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Changes in the Bathymetry and Volume of Glacial Lake Agassiz between 9200 and 7700 ^{14}C yr B.P.

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Computer reconstructions of the bathymetry of the lake were used to quantify variations in the size and form of Lake Agassiz during its final two phases (the Nipigon and Ojibway phases), between about 9200 and 7700 ^{14}C yr B.P. (ca. 10,300–8400 cal yr B.P.). New bathymetric models for four Nipigon Phase stages (corresponding to the McCauleyville, Hillsboro, Burnside, and The Pas strandlines) indicate that Lake Agassiz ranged between about 19,200 and 4600 km^3 in volume and 254,000 and 151,000 km^2 in areal extent at those times. A bathymetric model of the last (Ponton) stage of the lake, corresponding to the period in which Lake Agassiz was combined with glacial Lake Ojbway to the east, shows that Lake Agassiz–Ojibway was about 163,000 km^3 in volume and 841,000 km^2 in areal extent prior to the final release of lake waters into the Tyrrell Sea. During the Nipigon Phase, a number of catastrophic releases of water from Lake Agassiz occurred as more northerly (lower) outlets were made available by the retreating southern margin of the Laurentide Ice Sheet; we estimate that each of the four newly investigated Nipigon Phase releases involved water volumes of between 1600 and 2300 km^3. The final release of Lake Agassiz waters into the Tyrrell Sea at about 7700 ^{14}C yr B.P. is estimated to have been about 163,000 km^3 in volume.

Key Words: **Lake Agassiz; Lake Ojibway; bathymetry; volume.**

INTRODUCTION

Lake Agassiz was the largest of the proglacial lakes that formed in North America during the last deglaciation, as continental drainage was impounded against the retreating southern margin of the Laurentide Ice Sheet (LIS). The size of Lake Agassiz varied considerably during its 4000-yr history, at various times covering parts of the Canadian provinces of Saskatchewan, Manitoba, Ontario, and Québec, and the U.S. states of North Dakota, South Dakota, and Minnesota (e.g., Elson, 1967; Teller *et al.*, 1983; Smith and Fisher, 1993) (Fig. 1). Lake Agassiz is believed to have played a role in determining regional climate during the last deglaciation (Teller, 1987; Hu *et al.*, 1997; Hostetler *et al.*, 2000). Releases of large volumes of water from Lake Agassiz at various times in its history, associated with the deglaciation of new and lower outlets, impacted the rivers and basins that received the lake's overflow (e.g., Teller and Thorleifson, 1983; Lewis *et al.*, 1994; Fisher and Smith, 1994) and may have influenced ocean circulation and North Atlantic Deep Water production (e.g., Broecker *et al.*, 1989; Licciardi *et al.*, 1999; Barber *et al.*, 1999; Leverington *et al.*, 2000; Clark *et al.*, 2001).

In this paper, area and volume calculations and bathymetric maps are given for six stages of glacial Lake Agassiz (four stages of the Nipigon Phase and two stages of the Ojibway Phase) that together span the final 1500 yr of the lake, which took place between about 9200 and 7700 ^{14}C yr B.P. (ca 10,300–8400 cal yr B.P., using Stuiver and Reimer, 1993). This research extends the work of Leverington *et al.* (2000), in which bathymetric models for seven earlier stages of Lake Agassiz were determined.

BACKGROUND

As the LIS retreated during the last deglaciation of North America, meltwaters collected in proglacial lakes where drainage was impeded by ice (e.g., Teller, 1987). Lake Agassiz formed about 11,700 ^{14}C yr B.P. when the Red River Lobe of the LIS began its final retreat northward across the divide between the Hudson Bay and Mississippi River drainage basins, ponding water against the southern margin of the LIS (Elson, 1967; Bluemle, 1974; Clayton, 1983). Based on investigations of preserved offshore lake sediments, outlet channels, and strandline segments, the size of Lake Agassiz is known to have varied considerably during its history, driven by isostatic rebound, changing ice-sheet configurations, and the consequent opening and closing of drainage routes (e.g., Elson, 1967; Zoltai, 1967; Teller and Thorleifson, 1983; Smith and Fisher, 1993). The last stages of Lake Agassiz involved confluence with glacial Lake Ojibway to the east (Elson, 1967) and the ultimate drainage of these waters into the Tyrrell Sea (Hudson Bay) by about 7700 ^{14}C yr B.P. (Vincent and Hardy, 1979; Dredge and Cowan, 1989; Veillette, 1994; Barber *et al.*, 1999).

At numerous times in the history of Lake Agassiz, large volumes of water were released when lake levels dropped after lower outlets were deglaciated. We believe that most releases

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involved relatively rapid outlet deglaciation and occurred as single catastrophic events. However, releases involving slower outlet deglaciation (e.g., at more complex outlet systems involving multiple channels) may have occurred as a series of smaller catastrophic events that occurred over a longer time frame. Today, extensive boulder and cobble lags are preserved in modern river valleys that once acted as Lake Agassiz overflow channels (Teller and Thorleifson, 1983).

