Paleotopographic reconstructions of the eastern outlets of glacial Lake Agassiz

David W. Leverington and James T. Teller

Abstract: Paleotopographic reconstructions of the eastern outlets of glacial Lake Agassiz provide a foundation for understanding the complex manner in which terrain morphology controlled the routing of overflow through the eastern outlets during the lake's Nipigon Phase (ca. 9400–8000 ^{14}C years BP) and for understanding the causes of outlet-driven declines in lake level during that period. Although flow paths across the divide between the Agassiz and Nipigon basins were numerous, eastward releases from Lake Agassiz to glacial Lake Kelvin (modern Lake Nipigon) were channeled downslope into a relatively small number of major channels that included the valleys of modern Kopka River, Ottertooth Creek, Vale Creek, Whitesand River, Pikitigushi River, and Little Jackfish River. From Lake Kelvin, these waters overflowed into the Superior basin. The numerous lowerings in lake level between stages of the Nipigon Phase, controlled by topography and the position of the retreating southern margin of the Laurentide Ice Sheet, had magnitudes of between 8 and 58 m, although some of these drawdowns may have occurred as multiple individual events that could have been as small as several metres. The total volumes of water released in association with these drops were as great as 8100 km^3, and for all Nipigon stages were probably between about 140 and 250 km^3 per metre of lowering. The topographic reconstructions demonstrate that Lake Agassiz occupied the area of glacial Lake Nakina (located northeast of modern Lake Nipigon) by the The Pas stage (ca. 8000 ^{14}C years BP) and that Lake Agassiz drainage through the Nipigon basin to the Great Lakes ended before the succeeding Gimli stage.

Résumé : Des reconstructions paléotopographiques des chenaux du côté est du lac glaciaire Agassiz fournissent une base pour comprendre la façon complexe selon laquelle la morphologie de terrain contrôlait le cheminement du débordement par les déversoirs vers l'est durant la phase Nipigon du lac (9400–8000 années ^{14}C avant le présent) et pour comprendre les causes des baisses du niveau de lac causées par les déversoirs durant cette période. Même s'il existait de nombreux chemins d'écoulement traversant la ligne de partage des eaux entre les bassins d'Agassiz et de Nipigon, l'eau sortant à l'est du lac Agassiz vers le lac glaciaire Kelvin (le lac Nipigon actuel) était canalisée vers le bas de la pente dans un nombre relativement restreint de chenaux majeurs qui comprenaient les vallées actuelles de la rivière Kopka, du ruisseau Ottertooth, du ruisseau Vale, de la rivière Whitesand, de la rivière Pikitigushi et de la rivière Little Jackfish. À partir du lac Kelvin, ces eaux se déversaient dans le bassin du Supérieur. Les nombreux abaissements de niveau de lac entre les étages de la phase Nipigon, contrôlés par la topographie et la position de la bordure sud, en retrait, de l'inlandsis Laurentien, avaient des amplitudes de 8 à 58 m, bien que quelques-uns de ces abaissements aient pu être des événements multiples individuels de quelques mètres seulement. Les volumes totaux d'eau relâchée, associés à ces abaissements, ont atteint jusqu'à 8100 km^3 et, pour tous les étages Nipigon, les abaissements étaient probablement de 140 à 250 km^3 par mètre d'abaissement. Les reconstructions topographiques démontrent que le lac Agassiz occupait la région du lac glaciaire Nakina (situé au nord-est du présent lac Nipigon) à l'époque de l'étage The Pas (vers 8000 années ^{14}C avant le présent) et que le drainage du lac Agassiz à travers le bassin de Nipigon vers les Grands Lacs a cessé avant l'étage suivant de Gimli.

[Traduit par la Rédaction]

Introduction

During the Nipigon Phase of glacial Lake Agassiz (ca. 9400–8000 ^{14}C years BP; 10 400 – 8800 cal years BP), overflow was routed into the Nipigon basin through a complex system known collectively as the *eastern outlets* (Elson 1957, 1967; Zoltai 1965*a*, 1967; Teller and Thorleifson 1983, 1987). These outlets consisted of a series of eastward flow paths that decreased in elevation toward the north; thus, as the southern margin of the Laurentide Ice Sheet retreated northward during the Nipigon Phase, progressively lower outlets were opened to glacial Lake Kelvin (modern Lake Nipigon), and, correspondingly, the level of Lake Agassiz declined.

Field studies have provided the basis for understanding the nature of the eastern outlets and their role in the late Quaternary history of central North America (e.g., Zoltai

Received 16 January 2003. Accepted 15 May 2003. Published on the NRC Research Press Web site at http://cjes.nrc.ca on 25 September 2003.

Paper handled by Associate Editor R. Gilbert.

D.W. Leverington.[1] Center for Earth and Planetary Studies, Smithsonian Institution, Washington, DC 20560-0315, U.S.A.
J.T. Teller. Department of Geological Sciences, University of Manitoba, Winnipeg, MB R3T 2N2, Canada.

[1]Corresponding author (e-mail: leveringtond@nasm.si.edu).

 doi: 10.1139/E03-043

1965*a*, 1965*b*, 1967; Thorleifson 1983; Teller and Thorleifson 1983, 1987; Teller and Mahnic 1988; Lemoine and Teller 1995). Interpretations have been hindered, however, by the paucity of preserved Lake Agassiz shoreline features in the region around the divide between the Agassiz and Nipigon basins, the generally low topographic relief along the divide, the lack of easy ground access to the region, and the absence of detailed topographic data.

The purpose of this research is to generate and interpret high-resolution digital topographic models of the eastern outlet region for all recognized stages of the Nipigon Phase of Lake Agassiz, to increase understanding of the eastern outlet system, and to provide an improved framework for guiding future field-based investigations. For each investigated stage, the corresponding topographic reconstruction was used to (*i*) approximate the position and configuration of the Lake Agassiz shoreline in the vicinity of the eastern outlets, (*ii*) determine the position and morphology of the drainage divide separating the Lake Agassiz basin from the Nipigon basin, (*iii*) identify major drainage routes from Lake Agassiz to Lake Kelvin, and (*iv*) further quantify aspects of the overflow and outburst history of Lake Agassiz.

Lake Agassiz overview

During deglaciation, the retreating southern margin of the Laurentide Ice Sheet (LIS) gradually exposed large expanses of the North American continent, including the structural and topographic basin of north-central North America, the central part of which today contains the waters of Hudson Bay (Teller 1987). Located within this basin, the LIS acted to impede northward drainage, at times causing waters draining from surrounding regions to pool against the ice, forming proglacial lakes. Although many of these lakes were relatively small and short-lived, the largest, Lake Agassiz, was a major feature of late-glacial North America for most of its 5000 calendar year existence (e.g., Upham 1895; Elson 1967; Teller 1987) (Fig. 1). Glacio-isostatic rebound and changing ice-sheet configurations caused the size of Lake Agassiz to vary considerably during its history (e.g., Elson 1967; Teller 1985; Leverington et al. 2000, 2002*a*; Teller and Leverington, in preparation[2]), and numerous catastrophic releases of water occurred when lake levels dropped after lower outlets were deglaciated (e.g., Teller and Thorleifson 1983; Teller 1985; Leverington et al. 2002*a*). Lake Agassiz overflows and outbursts were important influences on the rivers and lakes that received them (e.g., Clayton 1983; Teller and Thorleifson 1983; Teller 1985, 1987, 1990*a*; Teller and Mahnic 1988; Lewis et al. 1994), and both outbursts and major reroutings of overflow from Lake Agassiz may have influenced the North Atlantic ocean–climate system (e.g., Broecker et al. 1989; Teller 1990*b*; Barber et al. 1999; Clark et al. 2001; Teller et al. 2002; Fisher et al. 2002).

The history of Lake Agassiz, which extended from about 11 700 to 7700 ^{14}C years BP, has been divided into five major phases: Lockhart, Moorhead, Emerson, Nipigon, and Ojibway (Fenton et al. 1983; Teller and Thorleifson 1983) (Fig. 2). During the Lockhart Phase (about 11 700 to 10 800 ^{14}C years BP) (Fenton et al. 1983; Fisher 2003), drainage was through the lake's southern outlet to the Gulf of Mexico, via the Minnesota and Mississippi river valleys (Elson 1967) (Fig. 1, outlet S). The Lockhart Phase was terminated when the Kaministikwia route to Lake Superior was deglaciated, causing a rapid drop in lake level and the abandonment of the southern outlet (e.g., Fenton et al. 1983; Teller and Thorleifson 1983) (Fig. 1, outlet K). During the Moorhead Phase, Lake Agassiz gradually expanded and transgressed southward due to a combination of differential glacio-isostatic rebound and a readvance of the LIS across drainage routes to the east (Elson 1967; Teller and Thorleifson 1983; Thorleifson 1996; Teller 2002). By the end of the Moorhead Phase, the southward-transgressing waters of Lake Agassiz reached the southern outlet for a brief time (Fig. 2), and outflow was once again south to the Gulf of Mexico (Thorleifson 1996; Fisher and Souch 1998; Teller 2001). During the Emerson Phase (about 10 100 to 9400 ^{14}C years BP), Lake Agassiz drainage was mainly through the deglaciated northwestern outlet (the Clearwater Spillway) to the Arctic Ocean via the Mackenzie River valley (Smith and Fisher 1993; Fisher and Smith 1994; Fisher and Souch 1998; Thorleifson 1996; Teller 2001) (Fig. 1, outlet NW; Fig. 2).

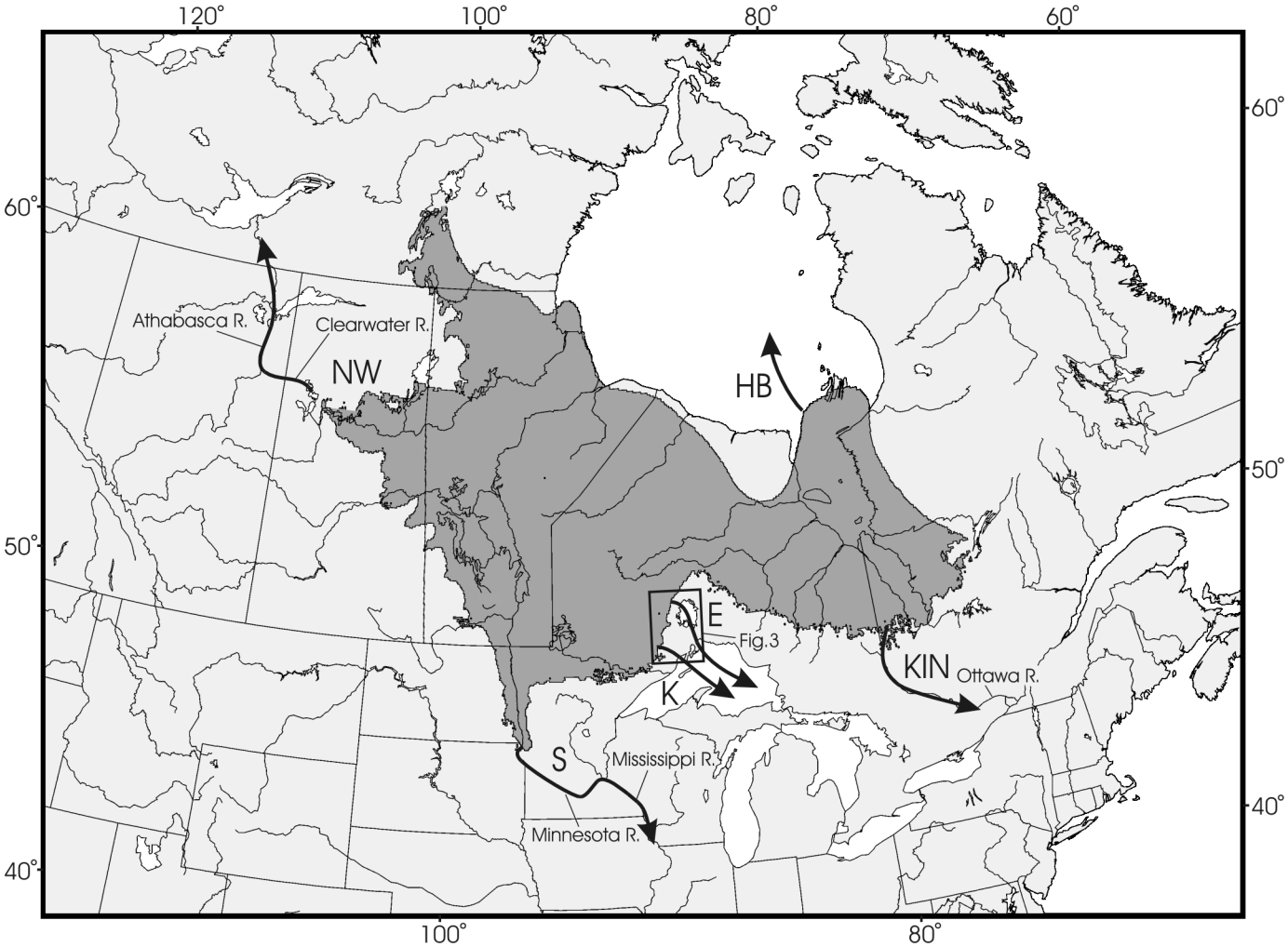
By about 9400 ^{14}C years BP, both the southern and northwestern outlets had been abandoned (Fig. 2), and for the next ~1400 ^{14}C years drainage was east through progressively lower and more northerly outlets to the Nipigon basin (defining the Nipigon Phase) (Elson 1967; Zoltai 1967; Thorleifson 1983, 1996; Teller and Thorleifson 1983; Fisher 2003) (Fig. 1, outlet E). Lake Agassiz gradually shifted northward during this phase, as it followed the receding southern margin of the LIS. At the beginning of the Ojibway Phase (about 8000 ^{14}C years BP), Lake Agassiz merged with glacial Lake Ojibway to the east (e.g., Hardy 1977; Vincent and Hardy 1979; Teller and Thorleifson 1983; Veillette 1994), forming a water body that extended from northern Manitoba to western Quebec. Associated with this merger was the abandonment of the outlets to the Nipigon basin, and the southeastward drainage of lake waters through the Angliers outlet (and, later, the nearby Kinojévis outlet) to the Ottawa River (Hardy 1977; Vincent and Hardy 1977, 1979; Veillette 1994) (Fig. 1, outlet KIN). By the end of the Ojibway Phase, Lake Agassiz–Ojibway extended as much as 1500 km along the southern margin of the LIS. At about 7700 ^{14}C years BP (Barber et al. 1999), the stagnant remains of the confining ice margin were breached, causing the lake to catastrophically drain northward into the Tyrrell Sea (Hudson Bay) (Hardy 1977; Vincent and Hardy 1979; Klassen 1983; Dredge 1983; Veillette 1994; Barber et al. 1999; Leverington et al. 2002*a*; Teller et al. 2002; Clarke et al. 2003) (Fig. 1, HB). By the end of the 5000 calendar year existence of Lake Agassiz, its waters had covered a total surface area of 1.5 million km^2.

