The subglacial origin of the Lake Agassiz–Ojibway final outburst flood

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Deglaciation of North America resulted in the development of the ice-dammed lake Agassiz–Ojibway along the southern margin of the Laurentide Ice Sheet[1–5] and its catastrophic northward drainage ~8.47 kyr ago[6]. This sudden outburst of fresh water may have weakened the Atlantic ocean overturning circulation and triggered the cold event that occurred 8.2 kyr ago[6,7]. Geological evidence of this flood has been documented in a red sedimentary bed in cores collected in Hudson Strait[6,8] and by submarine features in Hudson Bay[9]. However, there have been few constraints on the manner in which the lake drained: for example, by flow over the ice sheet or beneath it, in one or several pulses[10] and where the flood routes were located[5,11]. Here we present seafloor images obtained using multibeam sonar, which reveal that the outburst flood displaced icebergs to produce arcuate (arc-shaped) scours on the seafloor with a dominant east-northeast–west-southwest orientation. The flood also produced sandwaves in areas unaffected by the arcuate scours, indicating they were protected from iceberg scouring by overlying ice during the event. We suggest that these sandwaves, along with submarine channels inferred from the data, indicate that Laurentide ice was lifted buoyantly, enabling the flood to traverse southern Hudson Bay under the ice sheet.

Glacial features on the Hudson Bay seafloor are well preserved because postglacial sedimentation and sea ice disturbance are mostly restricted to coastal areas[12]. Although these features were used to reconstruct the outburst flood[5,13], their origin, distribution and character remain poorly known owing to lack of data. On land, evidence from the lake palaeoshorelines suggests a two-pulse discharge[10], with a first and more important flood followed by a smaller one[14]. If the drainage did actually take place as two pulses, it is not known whether these pulses were successive or separated by a latency period that enabled the lake to refill[11]. The new seafloor images provided by more than 10,500 km of multibeam sonar lines in Hudson Bay and Strait (Fig. 1) reveal with great detail arcuate iceberg scours, sandwaves and channels previously suspected to be of late-glacial age[9].

Arcuate iceberg scours (Figs 2,3a,b; see Supplementary Information, Fig. S1) are observed in western Hudson Bay between −80 and −205 m. They are less than 1 km long and generally incised less than 3 m deep. The absence of icebergs today in the region indicates that they were produced during deglaciation. Previous data[9] revealed that the scours tended to be convex northward. The new data reveal that they are generally convex to the ENE, with other convexities to the WSW, NNW and NW (Fig. 2). Such a high concentration of preferentially oriented arcuate scours showing similar geometries over hundreds of square kilometres remains undocumented. These scours were suggested to have been produced by either (1) tidal resonance in a former calving bay, which could have entrained icebergs into a circular motion, hence forming swirling circular scours, or (2) iceberg remobilization by the outburst-flood high-energy currents[9]. It was suggested[5] that they were produced by the flood current, which moved large multikeeled tabular icebergs around one ice keel that acted as a pivot while the other keels scoured the seafloor to form a surrounding arc. The multibeam data reveal that the scours mostly form parabolae rather than circles or half-circles (Fig. 3a,b). Their geometry and orientation eliminate the tidal currents and pivoting iceberg hypotheses—tides would have generated scours without preferential orientations whereas multikeeled pivoting icebergs would have formed half-circles rather than parabolae. Arcuate scours were not all produced simultaneously, because they occasionally cross-cut each other, in some cases in the same direction (Fig. 3a), but the limited number of cross-cutting scours indicates a short-lived scouring event. Rapidly shifting winds have been hypothesized to explain the formation of curved iceberg scours observed in the southern Lake Agassiz basin[15]. However, winds would have acted over a longer time period and formed complex sets of cross-cutting scours with more diverse orientations and geometries than those observed in Hudson Bay. Regardless of the exact mechanism that produced the arcuate scours of Hudson Bay, their preferential orientation, high concentration, similar geometry, dominant orientations that coincide with those of larger sandwaves, occasional cross-cutting with other scours with convexities in the same direction, and location within a specific sector of the bay indicate that they were formed by short-lived unidirectional high-energy currents that remobilized icebergs floating in a former calving bay. In this context, the most likely event producing them is the final lake drainage.