The history of Lake Agassiz can be divided into five main phases: Lockhart, Moorhead, Emerson, Nipigon, and Ojibway (Fenton *et al*., 1983; Teller and Thorleifson, 1983). The Lockhart Phase extended from about 11,700 to 11,000 ^{14}C yr B.P., and the Herman beaches outline the extent of Lake Agassiz in the southern end of the basin at this time (Upham, 1895; Fenton *et al*., 1983; Hobbs, 1983). Drainage during the Lockhart Phase was through the southern outlet (Minnesota River Valley; e.g., Elson, 1967; Fenton *et al*., 1983) (Fig. 1).

The Moorhead Phase was a low-water phase that extended from about 11,000 to 10,100 ^{14}C yr B.P. and was initiated by a significant drop in lake level from the Herman strandlines following deglaciation of an eastern overflow route to the Great Lakes through the Kaministikwia route (Clayton, 1983; Teller and Thorleifson, 1983; Thorleifson, 1996) (Fig. 1). During the Moorhead Phase, isostatic rebound gradually raised lake level to the Norcross strandline (Thorleifson, 1996).

The Emerson Phase extended from about 10,100 to 9400 ^{14}C yr B.P. and was initiated after drainage to the east was blocked by ice readvances. Most overflow during the Emerson Phase was through the northwestern outlet (Fig. 1), although changing ice configuration, isostatic rebound, and outlet erosion resulted in several short episodes of southward overflow (Teller, 2001). Recognized strandlines of the Emerson Phase include the Norcross, Tintah, and Upper Campbell.

The next phase of Lake Agassiz, the Nipigon Phase, extended from about 9400 to 8200 ^{14}C yr B.P. and was initiated by the deglaciation of the Kaiashk outlet, which allowed overflow into the Nipigon and Superior basins (Teller and Thorleifson, 1983). This led to the final abandonment of the southern and northwestern outlets. During the Nipigon Phase, the waters of Lake Agassiz gradually shifted northward with the retreat of the LIS, and the elevation of the lake surface incrementally dropped each time new (lower) outlets were opened and as outlet channels were deepened by erosion (Elson, 1967). Commencing with the Lower Campbell level, a series of about a dozen strandlines developed during the Nipigon Phase; each formed as a transgressive beach (Teller, 2001), and each was abandoned when lower outlets were opened (Leverett, 1932; Johnston, 1946; Elson, 1967; Fenton *et al*., 1983).

The Ojibway Phase began when Lake Agassiz combined with glacial Lake Ojibway at about the Ponton stage of Lake Agassiz.