The eastern outlets to the Nipigon basin

The location and form of routes of overflow from Lake Agassiz were primarily controlled by two factors: (*i*) the position of the LIS; and (*ii*) terrain morphology, which was

[2] Glacial Lake Agassiz: A 5000-year history of change and its relationship to the isotopic record of Greenland. In Preparation.

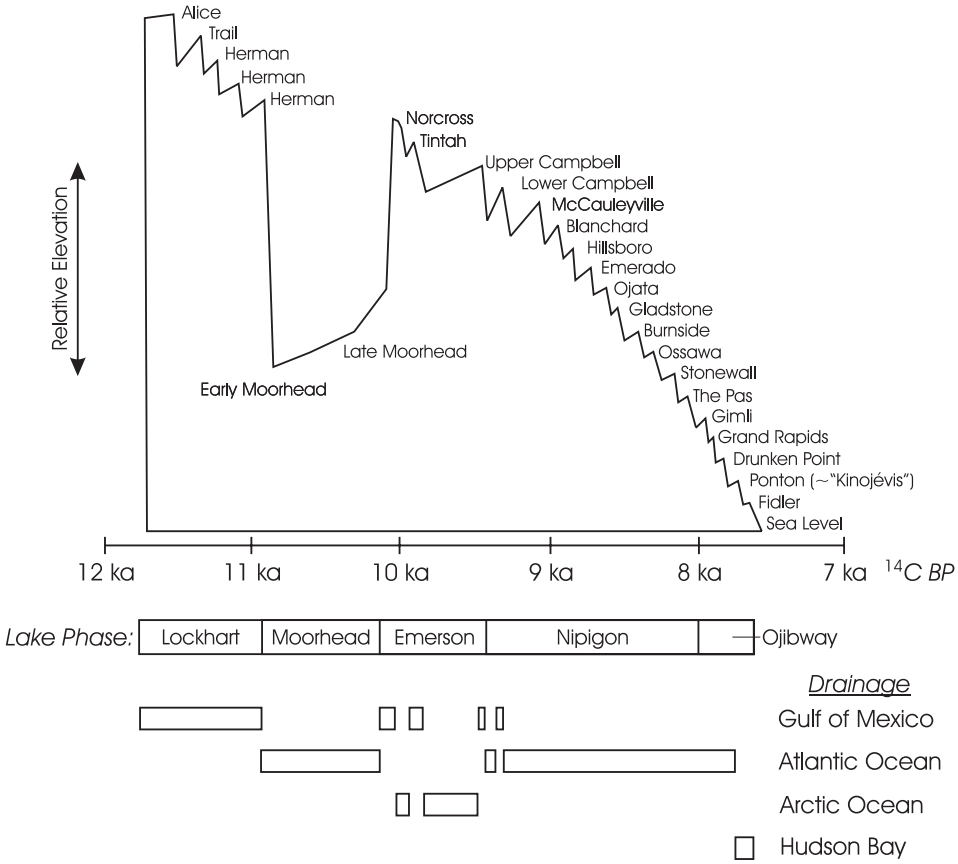
Fig. 1. Map showing the 1.5 million km^2 total area that Lake Agassiz occupied over its 5000 calendar-year history (shaded); the lake gradually shifted from south to north, following the retreating southern margin of the LIS, with the earliest lake stages confined to the southernmost portion of the indicated area and the final stages occupying the lowlands south of modern Hudson Bay. Primary routes of overflow are labeled as follows: E, region of eastern outlet systems to the Superior basin via the Nipigon basin, shown in Fig. 3; HB, general outburst direction of the final release of Lake Agassiz waters into the Tyrrell Sea (modern Hudson Bay); K, Kaministikwia route to the Superior basin; KIN, Angliers and Kinojévis outlets to the St. Lawrence River valley via the Ottawa River; NW, northwestern outlet to the Arctic Ocean via the Clearwater and Mackenzie river valleys; S, southern outlet to the Gulf of Mexico via the Minnesota and Mississippi river valleys.



itself influenced over time by dynamic processes such as fluvial erosion and differential glacio-isostatic rebound. During the Nipigon Phase, drainage from Lake Agassiz was routed through increasingly northern (and lower) outlets that crossed the Continental Divide in northwestern Ontario, carrying outflow eastward into the Nipigon and Great Lakes basins, and ultimately into the Atlantic Ocean through the St. Lawrence River valley (Elson 1967; Zoltai 1967; Clayton 1983; Teller 1985) (Fig. 1, 3). Most drainage paths of the eastern outlet complexes have been recognized through extrapolation of Lake Agassiz strandlines to cols on the drainage divide (Thorleifson 1983; Teller and Thorleifson 1983). Although the eastern outlet overflow routes are today mainly occupied by streams and lakes, widespread coarse sand units and extensive cobble and boulder lags that extend across the floors of some of these valleys attest to their past history as channels for high-volume flows from Lake Agassiz (e.g., Zoltai 1965*a*, 1965*b*, 1967; Thorleifson 1983; Teller and Thorleifson 1983; Schlosser 1983; Lemoine and Teller 1995).

The recognized outlets into the Nipigon basin have been arbitrarily divided into five main channel complexes: from south to north, the Kaiashk, Kopka, Pillar, Armstrong, and Pikitigushi (Zoltai 1965*a*; Thorleifson 1983; Teller and Thorleifson 1983, 1987) (Fig. 3). The topography of the region containing these channel complexes is mainly bedrock controlled (Zoltai 1965*a*). Archean rocks are exposed in the area west of the region's drainage divide, and the associated relief is generally subdued, rarely exceeding 30 m (Thorleifson 1983; Teller and Thorleifson 1983). Channels crossing the divide are relatively shallow and poorly defined in the area immediately east of the drainage divide. Farther to the east of the divide, where Proterozoic volcanic and sedimentary rocks overlie Archean materials, many channels merge and become deeper, with Proterozoic diabase units commonly forming mesas and

Fig. 2. Schematic depiction of Lake Agassiz lake-level fluctuations as a function of time (after Thorleifson 1996; Teller 2001). Routing of overflow of Lake Agassiz waters is indicated, and both stage and phase names for the lake are shown.

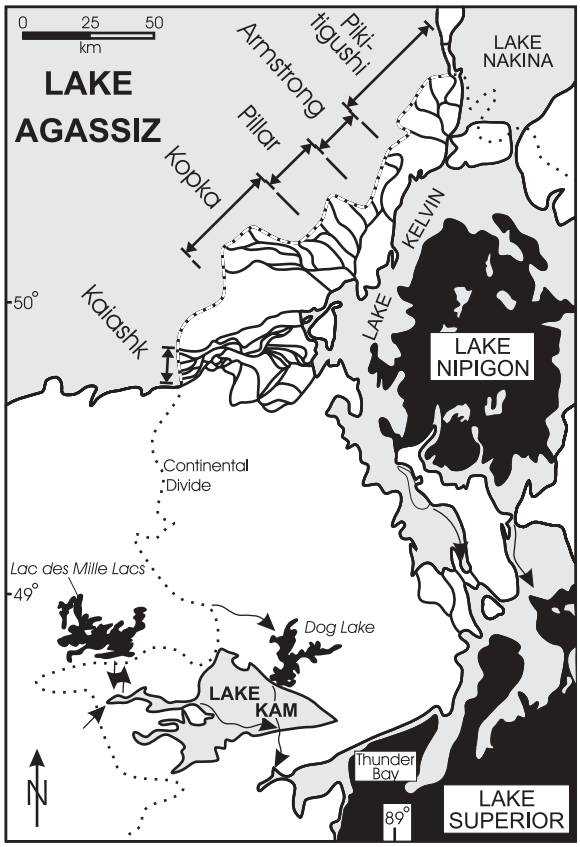


cuestas in between them with a relief that typically exceeds 100 m and can be as much as 300 m (Thorleifson 1983; Teller and Thorleifson 1983). The morphologies of the eastern-outlet drainage routes were in many cases strongly influenced by the dichotomy in near-surface bedrock geology: near the divide, overflow routes typically consist of anastomosing channels shallowly incised into Archean granite, whereas closer to the Nipigon basin these channels converge and can be incised 50 to >100 m into Proterozoic diabase units, in places forming relatively narrow channels with near-vertical walls, in some cases following faults and other lines of structural weakness (Teller and Thorleifson 1983). Associated with some eastern outlet channels are 50–100 m deep plunge basins and extensive blankets of large (>0.5 m) rounded boulders (Teller and Thorleifson 1983). Some channels are associated with deltaic or subaqueous fan deposits where they are interpreted to have emptied into the Nipigon basin (e.g., Zoltai 1967; Teller and Thorleifson 1983). Today, channels from the divide to Lake Nipigon have overall gradients of up to about 7 m per kilometre (Teller and Thorleifson 1983).

Varved clay deposits, in places covered by sand units, are distributed across a number of regions surrounding modern Lake Nipigon, including most notably the areas to its north and northeast (Zoltai 1965*a*, 1965*b*; Thorleifson and Kristjansson 1993; Lemoine and Teller 1995) (Fig. 4). To the west of Lake Nipigon, the varved clay is restricted to a narrow coastal strip and to river valleys (Zoltai 1965*a*; Lemoine and Teller 1995). The varved clay deposits proximal to Lake Nipigon are interpreted to have been deposited in Lake Kelvin during the Holocene (Lemoine and Teller 1995). Extensive sand and coarse gravel deposits occur in the Lake Nipigon basin, and those found to the west of modern Lake Nipigon (Fig. 4) have been interpreted to be related to Lake Agassiz overflow and subsequent reworking in a glaciolacustrine environment (e.g., Zoltai 1965*a*; Lemoine and Teller 1995). Large interlobate and end moraines have been identified in the region of the eastern outlets (e.g., Zoltai 1965*a*; Dyke and Prest 1986) (Fig. 4). Numerous minor moraines are distributed through much of the region (Fig. 4) and are oriented at right angles to the latest direction of ice flow indicated by local striae and eskers (Zoltai 1965*a*). The deglaciation and opening of each new outlet into the Nipigon basin may have been accompanied by a rapid drop in lake level and a corresponding catastrophic release of water from Lake Agassiz (Teller and Thorleifson 1983, 1987); previous studies have shown that the largest of these releases may have had a volume of more than 7000 km^3 (Leverington et al. 2000, 2002*a*; see also Teller and Thorleifson 1987). Although these outbursts, as well as the sustained levels of overflow that followed them, must have had a major impact on the evolution of the morphology of the eastern channels, it is not yet clear to what extent events prior to those of the most recent deglaciation influenced the formation and evolution of these channels.

Flow from Lake Agassiz would have been directed southward from Lake Kelvin to the Superior basin through a separate

Fig. 3. The eastern outlets of Lake Agassiz (after Teller and Thorleifson 1983). The locations of the five main eastern outlet systems (from south to north: Kaiashk, Kopka, Pillar, Armstrong, and Pikitigushi), which extended eastward from the Continental Divide (dotted line), are shown. The approximate extents of glacial lakes Kelvin, Nakina, and Kam are also given. Major modern water bodies are shown in black.



southern complex of outlets (Fig. 3) (Teller and Thorleifson 1983; Teller and Mahnic 1988). These outlets consist of channels with widths of up to several kilometres and are typically bounded by vertical diabase walls with relief of 50–200 m.

Topographic models of the eastern outlets

Methodology

The paleotopography of a region affected by differential glacio-isostatic rebound can be determined by establishing the magnitude of rebound across that region and subtracting it from modern elevations (Mann et al. 1999; Leverington et al. 2002*b*). The magnitude of rebound varies both spatially and temporally and is often established in a region by measuring the elevations of raised beaches formed at a particular time of interest and in association with an extensive body of water (e.g., Andrews 1970). Isobases (contours of equal isostatic rebound) can be drawn from the elevations of raised beaches and can be used to define the regional rebound (or *rebound surface*) since the beaches formed. Databases of paleotopography generated by subtracting rebound data from modern elevations can be used for the quantitative characterization of past terrain morphology and surface processes (Lambeck 1996; Mann et al. 1999; Leverington et al. 2000, 2002*a*, 2002*b*; Teller et al. 2002; Schaetzl et al. 2002).

In this research, databases of paleotopography were generated for the eastern outlet region by subtracting rasterized (gridded) rebound surfaces from a database of modern elevations for each of 11 stages of Lake Agassiz that together span the lake's Nipigon Phase, as well as the stage that immediately preceded and the one that followed this phase. The grid spacing utilized for the topographic reconstructions was 1/4800 of a degree, or about 15 m in the east–west direction and 24 m in the north–south direction. The database of modern elevations for the eastern outlet region (Fig. 5) was generated through interpolation from modern topographic contours and associated stream vectors extracted from 35 digital National Topographic System (NTS) 1 : 50 000 scale maps (Centre for Topographic Information 2002) using the TOPOGRID algorithm for generating hydrologically enhanced models (Environmental Systems Research Institute 2001; see also Hutchinson 1988, 1989). The rebound surfaces used in this research were interpolated from the regional isobases and associated rebound curves of Thorleifson (1996) (modified after Teller and Thorleifson 1983) using the triangulated irregular network (TIN) algorithm (Peuker et al. 1978); isobase values were expressed in metres above modern sea level. For each lake stage, topographically determined drainage properties in the area of the drainage divide were determined using the ArcGIS GRID application and the ArcGIS Hydrology Modeling tool (Environmental Systems Research Institute 2001).

Models of the eastern outlet region

Figures 6*a*–6*m* are paleotopographic maps of the northern region of the Nipigon basin and the area of the drainage divide separating it from the Lake Agassiz basin (see Table 1 for names of modern geographic features). Included are the 11 recognized stages of the Nipigon Phase of Lake Agassiz from the Lower Campbell stage to the The Pas stage (Fig. 2), as well as the stages that immediately preceded (Upper Campbell stage) and followed (Gimli stage) the Nipigon Phase. If the preserved Lake Agassiz beach sediments to the west of the study area represent transgressive strandlines for stages that were associated with relatively stable outlet configurations (with shoreline sediments being stranded at the transgressive maximums of these lake stages just before lower outlets were opened; Teller 2001), the paleotopographic models approximately represent the topography and lake level associated with each respective lake stage immediately prior to the termination of the stage.

