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A Laurentide outburst flooding event during the last interglacial period

Joseph A. L. Nicholl[1]*, David A. Hodell[1], B. David A. Naafs[2†], Claude Hillaire-Marcel[3], James E. T. Channell[4] and Oscar E. Romero[5]

Episodes of ice-sheet disintegration and meltwater release over glacial–interglacial cycles are recorded by discrete layers of detrital sediment in the Labrador Sea[1,2]. The most prominent layers reflect the release of iceberg armadas associated with cold Heinrich events[3], but the detrital sediment carried by glacial outburst floods from the melting Laurentide Ice Sheet is also preserved[4]. Here we report an extensive layer of red detrital material in the Labrador Sea that was deposited during the early last interglacial period. We trace the layer through sediment cores collected along the Labrador and Greenland margins of the Labrador Sea. Biomarker data, Ca/Sr ratios and δ^{18}O measurements link the carbonate contained in the red layer to the Palaeozoic bedrock of the Hudson Bay. We conclude that the debris was carried to the Labrador Sea during a glacial outburst flood through the Hudson Strait, analogous to the final Lake Agassiz outburst flood about 8,400 years ago, probably around the time of a last interglacial cold event in the North Atlantic[5]. We suggest that outburst floods associated with the final collapse of the Laurentide Ice Sheet may have been pervasive features during the early stages of Late Quaternary interglacial periods.

During Integrated Ocean Drilling Program (IODP) Expedition 303 (ref. 1), a distinctive red layer was noted in cores from the Eirik Drift (Site U1305: 57°29′ N, 48°32′ W, 3569 m water depth) and Orphan Knoll (Site U1302: 50°10′ N, 45°38′ W, 3459 m) in the Labrador Sea (Fig. 1). The red layer is ∼10 cm thick at Site U1305 and ∼20 cm thick at U1302 (Figs 2–4). The base of the layer is very sharp at both sites, suggesting rapid onset of deposition with little bioturbation. At Site U1305, the top of the layer is well defined, whereas at Site U1302 the top of the layer is more diffuse with a distinct tail, probably the result of mixing by bioturbation. The bright red colour of the layer is distinctive and marked by anomalously high values of a^* (red–green colour parameter) at both sites. A peak in the first derivative of the reflectance spectrum at 565 nm suggests that the red colour is primarily imparted by haematite in the sediment[6] (see Supplementary Information).

Core scanning X-ray fluorescence (XRF) measurements show high values of Ca/Sr in the red layer interval at both sites (Figs 3 and 4), indicating an increase in the proportion of strontium-poor detrital carbonate relative to strontium-rich biogenic carbonate[7]. The peak carbonate content of the sediment within the layer is ∼30% at Site U1305 and ∼40% at Site U1302. At Site U1305, the carbonate peak corresponds to a significant increase above background levels whereas at Site U1302 the increase is less

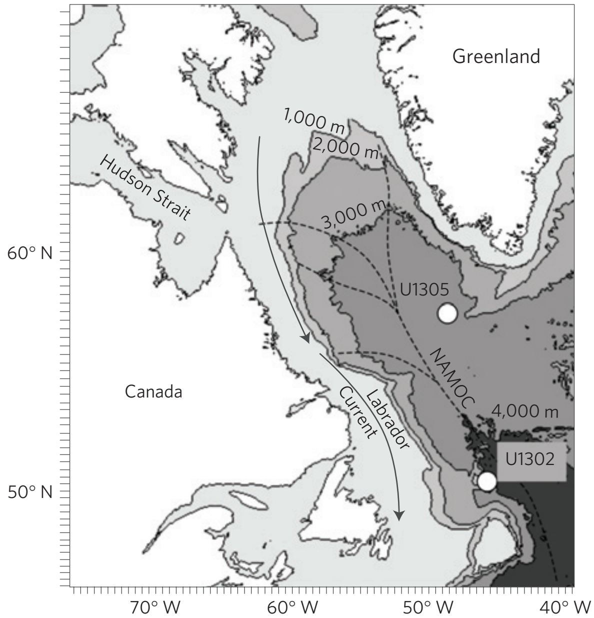

Figure 1 | Location map of the study area. Site U1302 is located on Orphan Knoll and Site U1305 on Eirik Drift. The NAMOC is marked with dashed lines. The Labrador Current is the primary surface current distributing material from the mouth of the Hudson Strait.

pronounced, most likely owing to relatively higher deposition rates of synsedimentary biogenic carbonate during the interval. Bulk carbonate δ^{18}O shows a strong decrease to values of about −5‰ (versus Vienna PeeDee Belemnite) within the red layer at both sites, which is typical of detrital carbonate from Hudson Bay[8].

