Journal of Paleolimnology **22:** 71–80, 1999.

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The volume and paleobathymetry of glacial Lake Agassiz

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Received 19 February 1998; accepted 3 August 1998

Key words: Lake Agassiz, volume, area, paleobathymetry, computer model

Abstract

During the last retreat of the Laurentide Ice Sheet in North America, many proglacial lakes formed as continental drainage was impounded against the southern and western ice margin. Lake Agassiz was the largest of these lakes. The bathymetry of Lake Agassiz at the Herman and Upper Campbell beach levels – formed at about 11.5–11.0 ka and 9.9–9.5 ka, respectively – was computer modelled in this study by first collecting data for the isostatically-deformed paleowater planes of the two lake levels (derived from isobase lines constructed from beach elevations), and then subtracting these from the modern topography of the former lake floor. Pixels with dimensions of 1/30 X 1/30 of a degree were used in the model. Using these data, the area and volume of the lake were also calculated: at the Herman level these were ~152 500 km^2 and ~13 100 km^3 respectively; at the Upper Campbell level these were ~350 400 km^2 and ~38 700 km^3. Contour maps showing the paleobathymetry of both periods in the lake's history were also constructed. Determining the paleobathymetry and volume of Lake Agassiz is an important step in understanding the impact that the lake had on its surrounding environment and on the rivers, lakes, and oceans into which it flowed.

Introduction to Lake Agassiz

Lake Agassiz was the largest lake in North America during the last deglaciation. Between 11.7 and 7.5 ka, the lake covered parts of Manitoba, Saskatchewan, Ontario, North Dakota, and Minnesota (see Teller & Clayton, 1983a). It formed along the retreating margin of the Laurentide Ice Sheet which dammed northward-draining rivers flowing to Hudson Bay, impounding the drainage of about 2 million km^2 (Teller & Clayton, 1983b). The history of Lake Agassiz is complex. Its size and volume were related to the location of the ice margin (which formed its northern boundary) and the elevation and location of its overflow channels, all of which changed through time. Differential isostatic rebound also played an important role in determining the lake's size, areal distribution, and history, as comparatively rapid uplift in the newly deglaciated northern regions led to a southward shift in the mass of water; this was partially offset by the abandonment of some outlets for new (and relatively lower) routes.

The history of glacial Lake Agassiz is recorded by beaches and wave-cut shorelines, offshore sediments, and outlet channel deposits (e.g. Teller & Clayton, 1983a; Teller, 1985; Smith & Fisher, 1993). Some have argued that Lake Agassiz played a pivotal role in triggering the abrupt change in ocean circulation and climate during the Younger Dryas cold episode (11–10 ka) (e.g. Broecker et al., 1988, 1989); however, basic questions remain about the lake itself, which oceans received its overflow, and when specific overflow events occurred (e.g. Smith & Fisher, 1993; Fisher & Smith, 1994; Rodrigues & Vilks, 1994; Keigwin & Jones, 1995; deVernal et al., 1996).

A lake the size and volume of Lake Agassiz must have had a considerable impact on many aspects of late-glacial North America, so an understanding of the volume and distribution of its waters through time is important. Dated strandlines and ice margins constrain the areal extent of the lake at various points in time. Maps depicting changes in lake extent may be found in, for example, Elson (1967), Dyke & Prest (1987), Fenton et al. (1983), Schreiner (1983), Klassen (1983), Teller (1985), and Thorleifson (1996). Several estimates have been made of the volume of water leaving the lake at specific points in time, as its level dropped from one strandline to another (e.g. Teller & Thorleifson, 1983; Teller, 1990a, b; cf. Teller, 1987). However, there are no published maps of the lake's paleobathymetry, nor has there been a precise calculation of the lake's total volume.

In this paper, we present area and volume calculations, and bathymetry maps of Lake Agassiz at two different times in its history. The times chosen correspond to the formation of two widespread, isostatically-deformed beaches – the Herman and the Upper Campbell beaches as outlined by Teller et al. (1983), Teller (1985, 1987) and Thorleifson (1996) – whose dates of formation were about 11.5–11 ka and 9.9–9.5 ka, respectively (Fenton et al., 1983; Thorleifson, 1996) (see Figures 1 & 2).