In each map, elevations are given with respect to the named lake level, represented within the Lake Agassiz basin by a strandline, with elevations above the level of Lake Agassiz given in shades of green, elevations between the levels of lakes Agassiz and Kelvin given in shades of red, and elevations below the level of Lake Kelvin given both in shades of blue (for Lake Kelvin itself) and red (for non-Kelvin areas, if present in this elevation range). Where ice-free, the red–green contacts west of the outlet divide represent the shoreline of Lake Agassiz.

The levels of Lake Kelvin during the Nipigon Phase are uncertain. For the purposes of this study, lake levels were estimated by assuming that the location of the lake's southern

Fig. 4. Map of eastern outlet study area, showing the positions and extents of major interlobate and end moraines (Zoltai 1965*b*; Dyke and Prest 1986) and selected surficial sedimentary units (simplified after Zoltai 1965*b*). The orientations of minor moraines are indicated (simplified after Zoltai 1965*b*), as are the positions of major modern topographic divides (after Canada Centre for Remote Sensing 1994). Major moraines are labeled as follows: a, Kaiashk; b, Nipigon; c, Crescent; d, Onaman; e, Sioux Lookout. Local concentrations of cobbles and boulders in valleys located between the Continental Divide and modern Lake Nipigon (e.g., Thorleifson 1983; Teller and Thorleifson 1983; Schlosser 1983) are not shown. Boxes defined by lines of longitude and latitude match the extents of corresponding 1 : 50 000 scale National Topographic System (NTS) map sheets.

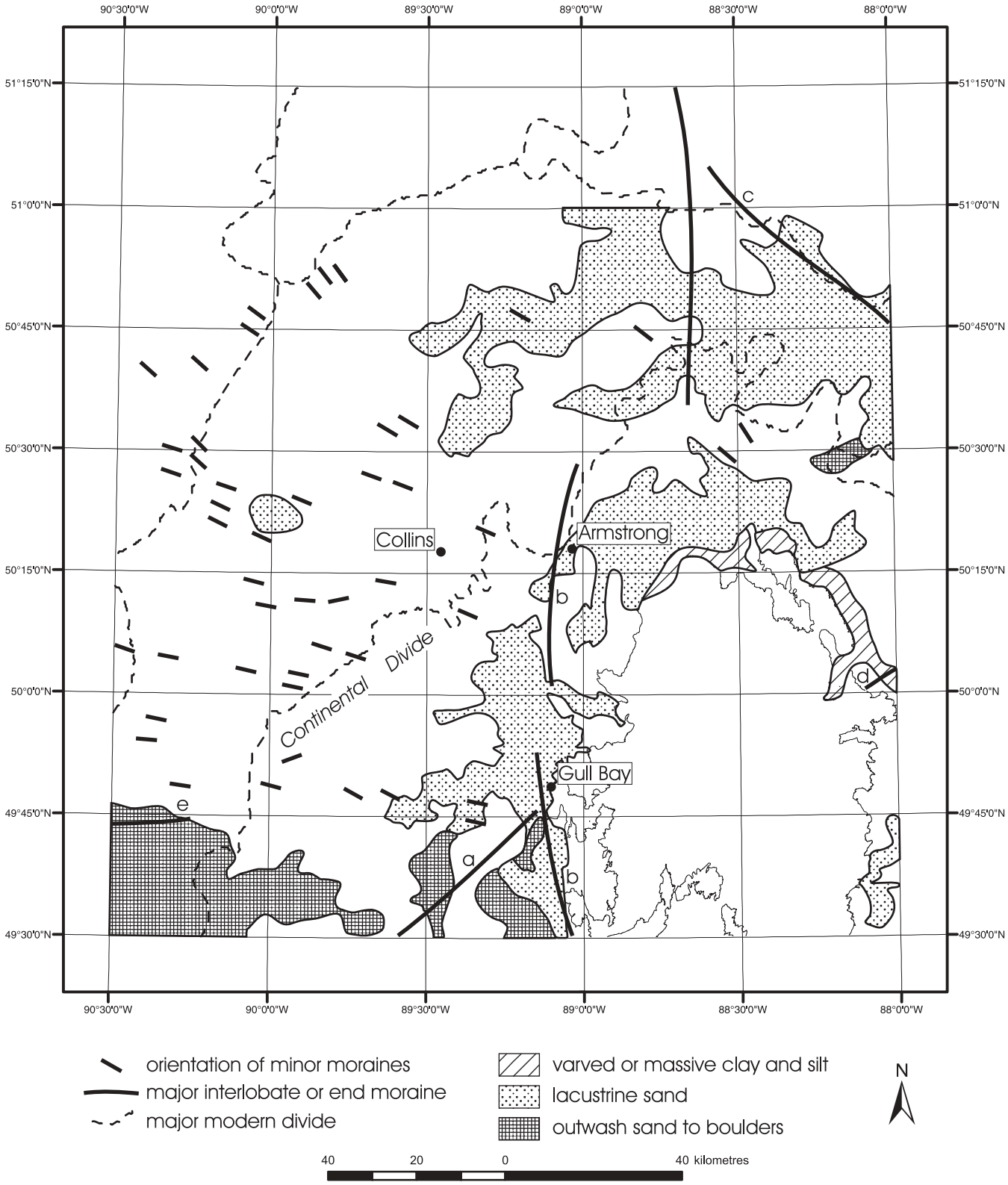
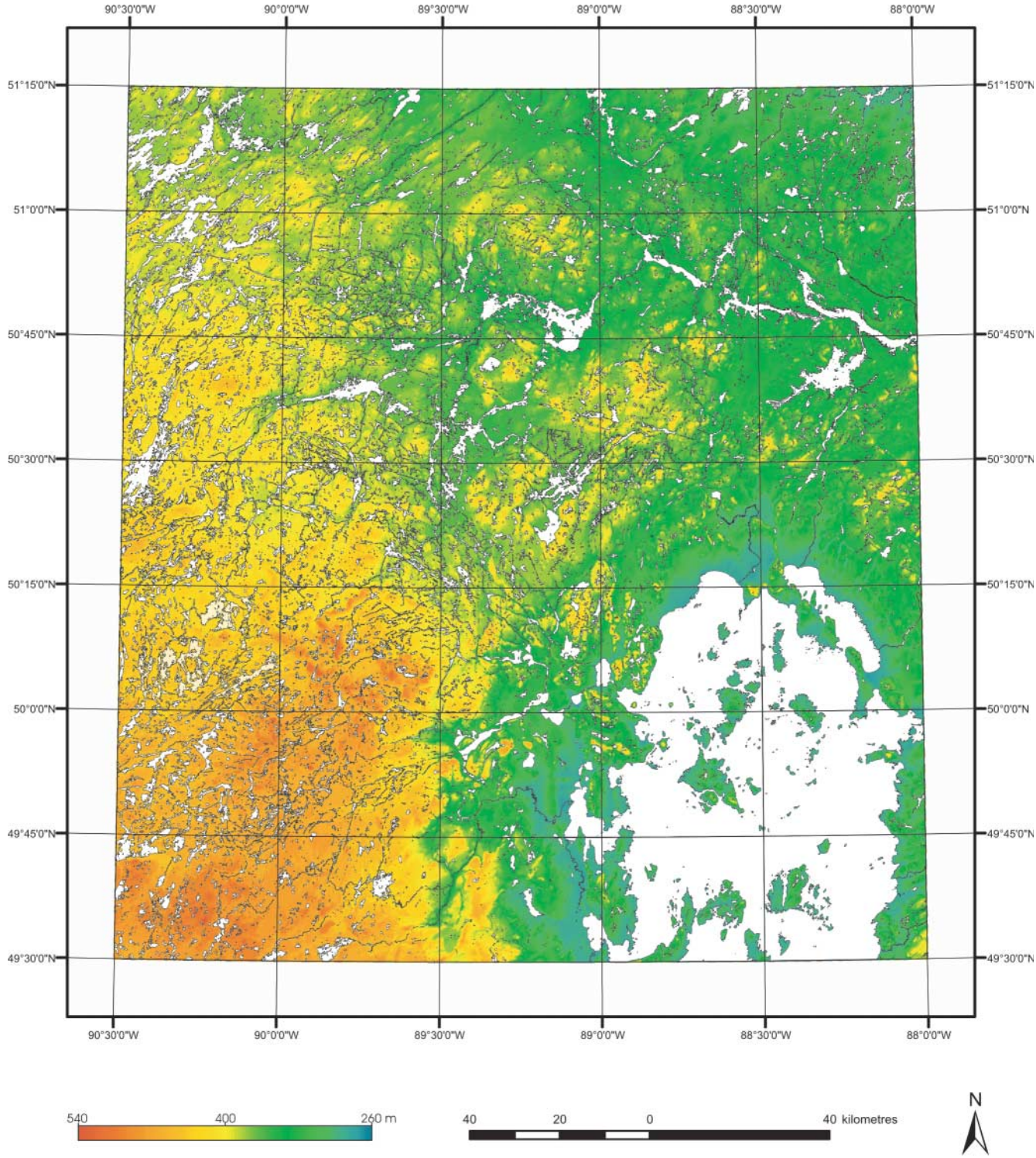


Fig. 5. Map of modern topography for the eastern outlet study area, generated through spatial interpolation from 1 : 50 000 scale contour and drainage vectors derived from 35 NTS digital maps (Centre for Topographic Information 2002). Modern water bodies are given in white. Map extent is identical to that of Fig. 4. Boxes defined by lines of longitude and latitude match the extents of corresponding 1 : 50 000 scale NTS map sheets.



drainage divide was in the region of modern Black Sturgeon Creek, which is today at an elevation of about 270 m above sea level (asl). Extensive sand and clay deposits located west of modern Lake Nipigon (e.g., Zoltai 1965*a*, 1965*b*; Thorleifson 1983; Teller and Thorleifson 1983, 1987; Teller and Mahnic 1988; Lemoine and Teller 1995) (Fig. 4) suggest that the western margins of Lake Kelvin may have extended more than 30 km west of the margins of modern Lake Nipigon. A

Fig. 6. Stage-specific topographic models of the eastern outlet region on both sides of the drainage divide separating Lake Agassiz from the basin of glacial Lake Kelvin (modern Lake Nipigon). Maps corresponding to 13 stages of Lake Agassiz are given, including 11 Nipigon Phase stages (approximately corresponding to the time range between 9400 and 8000 ^{14}C years BP) and the non-Nipigon stages that immediately preceded and followed the Nipigon Phase. Note that there is a general northeastward shift in area shown by successively younger maps (compare to modern regional map, Fig. 5). Areas of modern water bodies are given in white. Selected modern drainage routes are labeled by numbers within circles, and selected modern valleys are labeled by letters within squares (see Table 1 for names); the location of the town of Armstrong is indicated by the letter A within a triangle in Figs. 6*i* and 6*k*–6*m*. Elevations are specified with respect to the level of Lake Agassiz; elevations above the level of Lake Agassiz are given in shades of green, elevations between the levels of lakes Agassiz and Kelvin in shades of red, and elevations below the level of Lake Kelvin in shades of blue (for Lake Kelvin itself) and red (for non-Kelvin areas, if present in this elevation range). Except where ice margins are not located in the mapped area, each map uses two broken lines to indicate positions of the northward-retreating ice margin at the beginning and end of lake drawdown. Outlet paleodivides are indicated by yellow semitransparent shapes. The major segments of eastern-outlet overflow routings are given in each map for the period of lake drawdown and are indicated by blue arrows; arrow segments are solid where flow would have been well constrained by topography and broken where flow direction is generalized due to irregular topography or pooling. Areas where significant pooling of Lake Agassiz outflow likely occurred are indicated by purple wave symbols. Boxes defined by lines of longitude and latitude match the extents of corresponding 1 : 50 000 scale NTS map sheets.

lake of such an extent, however, would have required a southern divide with a modern elevation of about 330 m asl, which is about 60 m higher than can be accounted for by modern topography. Because there is no clear evidence that the divide elevations necessary to produce a very extensive Lake Kelvin were attained during the Nipigon Phase (see Discussion section), the blue-shaded extents of Lake Kelvin shown in Fig. 6 were based on the lower (topographically determined) outlet level.

The positions of outlet paleodivides during the Nipigon Phase were a function of terrain geometry along the drainage corridor (defined by the southern margin of the LIS and the northern margin of land above the level of Lake Agassiz) that connected lakes Agassiz and Kelvin. The positions of outlet paleodivides were determined in this study through analyses of the geometry of subbasins in the paleotopographic databases and are indicated for relevant regions in Fig. 6 by yellow semitransparent shapes. Outlet paleodivides often roughly coincided with the locations of modern drainage divides, including the Continental Divide (see Fig. 4).

The major segments of eastern-outlet overflow routings are given in each map by blue arrows for the full period of lake drawdown (thus, in some cases both early and late routings are shown). Arrow segments are solid where flow would have been well constrained by topography and broken where flow direction is generalized due to irregular topography or pooling. Relatively large areas of pooling are indicated by purple wave symbols.