Organic biomarkers provide further evidence of the source of the red layer. At both sites the red layer contains high abundances of a suite of organic compounds normally absent in recent sediments. These petrogenic compounds include carotenoid-derived aromatic hydrocarbons (for example, isorenieratane and palaerenieratane), aromatic steroids and secohopanoids (see Supplementary Information). The relative abundances of these compounds are approximately three times higher at Site U1302 than at Site U1305. Outside the red layer, their abundances are low or below detection limits. The samples with a high petrogenic compound abundance typically have low (0.4–0.8) C_{33}/C_{34} hopane and

[1]Godwin Laboratory for Palaéoclimate Research, Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK, [2]Alfred Wegener Institute for Polar and Marine Research, Department of Marine Geology and Paleontology, D-27568, Bremerhaven, Germany, [3]GEOTOP, Université du Québec à Montréal, Montréal, Québec H3C 3P8, Canada, [4]Department of Geological Sciences, University of Florida, Gainesville, Florida 32611, USA, [5]Institute of Earth Sciences of Andalucia, Universidad de Granada, Granada, 18002 Granada, Spain. †Present address: School of Chemistry, University of Bristol, Bristol BS8 1TS, UK. *e-mail: jaln2@esc.cam.ac.uk.

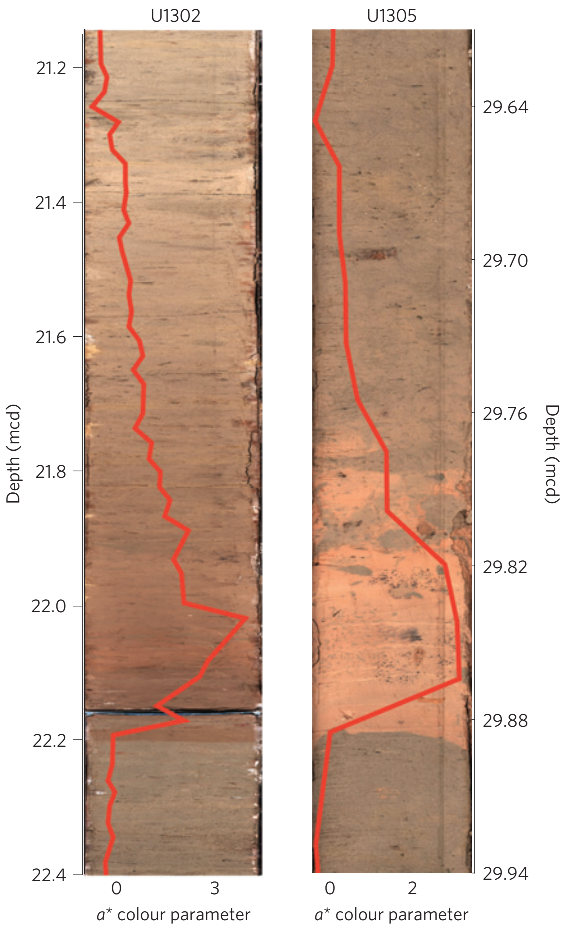

Figure 2 | Line-scan images showing the red layer at Sites U1302 and U1305. The red lines show the *a** colour reflectance parameter, indicating increased redness over the layer at both sites. Note the different depth scales on the two cores. The dark line at 22.16 m in Site U1302 is a section break in the core.

