly but only for the selected sets of data that span millennial periods or intervals of time that represent possible lake phases within the full palaeohydrograph. The line fitted to these 'elevation v. age' data is projected to the present (zero age), which provides an estimate (the *y*-axis intercept) for the outlet lake level during that interval. Local GIA relative to this outlet lake level is estimated by the slope of the fitted line, as in Lake Michigan (see above; Baedke & Thompson 2000). This process is repeated for different strandplains until a close fit among all the same intervals is achieved. Although this method reduces the amount of data used to interpret the long-term process of GIA, it helps quantify a common intercept among strandplain palaeohydrographs in specific time periods. Evaluation of changes in slopes and *y*-axis intercepts of lines fitted to adjacent intervals may indicate a possible change in outlet location or conveyance through time.

Changes in the outlet

Changes in lake-basin outlet location or conveyance (water level) owing to shifts in climatic water supply, outlet erosion or sedimentation may be recorded geologically in various strandplains within the same basin. The location of an outlet is determined by identifying long-term patterns in elevation across strandplains (Baedke *et al.* 2004; Johnston *et al.* 2007*b*). These long-term elevation patterns are a function of both lake level and GIA changes. However, it is the difference in ground-surface movement or GIA between the outlet and study site that allows one to determine a change in the outlet location. A long-term fall in strandplain palaeohydrograph elevations indicates that the study site is rising more rapidly than the ground surface at the outlet, which controls the water plane in the lake basin. When compared with the modern pattern of GIA in the Great Lakes (Mainville & Craymer 2005), this observation indicates that the outlet or isobase through the outlet is generally south and west of the study site. Conversely, a long-term rise in strandplain palaeohydrograph elevations where the strandplain site is subsiding relative to the lake outlet indicates that the outlet isobase is generally north and east of the study site. Calculating GIA using the residual or interval (lake-phase) approach will quantify this pattern. Experience shows that sites being uplifted from a lake are commonly little-affected by subsequent coastal processes and produce a relatively complete record of lake-level change. On the other hand, sites that are subsiding relative to lake level may be inundated, eroded and reworked if there is not ample sediment supply to aggrade or prograde along with the rising water level.

A change in the slopes and *y*-axis intercepts of lines fitted to adjacent intervals may indicate a possible outlet change through time. Johnston *et al.* (2012) used this approach to identify a change in a common intercept among strandplains in the Lake Superior basin (Fig. 5) and interpreted this change as an outlet change from Port Huron to Sault Ste Marie approximately one millennium ago (Fig. 1). Although this interpretation is supported by long-term pattern changes in cross-strandplain elevations and sedimentation (Johnston *et al.* 2007*b*), the intercept values (elevations) can be confirmed by field investigation of strandplains near the present outlet. This would confirm the baseline lake level used to adjust each strandplain palaeohydrograph within the basin to create the outlet palaeohydrograph.

If the rate of GIA calculated from strandplain palaeohydrographs compares well to rates of GIA calculated from instrumental lake-level records, then these modern rates can be applied back in time for at least the period of the strandplain record length. However, geological and historical gauge rates of GIA often do not compare well (Baedke & Thompson 2000), and this discontinuity may indicate changes in lake level because of climatic shifts in water supply or erosion or sedimentation at the outlet. The detailed geological records of water-level change in strandplains of beach ridges include possible changes in outlet conveyance or climate influences on water volume. If rates of GIA in strandplain palaeohydrographs from one lake basin differ by unique values, they may indicate local or regional rate changes through time. However, if rates of GIA differ by a common value different than historical gauge rates in one lake basin, then they may indicate a change in the outlet or volume of water in the basin related to climate. Differentiation between these effects and GIA requires auxiliary data, such as independent palaeoclimatic data (based on tree ring, pollen assemblage, and stable isotope data), are required to relate common long-term elevation changes among palaeohydrographs to water-level losses or gains owing to climate. Independent data, such as remnant deposits near the outlet, are required to identify a change in the outlet that may be related to erosion or sedimentation. Johnston *et al.* (2012) used data from the Ipperwash strandplain along the southeastern shores of Lake Huron to create a preliminary baseline to evaluate data collected in lakes Michigan (Baedke & Thompson 2000) and Superior (Johnston *et al.* 2012). Collecting the contemporary elevation and age for the peak Nipissing phase near the Port Huron outlet provided a baseline for older shoreline data, approximately 4500 calendar years BP (Thompson *et al.* 2014).