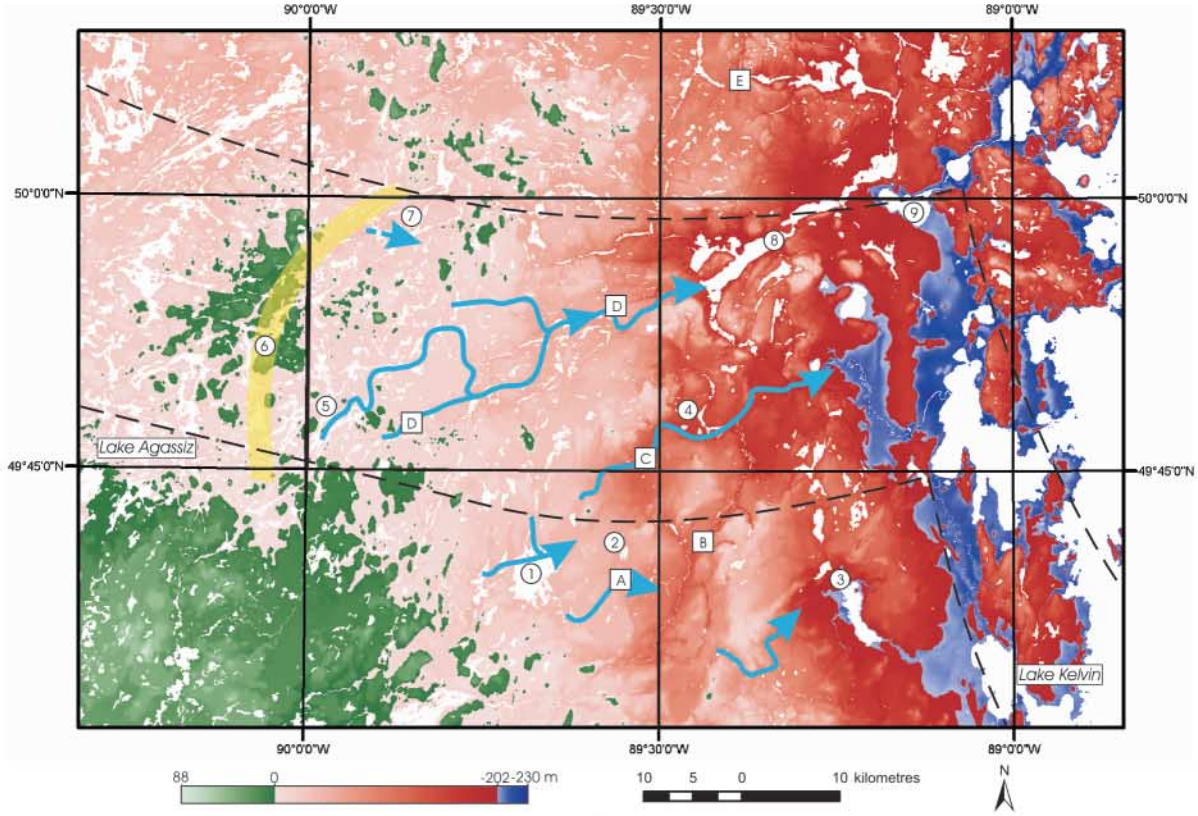
The southern margins of the LIS were constrained in this study by (*i*) the orientations of the minor moraines located north and west of modern Lake Nipigon (Fig. 4), and (*ii*) knowledge that certain outlets had to have been closed in order for specific stages of Lake Agassiz to have existed. In the paleotopographic maps, positions and orientations of the ice margin for each stage are shown by broken black lines. Figures 6*a*–6*k* each include two broken lines that indicate possible positions of the ice margin at the beginning and end of lake drawdown.

Upper Campbell stage (Fig. 6a)

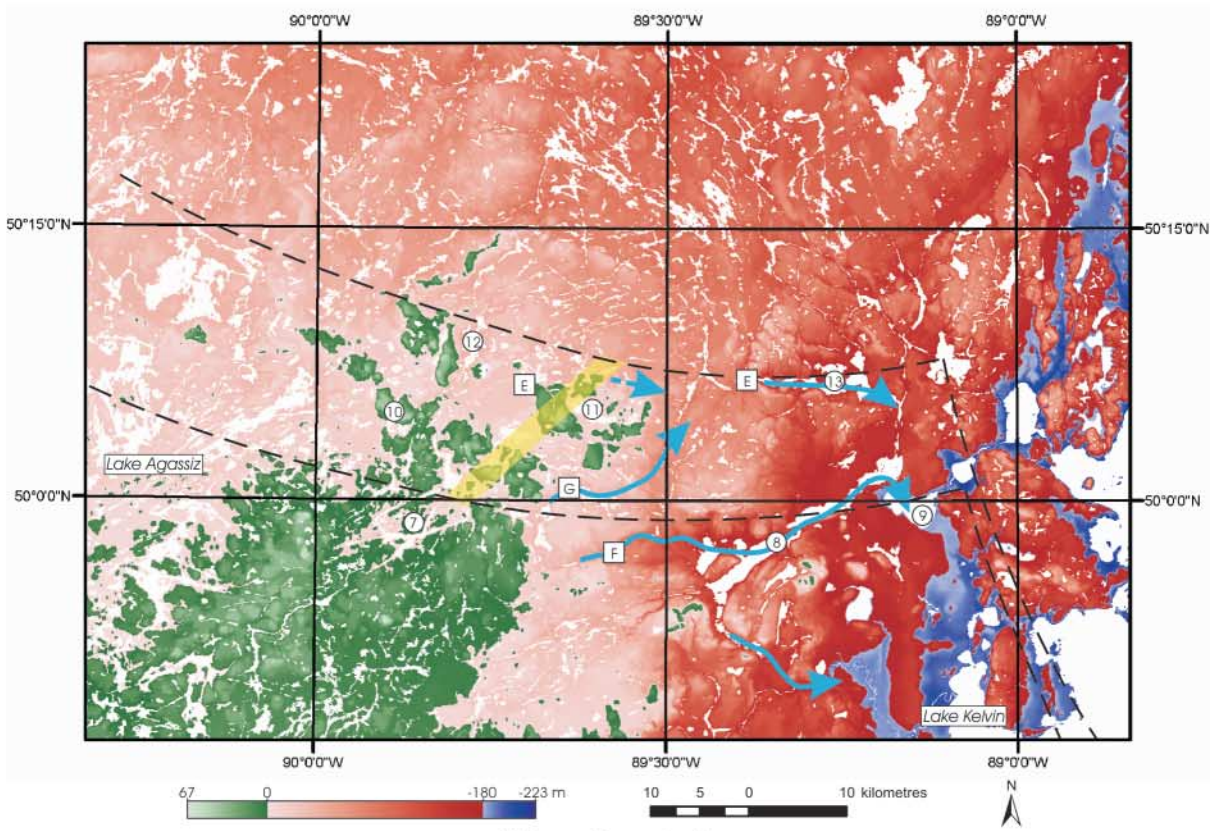
The reduction in the level of Lake Agassiz between the end of the Upper Campbell stage and the end of the subsequent Lower Campbell stage would have been about 20 m (Table 2). The initial opening of eastern drainage at the end of the Upper Campbell stage probably occurred in the area of Kashishibog Lake (5, Fig. 6*a*), the main divide feature of the Kaiashk Outlet (Fig. 3) (see also Zoltai 1965*a*; Thorleifson 1983; Teller and Thorleifson 1983, 1987). Initial Lake Agassiz overflow to Lake Kelvin would have occurred through segments of the Roaring River (A) and Gull River (B) valleys to the area east of Kabitotikwia Lake (3). As the ice retreated north, flow would likely have followed parts of the Pantagruel Creek valley (C). Subsequent flow would have followed Ottertooth Creek (D) directly from the area of Kashishibog Lake (5), reaching Lake Kelvin southeast of modern Obonga Lake (8). After a drop in lake level of ~10 m, the drainage route across the Kashishibog Lake (5) area would have closed, with drainage first occurring through the area of Siesse Lake (6) and subsequently through the Uneven Lake (7) area.

Lower Campbell stage (Fig. 6b)

During the Lower Campbell stage, eastward drainage to the Nipigon basin was temporarily halted in the eastern-outlet region (e.g., Teller 2001), and the waters of Lake Agassiz transgressed toward and ultimately drained through the lake's southern outlet (Fig. 1) until eastward drainage was again opened at the end of the Lower Campbell stage. The reduction in the level of Lake Agassiz between the end of the Lower Campbell stage and the end of the subsequent McCauleyville stage would have been about 11 m (Table 2). The initial opening of eastern drainage at the end of the Lower Campbell stage occurred in the area northeast of Uneven Lake (7, Fig. 6*b*). Although initial drainage may have been constrained by the ice margin to flow through the lower reaches of the Kaiashk System (with flow along the area of Wig Creek (F) into Lake Kelvin in an area southeast of modern Obonga Lake (8)), subsequent retreat of the ice margin would have allowed flow to the Obonga (8) and Kopka (9) lake areas along a route within the Kopka System (Thorleifson 1983; Teller and Thorleifson 1983, 1987), from Scalp Creek (G) to the lower reaches of the Kopka River valley (E). By the end of lake drawdown, the outlet divide in the area of Uneven (7), Lookout (10), and North Whalen (11) lakes would have become closed, with overflow instead being routed north of the areas of Aldridge (12) and North Whalen (11) lakes, and east along segments of the Kopka River valley (E) to the Kopka Lake (9) area.

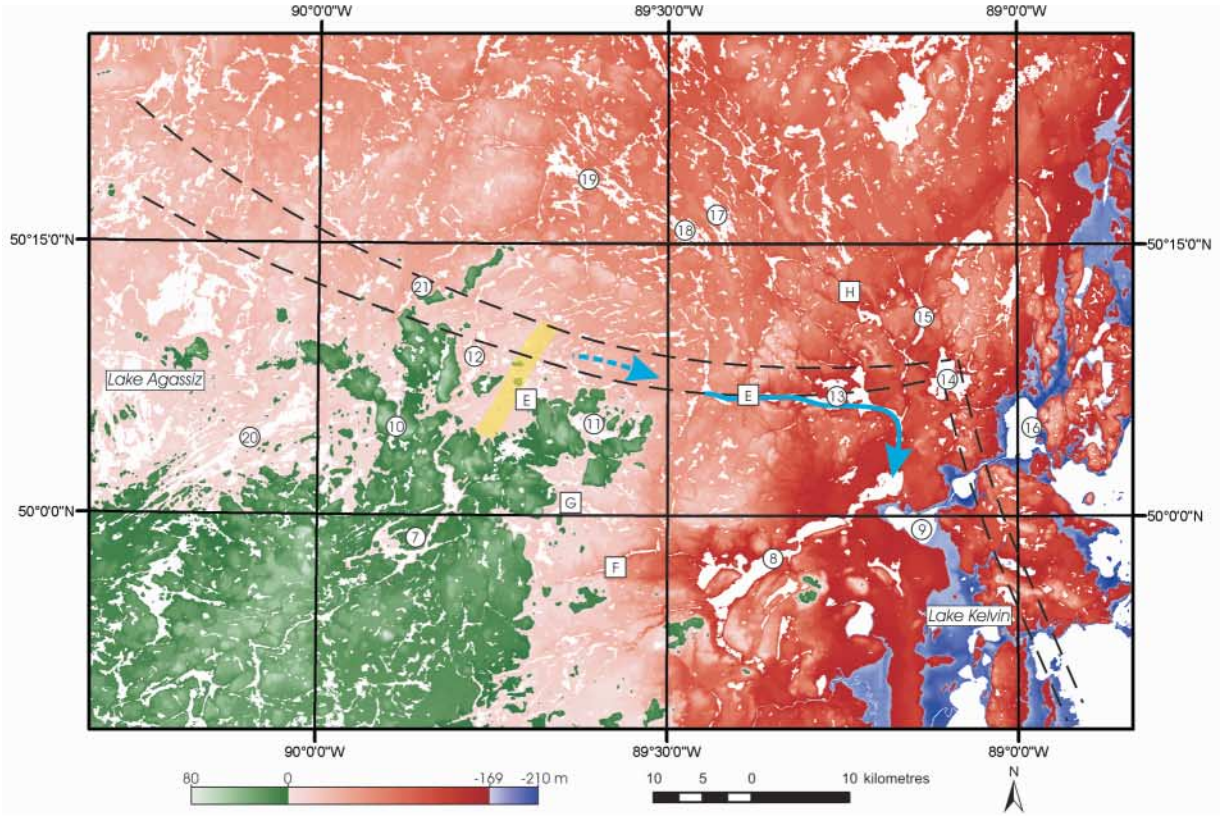


a) Upper Campbell

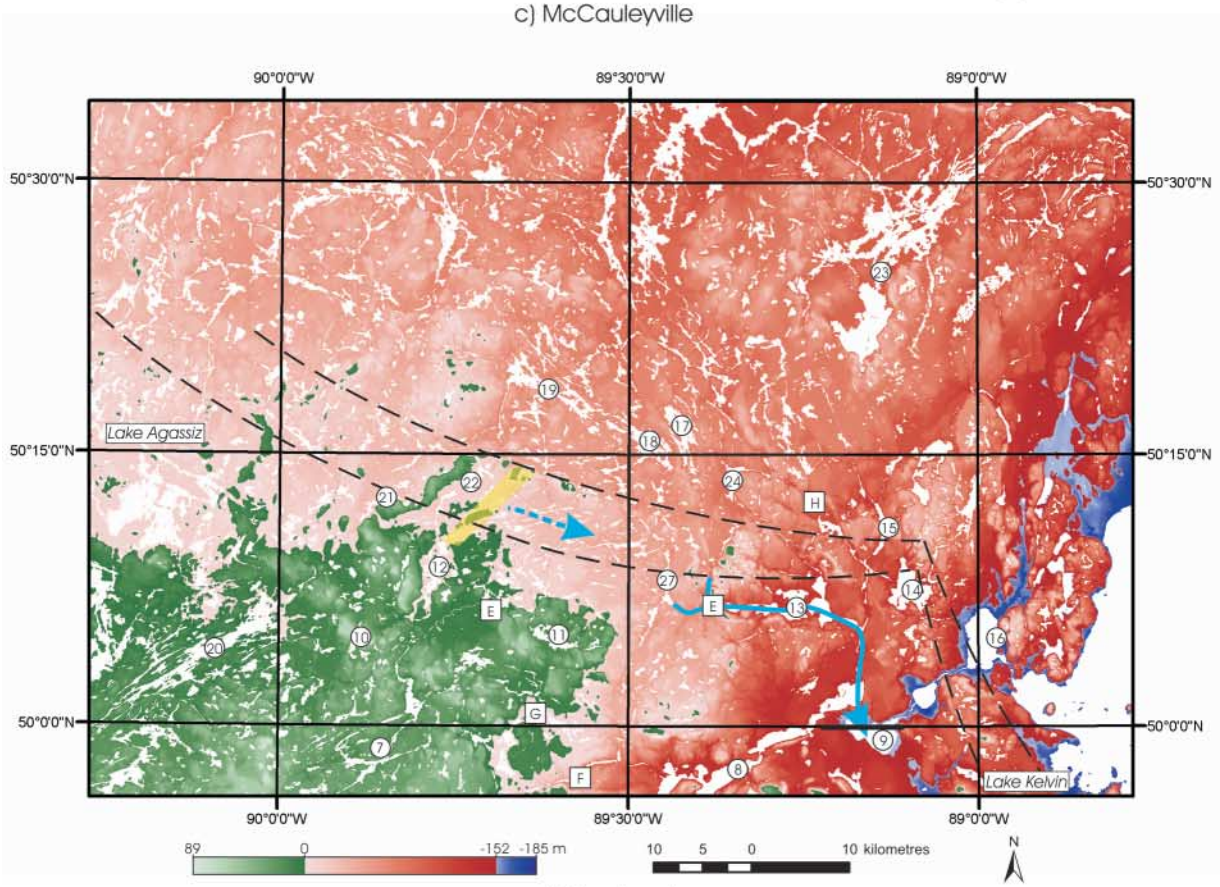


b) Lower Campbell

Fig. 6 (*continued*).