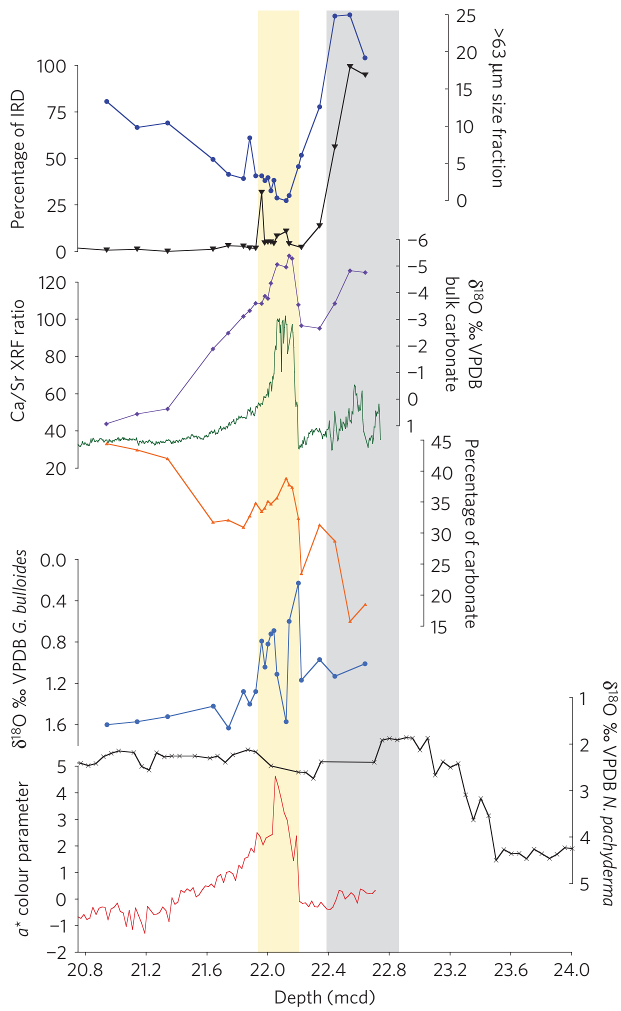

Figure 3 | Data from Site U1302. From top to bottom: weight per cent of sediment in the >63 μm size fraction (dark blue), percentage of grains that are IRD (black with triangles), $\delta^{18}O$ of bulk carbonate (purple), Ca/Sr measured by core-scanning XRF (green), weight per cent carbonate of the bulk sediment (orange), $\delta^{18}O$ of *G. bulloides* (blue), $\delta^{18}O$ of *N. pachyderma* (black with crosses), *a** colour reflectance parameter (red). The coloured bar indicates the position of the red layer. The grey bar indicates the H11 ice-rafting event.

hopanoid ratios (see Supplementary Fig. S3). The distributions of petrogenic compounds found at Sites U1302 and U1305 and their low C_{33}/C_{34} hopane and hopanoid ratios are identical to those in detrital carbonate-rich Heinrich layers from the Labrador Sea and North Atlantic[9–11].

The biomarker signature is incompatible with recent sediments and, together with the high Ca/Sr and low $\delta^{18}O$ values, strongly indicates that the carbonate in the red layer is detrital material from Palaeozoic bedrock of the Hudson Bay region of eastern Canada[9,10], the same source region for the carbonate contained in most Heinrich layers[12]. However, whereas Heinrich layers always include ice-rafted debris (IRD), the red layer does not. At both sites, the red layer contains very little sand-sized (>63 μm) sediment, particularly at Site U1305. At Site U1302, point counting shows a major peak in IRD (almost 100% of >150 μm grains) that we identify as Heinrich Event 11 (H11), but this horizon occurs 40 cm below the red layer. A previous study from Site U1302-1303, featuring a longer scanning XRF record, similarly identified H11 as a peak in Ca/Sr (detrital carbonate) before the deposition of the red layer[2]. A minor peak in IRD concentration (~30% of >150 μm) at Site U1302 immediately above the red layer does not contain detrital carbonate IRD grains and is unlikely to share a source with the red layer. The relative lack of IRD immediately beneath the red layer indicates that it is distinct from H11.

Age models for Sites U1302-1303 and U1305 have been constructed using $\delta^{18}O$ records measured on the planktonic foraminifer *Neogloboquadrina pachyderma* (sinistral)[13] combined with relative palaeointensity records at Site U1302-1303 (ref. 2). At both sites the age models suggest that the red layer occurs after the transition to Marine Isotope Stage 5e (MIS 5e), at ~126 kyr BP (ref. 2). However, owing to meltwater discharges associated with deglaciation, the planktonic $\delta^{18}O$ decrease at these sites may predate the start of the last interglacial period in the global benthic $\delta^{18}O$ record[13], although the use of relative palaeointensity at Site U1302-1303 is designed to account for this effect[2]. Nevertheless, the red layer clearly post-dates H11 (~128.5 kyr BP; ref. 2), which records from the open Atlantic show occurred late during Termination II (refs 14,15), suggesting that the red layer occurs early during MIS 5e. Close to Site U1305, in Core MD99-2227, carbonate-rich layer DC5 (refs. 16), deposited during MIS 5e, possibly corresponds to the red layer.

