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ORIGINAL PAPER

Mapping the phases of Glacial Lake Algonquin in the upper Great Lakes region, Canada and USA, using a geostatistical isostatic rebound model

Scott A. Drzyzga · Ashton M. Shortridge · Randall J. Schaetzl

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Abstract This study reviews Glacial Lake Algonquin, examines the Main and two "Upper Group" phases in northern Michigan and nearby Ontario, reports their spatial extents, and reassesses the lake history in light of isostatic rebound. Our paper presents the most accurate and detailed maps of Glacial Lake Algonquin in this region that have yet been published. Fieldwork was conducted at 243 ancient shoreline sites, which yielded position data that support geostatistical models that represent differentially upwarped water planes. Model parameters that describe water plane tilt are reported for the Main, Ardtrea and Upper Orillia phases. Geostatistical water plane models were used to adjust a digital contemporary elevation model, thereby creating a digital proglacial elevation model for each phase. Maps of these phases and the data that support them suggest (1) proto-Cockburn Island, Ontario existed as an islet in the lake that was deglaciated before the outlet at North Bay, Ontario was opened, (2) the Main and Ardtrea phases of the lake extended into the northern Lake Michigan basin, and (3) the Main and Ardtrea water planes intersect at places near Little Traverse Bay (by Lake Michigan) and Thunder Bay (by Lake Huron). Mapped isobases generally conform to those published in other works and suggest the regional pattern of isostatic adjustment has not changed substantially during the last 13,000 years.

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S. A. Drzyzga (✉)
Department of Geography and Earth Science, Shippensburg University, Shippensburg, PA 17257, USA
e-mail: sadrzy@ship.edu

A. M. Shortridge · R. J. Schaetzl
Department of Geography, Michigan State University, East Lansing, MI 48824, USA

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Introduction

Glacial Lake Algonquin (hereafter, GLA) is the name given to a sequence of extensive, proglacial lakes in the upper Great Lakes region. The lake maintained relative high water levels from 13.1 to 12.5 cal (11.3–10.5) ka BP (Karrow et al. 1975). (Previously reported radiocarbon ages were converted to calendar dates using the calibration curve of Fairbanks et al. (2005).) It covered land areas around northern Lakes Michigan and Huron, Georgian Bay, and southeastern Lake Superior (Fig. 1), and drained by 11.4 cal (10.0) ka BP (Harrison 1972; Karrow 2004). Outlets were uncovered successively as the Laurentide ice sheet receded from the North Bay area and, as a result, the lake surface fell in stages (Harrison 1972; Finamore 1985; Karrow 2004). Also, the land surface rebounded

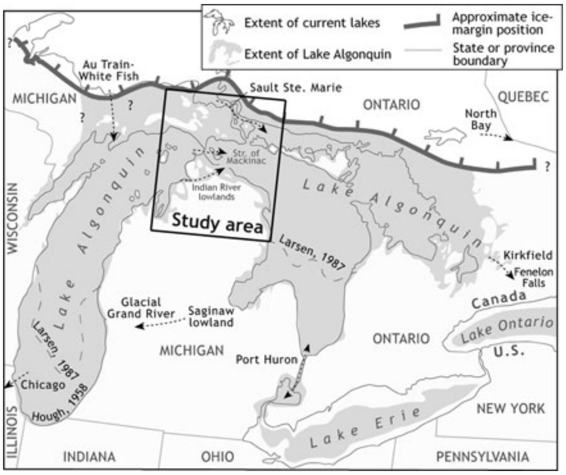

Fig. 1 Study area and two possible maximum extents of Glacial Lake Algonquin, after Hough (1958) and Larsen (1987). The *line* that represents the then-retreating ice margin is an approximation

upward as the weight of ice was removed (Gilbert 1898; Clark et al. 1994; Lewis et al. 2005). Locations in northern Michigan and nearby Ontario rebounded at rates faster than locations in southern Michigan and northern Indiana (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1977, 2001), which are farther from the former centers of greater ice loading. As a result, the former water planes of GLA are differentially uplifted and tilted in a north-northeasterly direction toward regions of thicker and longer-lasting ice (Gilbert 1898; Larsen 1987; Lewis et al. 2005).

Much has been written about the formation and evolution of GLA (Spencer 1891; Gilbert 1898; Goldthwait 1908; Leverett and Taylor 1915), but a clear consensus about the elevations, spatial extents and timings of its many phases is lacking (Hough 1958; Futyma 1981; Larsen 1987; Schaetzl et al. 2002). The uncertainties prompted instrumental surveys of relict shoreline features by Taylor (1894, 1895), Goldthwait (1908, 1910), Stanley (1936, 1937, 1945), Deane (1950), Cowan (1985), Karrow (1986, 1987, 1988, 2004) and others, as well as Global Positioning System (GPS) surveys by Schaetzl et al. (2002) and Drzyzga (2007a), but many uncertainties remain. Knowledge of the water planes and isostatic rebound associated with this lake has significant intrinsic and theoretical value. Heath and Karrow (2007) noted, for example, that geophysical modelers use GLA to work on questions regarding isostatic rebound, and by those working to understand glacial ice and paleoclimatic conditions. Archeologists have used information about GLA shorelines to interpret early Paleo-Indian settlements and to target potential field sites (Krist and Schaetzl 2001). Clear knowledge of GLA shoreline locations has assisted contemporary mapping efforts in Michigan (Schaetzl RJ, per. comm.).

Schaetzl et al. (2002) modeled GLA using 146 records of location (x, y) and elevation (z) taken from relict wave-cut bluffs. Their data partially revealed the extents of at least six phases in northern Michigan, and they concluded that pro- and postglacial lake surfaces can be effectively identified and correlated via examinations of position (x, y, z) data and reconstructed within a GIS environment. In this work, we employ more powerful models on an expanded dataset using points collected by Schaetzl et al. (2002) and many new observations. Our work also integrates information and data collected by others at Sault Ste. Marie (Cowan 1985), St. Joseph Island (Leverett 1913; Karrow 1987) and Cockburn Island, Ontario (Leverett 1913; Chapman and Putnam 1966; Drzyzga 2007a), as well as others at Beaver Island, Michigan (Dietrich 1978) and across northern Michigan. Relict shoreline features situated among contemporary Lakes Huron, Michigan and Superior link the evolutionary histories of these lakes and provide opportunities to re-evaluate correlations others have made between phase names and relict shoreline elevations (Farrand and Drexler 1985; Schaetzl et al. 2002).