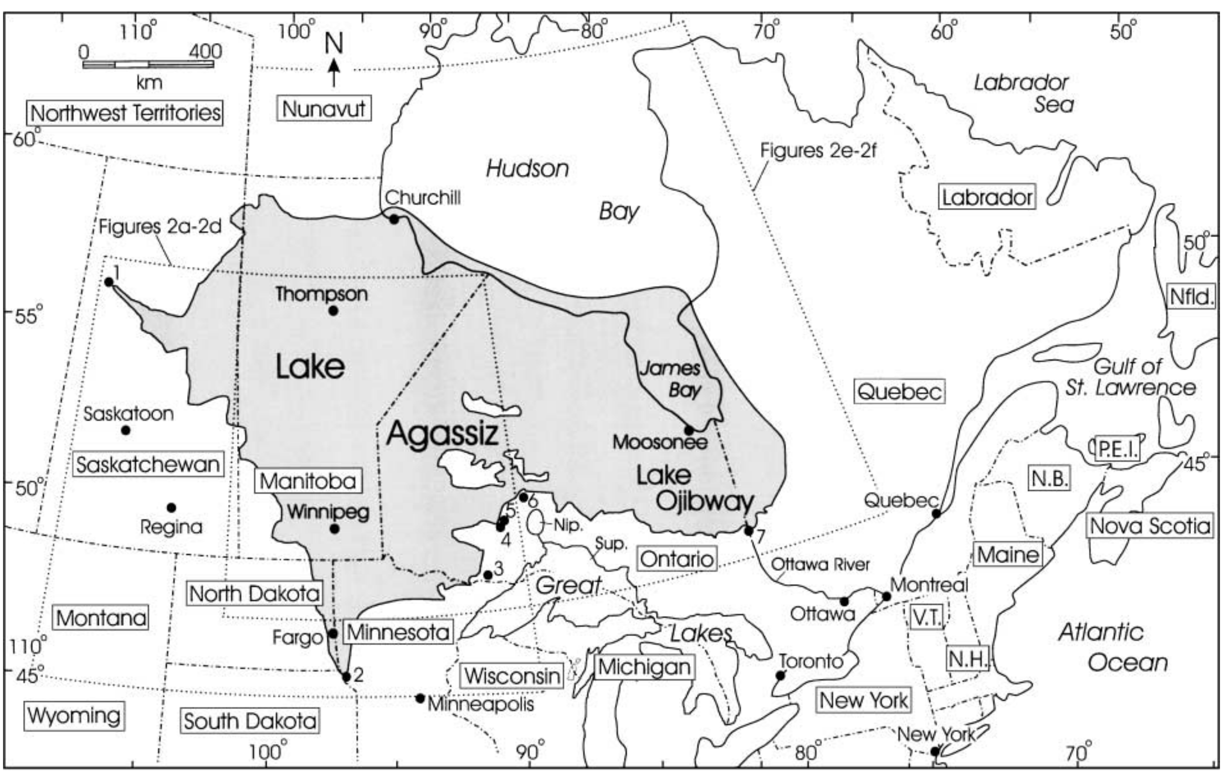

FIG. 1. Map showing the total geographic coverage of Lake Agassiz over its 4000-yr history (modified after Teller *et al*., 1983, and Dredge and Cowan, 1989). Lake Agassiz outlets mentioned in the text are labeled as follows: 1, northwestern outlet (Clearwater spillway); 2, southern outlet (Minnesota River Valley); 3, Kaministikwia route; 4, Kaiashk system; 5, Kopka system; 6, Pikitigushi system; and 7, Kinojévis outlet to the Ottawa River Valley. Locations of the Nipigon and Superior basins are identified ("Nip." and "Sup.").

Lake Agassiz–Ojibway drained through the Kinojévis outlet to the Ottawa River Valley until the LIS no longer provided a barrier to northward outflow into the Tyrrell Sea (Vincent and Hardy, 1979). Catastrophic northward drainage into the Tyrrell Sea, possibly initiated in the region north of modern James Bay, is believed to have followed the collapse of the confining ice margin at about 7700 ^{14}C yr B.P. (Barber *et al*., 1999; Craig, 1969; Hardy, 1977; Vincent and Hardy, 1979; Veillette, 1994; Barber *et al*., 1999).

METHODOLOGY

In a previous study (Leverington *et al*., 2000), bathymetric models of seven stages of the Lockhart, Moorhead, Emerson, and (earliest) Nipigon phases (including those corresponding to the Herman, Norcross, Tintah, Upper Campbell, and Lower Campbell strandlines) were generated. The research presented here builds on the previous study by generating bathymetric models of four stages of the Nipigon phase (corresponding to the McCauleyville, Hillsboro, Burnside, and The Pas levels) and two stages of the Ojibway phase (corresponding to the Kinojévis level and possible Fidler level) (Teller and Thorleifson, 1983). Our informal "Kinojévis stage" roughly corresponds to the recognized Ponton strandline (e.g., Teller and Thorleifson, 1983) and was used to define Lake Agassiz–Ojibway when it drained through the Kinojévis outlet (Fig. 1).

For each stage, lake bathymetry was calculated by subtracting a stage-specific *rebound surface* from a database of modern elevations. A rebound surface is defined by values interpolated from isobase data and describes the relative glacio-isostatic rebound that has occurred over a region since a given time (Mann *et al*., 1999). The geometry of a rebound surface matches the geometry of the corresponding (and now differentially rebounded) water plane. The subtraction of a rebound surface from a database of modern topography adjusts topography for the effects of isostatic rebound, providing a basis for the estimation of lake volume and area, as well as the positions of paleo-shorelines (Leverington *et al*., 2000, in press).

Calculations of volumes and areas of Lake Agassiz necessitated the definition of the lake's northern (ice-contact) margins with the LIS. Because the configuration of the ice-contact margin of Lake Agassiz is not precisely known for specific points in time, calculations of lake parameters were made for each Nipigon stage using three different ice margins: (1) a "favored" ice margin (based on previously published margins; see below); (2) an ice margin with the same form as the favored margin but shifted by 1° of latitude (about 111 km) to the north; and (3) an ice margin with the same form as the favored margin but shifted by 1° of latitude to the south. The use of three ice margins to define each stage helps to emphasize the uncertainty with which volume and area calculations for Lake Agassiz are carried out and provides what we feel are realistic ranges for lake volumes and areas. For comparison purposes, calculations using offset ice margins were additionally made for the seven earlier stages of the lake investigated previously (Leverington *et al*., 2000).

DATA COLLECTION

Database of Modern Elevations

The primary source of modern elevations used in this research was Version 1.0 of the *GLOBE* database (*GLOBE* Task Team, 1999). The *GLOBE* database is a global digital elevation model with a latitude–longitude grid spacing of 30 arc sec (Hastings and Dunbar, 1999). The *GLOBE* database does not contain bathymetric data for Hudson Bay nor for lakes, including Lake Winnipeg. While supplementary bathymetric data for lakes was not considered necessary for this exercise (average lake depths in the region are less than 15 m), the *ETOPO5* database (National Geophysical Data Center, 1988; 5 arc min grid spacing) was used as a source of modern bathymetric data for Hudson Bay.