Modelling techniques

Introduction

Computer modelled images of the Agassiz basin were generated using two data sets: (1) the modern elevations of the former water planes of Lake Agassiz, as determined from strandline and isobase diagrams (Teller & Thorleifson, 1983) and (2) the modern topographic

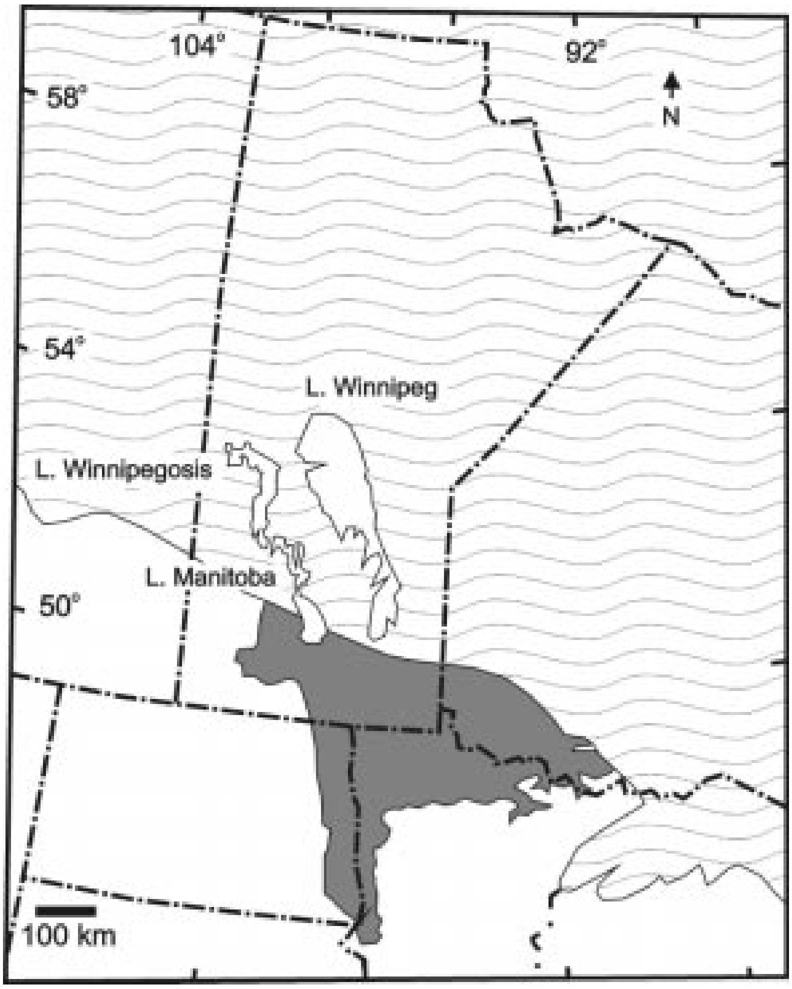


Figure 1. Extent of Lake Agassiz at the Herman level. Wavy pattern = Laurentide Ice Sheet; Dark shading = Herman level of Lake Agassiz (after Thorleifson, 1996; Teller et al., 1983).