We seek to expand and refine knowledge of GLA. This work advances the exploration and visualization traditions of geographic research by building upon pioneering land surveys conducted more than a century ago, contributing new data that fill gaps recognized by Cowan (1985), Schaetzl et al. (2002) and Heath and Karrow (2007), leveraging modern geostatistical techniques, and employing geotechnology to digitally recreate and visualize these paleolandscapes. This work offers improved maps of the Main and Ardtrea phases, and the first known map of the Upper Orillia phase in northern Michigan.

Review of regional Quaternary history and setting

The Great Lakes water basins are largely products of repeated scouring and erosion of preglacial bedrock valley systems by continental glaciers. The last major advance of the Laurentide ice sheet covered the entire region and reached its maximum extent by 21.8 cal (18.3) ka BP (Curry and Petras 2011). After oscillating for a few thousand years, the ice margin retreated northward, which allowed large lakes to form in topographic lows where waters were impounded by glacial ice to the north and high topography elsewhere (Hough 1963; Farrand and Drexler 1985; Hansel and Mickelson 1988; Kincare and Larson 2009). Relict shoreline features, e.g., wave-cut bluffs, beach ridges, spits and deltas, mark the margins of many pro- and postglacial lakes that formed during these retreats (Cowan 1985; Karrow 1988; Krist and Schaetzl 2001; Capps et al. 2007; and references therein). The Laurentide ice sheet withdrew from the Great Lakes region roughly 10.7 cal (9.5) ka BP (Karrow 2004).

The Two Rivers Phase glacial readvance covered the northern half of the Lake Michigan basin and a northwestern part of the Lake Huron basin. The readvance is well dated because it covered a spruce forest; numerous radiocarbon dates on this wood indicate it occurred at 13.7 cal (11.9) ka BP (Broecker and Farrand 1963; Kaiser 1994). It blocked the Straits of Mackinac that had, at times, allowed water to flow between the basins (Hansel and Mickelson 1988). As the ice margin retreated northward from the advance, water bodies in the Michigan and Huron basins expanded northward onto the isostatically depressed landscape. They became confluent when the Indian River lowlands (Fig. 1) were exposed and, slightly later, when the Straits of Mackinac were exposed (13.0 cal (11.2) ka BP according to Larsen 1987). Continued retreat allowed a single expanding lake (GLA) to transgress Michigan's eastern Upper Peninsula and to occupy a southeastern part of the Superior basin (Cowan 1985; Larson and Schaetzl 2001; Kincare and Larson 2009).

Spencer was the first to name (1888) and describe (1891) GLA, but Leverett and Taylor (1915) produced the first authoritative report of its geological history. Leverett and Taylor (1915) described four sets of shoreline strands found high throughout northern Michigan. Southwardly, they occur at progressively lower elevations until they converge near Traverse City (Lake Michigan side) and Harrisville (Lake Huron side). Observations of convergence supported competing hypotheses of crustal movement circa the turn of the Twentieth century. Gilbert (1898) believed the tilted shorelines were outcomes of an isostatic recovery process. He surmised isostatic depression of the Earth's crust by the advancing weight of a glacial ice sheet and subsequent rebound as the weight of ice diminished during and after glacial retreat. Gilbert (1898) adopted a plastic model of crustal movement wherein patterns of shoreline deformation and tilt reflect a smooth and continuous process of differential isostatic adjustment. Goldthwait (1908, 1910), however, hypothesized crustal stability in the southern parts of the region, allowing the GLA shoreline to remain horizontal in the south while episodic tectonic spasms somewhere in the northern region forced crustal uplift. He invoked a hinge metaphor to represent the boundary between the regions. Goldthwait's (1908) hinge and rigid model of crustal movement explained how a single shoreline could appear to split into multiple shorelines that splay with increasing distance northward. Leverett and Taylor (1915) adopted the hinge for use in their landmark manuscript, which, in effect, installed the rigid model of crustal movement as the proper geologic context for conducting subsequent geomorphic research and interpreting relict shorelines during the next 60 years (e.g., Stanley 1936; Deane 1950; and Hough 1958).

Not until the 1970 s did works like Clark and Persoage (1970) and the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1977) report that the entire Great Lakes watershed was undergoing differential vertical movements associated with postglacial recovery—not only those locations north of a supposed hinge. The isostatic adjustment pattern was shown to be smooth, continuous, and to increase from southwest to northeast and towards the former centers of ice loading. Locations along the southern shore of Lake Michigan were adjusting at rates slower than locations near the Port Huron outlet of Lake Huron, but adjusting nonetheless. The Committee published a second report (2001) that confirmed the process was ongoing and noted that water levels along the southern shores of the Great Lakes are slowly rising (i.e., transgressing) as the land there subsides. These reports, in effect, debunked Goldthwait's (1908) rigid earth model. Others (e.g., Tushingham and Peltier 1991; Clark et al. 1994, 2007; Mainville and Craymer 2005) conducted similar or related experiments and obtained similar results.

We focused on the stranded GLA shorelines in the northern Great Lakes region including, in descending order, (1) the highest or *Main* phase of Lake Algonquin (Spencer 1891; Leverett and Taylor 1915), (2) an *Upper Group* containing the Ardtrea, Upper Orillia and Lower Orillia shorelines/phases that Deane (1950) identified first in Ontario's Lake Simcoe district, (3) a *Lower Group* containing the Wyebridge, Penetang, Cedar Point and Payette shorelines/phases that Stanley (1936) identified first on Ontario's Penetanguishene Peninsula, and (4) the very low Sheguiandah and Korah shorelines/phases that Hough (1958) identified first near Sault Ste. Marie, Ontario. Karrow et al. (1975) reported radiocarbon dates indicating GLA existed between 13.1 and 12.5 cal (11.3–10.5) ka BP, but phase initiations and durations have not yet been dated. GLA drained by 11.4 cal (10.0) ka BP (Harrison 1972; Karrow 2004) after a low outlet near North Bay, Ontario (Fig. 1) became deglaciated, initiating a long series of low-water lakes within the Lake Michigan and Huron basins (Kincare and Larson 2009).