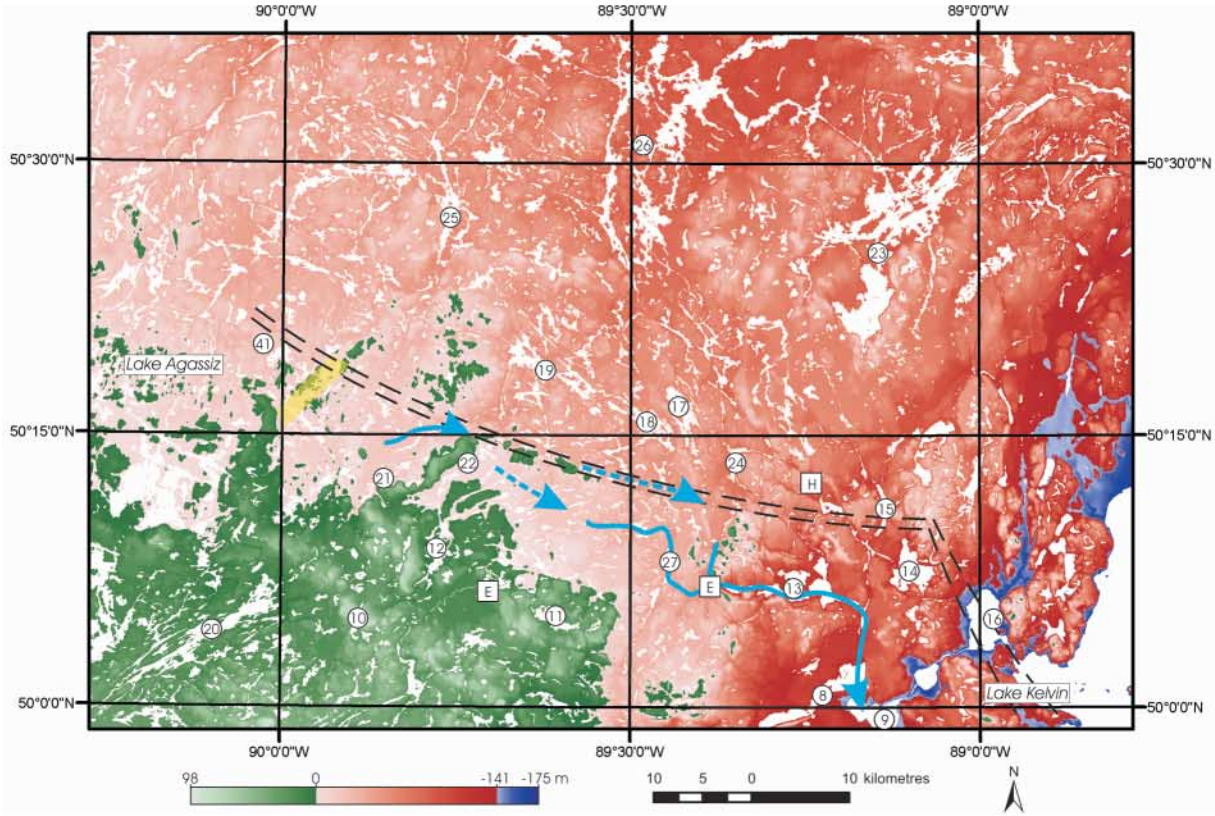


c) McCauleyville

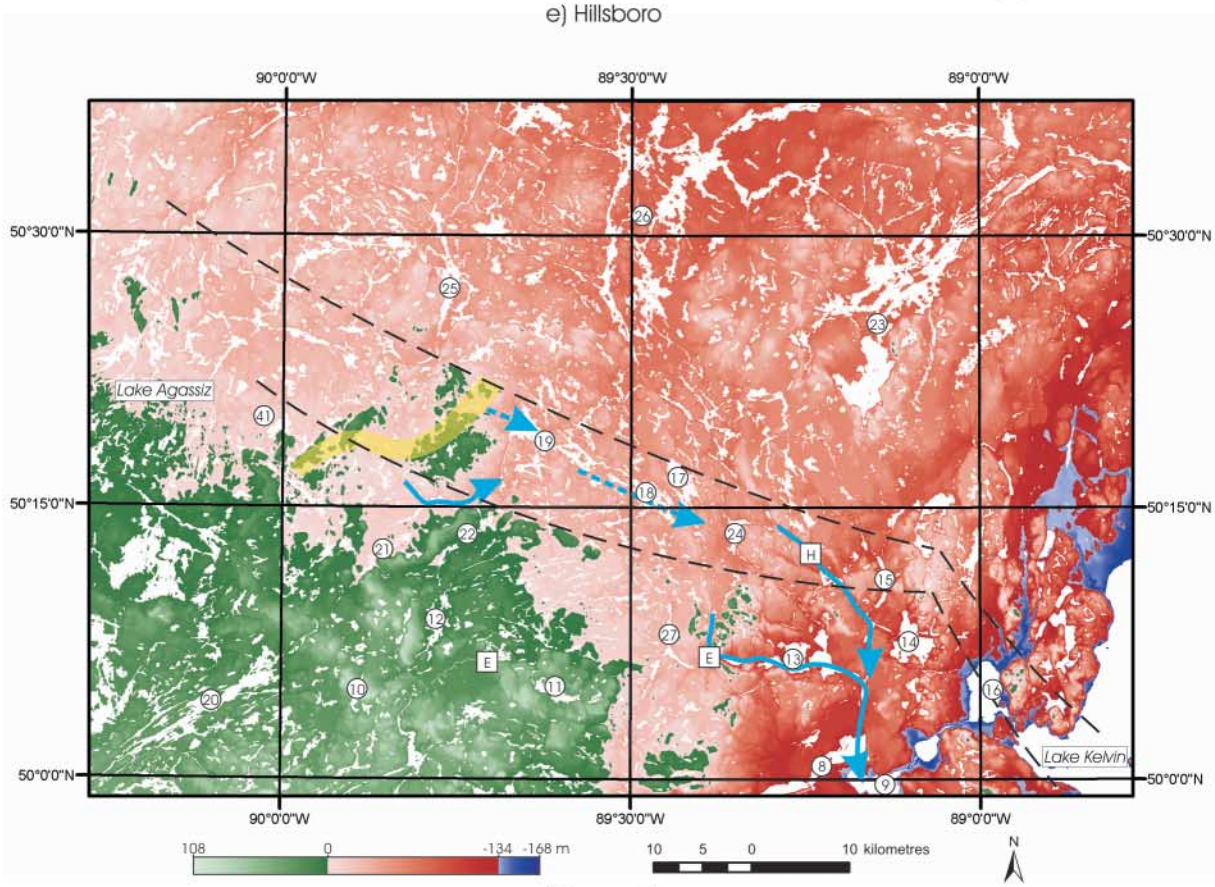


d) Blanchard

Fig. 6 (*continued*).

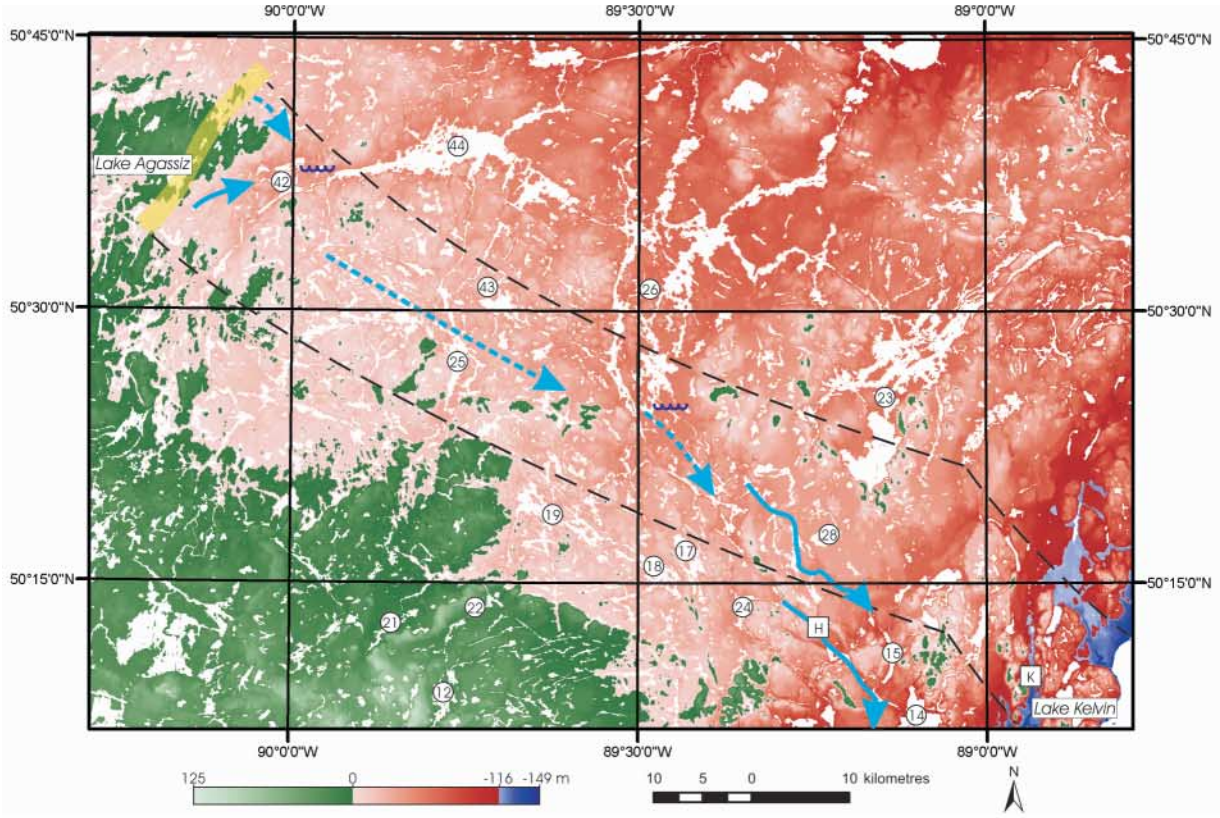


e) Hillsboro

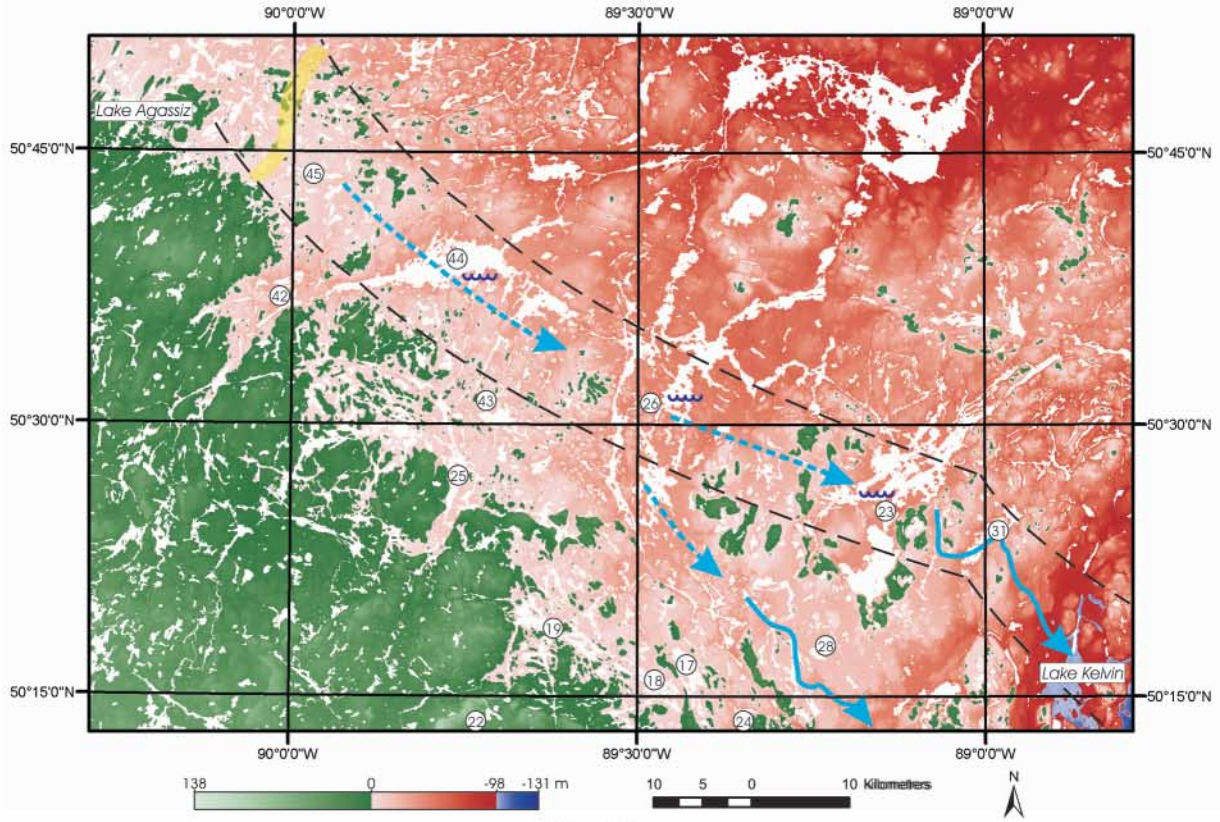


f) Emerado

Fig. 6 (*continued*).