Rebound Surfaces

Rebound surfaces were spatially interpolated using the "triangulated irregular network" algorithm (see Mann *et al*., 1999) from point data taken from isobases and strandline rebound curves plotted by Teller and Thorleifson (1983) and Thorleifson (1996); where necessary, rebound data were linearly extrapolated to the north when working with north-shifted ice margins. The form of the rebound curve used to reconstruct lake bathymetry at the Kinojévis stage was based on that for the Ponton stage (Thorleifson, 1996), with the trends of associated isobases modified in the east so that the 300-m isobase approximately intersects the Kinojévis outlet (see Vincent and Hardy, 1979, their fig. 3-I). The number of isobase points used to define rebound surfaces ranged from 270 (McCauleyville) to 437 (Kinojévis).

Ice Margins

The ice margins of the four investigated stages of the Nipigon Phase were modified from those of Thorleifson (1996), with drainage allowed through appropriate eastern outlets (Fig. 1). The ice margin used to help define the two investigated stages of the Ojibway Phase was based on the margins of Dredge (1983), Dyke and Prest (1987), and Vincent and Hardy (1979), with extrapolation from these margins in the region west of James Bay. The faces of all ice margins were treated as vertical.

AREA, VOLUME, AND BATHYMETRY

Volumes, areas, and maximum depths for 13 stages of Lake Agassiz in the period 11,700 to 7700 ^{14}C yr B.P. (ca. 13,600–8400 cal yr B.P.) are given in Table 1. Values in this table are given for "favored" ice margins, as well as for ice configurations in which these preferred ice margins were shifted north and south by 1° of latitude. Bathymetric maps for the first seven stages in Table 1 are given in Leverington *et al*. (2000). Bathymetric maps for the last six stages in this table, corresponding to the period from 9200 to 7700 ^{14}C yr B.P. (ca. 10,300–8400 cal yr B.P.),

TABLE 1
Area, Volume, and Maximum Depth Values for 13 Stages of Lake Agassiz

Lake phase	Lake stage	^{14}C yr B.P.	Ice margin[a]	Area (km^2)	Volume (km^3)	Max. depth (m)
Lockhart	Herman	10,900	North	214,000	24,700	321
			Favored	134,000	10,900	231
			South	66,000	3500	157
Moorhead	Early Moorhead	10,700	North	193,000	23,700	338
			Favored	117,000	10,800	247
			South	61,000	3700	173
	Late Moorhead	10,300	North	271,000	36,500	363
			Favored	185,000	19,700	258
			South	120,000	10,100	227
Emerson	Norcross	10,100	North	254,000	27,300	275
			Favored	166,000	13,300	243
			South	94,000	5400	180
	Tintah	9900	North	276,000	30,100	274
			Favored	184,000	15,700	233
			South	114,000	7100	184
	Upper Campbell	9400	North	382,000	39,500	281
			Favored	263,000	22,700	233
			South	156,000	10,700	190
Nipigon	Lower Campbell	9300	North	355,000	33,600	262
			Favored	240,000	19,100	214
			South	142,000	9000	173
	McCauleyville	9200	North	329,000	29,700	250
			Favored	219,000	16,400	199
			South	128,000	7700	160
	Hillsboro	8900	North	368,000	34,500	260
			Favored	254,000	19,200	199
			South	163,000	10,500	160
	Burnside	8500	North	309,000	22,300	210
			Favored	202,000	10,300	147
			South	115,000	4900	131
	The Pas	8200	North	238,000	12,100	203
			Favored	151,000	4600	96
			South	75,000	1800	63
Ojibway	Kinojévis[b]	7700	Favored	841,000	163,000	773
	Fidler[c]	<7700	Favored	408,000	49,900	421

[a] "North" and "South" refer to 1° latitude shifts from "favored" positions of Laurentide Ice Sheet margins.
[b] Combined Lake Agassiz–Ojibway.
[c] Possible final stage.

are shown in Figs. 2a–2f. Except where noted, the discussion below is given with respect to lake parameters estimated using the "favored" ice margins.

The volumes of most of the smaller stages shown in Table 1 (e.g., Herman and Burnside) are roughly comparable to that of modern Lake Superior (about 12,200 km^3; Herdendorf, 1984), although the smallest investigated stage (The Pas) is only about as large as modern Lake Michigan (about 4900 km^3; Herdendorf, 1984). Volumes of the lake when at the Upper Campbell, Lower Campbell, and Hillsboro strandlines are roughly comparable to the total volume of the modern Great Lakes (about 22,700 km^3; Herdendorf, 1984). The size of Lake Agassiz increased greatly at the beginning of the Ojibway Phase, when Lake Agassiz merged with glacial Lake Ojibway to the east; this combined lake grew considerably during the Ojibway Phase, since northward shifts of the LIS southern margin during this phase did not expose new and lower drainage routes. The Kinojévis stage of Lake Agassiz–Ojibway (Fig. 2e) dwarfed all other investigated stages, with an area of about 841,000 km^2 and a volume of about 163,000 km^3. This volume is less than, but roughly consistent with, previous estimates of the final size of Lake Agassiz–Ojibway produced by Veillette (1994) (230,000 km^3) and Barber *et al*. (1999) (about 200,000 km^3), who used more coarse techniques for their estimates. The volumes of the Agassiz and Ojibway sides of this lake were about 102,000 km^3 and 61,000 km^3, respectively, when divided at 80°W longitude.