GLA water levels rested along fields of equal gravitational potential, which can be approximated by horizontal planes (Clark et al. 1994). Field evidence from many different sources (Karrow 1988; Krist and Schaetzl 2001; and references therein) has confirmed that wind and wave action formed conspicuous shoreline features on or near these planes. Observations of stranded *sets* of stratified shoreline features support the theory that lake levels fell in discrete stages (Lawson 1891; Leverett and Taylor 1915; Stanley 1936; Deane 1950; Hough 1958). Observations of northward-trending tilt support the theory that the land surface was differentially uplifted as the ice sheet retreated and the weight of ice diminished (Gilbert 1898; Clark et al. 1994, 2007). Greater tilt at northern locations, coupled with lesser tilt at southern locations, supports the theory that the ice sheet originated in the north and was thickest there (Clark et al. 1994, Lewis et al. 2005). Observations of greater tilt among high shorelines and lesser tilt among low shorelines at proximate locations support the theory that rates of differential uplift decreased over time (Larsen 1987). These theories, taken together, provide a context for interpreting new observations and an opportunity for reconstructing GLA water planes within a geocomputational environment.

Materials and methods

Fieldwork and data processing

Frank Taylor stressed the importance of studying the islands of GLA when he wrote:

> …[they] can hardly be overestimated, especially if they are situated well out from the mainland. Each one furnishes a new point of support for the restoration of the water plane and must prove valuable in the ultimate study of the earth's history as disclosed in the deformation of former water levels (Taylor 1895).

Reports subsequent to Taylor's (1895) study of the ancient Munuscong Islands include proto-Mackinac Island (Stanley 1945), proto-Beaver Island (Dietrich 1978), proto-St. Joseph Island (Karrow 1987) and proto-Cockburn Island (Drzyzga 2007a). Accordingly, special attention was paid during this work to shorelines on these and other contemporary uplands that might have existed as islands in GLA.

This work employs the same site selection criteria and data processing methods described by Schaetzl et al. (2002) and Drzyzga (2007a). Initially, Natural Resources Canada (1:50,000) and USGS (1:24,000) topographic maps were collected for the region and sites described in published work were plotted on them. One objective was to use, but also to add to, the 146 records of shoreline positions obtained by Schaetzl et al. (2002), which were already informed by descriptions of relict landforms in the literature (Leverett and Taylor 1915; Futyma 1981; Farrand and Drexler 1985). New sites were targeted wherever mapped contours suggested shoreline features such as wave-cut bluffs or the eroded headlands attached to large spits (Krist and Schaetzl 2001).

Several opportunities existed to substantially yet efficiently improve the dataset built by Schaetzl et al. (2002)—the impetuses for our work. First, we expanded the study area (Fig. 2) to include relict shoreline features near Sault Ste. Marie (Cowan 1985), St. Joseph Island (Leverett 1913; Karrow 1987) and Cockburn Island, Ontario (Chapman and Putnam 1966; Drzyzga 2007a, b), as well as others on Beaver Island, Michigan (Dietrich 1978) and near Traverse City, Michigan (Kincare and Larson 2002). Locations near Sault Ste. Marie and on St. Joseph Island are important because they are well-known and uniquely

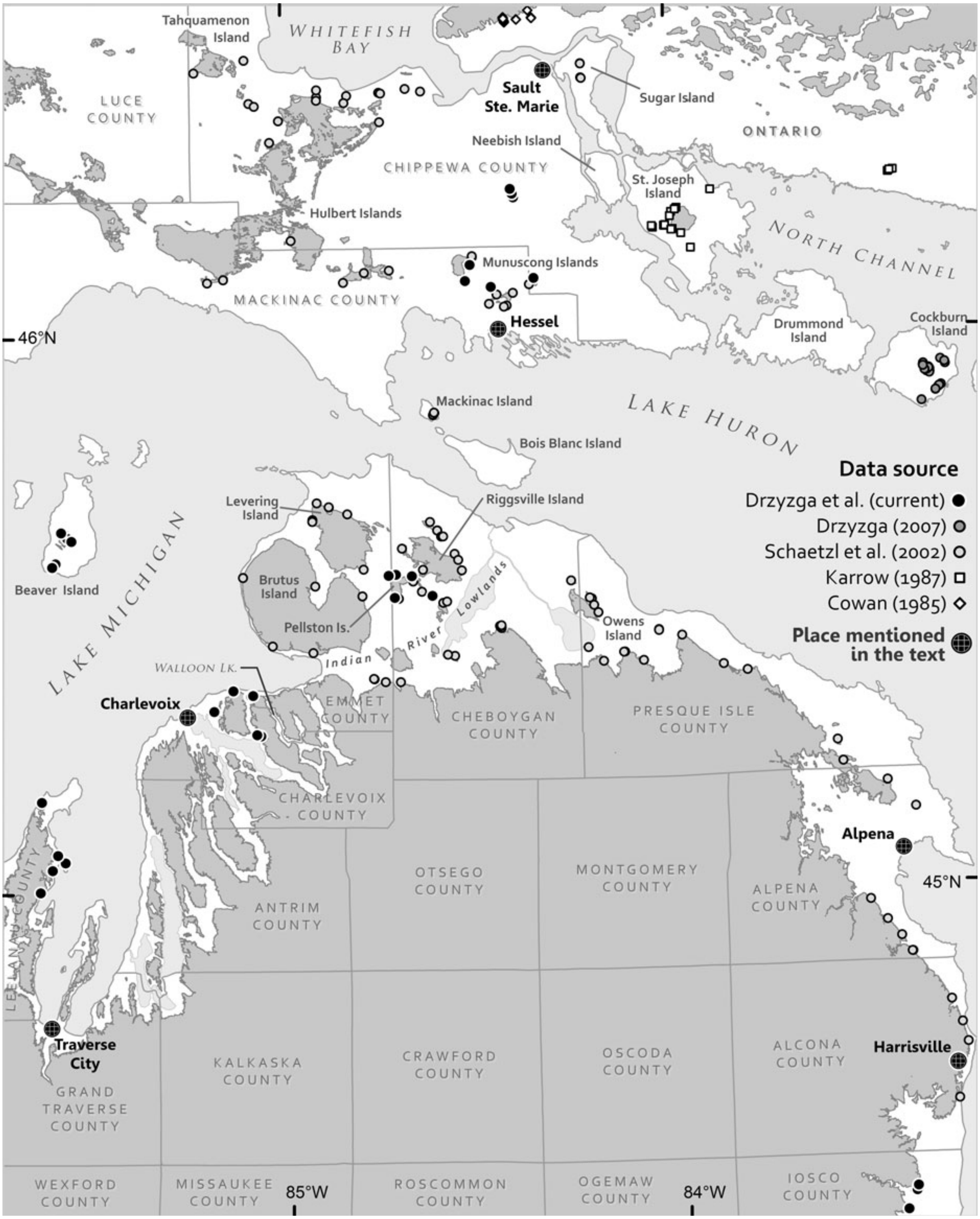

Fig. 2 Relict wave-cut bluff locations, for all lake phases, by source. Also shown are contemporary lake areas (*light grey*) and land areas that were, as determined during this work, subaerial (*dark grey*) or subaqueous (*white*) during the Main phase of Glacial Lake Algonquin