Sandwaves are interpreted to have been formed during late-glacial times owing to the absence of very high-energy currents today in Hudson Bay[16] (Fig. 2) and to their partial burying under postglacial sediments[9]. Other catastrophic lake-drainage events have produced similar features, such as the Lake Missoula[17,18] and Altai Mountains[19] floods. The multibeam data reveal that sandwaves extend over more than 900 km across southern Hudson Bay, a much larger area than was previously known[9] (Fig. 2). Sandwaves (Fig. 3c,d; see Supplementary Information, Fig. S1) are observed S and SE of the arcuate iceberg scour zone between −100 and −190 m. They have a mean height (h_m) and wavelength (l_m) of 1.7 and 88 m, respectively: dimensions comparable to

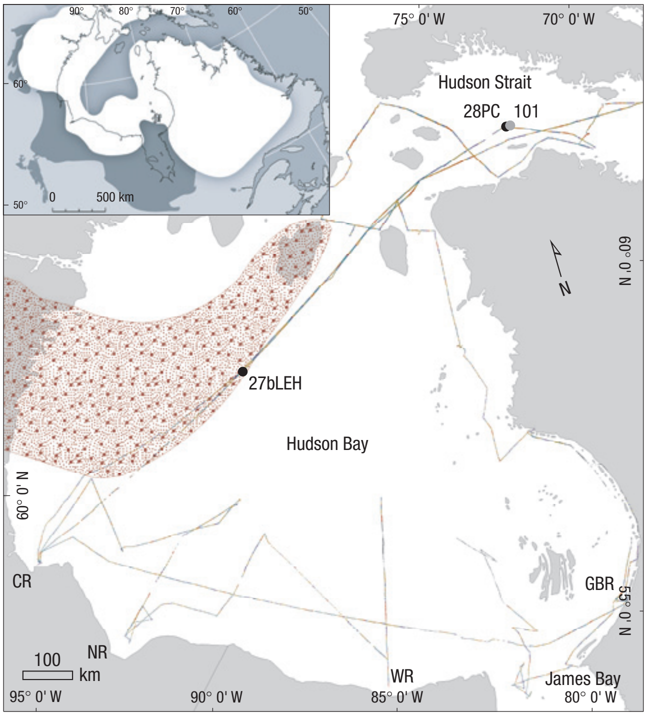

Figure 1 Map of Hudson Bay and Strait. Multibeam data (lines), locations of sediment cores containing the red layer (27bLEH and 28PC, this study; core 101, ref. 8) and the ferruginous till dispersal train (red speckles)[21] are shown, along with locations of the Churchill (CR), Nelson (NR), Winisk (WR) and Grande-Baleine (GBR) river mouths. Inset, the extent of Lake Agassiz–Ojibway (dark grey) and of the Laurentide Ice Sheet (white) 8.45 kyr ago (modified from ref. 13).

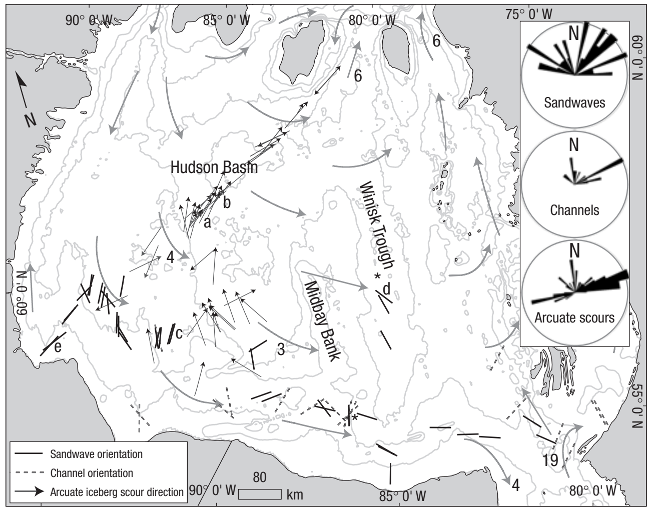

Figure 2 Locations and orientations of seafloor features inferred from multibeam data. Locations of Hudson Bay seafloor images (Fig. 3) are shown by letters **a**–**e**. Submarine features are located at the centres of their respective symbols shown on the map. Black arrows indicate perpendiculars to the arcs of the scour convexities, with the arrowheads pointing toward the convex side. Positions of channels mapped in ref. 9 are also shown (asterisks). Grey arrows indicate the modern surface circulation pattern and numbers indicate current velocities (cm s^{-1}) (ref. 16). 50 m isobaths are also shown.