The bathymetric model of the Fidler stage (Fig. 2f), a possible final lake stage, is given here only for regions west of the Cochrane II ice advance (this advance is described by Vincent and Hardy, 1979, and Veillette, 1994). The level of the Fidler stage is based on Klassen's (1983) identification of a beach along a moraine in northern Manitoba, which today lies about 80 m below the Ponton beach. As reconstructed in this research, the Fidler level is too low to have been associated with the Kinojévis or any other known outlet in the region (see also Klassen, 1983, and Thorleifson, 1996). If the Fidler beach does represent the last stage of Lake Agassiz, the final drainage of the lake would have occurred in two steps, perhaps separated in time by as much as a few decades. In this reconstruction, complete drainage from the Kinojévis stage must have been prevented by ice related to the Cochrane II advance, causing some waters in the western (Agassiz) side of the lake basin to be temporarily held back. This would have allowed the Fidler strandline time to form before the final drainage into the Tyrrell Sea. Alternatively, it is possible that the trends of the isobases we used (cf. Teller and Thorleifson, 1983; Thorleifson, 1996) to reconstruct the Fidler stage are not valid in the eastern region and that, contrary to our present understanding, the Fidler strandline in fact did intersect the Kinojévis outlet. Finally, it is also possible that the localized deposits in northern Manitoba currently cited as evidence for a stable Fidler standline (Klassen, 1983, p. 111) have been misinterpreted and that the Kinojévis stage was instead the final stable lake stage. The Fidler stage as reconstructed in this research is calculated to have had a volume and area of about 49,900 km^3 and 408,000 km^2, respectively.

Maximum lake depths ranged between about 200 and 260 m for investigated stages from the Herman to the Hillsboro (Table 1). The subsequent Burnside and The Pas stages had maximum depths that were markedly less than this range (147 and 96 m, respectively), resulting in relatively small lake volumes despite their considerable surface areas. After lakes Agassiz and Ojibway combined, maximum lake depths increased dramatically. The maximum depth of the Kinojévis stage was about 773 m. The deepest waters of all 13 investigated stages of Lake Agassiz were generally located along the LIS margin (Fig. 2; see also Leverington *et al*., 2000).

For the McCauleyville (Fig. 2a), Hillsboro (Fig. 2b), and Burnside (Fig. 2c) stages, overflow from Lake Agassiz was