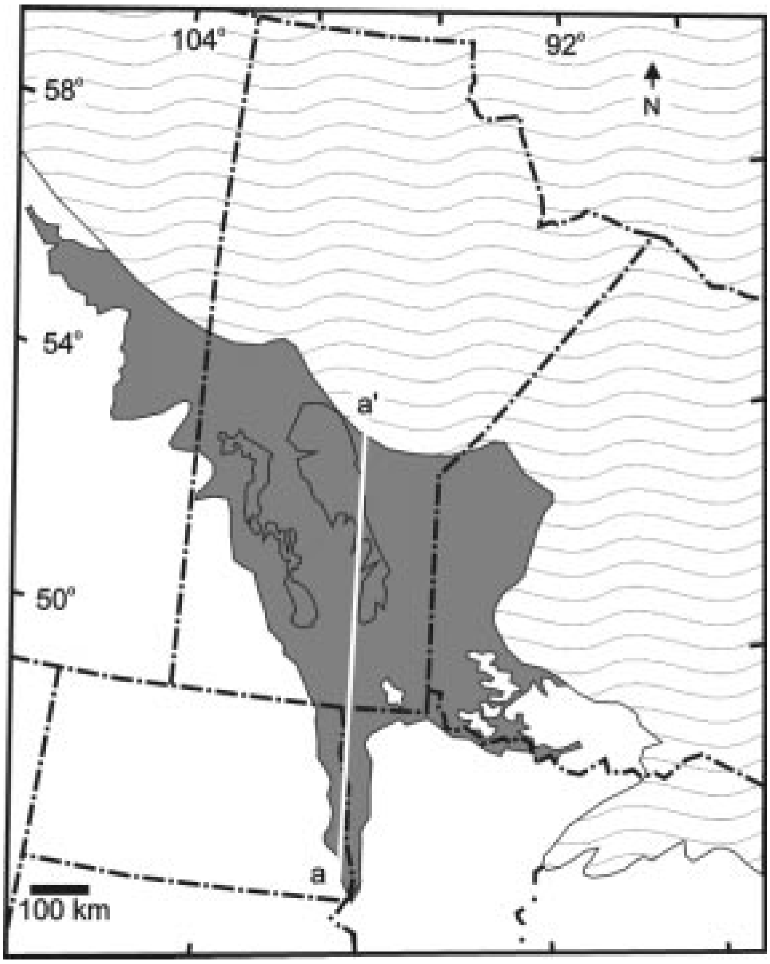


Figure 2. Extent of Lake Agassiz at the Upper Campbell level. Wavy pattern = Laurentide Ice Sheet; Dark Shading = Upper Campbell level of Lake Agassiz (after Teller et al.,1983); a – a′ is the location of cross sections shown in Figure 3.

surface of the offshore basin of the lake. The paleo-elevation of a point within the Lake Agassiz basin was calculated by subtracting that particular location's amount of differential rebound (relative to the southern outlet) from its modern topographic value (see Figure 3). Values (either isobase or modern basin topography) between control points were estimated by spatial interpolation. The configurations of the lake floor at the times when the Herman and Upper Campbell beaches formed were estimated by subtracting the interpolated *rebound surface* from the spatially interpolated modern topographic surface over the entire basin. The term 'rebound surface' refers to a three-dimensional model of isobase values, generated by spatial interpolation between values taken from isobase lines drawn by Teller and Thorleifson (1983).

Data collection

Control points for modern topography

The generation of the modern topographic surface was based on a representative selection of over 1600 points distributed within the Lake Agassiz basin and along its shorelines. For portions of the lake basin within Canada, National Topographic Series (NTS) maps were used (1:50 000, with 25-foot or 10-meter contour intervals). Elevations from the lake basin within the United States were obtained using United States Geological Survey (USGS) maps (1:100 000 and 1:24 000, with contour intervals of 5–10 meters and 5 feet, respectively). To maintain a similar density of data points throughout the Agassiz basin, large-scale USGS maps (1:24 000) were grouped to cover an area equiva-