At Site U1302, we measured $\delta^{18}O$ of the planktonic foraminifer *Globigerina bulloides*, which inhabits the surface mixed layer[17] and shows a distinct decrease in $\delta^{18}O$ values within the red layer of up to ~1‰ (Fig. 3), suggesting either the addition of fresh water into the surface water, or the mixing of isotopically light brines

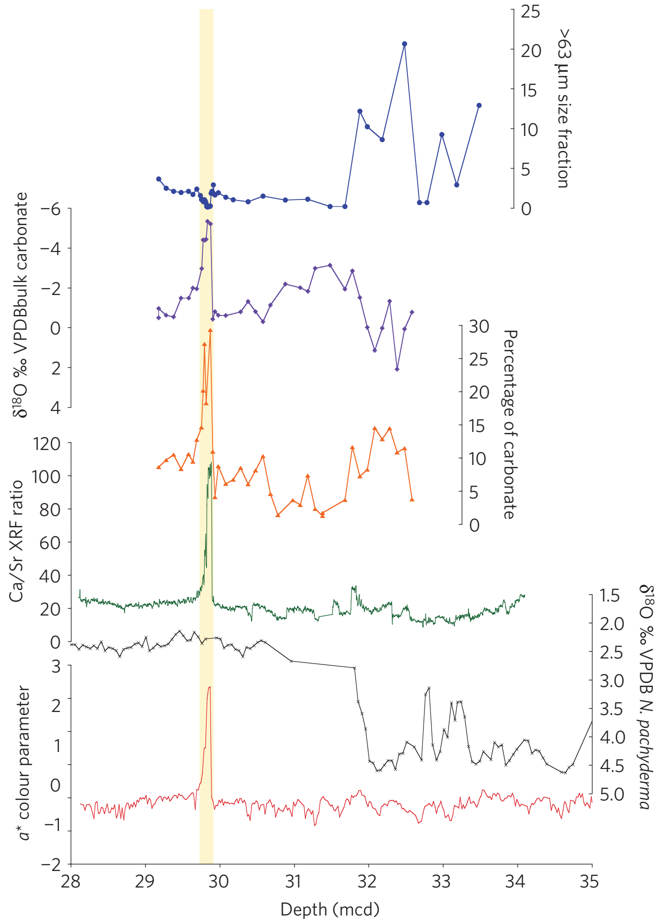

Figure 4 | Data from Site U1305. From top to bottom: weight per cent of sediment in the >63 µm size fraction (dark blue), $\delta^{18}O$ of the carbonate in the bulk sediment (purple), weight per cent carbonate of the bulk sediment (orange), Ca/Sr measured by core scanning XRF (green), $\delta^{18}O$of *N. pachyderma* (black), *a** colour reflectance parameter (red). The coloured bar indicates the position of the red layer.

resulting from sea-ice spreading linked to the freshening event[13]. A similar $\delta^{18}O$ decrease is not seen in the red layer in *N. pachyderma*, which has a deeper habitat than *G. bulloides*[17] and is sensitive to the formation of brines[13], suggesting that the lowered *G. bulloides* $\delta^{18}O$ is recording freshwater release into the shallow mixed layer[17].

The lack of coarse IRD within the red layer indicates that it was not deposited directly by iceberg rafting. Deposition of the red layer from surface plumes of suspended sediment is also unlikely, as both sites are several hundred kilometres from the mouth of the Hudson Strait, a likely conduit for material from Hudson Bay, and, in the case of Site U1305, upstream of the present-day surface water currents in the region[18]. Thus, the two sites studied are out of the range of direct plume deposition[19], although we cannot totally discount some transport of fine particulate material by sea ice. Nevertheless, we propose that the most likely mode of transport and deposition was through turbidity currents along the sea floor. The Northwest Atlantic Mid-Ocean Channel (NAMOC) that extends down the centre of the Labrador Sea provides a conduit through which turbidity currents can flow, occasionally overspilling their banks to deposit material to either side[20,21]. This creates a route by which sediment released through the Hudson Strait could reach the two sites without the need to invoke ice rafting or surface plume transportation. The lack of a similar detrital carbonate-rich red layer at Site U1306, which is close to Site U1305 but at a shallower depth and farther from NAMOC, lends support to this proposed mechanism of deposition and provides further evidence against ice rafting.