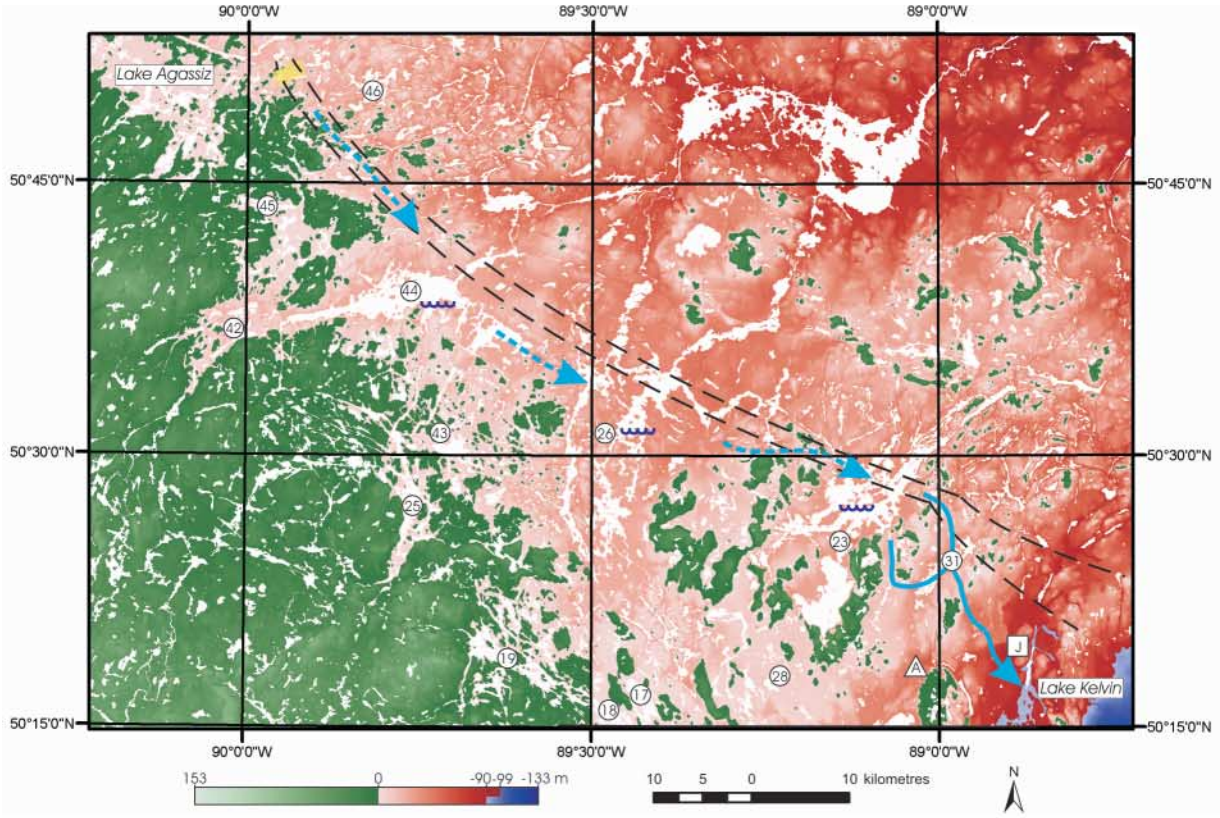


g) Ojata

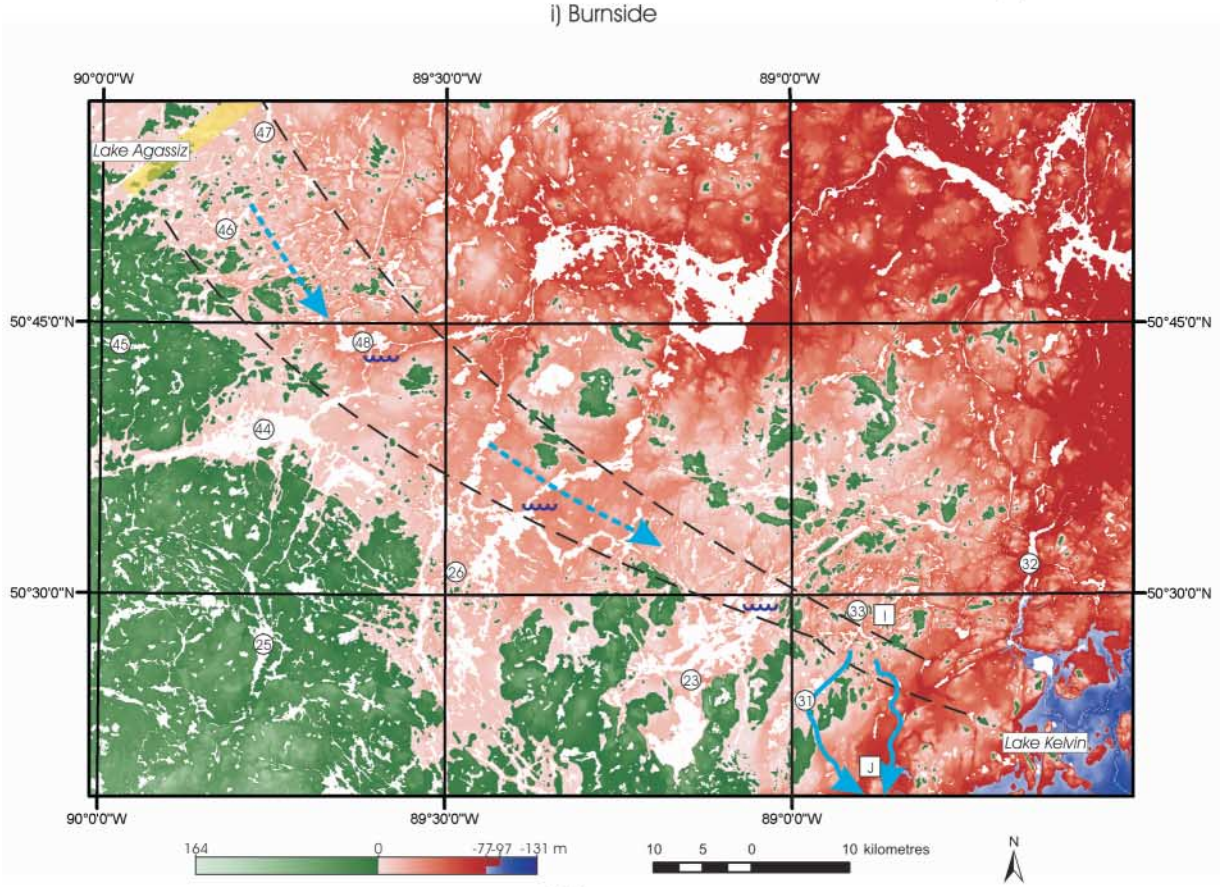


h) Gladstone

Fig. 6 (*continued*).

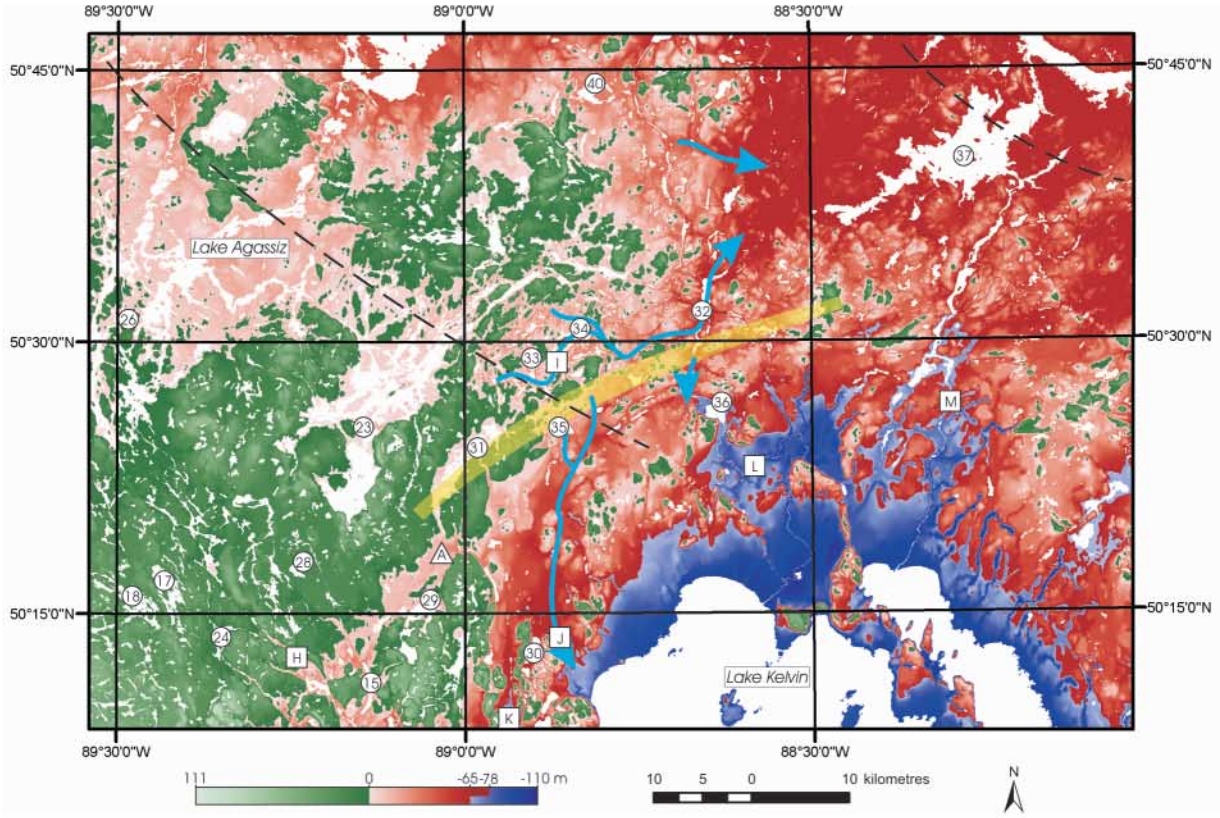


i) Burnside

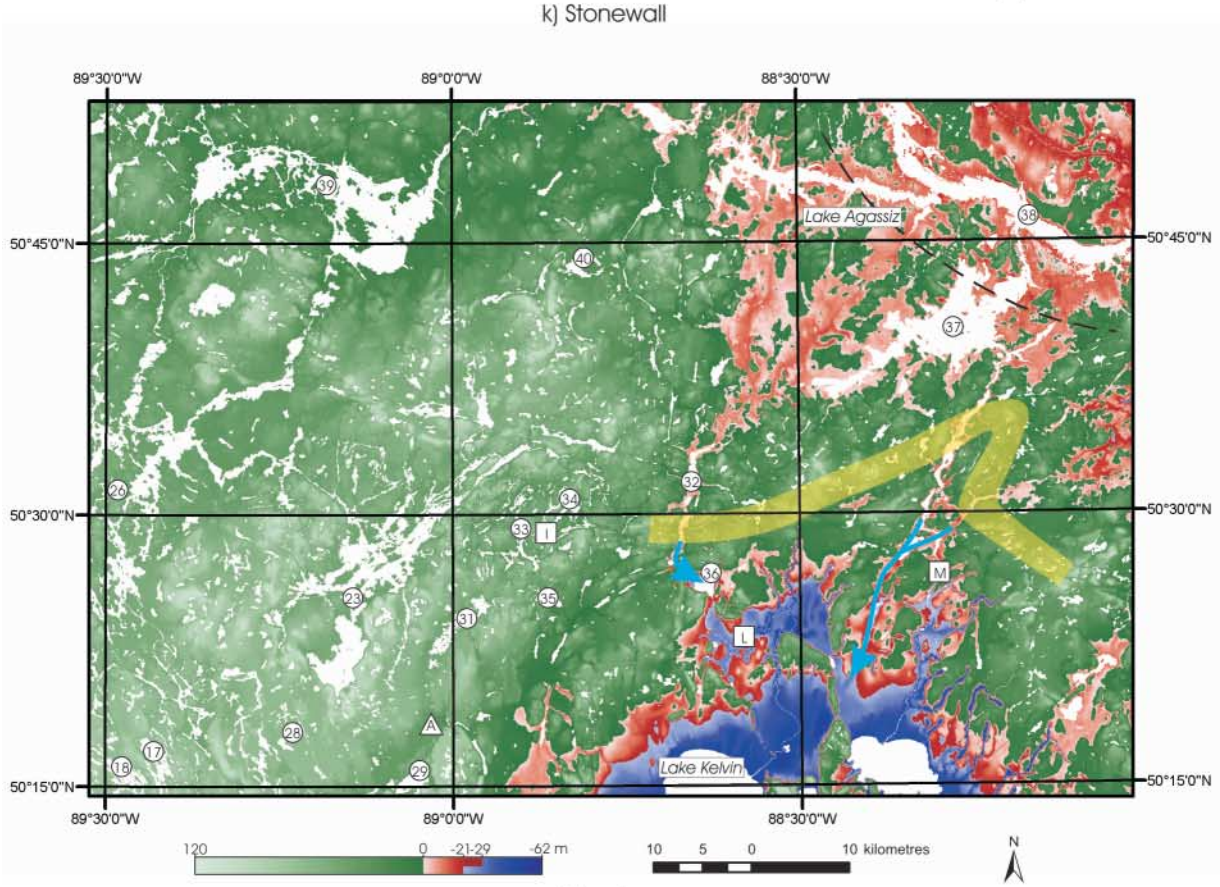


j) Ossawa

Fig. 6 (*continued*).

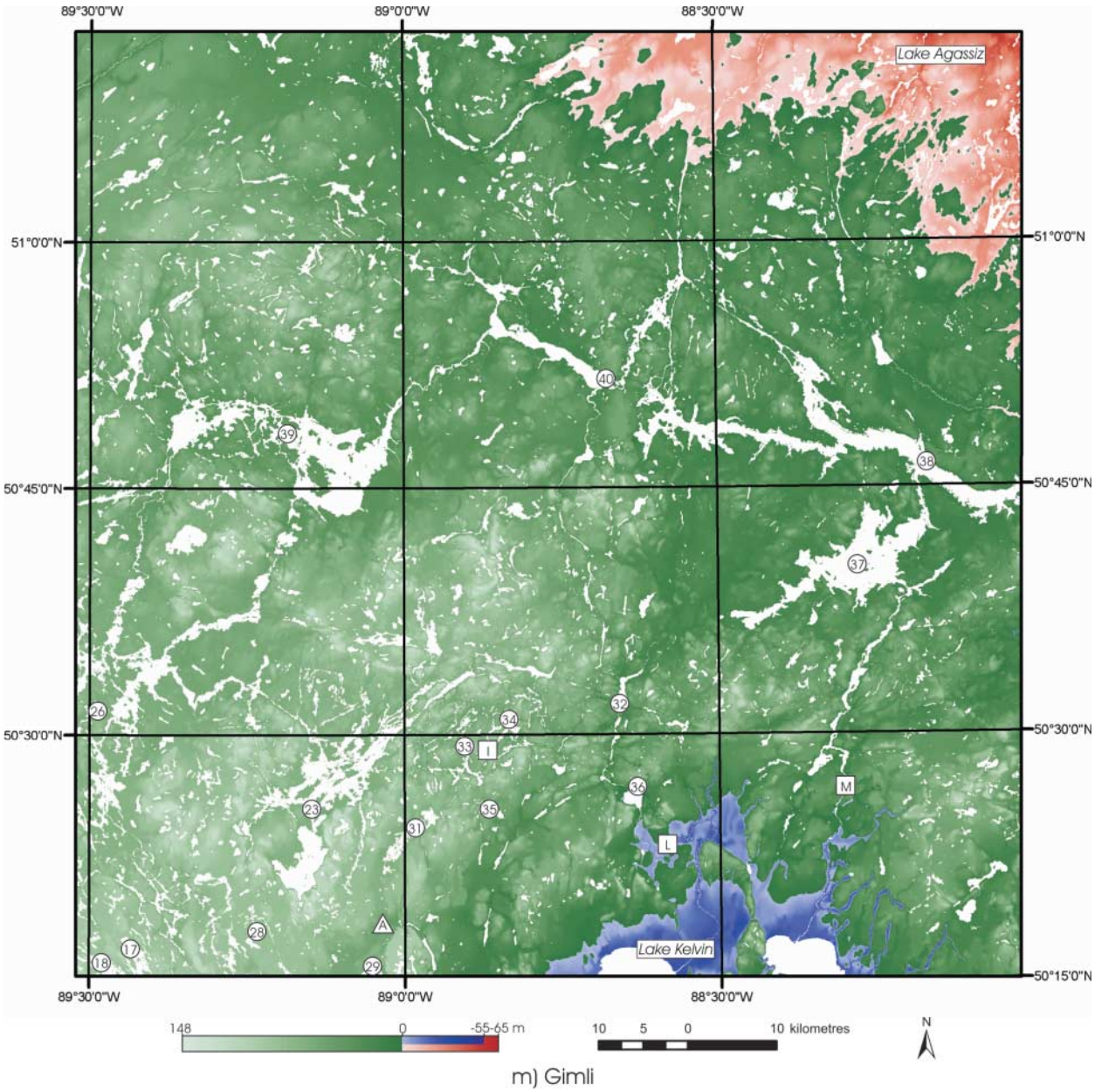


k) Stonewall



l) The Pas

Fig. 6 (*concluded*).