Patterns in the outlet palaeohydrograph

Strandplains of beach ridges in the LGL reduced to outlet palaeohydrographs provide glimpses of lake-level variations before the past century and a half of instrumental records. Detail of the high-resolution geological record preserved in strandplain beach sequences allows one to identify past trends and patterns in water-level fluctuations that may add to the instrumental record and aid the future management of the LGL system. Three patterns of change are preserved in upper Great Lakes strandplains on time scales of decades, centuries and millennia. The first pattern is based on Thompson's (1992) study, which found that beach ridges in Lake Michigan strandplains formed, on average, about every three decades. Although this period corresponds to findings from many beach ridge systems around the world (Tanner 1995), Hanrahan *et al.* (2009), using instrumental data from Lake Michigan–Huron, suggested that this pattern comprised an intermodulation of two near-decadal signals. More recent investigation of Wisconsin small inland lakes and aquifers supports a near-decadal oscillation for the past 70 years in Lake Michigan–Huron (Watras *et al.* 2014). The second pattern of approximately 160 years' duration includes groups of four to six beach ridges separated by wider-than-average wetlands, first identified in strandplains of Lake Michigan (Thompson & Baedke 1995). These beach ridge groups correspond to cross-strandplain patterns in geomorphic and sedimentologic characteristics of strandplains in Lake Michigan (Thompson & Baedke 1997) and Lake Superior (Johnston *et al.* 2012). A timescale of about a century and a half was suggested for these groups of ridges based on the average timing of beach-ridge development estimated for all sites in Lake Michigan (29–38 years per ridge) and in Lake Superior (17–45 years per ridge). The third and longest-period pattern includes sets of beach ridges formed over one or more millennia and is associated with the established lake phases in the LGL. These phases include the Nipissing and Algoma lakes of the upper Great Lakes (lakes Superior, Michigan, and Huron; Figs 2a & 4), and the Sault and Sub-Sault phases of Lake Superior alone (Fig. 4).

Thompson (1992) suggested that beach ridges form in the final stages of a lake-level rise and grow in height and prograde during the subsequent lake-level fall. Thompson & Baedke (1995) provided a conceptual model for this form of development, arguing that a brief period of aggradation was needed to produce over-thickened foreshore sediments and elevated foreshore bases beneath each ridge. They presented a mechanism that would not only produce individual beach ridges, but that also would develop groups of ridges associated with the longer-term lake-level changes and concomitant changes in sediment supply. Thompson & Baedke (1997) argued that sediment supply alone, however, does not account for the development of beach ridges in Lake Michigan because a similar pattern of beach ridge development was seen throughout the basin, even though each embayment had a unique sediment supply, sediment calibre and wave climate. The only common element between embayments was lake level. Later, Johnston *et al.* (2007*a*), using GPR, showed that an erosional/ravinement surface occurs between each beach ridge that is onlapped by upward-building sigmoidal surfaces. They also argued that this pattern could form only by a rise in water level that erodes the shoreline landward (depositional transgression) and builds upward to a peak lake-level high (aggradation), with subsequent progradation during a lake-level fall (progradation and forced regression). Although studies indicate that sediment supply (Tamura 2012) and upward growth of offshore bars may also be instrumental in the development of beach ridges, this does not appear to be the case in the atidal upper Great Lakes, based on GPR signatures and nearshore facies characteristics. Recent studies in the upper Great Lakes have moved on from determining the mechanisms of beach-ridge development and gross changes in lake level through time to studies that have more strategic purposes, for example, increasing the detail in the younger part of the geology record to more closely integrate with historical records, and examining in more detail the spatial distribution of GIA and precise timing of outlet activation and abandonment.

Interpreting the contemporary strandplain

The present distribution of beach ridges and the apparent changes in lake level they imply contain many preserved clues that can be interpreted from surface landforms and subsurface sediment characteristics. Analysis of strandplains in the upper Great Lakes guides the identification of features in aerial and field observations that are used for immediate interpretation of past short- and long-term changes in lake level (Thompson *et al.* 2004; Johnston *et al.* 2007*b*). This knowledge is helping to plan new focused fieldwork that saves time and money. The greatest difficulty in interpreting contemporary strandplains arises from attempts to decipher the part of the record that is missing (depositional hiatus or ridge erosion after formation) and in differentiating water-level fluctuations from GIA. Areas that have no record commonly include the youngest or lakewardmost part of strandplains and areas associated with millennial high lake-level phases because they tend to occur where embayments are laterally filled with sediment and the coastline has been straightened. In these places, the accommodation space has decreased, thus limiting the continuing development of beach ridges. Moreover, it is in the critical lakeshore areas that the most anthropogenic disturbance occurs, often associated with urban development. Embayment filling, coastal straightening and erosion of previously deposited beach ridges in embayed areas have occurred in the Great Lakes strandplains at different times in the past, mainly within the last few millennia. Cross-strandplain geomorphic characteristics, such as a change in beach-ridge crest orientation, were used to identify areas of missing record in the youngest part of the Tahquamenon Bay strandplain in Lake Superior (Johnston *et al.* 2004; Figs 1, 4 & 5). At this site, a wedge of the youngest beach ridges with different orientation to the next landward set makes up only a portion of the lateral sequence deposited during the most recent millennial lake phase, the Sub-Sault. A lack of preserved record from the previous Sault phase was shown to be associated with changes in accommodation space, water level, sediment supply and the lake outlet (Johnston *et al.* 2004, 2012). Recognizing sets or groups of beach ridges based on geomorphic criteria in strandplains helps identify potential areas of missing record where, for example, the rate of water-level rise was rapid enough to outpace the rate of sediment supply. This phenomenon occurred in the Manistique/Thompson strandplain in Lake Michigan (Fig. 1, site 8), where a later portion of a millennial lake phase deposited after the Algoma phase was preserved, but the earlier part of the record was not (Baedke & Thompson 2000). The missing record may also be associated with a change in the location of a lake outlet, which will alter the relationship of GIA and the water plane between the outlet and strandplain study site (see 'Basin or outlet palaeohydrograph' section above).