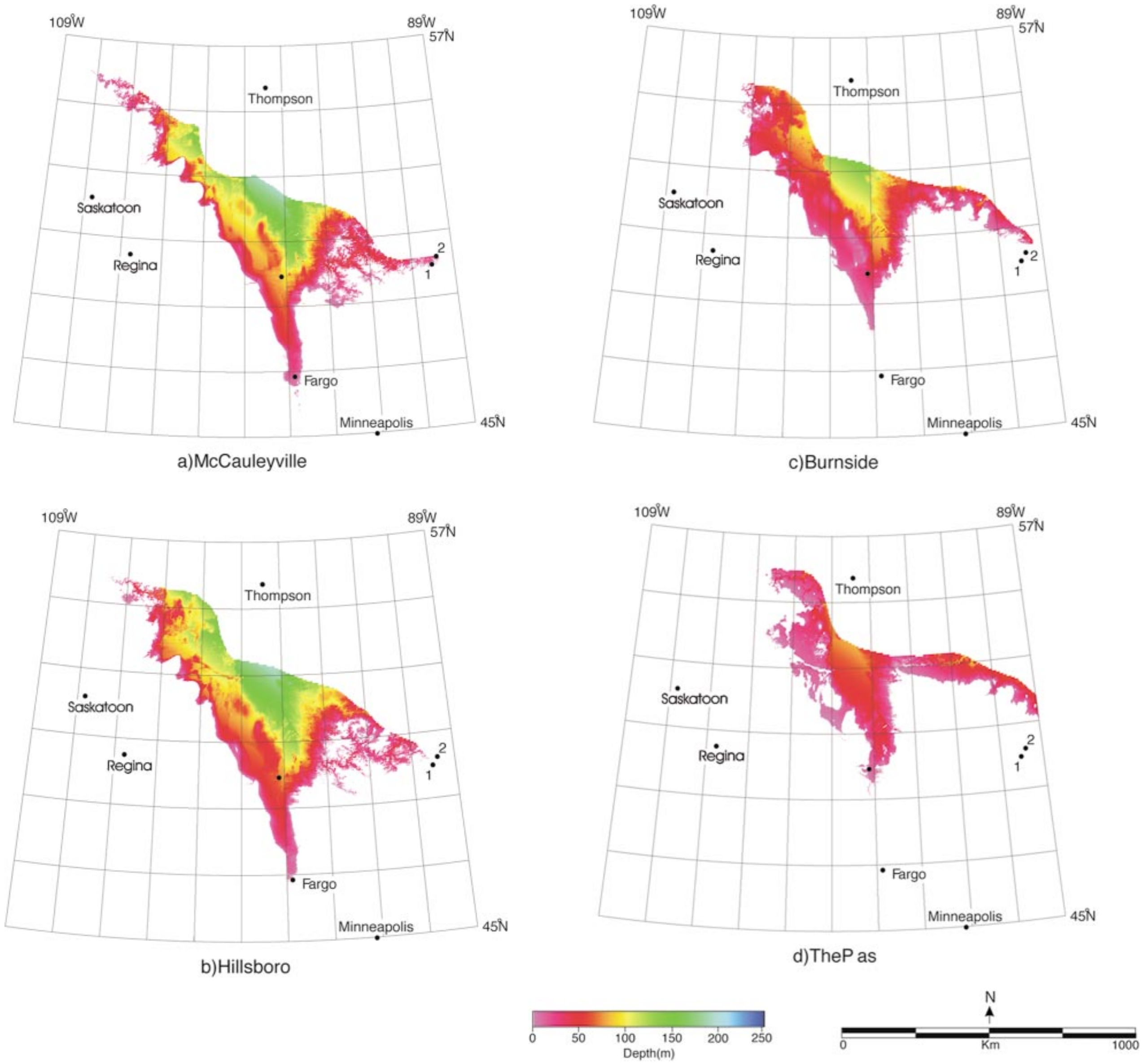

FIG. 2. Bathymetric models for six stages of Lake Agassiz during the Nipigon and Ojibway phases, at (a) 9200, (b) 8900, (c) 8500, (d) 8200, (e) 7700, and (f) shortly after 7700 ^{14}C yr B.P. Maximum depth is 773 m (Lake Ojibway portion of the Kinojévis stage). Grid cells are 2° by 2°. The locations of two eastern outlets mentioned in the text are labeled as follows: 1, the Kaiashk system; 2, the Kopka system. These two outlet positions are based on their approximate westernmost extents along the continental divide. The outline of modern-day Hudson Bay and James Bay is given in 2e and 2f. In 2e and 2f, the ice-margin segment southwest of James Bay speculatively treats the ice in this region as a western component of the Cochrane II surge. The scales for *2a–2d* are different from the scales for *2e–2f*.

eastward into the Nipigon basin through progressively lower channels of the Kopka system (#5, Fig. 1; #2, Fig. 2), (cf. Teller and Thorleifson, 1983). For the The Pas stage of Lake Agassiz (Fig. 2d), drainage was into the Nipigon basin through the Pikitigushi system (east of the area shown in Fig. 2d). For the Kinojévis stage (Fig. 2e), overflow was south into the Ottawa River Valley through the Kinojévis outlet (e.g., Vincent and Hardy, 1979). For the Fidler stage (Fig. 2f), drainage may have been beneath the stagnant LIS into the Tyrrell Sea (e.g., Dredge, 1983; Klassen, 1983), or around the remaining ice dam along the eastern side of Lake Agassiz (e.g., Thorleifson, 1996).

The lake parameters presented in Table 1 highlight the wide range in lake size that is possible for individual lake stages, depending on the selected position and configuration of the northern ice margin of the lake. Typically, a 1° northward shift of ice from the favored ice margins results in an expansion of lake areas to about 150% of the areas estimated using the favored ice configurations; a 1° southward shift results in a decrease to about 60% of the areas estimated using the favored ice configurations.