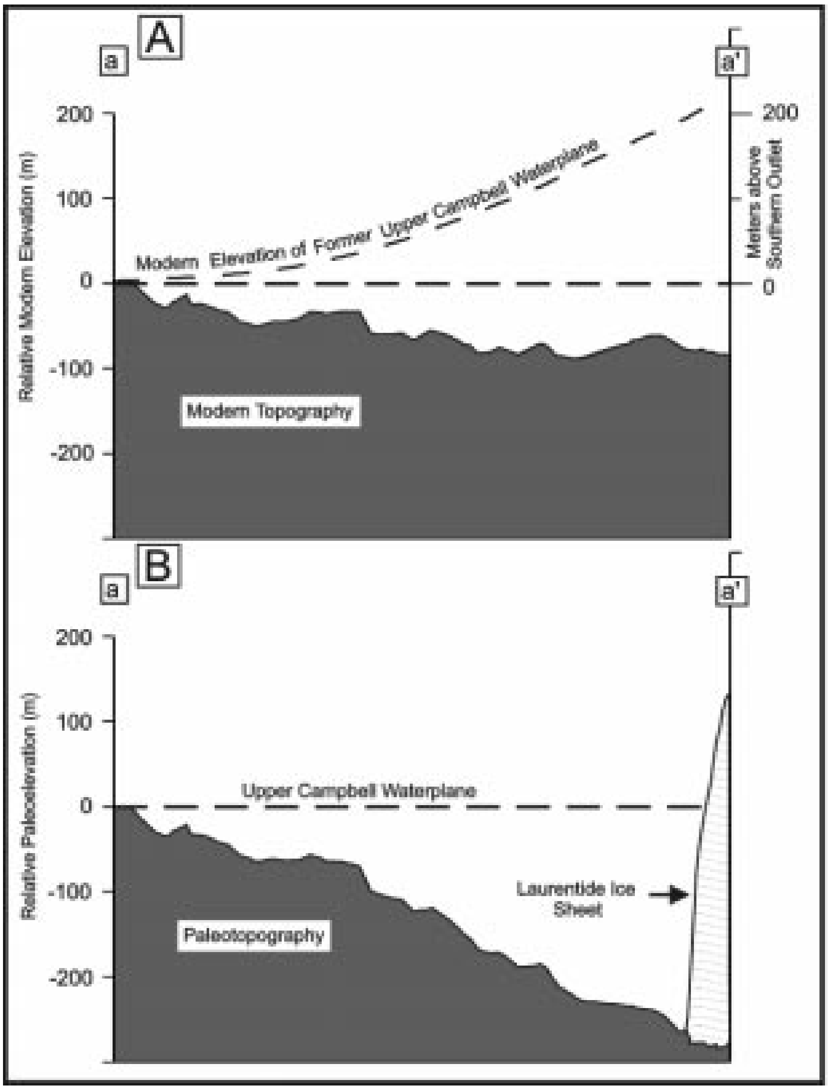


Figure 3. Cross sections showing the topography of the floor of Lake Agassiz (A) today and (B) at the time when the Upper Campbell beach formed. The amount of uplift in relation to the southern outlet since formation of the Upper Campbell beach is shown by the curved dashed line in A. The paleoelevation of the lake floor, shown in B, was calculated by subtracting the amount of differential uplift (the rebound surface) from the modern topographic surface. The Laurentide Ice Sheet is represented schematically. Location of cross section is shown in Figure 2.

lent to that of a Canadian NTS 1:50 000 scale map sheet. For map sheets that fell entirely within the lake basin, a single representative elevation point was recorded from the center portion of the map sheet (or groups of 1:24 000 map sheets), using either a contour line or a mapped benchmark. For map areas that included shorelines, offshore data points were collected halfway between the edge of the map sheet and the shoreline. Data points for areas presently covered by large lakes, such as Lakes Manitoba, Winnipeg, and Winnipegosis (Figure 1), were obtained from bathymetric charts. Where necessary, additional data points were collected at closer intervals to better define topographic features such as islands and narrower reaches of Lake Agassiz. The use of modern topography for calculating the paleobathymetry of Lake Agassiz does not consider the volume of sediment deposited in the lake basin (such as glacial and post-glacial sedimentation in Lakes Winnipeg and Manitoba) since the time of the two Lake Agassiz phases considered in this paper. The volumetric calculations presented here assume that the effect of post-Lake Agassiz deposition, as well as erosion in the basin, is minimal compared to the very large volume of the lake.

Control points for rebound surfaces

In order to define the isostatically-deformed surfaces of Lake Agassiz (i.e. its rebound surfaces) for the Herman and Upper Campbell beaches, the modern elevations of these strandlines were taken from the isobases plotted by Teller and Thorleifson (1983). The initial elevation for each datum was estimated from the strandline diagram by fitting a third-order polynomial equation (in the case of the Herman level) and a fourth-order polynomial equation (in the case of the Upper Campbell level) to the beach rebound curves. Additional control points were established by interpolation between the isobase lines. Where possible, Upper Campbell strandline elevations were compared to an independently collected database of Global Positioning System (GPS) beach elevations (Rayburn, 1997) in order to improve the accuracy of the Teller and Thorleifson (1983) strandline diagram. Based on this, the Teller and Thorleifson (1983) data was found to correctly represent differential rebound in the Agassiz basin, and any discrepancies between it and the GPS data were negligible.