situated between Lakes Huron and Superior, thereby effectively linking the evolutionary histories of these lakes. The correlations Cowan (1985) and Karrow (1987) made between GLA phases and stranded shoreline elevations can be used to revise correlations made by Farrand and Drexler (1985) and Schaetzl et al. (2002) in northern Michigan, which were seemingly extrapolated from distant locations across Lake Huron. Collecting and integrating data from the islands add needed support to previously unsampled sectors of the lake surface. Second, the geographic distribution of sampled positions obtained by Schaetzl et al. (2002) was not oriented along the generally accepted direction of differential isostatic uplift (approx. N 15°E; after Futyma 1981), but obliquely to it (N 35°W). Third, Schaetzl et al. (2002) and Drzyzga et al. (2002) used an undersized set of control points ($n = 8$) to assess the quality of sampled elevations ($n = 146$). We collected a larger set ($n = 18$) to better assess shoreline data quality.

GPS surveys and attribute collection activities were subjected to five constraints. First, the field season was limited to late fall and leaf-off conditions to optimize reception of GPS broadcasts, to mitigate multi-path errors associated with tree canopies, and to precede heavy winter snows. Second, data were collected during temporal windows that framed optimal satellite-receiver geometries. GPS receiver software can calculate positions under a plethora of satellite constellations, but few satellite-receiver geometries are sufficient for the taking of accurate and precise *vertical* measurements. Mission planning software and satellite ephemeris data were used to select suitable temporal windows; GPS surveys occurred during these windows only. Third, all position data were corrected using generally accepted post-processing techniques. Point clouds, each containing 300+ measurements taken at two-second intervals, were visually inspected for conspicuous evidence of multi-path errors, which were removed, and differentially corrected using CORS data (Snay and Soler 2008). Fourth, a point cloud averaging technique was used to estimate final position values for each site. Horizontal locations were referenced to the *World Geodetic System 1984* geographic coordinate system. Elevations were referenced to the *World Geodetic System 1984* and *GEOID03* (Roman et al. 2004) model of mean sea level. Data were formatted for use with the R computing environment and ESRI ArcGIS® software, and projected onto the metric Michigan GEOREF (NAD83) coordinate grid whenever maps or distance calculations were needed. Last and most important, all mapped sites were visited and inspected in the field. We looked for a "bouldery/gravelly lag" that often occurs on the bench surface just below the base of a wave-cut bluff (Fig. 3), as it provides "the most credible estimation of mean water level" (Schaetzl et al. 2002).

Wave-cut bluff "target" sites were selected for sampling if they exhibited a conspicuous bluff-to-beach morphology and presented a well-defined bluff toe (Fig. 4). Sites that exhibited signs of fluvial activity or slope failure, however, were deselected. On the bluff toe slope we excavated sediment with a bucket auger to a maximum depth of 1.5 m. If a bouldery/gravelly lag could not be detected, then sampling proceeded down-bluff or down-slope until a buried lag was found. Fortunately, most bluff sites exhibit a conspicuous lag of well-rounded boulders at or near the surface. Field notes were taken to describe the site, situation, and depth to the buried lag, which was used to adjust downward the elevation value obtained by GPS survey. We acknowledge that elevations measured along any wave-cut bluff represent the elevations of shore features from which the actual water levels may be *inferred*, but not precisely known (Lawson 1891). Nonetheless, we believe that we collected the best shoreline proxy data available. Sites without a gravel lag were omitted from analysis or, if measured, archived in a supplemental database.

A major difference exists between the method Schaetzl et al. (2002) used to correlate paleoshoreline sites with named lake phases and the method used during this work. Schaetzl et al. (2002) began correlating sites and phases in the Douglas Lake area of Michigan, worked their way east and west, and then proceeded north and south. They did so in an attempt to avoid the confusion that permeates the literature regarding phase names and stage elevations. We initially followed the same procedure, but encountered difficulties while attempting to reconcile their set of six phases at locations north of the Straits of Mackinac—where additional water planes are clearly evident. We began anew by correlating paleoshoreline data with GLA phases at Sault Ste. Marie, Ontario. Sly and Lewis (1972), Cowan (1985) and Karrow (1987) correlated features in Ontario with respect to the GLA phases named by Deane (1950), Stanley (1936) and Hough (1958), so it was relatively easy to interpret data at Cockburn Island in terms of those findings. Having recognized the connections Cowan (1985) made between Manitoulin Island and Sault Ste. Marie, and the connections Drzyzga (2007a) recognized between Cockburn Island and St. Joseph Island, it became clear that relict features in Michigan's Upper Peninsula and classified by Schaetzl et al. (2002) needed to be reclassified. Phase names were carried southwardly using relative differences in elevation and relative differences in shorezone development as aides; shorelines associated with the Upper Orillia phase, for example, are among the most strongly developed in the study area.

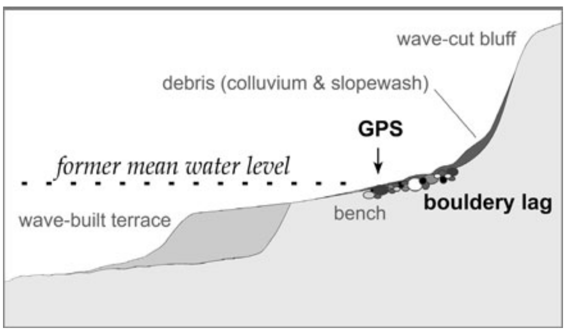

Fig. 3 Generalized expression of a wave-cut bluff, as commonly observed in the study area. We used the bouldery/gravelly lags at the bases of wave-cut bluffs as definitive shoreline indicators, and took our GPS measurement there. After Schaetzl et al. (2002)

Building water plane models

Any elevation value obtained from measurement is considered a random variable because it contains a component of truth and a component of uncertain error. A process that generates a random variable is a random process. Accordingly, a process for measuring elevations at locations over a region of interest is considered a spatial random process.