those of sandwaves produced by other outburst floods[17–19] (see Supplementary Information, Table S1). The largest sandwaves are observed offshore from Churchill River ($h_m = 2.9$ m; $l_m = 114$ m; $h_{max} = 9$ m) and Winisk River ($h_m = 2.9$ m; $l_m = 130$ m; $h_{max} = 4$ m). Their orientations show that they were generated by a NW-NE flow (Figs 2,3), which is not coherent with the modern day anticlockwise currents[16] (Fig. 2). Although sandwaves may be locally disturbed by iceberg scours, they are found only in areas unaffected by the arcuate scours. Because sandwaves and arcuate scours were produced by the flood, the only way the former features could have been preserved during the arcuate scouring event is by being protected by overlying glacial ice. This indicates that the high-energy water flow associated with the flood produced the sandwaves subglacially. The possibility that sandwaves were deposited after and above the arcuate scours over an area free of Laurentide Ice Sheet (LIS) cover is ruled out because the sediment cover between the sandwave ridge crests is too thin to have completely obliterated the scours. Sandwaves are not restricted to areas near narrow passages on the seafloor where an increase in flow velocity would be expected owing to bathymetric constrictions, but are rather found on relatively flat bottom. The overlying ice sheet created a constriction effect during the flood to sufficiently increase subglacial water flow velocities, leading to the formation of sandwaves even on a flat seafloor.

Channels form elongated depressions eroded in till and bedrock. They are interpreted[9] to have been formed by confined high-energy flow under the LIS, because modern currents[16] prevailing in the sector where they occur do not generate enough energy to erode them. Previous mapping[9] showed that they generally trend northward toward Winisk Trough, a deep basin (−370 m) located in central Hudson Bay (Fig. 2). The multibeam data show that channels are also present offshore from the Grande-Baleine and Nelson rivers and they are not restricted to offshore from Winisk River (Fig. 2). These features are observed between −50 and −180 m and have orientations ranging from SE–NW to SW–NE (Fig. 2). They are in many cases more than 8 m deep and more than 75 m wide, with widths reaching more than 1 km offshore from Nelson River (Fig. 3e). They are observed within the sandwave zone and south of the arcuate scour zone. Till observed on some channel floors[9] implies that channels were already at least partially eroded into the bedrock when it was deposited and when Lake Agassiz–Ojibway drained. Moreover, sediment ridges previously observed within some channel floors may represent eskers[9]. These ridges could not have been deposited during the same short-lived event that eroded the channels, also indicating that some channel floors were eroded before the flood.

The two sediment cores collected in central Hudson Bay (27bLEH) and western Hudson Strait (28PC) (Figs 1,4; see Supplementary Information, Fig. S2) show a distinctive bed of red sediments[20]. Sediments composing this bed originate from ferruginous till covering the seafloor of western Hudson Bay[21] (Fig. 1). During the outburst flood, till was remobilized and transported northward by high-energy currents. Core 28PC is well correlated[20] with core 101 (ref. 8), which was previously associated with the lake drainage[6]. On the basis of this correlation[20] and by correcting the ^{14}C ages presented in ref. 8 using new radiocarbon-reservoir age data[22], we can estimate the age of the red bed as between 7,760 and 7,860 yr BP (conventional ^{14}C date corrected by −590 yr), which is close to the estimated date of 7,700 yr BP (8,470 cal yr BP) for the final drainage of Lake Agassiz–Ojibway[6]. The cores show that the red bed is coarser grained and thicker in the southern region, indicating its proximity to the sediment source. Grain-size and physical-property data also