McCauleyville stage (Fig. 6c)

The reduction in the level of Lake Agassiz between the end of the McCauleyville stage and the end of the subsequent Blanchard stage would have been about 16 m (Table 2). Drainage during drawdown from the McCauleyville level would have involved eastward flow from the outlet divide near Aldridge Lake (12, Fig. 6*c*) to the Kopka River valley (E), with flow debouching in the area of Kopka Lake (9).

Blanchard stage (Fig. 6d)

The reduction in the level of Lake Agassiz between the end of the Blanchard stage and the end of the subsequent Hillsboro stage would have been about 10 m (Table 2). Drainage during drawdown from the Blanchard level would have involved eastward flow from the outlet divide near Beagle Lake (22, Fig. 6*d*) to the Kopka Lake (9) area via the Kopka River valley (E).

Hillsboro stage (Fig. 6e)

The reduction in the level of Lake Agassiz between the end of the Hillsboro stage and the end of the subsequent Emerado stage would have been about 8 m (Table 2). By the end of the Hillsboro stage, the outlet divide would have shifted westward to the area southeast of Mystery Lake (41, Fig. 6*e*). Drainage during the drawdown from the Hillsboro level would have involved eastward flow from the outlet divide to the Kopka Lake (9) area via segments of the Kopka River valley (E).

Emerado stage (Fig. 6f)

The reduction in the level of Lake Agassiz between the

Table 1. List of modern drainage routings and lakes identified in Fig. 6.

Map label	Drainage routing or lake
Modern river and creek valleys (labels in boxes)	
A	Roaring River
B	Gull River
C	Pantagruel Creek
D	Ottertooth Creek
E	Kopka River
F	Wig Creek + Paddon and Puddy lakes
G	Scalp Creek
H	Vale Creek
I	Big River
J	Whitesand River
K	Hoodoo Creek
L	Pikitigushi River
M	Little Jackfish River
Modern lakes (labels circled)	
1	Holinshead
2	Lighthall
3	Kabitotikwia
4	Pantagruel
5	Kashishibog
6	Siesse
7	Uneven
8	Obonga
9	Kopka
10	Lookout
11	North Whalen
12	Aldridge
13	Wigwasan
14	Waweig
15	Pillar
16	Wabinosh
17	Collins
18	Shawanabis
19	Onamakawash
20	Wapikaimaski
21	Gastmeier
22	Beagle
23	Caribou
24	Rushby
25	Granite
26	Smoothrock
27	McIntyre
28	Trail
29	Mackenzie
30	Walkover
31	Big
32	Ratte
33	D'Alton
34	Moonshine
35	Whidden
36	Pikitigushi
37	Mojikit
38	Ogoki Reservoir
39	Whitewater
40	Scallop
41	Mystery
Modern lakes (labels circled)	
42	Tew
43	Elf
44	Wabakimi
45	Lenouri
46	Burntrock
47	Webster
48	Kenoji

end of the Emerado stage and the end of the subsequent Ojata stage would have been about 18 m (Table 2). At the end of the Emerado stage, the outlet divide would have extended from the area east of Mystery Lake (41, Fig. 6*f*) to the area west of Onamakawash Lake (19). Initial drainage from the Emerado level would have involved eastward flow from the outlet divide to the Kopka Lake (9) area via segments of the Kopka River valley (E). Later drainage would have involved flow across the area of Lake Shawanabis (18) to the Vale Creek valley (H), with overflow again debouching in the Kopka Lake (9) area.

Ojata stage (Fig. 6g)

The reduction in the level of Lake Agassiz between the end of the Ojata stage and the end of the subsequent Gladstone stage would have been about 20 m (Table 2). By the end of the Ojata stage, the outlet divide would have shifted to the area west of Tew Lake (42, Fig. 6*g*). Initial drainage from the Ojata level would have involved eastward flow from the outlet divide to the Kopka Lake (9, see Emerado map, Fig. 6*f*) area via the general regions of Granite (25), Onamakawash (19), and Shawanabis (18) lakes and via Vale Creek valley (H). Later drainage would have involved flow across the general regions of Elf (43) and Smoothrock (26) lakes to a Pillar Lake (15) route to Lake Kelvin (initiating the opening of the Pillar System of Zoltai (1965*a*), Thorleifson (1983), and Teller and Thorleifson (1983, 1987)), with relatively large poolings of Lake Agassiz overflow forming in the regions of Tew (42) and Smoothrock (26) lakes.

Gladstone stage (Fig. 6h)

The reduction in the level of Lake Agassiz between the end of the Gladstone stage and the end of the subsequent Burnside stage would have been about 9 m (Table 2). Drainage from the Gladstone level would have involved eastward flow from the outlet divide, located northwest of Lenouri Lake (45, Fig. 6*h*), toward Lake Kelvin via the general regions of Wabakimi (44), Elf (43), and Smoothrock (26) lakes; Lake Agassiz overflow would have pooled to form relatively large water bodies in the first and last of these three regions. Drainage into Lake Kelvin in the area of Kopka Lake (9, see Emerado, Fig. 6*f*) would have initially occurred via a Pillar Lake (15) route, and later would have involved a route through the Big Lake (31) area, initiating the opening of the Armstrong System of Zoltai (1965*a*), Thorleifson (1983), and Teller and Thorleifson (1983, 1987).

Burnside stage (Fig. 6i)

The reduction in the level of Lake Agassiz between the

Table 2. Lake level drops that occurred after the terminations of recognized stages of the Nipigon Phase and were associated with releases of water to Lake Kelvin (based on the isobases of Thorleifson (1996) and Teller and Thorleifson (1983); see Leverington et al. (2000, 2002*a*) and Teller et al. (2002)).

Lake stage	Total lake level drop (m)	Total release (km^3)
Lower Campbell	11 (16)	2500
McCauleyville	16 (10)	3300
Blanchard	10	2500
Hillsboro	8 (7)	2000
Emerado	18	4500
Ojata	20	4400
Gladstone	9	1900
Burnside	13 (12)	2400
Ossawa	15	3100
Stonewall	58	8100

Note: Numbers in parentheses represent previous interpretations (Leverington et al. 2002*a*; Teller et al. 2002) that have been refined in this paper.

end of the Burnside stage and the end of the subsequent Ossawa stage would have been about 13 m (Table 2). Drainage from the Burnside level would have involved eastward flow from the outlet divide, located west of Burntrock Lake (46, Fig. 6*i*), toward Lake Kelvin via the general regions of Wabakimi (44), Smoothrock (26), and Caribou (23) lakes; Lake Agassiz overflow would have pooled to form relatively large bodies of water in these three regions. Drainage into Lake Kelvin would have occurred via routes through the Big Lake (31) area into the area of the Whitesand River valley (J).

Ossawa stage (Fig. 6j)

The reduction in the level of Lake Agassiz between the end of the Ossawa stage and the end of the subsequent Stonewall stage would have been about 15 m (Table 2). Drainage from the Ossawa level would have involved eastward flow from the outlet divide, located west of Webster Lake (47, Fig. 6*j*), toward Lake Kelvin via the general regions of Kenoji (48), Smoothrock (26), Caribou (23), and D'Alton (33) lakes; Lake Agassiz overflow would have pooled to form relatively large bodies of water in the first three of these lake areas. Drainage into Lake Kelvin would have occurred through either the Whitesand River valley (J) or a route involving the Big Lake (31) area.

Stonewall stage (Fig. 6k)

The reduction in the level of Lake Agassiz between the end of the Stonewall stage and the end of the subsequent The Pas stage would have been about 58 m, which is the largest drop between recognized lake stages of the Nipigon Phase (Table 2). By the end of the Stonewall stage, the outlet divide would have shifted to the area east and southeast of D'Alton Lake (33, Fig. 6*k*), and south of the area of Ratte Lake (32). Overflow at the outlet divide would have initially occurred southeast of D'Alton Lake (33), with drainage routed from the divide to Lake Kelvin via the Whitesand River valley (J). An initial reduction in lake level of about 6 m would have been associated with the closing of the Caribou Lake (23) region and the opening of overflow in the large region southeast of Scallop Lake (40), with drainage to the area of glacial Lake Nakina (Fig. 3). The level of Lake Agassiz would have dropped by about 52 m as the Lake Nakina area was flooded.

The Pas stage (Fig. 6l)

The reduction in the level of Lake Agassiz between the end of the The Pas stage and the end of the subsequent Gimli stage would have been about 18 m. By the end of the The Pas stage, part of the southern extent of Lake Agassiz would have occupied the glacial Lake Nakina area. Overflow to Lake Kelvin at this time would have been routed into the Pikitigushi System of Zoltai (1965*a*), Thorleifson (1983), and Teller and Thorleifson (1983, 1987), including the Pikitigushi lake (36, Fig. 6*l*) and river (L) system and the Little Jackfish River valley (M). The termination of southward drainage to Lake Kelvin at the end of the The Pas stage would have been associated with the transfer of overflow to the Ottawa River (Fig. 1), ending the Nipigon Phase of Lake Agassiz. The configuration of the strandline of the subsequent Lake Agassiz stage, the Gimli stage, is given in Fig. 6*m*.

Discussion

The reconstructions of the eastern outlet region presented in this paper (Fig. 6) provide a high-resolution framework for understanding the changing form and overflow routings of the region of the Agassiz–Nipigon drainage divide during the Nipigon Phase of Lake Agassiz (ca. 9400–8000 ^{14}C years BP). From the time of the Upper Campbell stage to the The Pas stage, the location of overflow across the drainage divide moved more than 100 km north and then east as it followed the receding southern margin of the Laurentide Ice Sheet (LIS). Lake Agassiz overflow during the Nipigon Phase was routed across numerous flow paths to the western and northern margins of glacial Lake Kelvin, with major routes including segments of the valleys of modern Kopka River, Ottertooth Creek, Vale Creek, Whitesand River, Pikitigushi River, and Little Jackfish River; these results are consistent with those of Thorleifson (1983) and Teller and Thorleifson (1987). The magnitudes of most drops in lake level from stage to stage were between about 8 and 20 m, although the largest, which occurred after the formation of the Stonewall beach, was almost 60 m (Table 2). The complexity of the morphology of the eastern outlets region suggests that some of the drops in lake level between lake stages would not likely have taken place as single events. Rather, multiple shifts in outlet position must have occurred at times, with individual lake lowerings believed to have been as small as several metres. It is possible that for some lake lowerings, outflow occurred, or at least began, as subglacial flows.

The largest northwest–southeast shifts in the positions of outlet divides between stages of the Nipigon Phase probably exceeded 80 km (e.g., compare the positions of the Ossawa and Stonewall divides, Figs. 6*j* and 6*k*). When the distances between the outlet divides and Lake Kelvin were greatest, Lake Agassiz outflow must have pooled in several large basins along the path to Lake Kelvin, forming short-lived but relatively large proglacial lakes in the areas of such modern lakes as Smoothrock, Tew, and Wabakimi (e.g., see Fig. 6*j*).

The volumes of Lake Agassiz stages during the Nipigon Phase are estimated to have ranged from about 20 000 km^3 at the beginning of the phase to about 4600 km^3 at the end, although depending on the position of the ice margin these volumes could have been half or double these values (Leverington et al. 2002*a*). Estimates of the volumes of water that were released to Lake Kelvin in association with the drops in level of Lake Agassiz determined here, generated using the ice margins given in Leverington et al. (2000, 2002*a*) and Teller and Leverington (in preparation), are given in Table 2. These estimates range between about 1900 and 4500 km^3, except for the release after the termination of the Stonewall stage, which at 8100 km^3 approached the magnitude of the largest releases in the history of Lake Agassiz (see Leverington et al. 2000, 2002*a*). The releases of water from Lake Agassiz through the eastern outlets were between about 140 and 250 km^3 for each metre of drop. These volumes of water, and the baseline overflow of drainage from the Lake Agassiz basin, would have flowed south from Lake Kelvin into the Superior basin and ultimately into the Atlantic Ocean.

The topographic reconstructions presented here suggest that, depending on the nature of the ice margin, overflow from Lake Agassiz may have entered the area of glacial Lake Nakina (Fig. 3) by the time of the Stonewall stage and that Lake Agassiz must have occupied this area by the The Pas stage. The abandonment of the Pikitigushi outlet system occurred at the end of this stage, terminating the Nipigon Phase with the transfer of Lake Agassiz overflow through the Lake Ojibway region to the area of the Angliers and nearby Kinojévis outlets in western Quebec (Fig. 1).