A *random field* is a conceptual model that is useful for representing the outcomes of a random spatial process. Model use assumes spatial variation can be expressed as the sum of: (1) a deterministic component with a constant or non-stationary mean, (2) a random and regionally structured error component and (3) a random but spatially unstructured error component. It is reasonable to model ancient water planes as random fields because each can be considered in terms of these three components. GLA water planes are differentially upwarped in a manner whereby modern elevations increase "toward the former ice centers" (Larsen 1987), so the uplift pattern can be modeled as an elevation trend with a non-stationary mean. Regionalized deviations from the trend can be modeled as random and regionally-structured covariation associated with site conditions. Goldthwait (1908) compensated for regionalized deviations in his work, albeit in a non-statistical sense, when he allowed for "five feet" (1.5 m) of discordance for "original variations in height … due to local conditions under which … [relict shoreline features] were constructed or cut." Unexplained deviations from the combination of the global trend and regional structure components can hence be captured by the remaining random and spatially unstructured error component. Following the

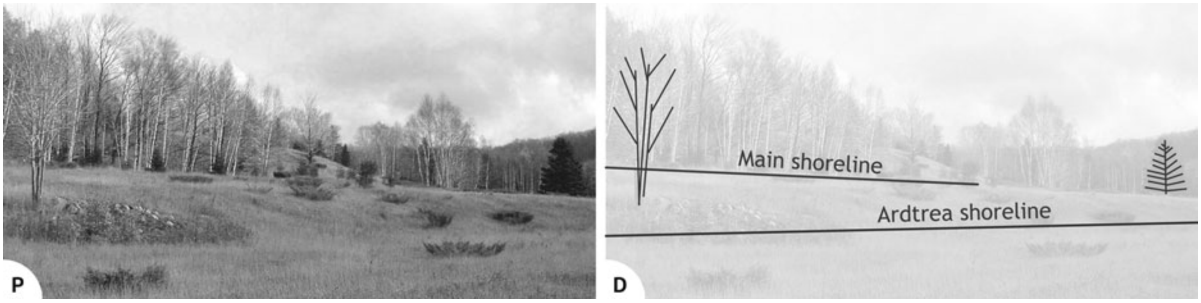

Fig. 4 Oblique photograph (P) and annotated diagram (D) of relict shoreline features at Cockburn Island, Ontario, looking approximately N 15°E, after Drzyzga (2007a). The *upper* bluff-to-beach sequence (tree-covered hill) indicates the Main phase. The *lower* (in the open foreground) indicates the Ardtrea phase. *Shoreline symbols* are exaggerated for display

general model for random fields outlined by Burrough and McDonnell (1998), paleoshoreline data were used to support reconstructions of three surfaces (Main, Ardtrea and Upper Orillia) (Eq. 1):

$$H_{phase}(\mathbf{u}) = m_{phase}(\mathbf{u}) + \varepsilon'_{phase}(\mathbf{u}) + \varepsilon''_{phase}(\mathbf{u}), \quad \forall \mathbf{u} \in R \tag{1}$$

where *phase* indicates a water plane by name; $H(\mathbf{u})$ represents the random field of water plane heights; $m_{phase}(\mathbf{u})$ represents the expected elevation trend of the plane; $\varepsilon'_{phase}(\mathbf{u})$ represents random and regionally-structured deviations from the trend; $\varepsilon''_{phase}(\mathbf{u})$ represents random and spatially unstructured errors; and $\mathbf{u}$ is the set of all locations in the region of interest, R.

Initial water plane surfaces were reconstructed using the general spatial prediction protocol of Bailey and Gatrell (1995). The protocol stipulates: (1) fit a suitable trend surface model to data using ordinary least squares and obtain residuals, (2) if residuals evince regional structure, then conduct a variography (exploratory analysis of spatial covariance among data) and select a suitable covariance model to capture the structure, (3) re-fit a suitable trend surface model to the data, using generalized least squares, to accommodate the spatial trend and the random and regionally structured error components, (4) examine the new set of residuals for anomalies or any remaining structure and, if needed, (5) iterate through steps 2 and 3 until stability is achieved. This protocol is useful for explicitly estimating the parameters that describe the trend component.

The theory of random fields can also be employed to predict outcomes at unsampled locations (i.e., interpolation) when used within a kriging framework (a general class of methods that uses information about spatial covariance among data to aide prediction making), which is particularly useful for digitally reconstructing water planes. Universal kriging is mathematically similar to the general spatial prediction protocol outlined above, except the set of trend parameters are estimated implicitly and not made explicit in the results (Bailey and Gatrell 1995). We employed universal kriging during final model runs because it allowed us to produce predicted elevation surfaces that pass through supporting data and estimates of prediction uncertainty at every location. These models improve upon ordinary trend surface models (e.g., those employed by Schaetzl et al. 2002) in two important ways: the surfaces utilize more information from data, resulting in superior fit, and the estimation of the trend coefficients is not affected by spatial covariance among data, leading to better parameter estimates.

Mapping the up-warped water planes of Glacial Lake Algonquin

Each water plane model (Main, Ardtrea and Upper Orillia) was described via a generalized least squares model, reconstructed via universal kriging, and output to raster form for use with GIS software. Water plane contours were derived from each raster. Next, the minimum measured paleoshoreline elevation value attributed to a water plane was subtracted from the respective water plane raster; the result represented differential rebound relative to the lowest sampled feature. Next, each relative rebound raster was subtracted from a contemporary digital elevation model (DEM), thereby generating a set of three proglacial elevation models that reflected the immense weight of the Laurentide ice sheet; this mapping method is similar the methods used by Krist and Schaetzl (2001), Drzyzga et al. (2002) and Leverington et al. (2002). Finally, elevations greater than the aforementioned lowest measured elevation were classified as *above water;* the balance was classified as *not above water*. This binary classification scheme served to cartographically flood the depressed landscape, reveal the extent of each lake surface as it was constrained by topography and, in effect, interpolate paleoshorelines at unsampled locations.

Results

The Glacial Lake Algonquin database

The GLA database contains 200 records that represent clearly-identifiable wave-cut bluffs throughout the region (Fig. 2). Copies of the database are available in Appendix A of Drzyzga (2007b) and the electronic supplement to this manuscript. We retained 110 of the 146 records collected by Schaetzl et al. (2002) and archived the other 36 in a supplemental database. Elevations obtained during this work at sites in the Munuscong Islands region, in the Indian River

Lowlands, and near the Au Sable River complement the values reported by Schaetzl et al. (2002); our efforts identified the same features and obtained nearly identical elevation values from them. Of the 36 points archived, four (taken near Douglas Lake, MI) mark anomalous features that (curiously) rest higher than the Main water plane ($\sim$225 m); the others mark offshore bars, barrier bars, or spits, and thus, were not collected according to our quality assurance procedures.