In total, more than 800 shoreline and offshore points along and between the isobase lines of Teller and Thorleifson (1983) were collected to generate the rebound surfaces for the Herman and the Upper Campbell lake levels. Where the trend of an isobase was parallel or sub-parallel to the shoreline of Lake Agassiz, extra data points were collected at 5 km intervals to provide improved resolution.

Surface interpolation procedure

The modern topographic surface of the Lake Agassiz basin was interpolated from the more than 1600 modern topographic control points (described previously). Similarly, a rebound surface was interpolated from the shoreline and isobase control points for each lake phase (344 control points for the Herman; 471 for the Upper Campbell). The process of interpolation was performed to extend and increase the limited number of data points over the full area of Lake Agassiz, which then became defined by tens of thousands of points (see below).

Control point values used to derive each of these surfaces were initially compiled in point-vector data format (i.e. in x, y, z - ‘longitude, latitude, elevation’ - coordinates). A triangulated irregular network (TIN) was generated from the point-vector data using the ARC-TIN software system (a module of the ARC-INFO GIS software system), run on a SUN-SPARC workstation. A TIN is a terrain model that utilizes a surface of continuous, connected triangular facets based on a Delaunay triangulation of irregularly-spaced points (Peuker et al., 1978). It is ideal for the generation of surfaces from point databases, and is particularly appropriate in the interpolation of the isobase surfaces, as straight-edged triangular facets allow for more rigorous interpolation of gently-curving or generally straight isobases. The TIN surfaces were converted to raster (grid) format using the main ARC-INFO software package. These raster surfaces were composed of individual square pixels with dimensions of 1/30 degree longitude by 1/30 degree latitude. All processes of interpolation were performed in a rectangular (latitude/longitude) coordinate system, with bounding longitudes of 90 degrees and 110 degrees west, and bounding latitudes of 40 degrees and 60 degrees north. All images presented in this paper were enhanced and re-projected from a rectangular projection to the Lambert Conformal Conic projection, using the PCI EASI-PACE software system run on a SUN-SPARC workstation. Interpolated isobase and topographic raster images for the Herman and Upper Campbell beach levels of Lake Agassiz are given in Figures 4 and 5, respectively.