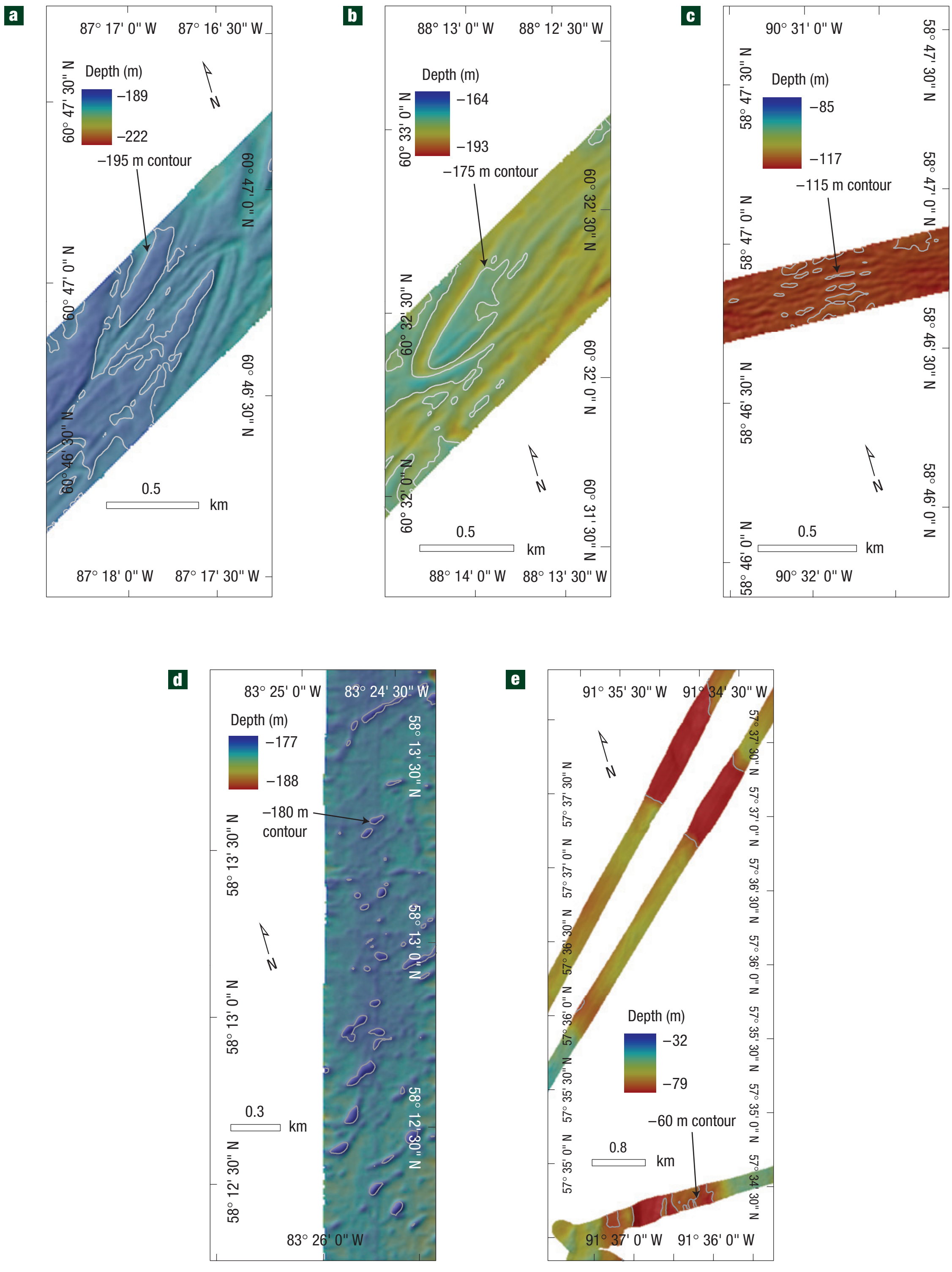

Figure 3 Seafloor images derived from the multibeam data. a, Arcuate iceberg scours with convexities dominantly to the ENE. Note the cross-cutting of the two scours with the same orientation. **b**, Arcuate iceberg scour with convexity to the WSW. **c**,**d**, Sandwaves (direction of flow is perpendicular to the ridge crests). **e**, Submarine channel. See Fig. 2 for the locations of the images. Multibeam data collected and processed by the Ocean Mapping Group, University of New Brunswick.

reveal that two stacked sequences of reverse to normal grading are present in both cores. Such reverse to normal grading is typical of hyperpycnites, that is, sediment layers deposited during major floods[23]. The apparent absence of hemipelagic sediments and ice-rafted debris between these two layers suggests that there was little time between these events. The absence of ice-rafted debris