Data collected previously by Cowan (1985: 10 bluffs at Sault Ste. Marie) and Karrow (1987: 19 bluffs at St. Joseph Island) were conflated with our own (Fig. 2). Dick Cowan (Cowan 1985) and Paul Karrow (Karrow 1987) graciously shared copies of their survey logs and field notes, and marked 1:50,000 scale topographic maps with the locations of their elevation profiles and shoreline feature observations. Bluff locations (x, y) were digitized from those map sheets and attributed with published elevations (z) and phase names.

We surveyed 85 additional features (Fig. 2) with GPS technology and described them with field notes. Our quality control procedure was to occupy nearby National Geodetic Survey monuments and benchmarks and compare our measured (n = 18) and their published values. The set of measurement errors among benchmark elevations ($\bar{x} = 0.16$ m, $\sigma = 0.77$ m, min $= -1.36$ m, max $= 1.70$ m) was not statistically different than zero (90% conf. int.) and measurement errors in location were negligible at every monument, so we infer the same are true of our shoreline data. After review, we attributed 61 of the 85 features to named GLA lake phases. The balance, less 18 duplicate records, is archived in the supplemental database.

Individually, each database record represents a point along an ancient shoreline. The newest records fill some large data gaps (Cowan 1985) and furnish new points of support (Taylor 1895) for the delineation of ancient water planes. In aggregate, they begin to outline several distinct GLA water planes: Main (57), Ardtrea (41), Upper Orillia (33), Lower Orillia (16), Wyebridge (12), Penetang (13), Cedar Point (17), Payette (7), Sheguiandah (3), Korah (1).

Glacial Lake Algonquin water plane models

This is the first work to model "Upper Orillia" (Deane 1950) shorelines in the study area and, in effect, it refines earlier models of the Main and Ardtrea phases and supersedes the Wyebridge model of Schaetzl et al. (2002). Our Main, Ardtrea and Upper Orillia models (Table 1), although similar to the water plane surfaces derived by Schaetzl et al. (2002), are superior in five ways. First, our models are supported by more paleoshoreline data, and these data cover larger geographic extents. Second, our data were collected along the expected pattern of uplift and, so, allowed us to better model non-stationary elevation drift across the uplifted water planes. Third, we used reduced second-order generalized least squares models to capture uplift trends and retained statistically significant terms only. Schaetzl et al. (2002) used full second-order ordinary least squares models that retained statistically insignificant terms, which renders their models less precise and, hence, less meaningful. Fourth, our geostatistical models take into account both the broad uplift trends and regionalized deviations from those trends; Schaetzl et al. (2002) focused on the broad trends only. And fifth, we discovered during geocomputation the need to rescale all horizontal coordinate values from the meter scale to the kilometer scale, and to reduce their magnitudes by translating the Michigan GEOREF (NAD83) planar coordinate system origin to Traverse City, Michigan, which is inside our study area. These actions mitigated nefarious rounding errors that are created by computer word overflows (Burrough and McDonnell 1998) during any trend surface analysis that employs large coordinate values and exponential terms. The models reported by Schaetzl et al. (2002) were infected with such rounding errors, despite their use of 32-bit processors, and, therefore, the parameter coefficients they reported cannot be considered fully precise. Our model coefficients (Table 1) express rates of uplift (m per km) that are more accurate, more precise and more user-friendly than the rates they reported (m per m).

GLA water planes are continuous, smooth, and show a general pattern of uplift that tends to increase in the study area from the southwest to the northeast, and towards the former centers of ice loading. The proglacial water plane surfaces generated here (Figs. 5, 6) resemble postglacial rebound surfaces derived from lake gauge data (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1977, 2001; Mainville and Craymer 2005) and from geophysical models (Tushingham and Peltier 1991; Clark et al. 2007). The similarities among our mapped contours and others' mapped isobases suggest

Table 1 Three water plane models with parameters estimated via generalized least squares

	Main	Ardtrea	Upper Orillia
Model parameters			
Intercept	212.3 m	208.3 m	199.9 m
x_{km}	−0.2405	−0.2008	−0.1442
$x_{km} * y_{km}$	0.0018	0.0016	0.0014
x_{km}^2	0.0012	0.0010	0.0009
y_{km}^2	0.0017	0.0017	0.0016
Model fitness			
adj. R^2	0.9930	0.9961	0.9900
F	1973	2547	793.4
ρ value	<0.0001	<0.0001	<0.0001
Residual standard error	2.01 m	1.42 m	2.69 m
Predictions at Hessel, MI (84.44°W, 46.01°N)			
Elevation (m ± SE)	257.2 ± 1.9	251.3 ± 1.4	240.4 ± 1.6
Gradient (m per km)	0.86	0.65	0.62
Aspect (°az)	199.0	200.5	206.9
Predictions at Charlevoix, MI (85.26°W, 45.32°N)			
Elevation (m ± SE)	218.1 ± 2.1	212.8 ± 1.4	206.8 ± 1.6
Gradient (m per km)	0.29	0.26	0.26
Aspect (°az)	169.7	175.2	190.1
Predictions at Alpena, MI (83.44°W, 45.06°N)			
Elevation (m ± SE)	219.6 ± 2.3	216.0 ± 1.4	210.9 ± 2.1
Gradient (m per km)	0.33	0.34	0.34
Aspect (°az)	205.9	207.3	212.5

As described above, the false origin of the Michigan GEOREF planar coordinate grid was translated to Traverse City, MI before computation; the intercept term can thus be interpreted with respect to that location. Predicted elevation and standard error values were obtained via universal kriging. Slope gradient and aspect values were derived from the predicted water plane surfaces

our models are reasonable, that they reflect the same ongoing isostatic rebound process and, importantly, that the pattern of isostatic recovery did not change markedly over the last 13,000 years.

The water plane models presented here are geostatistical models, with predicted elevation (Figs. 5, 6) and variance values (not shown) at each grid cell location. Accordingly, the distribution of elevation at any location and a statistical difference of means test can be used to estimate the probability that a bluff elevation, perhaps one surveyed at a future date, might belong to a modeled lake phase. The test result can be used to reject or fail to reject the null hypothesis of unequal means and, hence, to suggest a proper classification for the newly sampled site. Alternatively, a test result that fails to reject the null hypothesis, in the presence of sound physical evidence that a bluff belongs to a particular lake phase, will indicate the geostatistical model should be updated with information from the site.

Last, co-located elevations along any two statistical lake surfaces can now be compared using a spatial version of the two-sample difference of means test. Locations where water planes intersect should have mean elevations that are not statistically different from each other. Such locations should be flagged for additional field investigations and searched, for example, for cross-bedded or reworked sediments.