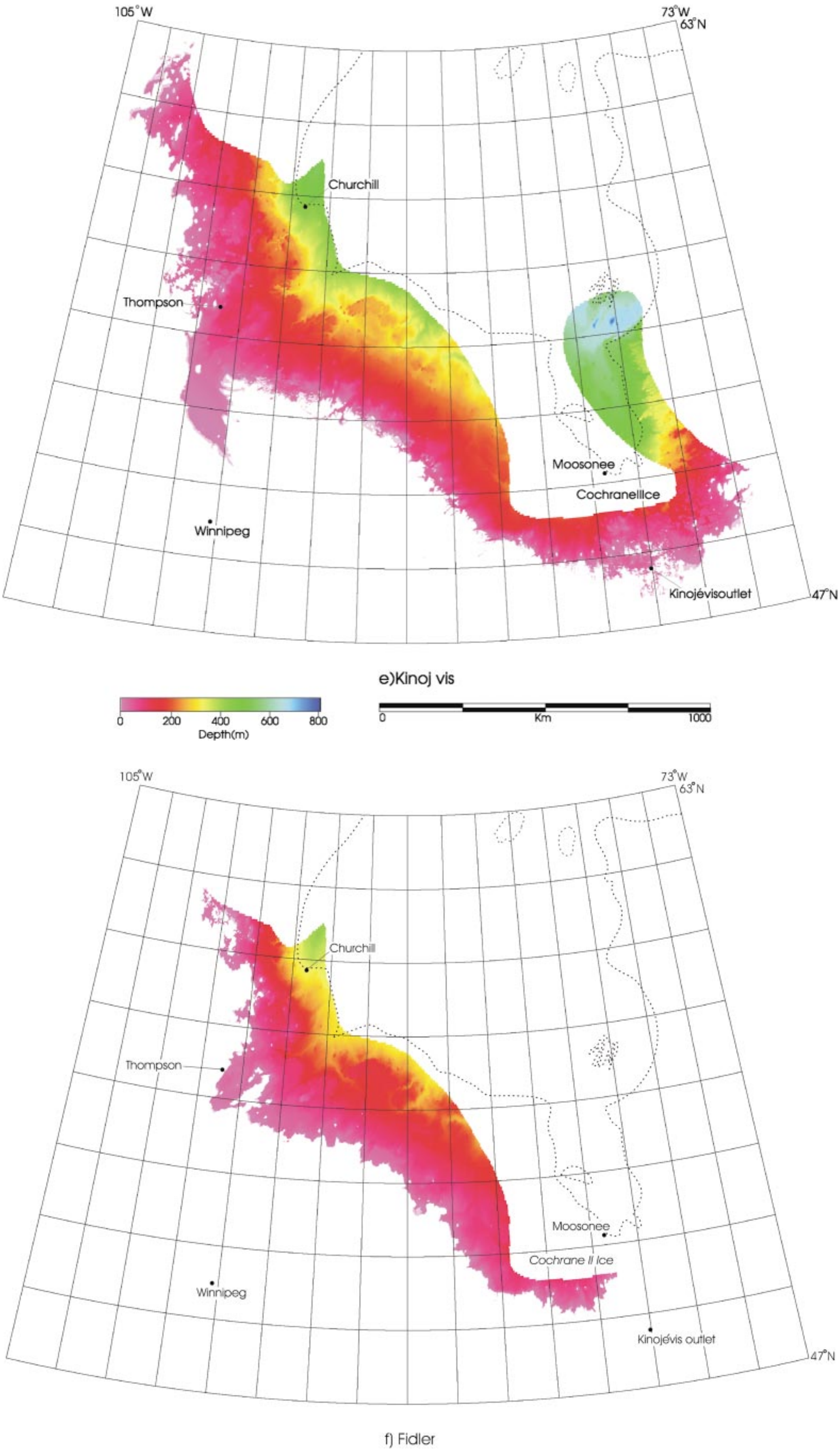

FIG. 2—*Continued*

The same shifts typically result in lake volumes that are about 200% and 45% of the volumes estimated using the favored ice configurations, respectively.

RELEASES OF WATER FROM LAKE AGASSIZ DURING THE NIPIGON AND OJIBWAY PHASES

Using the bathymetric databases discussed above, estimates were made of the volumes of water released at the terminations of the four Nipigon stages and two Ojibway stages investigated (Table 2). During retreat of the LIS during the Nipigon Phase, new outlets were periodically opened, resulting in a rapid draw down of the lake's surface and a reduction in lake volume. Because subsequent isostatic rebound led to a rise in lake level (south of the isobase passing through the active outlet), waters slowly deepened again and Lake Agassiz expanded until the LIS retreated and uncovered a lower outlet (Teller, 2001). The maximum extent of each transgression is marked by a Lake Agassiz strandline (Teller, 2001). However, the level to which the lake fell each time a new lower outlet was opened was not marked by any discernable sediment or morphology. Thus, our calculation of the drawdown of a specific Nipigon lake level was necessarily based on the difference between the elevation of the strandline at the start of the draw down and the lowest elevation in the outlet system through which that draw down occurred. An attempt was made to select channel floor elevations that related to Lake Agassiz outflow and not to subsequent incision. For the four Nipigon stages investigated in this research, the following elevation drops were determined mainly from Teller and Thorleifson (1983, their fig. 2) and topographic maps: (1) McCauleyville stage, 10 m; (2) Hillsboro stage, 7m; (3) Burnside stage, 12 m; and (4) The Pas stage, 12 m.

At the end of the Ojibway Phase, Lake Agassiz–Ojibway released its waters into the Tyrrell Sea. It is possible that this release occurred in a single rapid and catastrophic event, with a total volume of about 163,000 km^3 (Table 2). As discussed above, it is also possible that western (Agassiz) waters were retained for a short time behind stagnant ice of the LIS, after the initial release of water from the level of the Kinojévis outlet. If this occurred, the release at the termination of the Kinojévis stage would have involved the entire volume of the eastern (Ojibway) side, but only part (upper 103 m) of the western (Agassiz) side, which was held back by remaining ice of the Cochrane II advance (Fig. 2e). In this scenario, the subsequent release at the end of the Fidler stage would have involved the remaining volume of the western part of the basin, depicted in Fig. 2f.