Another common difficulty in interpreting contemporary strandplains is in making sense of cross-strandplain elevation trends, whether they are topographic map contours, field observations or strandplain palaeohydrographs based on subsurface sedimentary deposits in beach ridges (Figs 4 & 5). Contemporary cross-strandplain slopes are products of both a changing water plane and vertical ground surface movement owing to GIA. A falling, horizontal and rising water-level trend at the lake outlet appears to be more steeply falling and more nearly horizontal, respectively, in an uplifting strandplain site relative to the lake outlet (Fig. 6, upper part). Simply, a rise in lake level to a millennial-scale high-water-level phase across multiple beach ridges may appear with diminished or horizontal slope. This is especially pertinent in the older part of strandplain records and is described in Thompson *et al.* (2014) as a contemporary platform that represents a water-level rise to the peak Nipissing at a site north and east of the Port Huron outlet. Conversely, a falling, horizontal and rising water level at the lake outlet appears to be falling with lesser slope, or even rising continuously with greater slope, in a subsiding strandplain site relative to the lake outlet (Fig. 6, lower part). However, the relationship between GIA (vertical land movement) and age is generally described by a decaying exponential function (Lewis *et al.* 2005), particularly during or shortly after deglaciation, when rates of GIA are high. If an exponential rate of GIA was applied to the Great Lakes strandplains, one would expect slopes to be adjusted more in the older part of a strandplain than in the younger part. However, the similarity of linear and exponential models in Lake Michigan strandplain data suggests that rates of GIA for the past five millennia are well described by the near-straight portion of an exponential decay curve and are approximated well by a linear function (Baedke & Thompson 2000). Although applying a linear function to the contemporary cross-strandplain slope may not be ideal, the practice allows for immediate interpretation of past water-level change experienced at that site; it also allows one to recognize a possible common signal recorded at many sites in one basin. If the rate of GIA has been relatively high and the sequence of shorelines is relatively old, then a positive slope of the contemporary cross-strandplain in an area of uplift, or a negative slope in an area of subsidence relative to a lake outlet, may represent a horizontal or other water-level trend (Fig. 6). Preliminary interpretation of contemporary cross-strandplain trends requires an awareness of general patterns of GIA across the LGL and a preliminary chronology produced through geomorphic analysis; that is, beach ridges become progressively older with distance from the modern lakeshore. These models can then be refined by comparing many subsurface beach elevations and their OSL or ^{14}C ages among multiple strandplains in one basin.