Discussion

Glacial Lake Algonquin phases/stages and issues of rebound

The features at St. Joseph Island (Karrow 1987) and Cockburn Island (Drzyzga 2007a, b) are important because they add much needed support near the northern rims of GLA water planes and they provide clues about the deglaciation history of the area. The Laurentide ice sheet retreated northeastwardly after reaching its maximum extent (Karrow 1987; Larson and Schaetzl 2001). Lakes in the Michigan and Huron basins were joined when retreating ice uncovered the Indian River lowlands and, slightly later, the Straits of Mackinac, an event that Larsen places at approximately 13 cal (11.2) ka BP (after Hansel et al. 1985). Water levels in Glacial Lake Chicago (Lake Michigan basin) dropped to the Algonquin level in the Lake Huron basin, upon joining (Hansel et al. 1985), which left the outlet at Chicago abandoned (Hansel et al. 1985; Larson and Schaetzl 2001) and directed outflow to the Fenelon Falls outlets near Kirkfield, Ontario (Finamore 1985). Thus began the Main phase of GLA. The presence of Main phase shorelines at Cockburn Island suggests that the ice sheet retreated across the

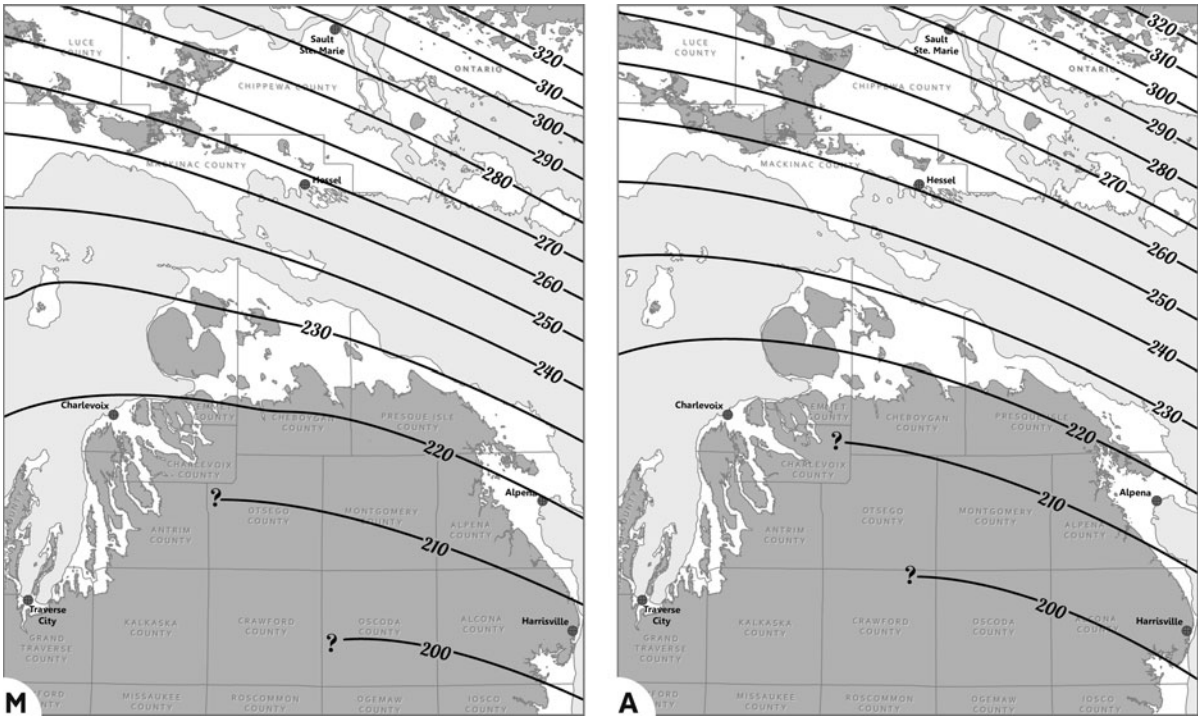

Fig. 5 Elevation fields of the (M) Main and (A) Ardtrea water planes of Glacial Lake Algonquin (10 m contours). Also shown are contemporary Great Lakes water areas (*light grey*) and contemporary land areas that were, as determined in this work, subaerial (*dark grey*) or subaqueous (*white*) during each phase. Note the land areas that emerged and the islands that coalesced between phases

island sometime during the early portion of this lake phase; early enough to allow bluff cutting and shoreline development to occur there. Karrow (1987) concluded that proto-St. Joseph Island was deglaciated about 12.9 cal (11.0) ka BP or shortly thereafter. Because Cockburn Island is situated along the same apparent isobase that runs through St. Joseph Island (Fig. 5), both islands were likely deglaciated at the same time. Therefore, locations between the Straits of Mackinac and the Cockburn Island-St Joseph Island region must have been deglaciated within, roughly, the intervening 100+ year period. Also, the presence of "lower group" shorelines on St. Joseph and Cockburn Island indicate that these islands continued to be subaerially exposed before the progressive deglaciation of the outlets near North Bay (Karrow 2004; Heath and Karrow, 2007). In sum, relict shoreline features at Cockburn Island (Figs. 2, 4) are important because they help locate the ice sheet margin and the northern extent Main Lake Algonquin, albeit roughly, within the context of this short time frame.

Karrow (1987) and Larsen (1987) noted the long-standing controversy regarding whether certain water planes in the GLA sequence are parallel, implying that changes in outlets were responsible for changes in water levels, or whether they converge toward a single outlet, which would implicate isostatic rebound as the sole cause of shoreline deformation and change. We found clear evidence of convergence between the Main and Ardtrea water planes, which agrees with earlier work (Deane 1950; Schaetzl et al. 2002). Proceeding southwardly: Main and Ardtrea bluffs at Cockburn Island are vertically separated by approximately 8 m (280 and 272 m, respectively); in the Munuscong Islands region they are separated by ~7 m (265 and 258 m, respectively); on Mackinac Island they are separated by ~6 m (242 and 236 m, respectively); and, in the Douglas Lake area, they are separated by ~4 m (225 and 221 m, respectively). These shorelines are difficult to differentiate at locations south of Little Traverse Bay (Lake Michigan) and at Thunder Bay (Lake Huron), perhaps because they were reworked or destroyed by the younger lake waters. Clear evidence of convergence between the Main and Ardtrea water planes suggests that differential uplift relative to the Fenelon Falls outlet was the cause of deformation and tilt during the Main and Ardtrea phases.