Generation of paleobathymetric images

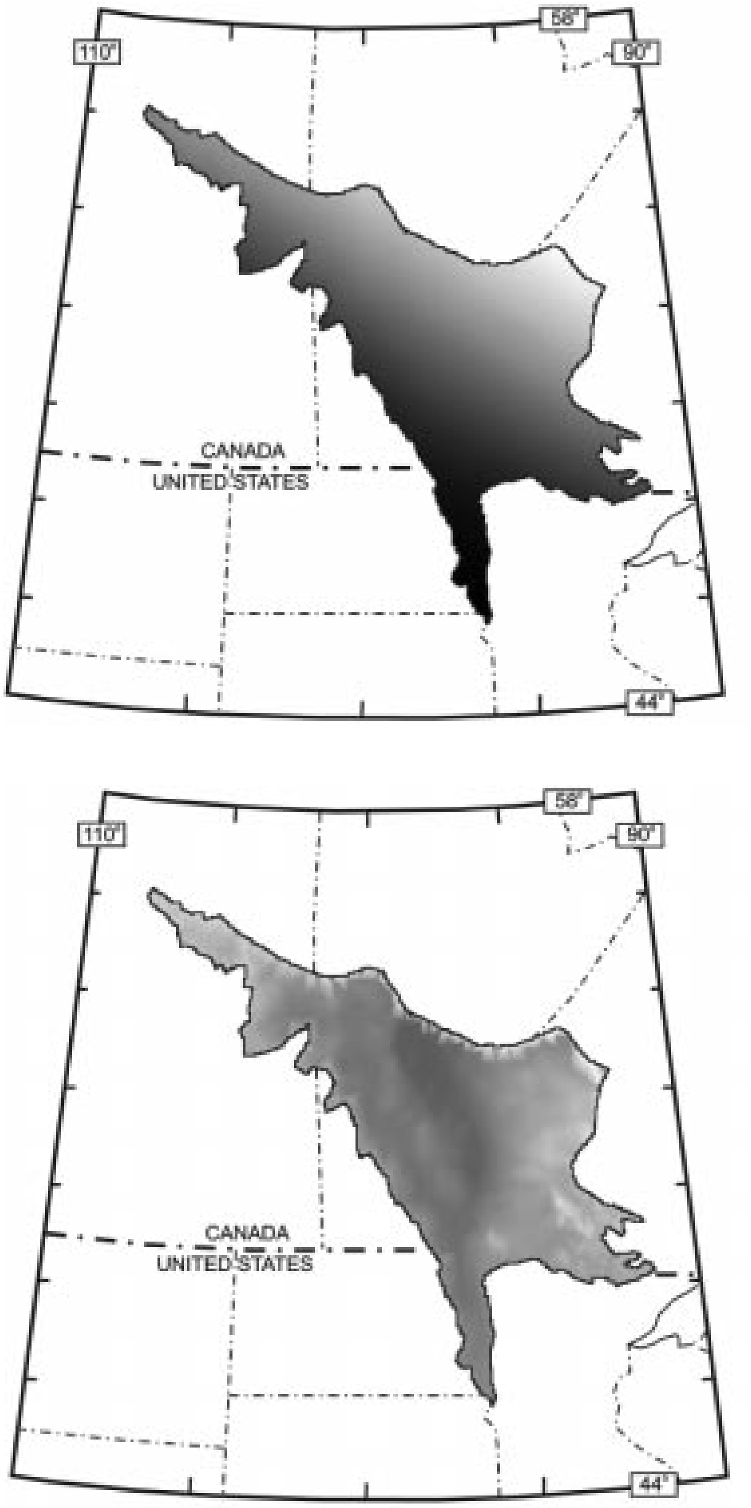
Raster isobase and modern topographic surfaces were used to generate images of paleobathymetry (Figures 6 and 7). The generation of each paleobathymetric image was relatively simple, since (1) both the rebound and modern topographic surfaces cover precisely the same geographical area, (2) both surfaces were generated in the same map projection, and (3) both surfaces had pixels with common dimensions (1/30 degree by 1/30 degree). Because the pixels for each of the surfaces were constructed to coincide, the rebound surface was simply subtracted from the modern topographic surface by subtracting each individual rebound surface pixel value from the corresponding topographic surface pixel value. Because the southern outlet is the locality least affected by isostatic rebound in the Agassiz basin, it was used as a ‘zero’ rebound point on the differentially deformed rebound surface; today the Herman and Upper Campbell strandlines have elevations of 317 and 299 m, respectively, at the southern outlet. The purpose

A

B

Figure 4. (A) Representation of the rebound surface of the Herman lake stage. Darker-toned areas represent values of least uplift; lighter-toned areas represent values of increasing uplift. (B) Modern topographic surface within the extent of the Herman level. Lighter-toned areas represent relatively high elevations; darker-tones represent areas of relatively low elevations. Elevations in the immediate vicinity of the ice margin were exaggerated for modelling purposes.

A



B

Figure 5. (A) Representation of the rebound surface of the Upper Campbell lake stage. Darker-toned areas represent values of least uplift; lighter-tones represent values of increasing uplift. (B) Modern topographic surface within the extent of the Upper Campbell level. Lighter-toned areas represent relatively high elevations; darker-tones represent areas of relatively low elevations.
Elevations in the immediate vicinity of the ice margin were exaggerated for modelling purposes.