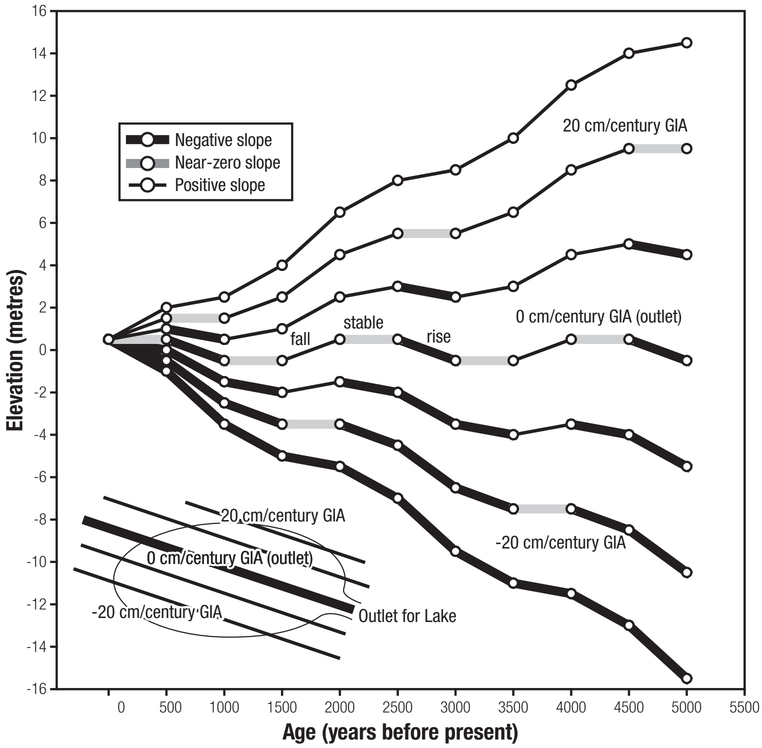

Fig. 6. Plot of elevation v. age showing how differently the changes in the slopes of outlet water-level fluctuations appear at strandplains undergoing various rates of vertical land movement (GIA) relative to the lake outlet. Positive elevations (upper part of plot) represent apparent slopes of inferred lake levels in uplifting strandplains north and east of an isobase through the outlet; negative elevations (lower part of plot) represent apparent slopes of inferred lake levels in subsiding strandplains south and west of an isobase through the lake outlet. Note how lake-level rises and falls about zero reference elevation at the outlet all appear as lake-level falls (of various slopes) at strandplain sites that are uplifting rapidly relative to the outlet (high positive GIA), as in the highest curve. Conversely, outlet lake-level changes are all expressed as lake-level rises (of various slopes) at strandplain sites that are subsiding rapidly relative to the outlet (most negative GIA), as in the lowest curve. Inset shows pattern and rate of GIA using isobase lines across a lake in reference to the outlet for the lake.

Major advancements from strandplain records

More than two decades of research in LGL strandplains has improved understanding of beach ridges, strandplain chronologies, palaeohydrograph construction and changes in lake-basin outlets. Thompson (1992) established the methodology of using subsurface basal foreshore elevations in beach ridges to reconstruct palaeolevel. Combining information from a conceptual model of beach-ridge formation (Thompson & Baedke 1995) with a systematic GPR survey of internal beach ridge architecture, Johnston *et al.* (2007*a*) showed that subsurface foreshore elevations record the final stages of a water-level rise when the rate of rise is decreasing (approaching a high and stable water-level elevation). Many cross-strandplain chronologies devised using ^{14}C and OSL methods in strandplains of the upper Great Lakes suggest that beach ridges form over at least a decade, most developing on average about every three decades. Variability in ^{14}C age models of strandplains occurs in lakes Michigan (Thompson & Baedke 1997) and Superior (Johnston *et al.* 2001, 2004). Paucity of preserved organic sediment in Lake Superior strandplains led to the use of OSL to create cross-strandplain age models. Comparison of ^{14}C and OSL ages in lakes Michigan and Superior strandplains argues for OSL as a viable alternative to ^{14}C, having similar accuracy and variability (Argyilan *et al.* 2005). Actual direct OSL dating of the quartz sand grains of the palaeoshore deposits provides a more accurate determination of the individual beach-ridge age than ^{14}C dating of the inter-ridge material. This also provides more accurate cross-strandplain age models and is becoming the standard procedure for this type of research in the Great Lakes region (Argyilan *et al.* 2010; Johnston *et al.* 2012). One of the more interesting events that strandplain data has helped refine is the separation of Lake Superior from lakes Michigan and Huron. Although faulting at the bedrock sill has been suggested (Johnston *et al.* 2004) as the cause, the role of GIA has remained the top contributor to explain sill uplift since first proposed by Farrand (1962). There is consensus that the lakes separated sometime after the Algoma millennial high-water-level phase, after approximately 2400 calendar year BP (Farrand 1962; Larsen 1994; Johnston *et al.* 2004). However, geomorphic and sedimentologic studies of cross-strandplain trends and palaeohydrographic reconstructions in Lake Superior strandplains indicate that the final separation occurred after the Sault phase, approximately one millennia ago (Johnston *et al.* 2000, 2007*b*, 2012). Current data from strandplains of Lake Huron are being compared with data from Lake Michigan (Baedke & Thompson 2000) to produce an outlet palaeohydrograph representative of this large, hydraulically connected lake. Comparison with the outlet palaeohydrograph of Lake Superior will help to decipher a more accurate understanding of GIA, water-level fluctuations and outlet conveyance. These refinements are expected to complement the instrumental lake-level record back through time. The extended record should then be used to augment knowledge of natural (climate-driven) fluctuations and to, thereby, contribute to the effective management of the large freshwater Great Lakes system.

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