Water volumes estimated to have been released at the terminations of the four Nipigon stages and two Ojibway stages are given in Table 2. For comparison purposes, calculations are also given for the terminations of selected stages from the earlier history of Lake Agassiz (Herman, Norcross, Tintah, and Upper Campbell). The Herman and Upper Campbell releases are discussed in Leverington *et al*. (2000). The Norcross and Tintah releases through the northwestern outlet (#1, Fig. 1) were estimated by assuming lake-level drawdowns of 40 to 52 m, and 30 m, respectively, at the terminations of these stages (see Fisher and Smith, 1994, and Teller, 2001).

Calculated releases at the terminations of the investigated Nipigon stages range between 1600 and 2300 km^3 (Table 2); these volumes are less than those calculated for the pre-Ojibway terminations of the Herman (9500 km^3), Norcross (7500 to 9300 km^3), and Upper Campbell stages (2500 to 7000 km^3) (Table 2; see also Leverington *et al*., 2000). The northward release from Lake Agassiz–Ojibway at the termination of the Kinojévis stage is estimated to have been about 163,000 km^3. If the release took place in two stages, the initial northward release from the level of the Kinojévis stage would have been about 113,100 km^3 (Table 2), and the subsequent release from the level of the Fidler stage would have been about 49,900 km^3 (see Tables 1 and 2). The final release(s) of Lake Agassiz–Ojibway

TABLE 2
Volumes of Water Released at Terminations of Selected Stages of Lake Agassiz

Lake phase	Lake stage	^{14}C yr B.P.	Ice margin[a]	Volume Released (km^3)
Lockhart	Herman[b]	10,900	North	17000
			Favored	9500
			South	3400
Emerson	Norcross	10,100	North	9300 to 11600
			Favored	7500 to 9300
			South	3200 to 3800
	Tintah	9900	North	9700
			Favored	5900
			South	3100
	Upper Campbell[b]	9400	North	3700 to 10500
			Favored	2500 to 7000
			South	1500 to 2500
Nipigon	Lower Campbell	9300	North	5400
			Favored	3700
			South	3100
	McCauleyville	9200	North	3200
			Favored	2100
			South	1200
	Hillsboro	8900	North	2500
			Favored	1600
			South	1100
	Burnside	8500	North	3600
			Favored	2300
			South	1300
	The Pas	8200	North	2600
			Favored	1600
			South	800
Ojibway	Kinojévis	7700	Favored	163,000 (or 113,100[c])
	Fidler	<7700	Favored	(49,900[c])

[a] "North" and "South" refer to 1° latitude shifts from "favored" positions of Laurentide Ice Sheet margins.
[b] Herman and Upper Campbell after Leverington *et al*. (2000).
[c] Volumes associated with hypothetical two-stage release from Kinojévis level.

were into the Tyrrell Sea, and ultimately into the North Atlantic Ocean.

SUMMARY AND CONCLUSIONS

Bathymetric models were generated for six stages of the Nipigon and Ojibway phases of Lake Agassiz by adjusting a digital database of modern elevations for isostatic rebound. These bathymetric models were used to determine lake extents, to verify drainage routings, and to calculate lake volumes and the magnitudes of abrupt drainage events. The largest of the four Nipigon Phase lake stages investigated was the Hillsboro stage, with a volume of 19,200 km^3 and an area of 254,000 km^2. The smallest investigated stage of the Nipigon Phase was the The Pas stage, with a volume of 4600 km^3 and an area of 151,000 km^2. The volume and area of Lake Agassiz–Ojibway when drainage was south through the Kinojévis outlet were about 163,000 km^3 and 841,000 km^2, respectively.

Calculated releases from Lake Agassiz into the North Atlantic Ocean through the Nipigon and Superior basins during the Nipigon Phase (ca. 9400–8000 ^{14}C yr B.P.), when lower outlets became ice free, range between 1600 and 3700 km^3. The northward release of water from Lake Agassiz–Ojibway into the Tyrrell Sea at the termination of the Kinojévis stage at about 7700 ^{14}C yr B.P. is estimated to have been about 163,300 km^3. Waters from the final drainage of this lake were routed through Hudson Bay and Hudson Strait into the North Atlantic Ocean.

The influence that Lake Agassiz outbursts, and associated reroutings of baseline overflow, may have had on ocean circulation and climate continues to be investigated (e.g., Broecker *et al.*, 1989; Fanning and Weaver, 1997; Licciardi *et al.*, 1999; Barber *et al.*, 1999; Leverington *et al.*, 2000; Clark *et al.*, 2001; Rind *et al.*, 2001; Teller *et al.*, in press). Many suggest that the addition of large volumes of water into the North Atlantic Ocean, either over short periods or as sustained (but smaller) changes in baseline runoff, may have substantially altered thermohaline circulation and production of North Atlantic Deep Water. The estimates of Lake Agassiz volumes and releases presented here provide a quantitative basis for evaluating the impact that Lake Agassiz may have had on North America and on the oceans into which it flowed. The potential impacts of freshwater outbursts from Lake Agassiz on ocean circulation and climate are explored by Teller *et al.* (in press).

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