A turbidity-induced overspill has been suggested to explain the presence of fine-grained material released through the Hudson Strait near Eirik Drift coincident with Heinrich events[22]. If the red layer did occur following Termination II then the Laurentide Ice Sheet would probably have been diminished in size, and possibly too small to produce a Heinrich-style surge. Besides, any such surge would have resulted in coarse-grained IRD at Site U1302 during or immediately adjacent to the red layer. Furthermore, the carbonate layers deposited during Heinrich events, including H11, do not exhibit a strong red colour, indicating a fundamental difference in the source and triggering mechanism of the two types of deposit.

A detrital carbonate-rich, red-coloured layer was deposited in the Hudson Strait during the final outburst of glacial Lake Agassiz, some 8.4 kyr ago[23–25]. A previous study has noted the deposition of the red layers after both Terminations I and II, and suggested that they signify extensive deglaciation of the Hudson Bay region[26]. The similarities between the sediment deposited and the relative timing of the final Lake Agassiz drainage event of Termination I, and the event described herein for the early last interglacial period suggest a common cause. The potential source for the red material in the sediment layer resulting from the final draining of Lake Agassiz is a till incorporating red Proterozoic rocks outcropping to the northwest of Hudson Bay[23,27], whereas the detrital carbonate probably originates from the Hudson Strait till overlying Palaeozoic carbonates[12]. If northwest Hudson Bay was indeed the source area for sediment incorporated into the early MIS 5e red layer, as it was for the final 8.4 kyr BP drainage event from Lake Agassiz, then a similar transport mechanism may have carried this material to the Labrador Sea.

To explain the occurrence of a large turbidite deposit, along with the transport and deposition of material from Hudson Bay, we suggest that the trigger for the deposition of the layer during early MIS 5e was a large glacial outburst flood from a precursor to glacial Lake Agassiz. Previous studies have shown that this is a viable mechanism to explain the deposition of turbidites in the Labrador Sea[4]. A decrease in $\delta^{18}O$ of *G. bulloides*, but not *N. pachyderma*, similar to that observed in the red layer, has been observed during the Lake Agassiz final drainage in a core close to Site U1302 (ref. 17), supporting this conclusion. However, the decrease in $\delta^{18}O$ of *G. bulloides* was smaller (approximately −0.5‰) during the Lake Agassiz drainage than for the MIS 5e event. During the Lake Agassiz drainage, no red material reached either of the sites analysed in this study, and no detrital carbonate reached Site U1305 (ref. 18), making the layer less extensive than the MIS 5e red layer. We speculate that the outburst flood during early MIS 5e may have been greater in magnitude than that of the last deglaciation, although further evidence is required to confirm this.

The Lake Agassiz final drainage event has been associated with the 8.2 kyr BP cooling event through a perturbation of the Atlantic meridional overturning circulation and/or through an atmospheric circulation reorganization following the collapse of the residual ice sheet in Hudson Bay[18]. The 8.2 kyr BP event is recognized in a variety of global climate signals including a cooling in the circum-North Atlantic[28,29]. Similar perturbations may have occurred multiple times during Termination I, even during periods of intermediate ice volume[30], and such events may have also occurred during previous terminations. The red layer described here may be related to cold event C28 in the North Atlantic[5], which was a period of sea surface cooling and change in circulation represented by a decrease in benthic foraminiferal $\delta^{13}C$, early during MIS 5e. Our observations suggest that the final outburst flood from Lake Agassiz during the last deglaciation was not unique. Glacial outburst floods from Lake Agassiz precursors may have been a common occurrence during earlier final collapses of the Laurentide Ice Sheet. Indeed, analogous detrital layers have been identified in interglacials dating back to ∼600 kyr BP at Site U1302-1303 (ref. 2) although these do not exhibit the distinctive red colour. It is possible that these layers resulted from a similar process. If this is the case, the associated deposits and climatic impacts of such events should be found in other high-resolution climate records.

Methods

Data. The data have been archived online at www.pangaea.de/.