The topographic reconstructions suggest that Lake Kelvin may not have flooded the entire area covered by sands to the west of modern Lake Nipigon (Fig. 4) as previously concluded (e.g., Zoltai 1965*a*), as a lake of this size would have required a higher (by ~60 m) southern divide than can be accounted for by modern topography. It is possible that there was blockage of southern Lake Kelvin drainage by a remnant ice mass or thick and extensive morainal materials (Zoltai 1965*a*) at the beginning of the Nipigon Phase, hypothetically allowing for the existence of an extended Lake Kelvin during this time, with the breach of these morainal materials prior to the Ossawa stage of Lake Agassiz. The smaller reconstruction of Lake Kelvin, however, is consistent with the topography of the region and the distribution of recognized strandlines and varved clays in the Lake Nipigon region (e.g., Zoltai 1965*a*, 1965*b*; Lemoine and Teller 1995). Under this reconstruction, the westernmost deposits of sands in the region of modern Lake Nipigon (e.g., Zoltai 1965*b*) would have been deposited into both lacustrine and nonlacustrine environments during both baseline and catastrophic releases from Lake Agassiz.

The interpretations of the morphological reconstructions of the eastern outlets presented in this paper have been performed with the recognition that the level of detail with which the models can be analyzed is limited by uncertainties regarding the precise nature of regional isostatic rebound, uncertainties regarding the extent and configuration of the confining ice margin, and the imperfect representation of late-glacial topography by the topographic model upon which the reconstructions are based. Due to the near absence of recognized Lake Agassiz nearshore deposits in the eastern outlet region, the rebound surfaces used in this study are necessarily based on extrapolation of isobase data from surrounding areas (Thorleifson 1983, 1996; Teller and Thorleifson 1983). Interpretations are also hindered by uncertainty with regard to the extent and timing of outlet incision along the divides that separated Lake Agassiz from Lake Kelvin, and Lake Kelvin from the Superior basin.

Within the limits imposed by these uncertainties, the topographic reconstructions presented here provide a new means of visualizing the extent of lakes Agassiz and Kelvin, and for understanding the changing morphology and overflow routing of the eastern outlets. By identifying specific strandline levels and routes of overflow, the topographic reconstructions provide a basis for guiding field-based investigations of the eastern outlet region and for the field evaluation of current models of rebound in the Nipigon basin. The methodology used in this research is applicable to aiding in the understanding of the other outlets of Lake Agassiz, and other high-resolution morphological features of interest in regions affected by glacial loading.

Conclusions

High-resolution topographic reconstructions of the eastern outlets of Lake Agassiz document the evolution of the morphology of the region around the drainage divide separating glacial lakes Agassiz and Kelvin during the Nipigon Phase of Lake Agassiz. The reconstructions demonstrate the complex manner in which the shoreline and outlet divides of Lake Agassiz evolved in the region during this time. Although flow paths in the immediate vicinity of the divide were numerous, eastward releases from Lake Agassiz were progressively channeled downslope into a relatively small number of major channels, including the valleys of modern Kopka River, Ottertooth Creek, Vale Creek, Whitesand River, Pikitigushi River, and Little Jackfish River.

Most drops in the level of Lake Agassiz that occurred between recognized stages of the Nipigon Phase had magnitudes of between 8 and 20 m, although the largest, which occurred during the transition from the Stonewall stage to the The Pas stage, was about 58 m. These drops would have been associated with catastrophic releases of water, with volumes between about 1900 and 8100 km^3, although some would likely have occurred as multiple smaller events, rather than as single large events. The volume of water released in association with the lake-level declines was likely between about 140 and 250 km^3 per metre of lake-level reduction. Drainage from Lake Agassiz into glacial Lake Kelvin would have occurred until the The Pas stage about 8000 ^{14}C years BP, with the transfer of drainage to the Ottawa River via glacial Lake Ojibway occurring by the Gimli stage.

Acknowledgments

Support for this research was provided by the Smithsonian Institution Lindbergh Fellowship (DWL) and a research grant from the Natural Sciences and Engineering Research Council of Canada (JTT). The authors thank Timothy Fisher and Michael Lewis for their helpful reviews.

References

Andrews, J.T. 1970. A geomorphological study of post-glacial uplift with particular reference to Arctic Canada. Institute of British Geographers, Special Publication 2.

Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., and Gagnon, J.-M. 1999. Forcing of the cold event of 8200 years ago by catastrophic drainage of Laurentide lakes. Nature (London), **400**: 344–348.

Broecker, W.S., Kennett, J., Flower, B., Teller, J.T., Trumbore, S., Bonani, G., and Wolfli, W. 1989. Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. Nature (London), **341**: 318–321.

Canada Centre for Remote Sensing. 1994. Drainage basins. Canada Watersheds Maps, Canada Centre for Remote Sensing, Natural Resources Canada, Ottawa, Ont., digital vector data, scale 1 : 2 000 000.

Centre for Topographic Information. 2002. National topographic data base (NTDB) maps. Centre for Topographic Information, Natural Resources Canada, Sherbrooke, Que., digital vector data, scale 1 : 50 000.

Clark, P.U., Marshall, S.J., Clarke, G.K.C., Hostetler, S.W., Licciardi, J.M., and Teller, J.T. 2001. Freshwater forcing of abrupt climate change during the last glaciation. Science (Washington, D.C.), **293**: 283–287.

Clarke, G., Leverington, D., Teller, J., and Dyke, A. 2003. Superlakes, megafloods, and abrupt climate change. Science, **301**: 922–923.

Clayton, L. 1983. Chronology of Lake Agassiz drainage to Lake Superior. *In* Glacial Lake Agassiz. *Edited by* J.T. Teller and L. Clayton. Geological Association of Canada, Special Paper 26, pp. 291–307.

Dredge, L.A. 1983. Character and development of northern Lake Agassiz and its relation to Keewatin and Hudsonian ice regimes. *In* Glacial Lake Agassiz. *Edited by* J.T. Teller and L. Clayton. Geological Association of Canada, Special Paper 26, pp. 117–131.

Dyke, A.S., and Prest, V.K. 1986. Late Wisconsinan and Holocene retreat of the Laurentide Ice Sheet. Geological Survey of Canada, Map 1702A, scale 1 : 5 000 000.

Elson, J.A. 1957. Lake Agassiz and the Mankato–Valers problem. Science (Washington, D.C.), **126**: 999–1002.

Elson, J.A. 1967. Geology of glacial Lake Agassiz. *In* Life, land, and water. *Edited by* W.J. Mayer-Oakes. University of Manitoba Press, Winnipeg, Man., pp. 36–95.

Environmental Systems Research Institute (ESRI). 2001. ArcGIS version 8.1 manual (on-line documentation). Environmental Systems Research Institute, Redlands, Calif.

Fenton, M.M., Moran, S.R., Teller, J.T., and Clayton, L. 1983. Quaternary stratigraphy and history in the southern part of the Lake Agassiz basin. *In* Glacial Lake Agassiz. *Edited by* J.T. Teller and L. Clayton. Geological Association of Canada, Special Paper 26, pp. 49–74.

Fisher, T.G. 2003. Chronology of glacial Lake Agassiz meltwater routed to the Gulf of Mexico. Quaternary Research, **59**: 271–276.

Fisher, T.G., and Smith, D.G. 1994. Glacial Lake Agassiz: its northwest maximum extent and outlet in Saskatchewan (Emerson Phase). Quaternary Science Reviews, **13**: 845–858.

Fisher, T.G., and Souch, C. 1998. Northwest outlet channels of Lake Agassiz, isostatic tilting and a migrating continental drainage divide, Saskatchewan, Canada. Geomorphology, **57**: 57–73.

Fisher, T.G., Smith, D.G., and Andrews, J.T. 2002. Preboreal oscillation caused by a glacial Lake Agassiz flood. Quaternary Science Reviews, **21**: 873–878.

Hardy, L. 1977. La déglaciation et les épisodes lacustre et marin sur le versant québécois des basses terres de la baie de James. Géographie physique et Quaternaire, **31**: 261–273.

Hutchinson, M.F. 1988. Calculation of hydrologically sound digital elevation models. *In* Proceedings of the 3rd International Symposium on Spatial Data Handling, Sydney, Australia, Aug. 1988. International Geographical Union, Columbus, Ohio, pp. 117–133.

Hutchinson, M.F. 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. Journal of Hydrology, **106**: 211–232.

Klassen, R.W. 1983. Lake Agassiz and the late glacial history of northern Manitoba. *In* Glacial Lake Agassiz. *Edited by* J.T. Teller and L. Clayton. Geological Association of Canada, Special Paper 26, pp. 97–115.

Lambeck, K. 1996. Shoreline reconstructions for the Persian Gulf since the last glacial maximum. Earth and Planetary Science Letters, **142**: 43–57.

Lemoine, R.M., and Teller, J.T. 1995. Late glacial sedimentation and history of the Lake Nipigon basin, Ontario. Géographie physique et Quaternaire, **49**: 239–250.

Leverington, D.W., Mann, J.D., and Teller, J.T. 2000. Changes in the bathymetry and volume of glacial Lake Agassiz between 11 000 and 9300 ^{14}C yr B.P. Quaternary Research, **54**: 174–181.

Leverington, D.W., Mann, J.D., and Teller, J.T. 2002*a*. Changes in the bathymetry and volume of glacial Lake Agassiz between 9200 and 7700 ^{14}C yr B.P. Quaternary Research, **57**: 244–252.

Leverington, D.W., Teller, J.T., and Mann, J.D. 2002*b*. A GIS method for reconstruction of late Quaternary landscapes from isobase data and modern topography. Computers and Geosciences, **28**: 631–639.

Lewis, C.F.M., Moore, T.C., Jr., Rea, D.K., Dettman, D.L., Smith, A.J., and Mayer, L.A. 1994. Lakes of the Huron basin: their record of runoff from the Laurentide Ice Sheet. Quaternary Science Reviews, **13**: 891–922.

Mann, J.D., Leverington, D.W., Rayburn, J., and Teller, J.T. 1999. The volume and paleobathymetry of glacial Lake Agassiz. Journal of Paleolimnology, **22**: 71–80.

Peuker, T.K., Fowler, R.J., Little, J.J., and Mark, D.M. 1978. The triangulated irregular network. *In* Proceedings of the Digital Terrain Models (DTM) Symposium, St. Louis, Mo., 9–11 May 1978. American Society of Photogrammetry, Falls Church, Va., pp. 24–31.

Schaetzl, R.J., Drzyzga, S.A., Weisenborn, B.N., Kincare, K.A., Lepczyk, X.C., Shein, K., Dowd, C.M., and Linker, J. 2002. Measurement, correlation, and mapping of glacial Lake Algonquin shorelines in northern Michigan. Annals of the Association of American Geographers, **92**: 399–415.

Schlosser, T.N. 1983. Surficial geology, western Lake Nipigon area, Ontario. M.Sc. thesis, University of Wisconsin, Milwaukee, Wis.

Smith, D.G., and Fisher, T.G. 1993. Glacial Lake Agassiz: the northwestern outlet and paleoflood. Geology, **21**: 9–12.

Teller, J.T. 1985. Lake Agassiz and its influence on the Great Lakes. *In* Quaternary evolution of the Great Lakes. *Edited by* P.F. Karrow and P.E. Calkin. Geological Association of Canada, Special Paper 30, pp. 1–16.

Teller, J.T. 1987. Proglacial lakes and the southern margin of the Laurentide Ice Sheet. *In* North America and adjacent oceans during the last deglaciation. *Edited by* W.F. Ruddiman and H.E. Wright. Geological Society of America, Decade of North American Geology, Vol. K-3, pp. 39–69.

Teller, J.T. 1990*a*. Volume and routing of late glacial runoff from the southern Laurentide Ice Sheet. Quaternary Research, **34**: 12–23.

Teller, J.T. 1990*b*. Meltwater and precipitation runoff to the North Atlantic, Arctic, and Gulf of Mexico from the Laurentide Ice Sheet and adjacent regions during the Younger Dryas. Paleoceanography, **5**: 897–905.

Teller, J.T. 2001. Formation of large beaches in an area of rapid differential isostatic rebound: the three-outlet control of Lake Agassiz. Quaternary Science Reviews, **20**: 1649–1659.

Teller, J.T. 2002. Reply to comment by P.F. Karrow. Quaternary Science Reviews, **21**: 2119–2122.

Teller, J.T., and Mahnic, P. 1988. History of sedimentation in the northwestern Lake Superior basin and its relation to Lake Agassiz overflow. Canadian Journal of Earth Sciences, **25**: 1660–1673.

Teller, J.T., and Thorleifson, L.H. 1983. The Lake Agassiz – Lake Superior connection. *In* Glacial Lake Agassiz. *Edited by* J.T. Teller and L. Clayton. Geological Association of Canada, Special Paper 26, pp. 261–290.

Teller, J.T., and Thorleifson, L.H. 1987. Catastrophic flooding into the Great Lakes from Lake Agassiz. *In* Catastrophic flooding. *Edited by* L. Mayer and D. Nash. Allen & Unwin, Boston, Mass., pp. 121–138.

Teller, J.T., Leverington, D.W., and Mann, J.D. 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. Quaternary Science Reviews, **21**: 879–887.

Thorleifson, L.H. 1983. The eastern outlets of Lake Agassiz. M.Sc. thesis, University of Manitoba, Winnipeg, Man.

Thorleifson, L.H. 1996. Review of Lake Agassiz history. *In* Sedimentology, geomorphology, and history of the central Lake Agassiz Basin. *Edited by* J.T. Teller, L.H. Thorleifson, G. Matile, and W.C. Brisbin. Geological Association of Canada, Field Trip Guidebook for GAC/MAC Joint Annual Meeting, pp. 55–84.

Thorleifson, L.H., and Kristjansson, F.J. 1993. Quaternary geology and drift prospecting, Beardmore–Geraldton area, Ontario. Geological Survey of Canada, Memoir 435.

Upham, W. 1895. The Glacial Lake Agassiz. U.S. Geological Survey, Monograph 25.

Veillette, J.J. 1994. Evolution and paleohydrology of glacial lakes Barlow and Ojibway. Quaternary Science Reviews, **13**: 945–971.

Vincent, J-S., and Hardy, L. 1977. L'évolution et l'extension des lac glaciaires Barlow et Ojibway en territoire québécois. Géographie physique et Quaternaire, **31**: 357–372.

Vincent, J-S., and Hardy, L. 1979. The evolution of glacial lakes Barlow and Ojibway, Quebec and Ontario. Geological Survey of Canada, Bulletin 316.

Zoltai, S.C. 1965*a*. Glacial features of the Quetico–Nipigon area, Ontario. Canadian Journal of Earth Sciences, **2**: 247–269.

Zoltai, S.C. 1965*b*. Thunder Bay surficial geology. Ontario Department of Lands and Forests, Map S265, scale 1 : 506 880.

Zoltai, S.C. 1967. Eastern outlets of Lake Agassiz. *In* Life, land, and water. *Edited by* W.J. Mayer-Oakes. University of Manitoba Press, Winnipeg, Man., pp. 107–120.