An imaginary line from just north of Charlevoix (Lake Michigan) to just south of Alpena (Lake Huron) approximates where the Main and Ardtrea water planes tend toward convergence, but scant physical evidence of Main phase shorelines exists near it. In Ontario, Karrow reported that the Main Lake Algonquin shoreline between Kincardine and Port Elgin, along the eastern shore of Lake Huron, "has been entirely removed by later shore erosion … by lower water levels after the Main Algonquin level" (Karrow 1988). We hypothesize that the same kind of bluff removal processes that occurred between Kincardine and Port Elgin, Ontario, also occurred at Charlevoix and south of Alpena. It seems reasonable to attribute observable shorelines in these areas to the last lake phase to act upon them; not the first or the highest. Therefore, we agree with Larsen's claim that the Main and Ardtrea shorelines of eastern Lake Huron predate the highest stranded shorelines in northern Lake Michigan, and that the apparent "Main" shoreline of Lake Michigan "may correlate with the Orillia shoreline of Ontario" (Larsen 1987). This does not mean that the Main or Ardtrea water planes did not extend into the Michigan basin, for evidence at Beaver Island suggests they did. It means only that many of the highest remaining GLA shorelines observable in the Lake Michigan basin correlate to younger lake phases.

Upper Orillia shorelines (Fig. 6) occur below Ardtrea shorelines at Cockburn Island, the Munuscong Islands, Mackinac Island, and in the Indian River Lowlands area. A review of elevation differences between them yields inconsistent evidence regarding convergence, but the reconstructed Ardtrea and Upper Orillia water plane models do intersect south of Harrisville, Michigan and near the mouth of the Au Sable River, at 196.3 m. This finding is provisional, however, because the Upper Orillia water plane model was supported by fewer data than was the Ardtrea water plane model. Of the two, the Upper Orillia model was noisier and subject to greater uncertainties.

The embayment that holds contemporary Walloon Lake (Fig. 2, near Charlevoix, MI) was likely last connected to GLA during the Upper Orillia phase.

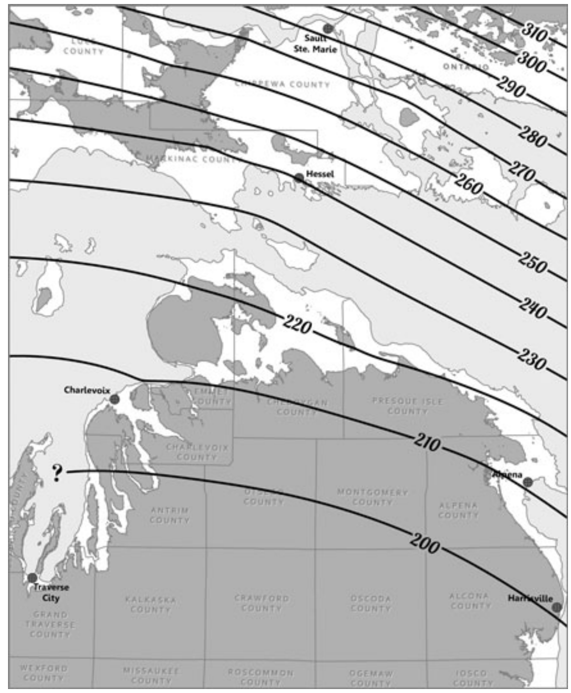

Fig. 6 Elevation field of the Upper Orillia water plane (10 m contours). Also shown are contemporary Great Lakes water areas (*light grey*) and contemporary land areas that were, as determined by this work, subaqueous (*white*) or subaerial (*dark grey*) during the phase. Note the land areas that emerged since the Ardtrea phase and the set of stranded inland lakes east of Charlevoix

Research on the oxygen isotope and pollen records stored in sediments at the bottom of Walloon Lake might reveal information about when the embayment separated from the greater lake, which could then be used to bracket the time it took GLA to transition from the Main phase to the end of the Upper Orillia phase at that location.

Few sites contain multiple wave-cut bluffs tied to later and lower water planes. Cockburn Island and the Munuscong Islands region, for example, hold bluff sites associated with the Upper Orillia and Penetang shorelines (Drzyzga 2007a). The vertical difference between them at Cockburn Island is 36 m, whereas the difference in the Munuscong Islands region is only 30 m. Decreasing vertical separation with decreasing latitude suggests convergence due to differential rebound. A difference between two points, however, is not sufficient for characterizing the entire field of differences between two water planes, so no valid conclusion can be drawn yet about the geospatial relationship between the Upper Orillia and Penetang water planes across the region.

Evidence of convergence between particular water planes in northern parts of the Huron basin notwithstanding, this research cannot resolve where GLA stood in the southern parts of the Huron and Michigan basins. Extrapolating the Main water plane model suggests the Main surface plunges below the contemporary Lake Michigan surface and, so, did not reach the outlet at Chicago (Larsen 1987; Clark et al. 2007). Yet, Capps et al. (2007) presented morphologic, stratigraphic and chronologic evidence of a relict shoreline of GLA age (12.5 cal (10.56) ka BP) in Indiana (Southern Lake Michigan basin) that rests above the present Lake Michigan surface. They attributed the feature to the Main phase that began in 13.1 cal (11.3) ka BP and, interestingly, not to any of the younger transgressing phases of the "same lake" (Heath and Karrow 2007) that ended in 12.5 cal (10.5) ka BP (Karrow et al. 1975). Regardless, the degree of spatiotemporal connectivity between the northern and southern parts of the Lake Michigan basin during GLA is still not yet understood.

The class of generalized least squares models, including universal kriging, is a promising method for reconstructing ancient lake surfaces. While these approaches require relatively large samples of shoreline data and longer quality control efforts, their ability to capture and account for second-order spatial structure in the identification of uplift trends produce theoretically and practically superior water plane models.

Conclusions

This research on GLA—its extents and stages during various lake phases—is a refinement and an elaboration of work by Schaetzl et al. (2002). We instituted, however, more rigorous quality assurance procedures and employed more robust methods that made the results presented here more accurate, precise and thus, potentially more useful. We presented maps of the Main, Ardtrea and Upper Orillia phases and contours showing the elevations of these water planes across a large area. The latter have two potential applications: (1) to serve as baseline data for others who might study isostasy within the Great Lakes region, and (2) to provide baseline information for field-based research, by documenting the elevations and locations of GLA shorelines. This work exhibits a form of scientific crossover and reveals the promise in combining extensive fieldwork and modern geostatistics to investigate spatial processes, like water plane deformation and isostatic recovery.

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