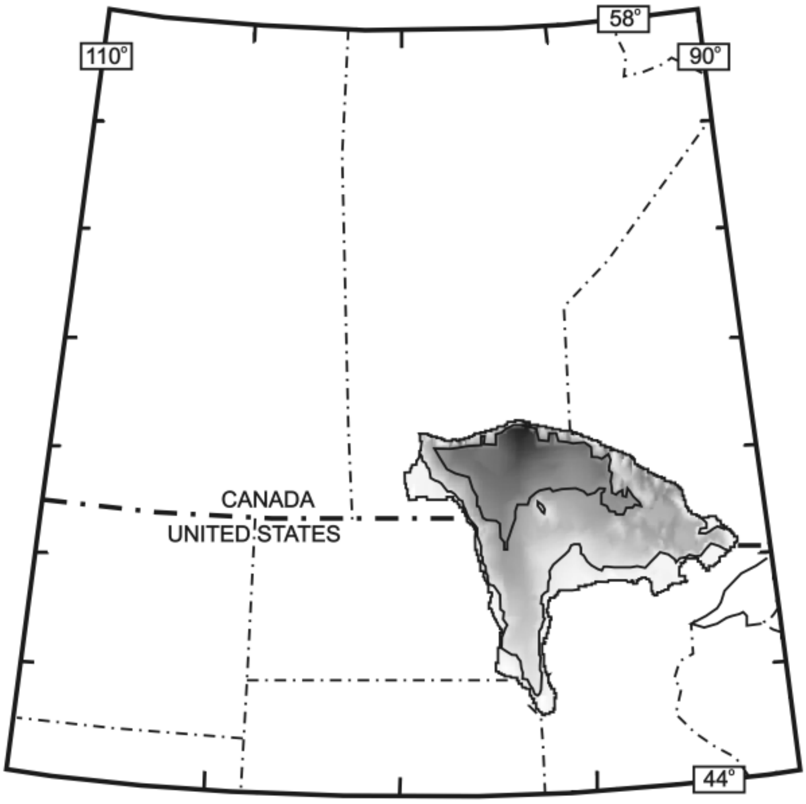


Figure 6. Paleobathymetric map of the Herman level. The first contour line within the basin and the small closed contour in southeastern Manitoba represent 20 m water depth; the second contour line represents 120 m water depth. Maximum depth = 270 m.

of this procedure was to downwarp modern elevations to paleo-elevations that existed during the time of the Herman and the Upper Campbell levels.

Volume and surface area calculations

The area of each pixel used to determine paleobathymetry varies inversely with latitude since the distance across 1/30 degree of longitude decreases from 3.7107 km at the equator to 0 km at the poles. The areas of individual pixels in each paleobathymetric image were approximated by employing standard cartographic equations (e.g. Robinson et al., 1995). The total area of Lake Agassiz at a given phase was calculated by summing the area of all pixels within a specific lake shoreline. In order to calculate the volume of Lake Agassiz for a specific lake phase, the areas of all pixels within the lake were multiplied by their respective depths below the lake surface, and these individual volume calculations were summed.

Area, volume, and bathymetry of Lake Agassiz

The area of Lake Agassiz at the Herman beach level was ~152 500 km^2, while the volume was ~13 100 km^3. Maximum depth during the Herman phase was approximately 270 m. The lake was deepest along the ice margin (Figure 6), where isostatic depression was greatest. The remainder of the lake was relatively shallow.

The area of Lake Agassiz during the Upper Campbell level was ~350 400 km^2, while the volume was ~38 700 km^3. The area (Figure 7) is almost exactly the same as that estimated by Teller & Clayton (1983b). Maximum depth during the Upper Campbell level was approximately 285 m. Again, the lake was deepest along the ice margin and in the basins of the modern Lakes Winnipeg and Manitoba (Figure 7). During both the Herman and Upper Campbell beach phases of Lake Agassiz, water in the southeastern region was shallow, and numerous islands and shallow-water shoals