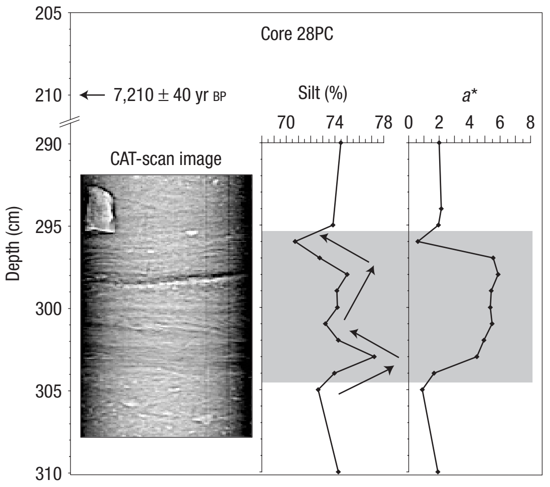

Figure 4 Grain-size characteristics of the red bed of core 28PC. The shaded zone highlights the red bed and the arrows indicate the grading. Note the two sequences of reverse and normal grading within the bed. An AMS ^{14}C date (BETA-221964) obtained on shell fragments is also shown. a^* values represent sediment colour ranging from $+60$ (red) to -60 (green). Ice-rafted debris (in lighter tones) is observed only above and below the red bed. Modified from ref. 20.

within the red bed and its presence in sediments above and below supports its rapid deposition.

The new seafloor data confirm the catastrophic nature of the Lake Agassiz–Ojibway final outburst flood. The sedimentary signature of the red bed deposited by the flood indicates that this event took place as two distinct and successive pulses. The observation of sandwaves across southern Hudson Bay in areas unaffected by arcuate iceberg scours indicates that they were formed below a protective overlying ice cover during the flood. We propose that the final outburst flood was triggered by hydraulic lifting due to the gradual thinning of the LIS following the formation of the south-flowing James Bay ice stream shortly before 8.6 cal kyr BP (ref. 24). Glacial lift-off is a well recognized trigger mechanism for ice-dammed-lake outburst floods[25]. It has been invoked to explain the rapid drainage of subglacial lakes in Iceland[26,27] and of some outflow pulses of Lake Missoula[18,28]. Ice-dam flotation occurs when the water level reaches 90% of the ice thickness, but this ratio can be reduced when the ice is heavily crevassed[26]. As occurred with the recent collapse of the Larsen B ice-shelf in Antarctica[29], a dense network of crevasses could have also developed on the LIS over Hudson Bay after the formation James Bay ice stream and before the lake drainage. During the flood, a lift-off could have enabled the high-pressure water of the lake to drain under the LIS along many routes in southern Hudson Bay. A hydraulic gradient[5] could have enabled the water to flow from the lake to the former calving bay after a connection was created between them by the ice lift-off. A multiroute outburst flood is also supported by the various directions of arcuate iceberg scours. Moreover, the widespread distribution of sandwaves and their presence outside channels indicate that the drainage routes were not restricted to these channels or to seams between the Keewatin and Québec–Labrador sectors of the LIS (ref. 5). Channels were probably not all eroded by the lake drainage event, owing to the presence of glacial deposits on some channel floors, implying a pre-lake drainage origin. The final outburst flood of Lake Agassiz–Ojibway therefore probably occurred as extensive sheet floods and along distinct flow routes, producing sandwaves and erosion channels, respectively, under buoyant glacial ice (that is, an ice-shelf). The larger sandwaves observed offshore from Churchill and Winisk rivers that coincide with the large number of arcuate scour convexities to the ENE, WSW, NNW and NW indicate that a stronger outflow originated from these sectors. Because sandwaves were produced subglacially, their southern limit represents the maximal northward extension of the lake and their northern limit reflects the extent of the ocean that had encroached in the heart of the LIS. These findings contribute to the understanding of palaeoceanographic records of the '8.2 kyr event', as well as the rapid land and sea surface changes associated with the complete disappearance of the LIS over Hudson Bay at this time.

METHODS

Multibeam data were collected using a Kongsberg Simrad EM-300 (12 kHz) echo-sounder onboard the CCGS Amundsen by the Ocean Mapping Group (University of New Brunswick) for the ArcticNet program. The multibeam data were processed using the SwathEd (Ocean Mapping Group) software. Data visualization and mapping was realized at Université Laval using the Fledermaus and ArcGIS softwares. The multibeam dataset can be seen on the Ocean Mapping Group website (www.omg.unb.ca). Colour reflectance measurements were made using a hand-held X-rite DTP22 digital swatch-book spectrophotometer and are reported as a^*, ranging from $+60$ (red) to -60 (green). The grain-size measurements were made with a Beckman–Coulter LS-13320 (0.04–2,000 μm) laser sizer. The grain-size data were then processed using the Gradistat software[30]. CAT-scan analysis was carried out at INRS-ETE[20]. The conventional ^{14}C date was corrected by -590 yr to account for the apparent age of the dissolved inorganic-carbon reservoir. This estimation was obtained by averaging the 16 reservoir ages available near core 28PC (ref. 22).

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