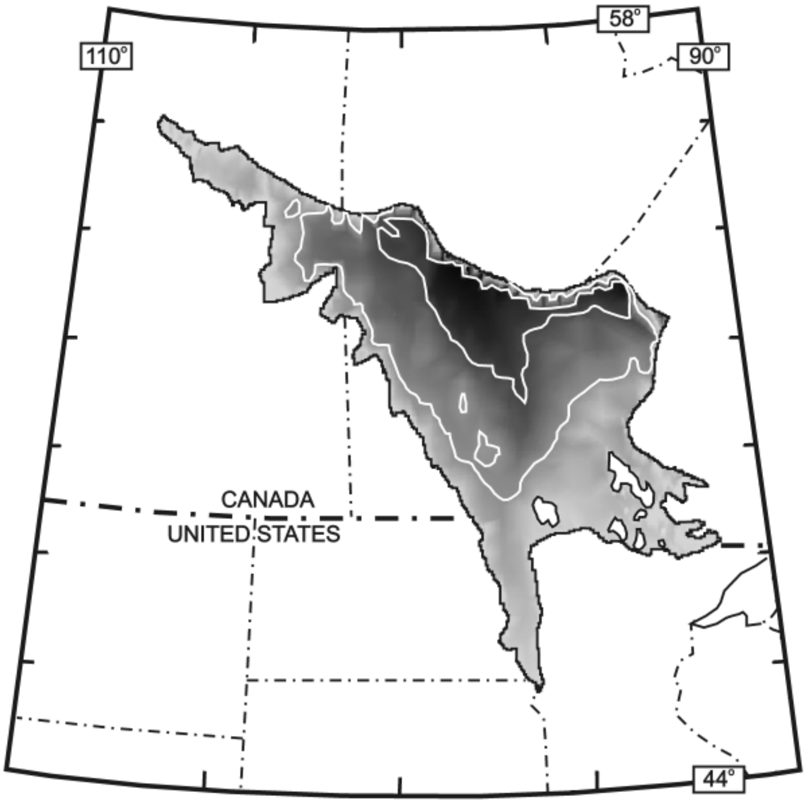


Figure 7. Paleobathymetric map of the Upper Campbell level. The first contour line within the basin and the small closed contours on the western side represent 100 m water depth; the next contour line represents 200 m water depth. Islands in the southeastern portion of the lake are shown in white. Maximum depth = 285 m.

characterize that part of the lake; these are shown as light toned areas on Figures 6 and 7.

Summary and conclusions

The difference between two spatially interpolated surfaces, constructed from the modern topography of the Lake Agassiz basin and from isostatically-deformed Lake Agassiz beaches, was used to reconstruct the paleobathymetry of the Herman and of the Upper Campbell levels of Lake Agassiz. Computer modelling enabled an accurate calculation of the lake area and its volume during these two periods. Results indicate that: (1) the Herman beach level (formed 11.5–11 ka) had an area of ~152 500 km^2, a volume of ~13 100 km^3, and a maximum depth of about 270 m and (2) the Upper Campbell level (formed 9.9–9.5 ka) had an area of ~350 400 km^2, a volume of ~38 700 km^3, and a maximum depth of approximately 285 m. The lake volume at the Upper Campbell level was about 1.5 times the total volume of all of the modern Great Lakes, and about 1.6 times greater than the volume of the world's largest modern freshwater lake, Lake Baikal (Hutchinson, 1957).

The greatest benefit of the computer methodology presented here is its flexibility, and its potential usage in additional simulations. This modelling approach allows for the calculation of areas or volumes at any lake stage or depth interval in the lake (useful, for example, in heat budget simulations), and the assemblage of elevation data for construction of cross sections and paleobathymetric maps. Predictions can be made about shoreline evolution caused by the extraction of a water layer of known thickness (e.g. during abrupt drops in lake level, such as those described by Teller & Thorleifson, 1983). With careful consideration of all information available, isobase modification can be applied to the model to show how it may change the depth, distribution, and areal extent of the lake. With available large-scale digital topographic map sheets, increased accuracy and detail is possible. Importantly, this modelling can now be used in helping assess the physical and climatological impact that this vast glacial lake had on the surrounding region, and on the rivers, lakes, and oceans into which it flowed.

Acknowledgements

We would like to thank Nancy Grant for contributing to the data collection, and for her input during an earlier modelling exercise. A Research Grant to J. Teller from the Natural Sciences and Engineering Research Council of Canada (NSERC) partially funded this research, as did an NSERC graduate scholarship to D. Leverington. Our appreciation to Harvey Thorleifson and Don Lemmen for their very helpful reviews of this paper.

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