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References

1. Channell, J. E. T. *et al.* Expedition 303 summary *Proc. IODP* **303/306,** http://dx.doi.org/10.2204/iodp.proc.303306.101.2006 (2006).
2. Channell, J. E. T. *et al.* A 750-kyr detrital-layer stratigraphy for the North Atlantic (IODP Sites U1302–U1303, Orphan Knoll, Labrador Sea). *Earth Planet. Sci. Lett.* **317,** 218–230 (2012).
3. Broecker, W., Bond, G., Klas, M., Clark, E. & McManus, J. Origin of the northern Atlantic's Heinrich events. *Clim. Dynam.* **6,** 265–273 (1992).
4. Shaw, J. & Lesemann, J-E. Subglacial outburst floods and extreme sedimentary events in the Labrador Sea. *Geol. Soc. Amer. Special Papers* **370,** 25–41 (2003).
5. Oppo, D. W., McManus, J. F. & Cullen, J. L. Evolution and demise of the Last Interglacial warmth in the subpolar North Atlantic. *Quat. Sci. Rev.* **25,** 3268–3277 (2006).
6. Deaton, B. & Balsam, W. L. Visible spectroscopy—A rapid method for determining hematite and goethite concentration in geological materials. *J. Sediment. Res.* **61,** 628–632 (1991).
7. Hodell, D. A., Channell, J. E. T., Curtis, J. H., Romero, O. E. & Röhl, U. Onset of Hudson Strait Heinrich events in the eastern North Atlantic at the end of the middle Pleistocene transition (∼640 ka)? *Paleoceanography* **23,** PA4218 (2008).
8. Hodell, D. A. & Curtis, J. H. Oxygen and carbon isotopes of detrital carbonate in North Atlantic Heinrich Events. *Mar. Geol.* **256,** 30–35 (2008).
9. Rosell-Mele, A., Maslin, M. A., Maxwell, J. R. & Schaeffer, P. Biomarker evidence for Heinrich events. *Geochim. Cosmochim. Acta* **61,** 1671–1678 (1997).
10. Rashid, H. & Grosjean, E. Detecting the source of Heinrich layers: An organic geochemical study. *Paleoceanography* **21,** PA3014 (2006).
11. Naafs, B. D. A., Hefter, J., Ferretti, P., Stein, R. & Haug, G. H. Sea surface temperatures did not control the first occurrence of Hudson Strait Heinrich Events during MIS 16. *Paleoceanography* **26,** PA4201 (2011).
12. Hemming, S. R. Heinrich Events: Massive Late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Rev. Geophys.* **42,** RG1005 (2004).
13. Hillaire-Marcel, C., De Vernal, A. D. & Mckay, J. Foraminifer isotope study of the Pleistocene Labrador Sea, northwest North Atlantic (IODP Sites 1302/03 and 1305), with emphasis on paleoceanographical differences between its inner and 'outer' basins. *Mar. Geol.* **279,** 188–198 (2011).
14. Lototskaya, A. & Ganssen, G. M. The structure of Termination II (penultimate deglaciation and Eemian) in the North Atlantic. *Quat. Sci. Rev.* **18,** 1641–1654 (1999).
15. Rasmussen, T. L. Deep sea records from the southeast Labrador Sea: Ocean circulation changes and ice-rafting events during the last 160,000 years. *Paleoceanography* **18,** 1018 (2003).
16. Evans, H. F. *et al.* Paleointensity-assisted chronostratigraphy of detrital layers on the Eirik Drift (North Atlantic) since marine isotope stage 11. *Geochem. Geophys. Geosyst.* **8,** Q11007 (2007).
17. Hillaire-Marcel, C. & Bilodeau, G. Instabilities in the Labrador Sea water mass structure during the last climatic cycle. *Can. J. Earth Sci.* **37,** 795–809 (2000).
18. Hillaire-Marcel, C., De Vernal, A. & Piper, D. J. W. Lake Agassiz final drainage event in the northwest North Atlantic. *Geophys. Res. Lett.* **34,** L15601 (2007).
19. Hesse, R., Khodabakhsh, S., Klaucke, I. & Ryan, W. B. F. Asymmetrical turbid surface-plume deposition near ice-outlets of the Pleistocene Laurentide ice sheet in the Labrador Sea. *Geo-Mar. Lett.* **17,** 179–187 (1997).
20. Hesse, R. Drainage systems associated with mid-ocean channels and submarine yazoos: Alternative to submarine fan depositional systems. *Geology* **17,** 1148–1151 (1989).
21. Hillaire-Marcel, C., de Vernal, A., Bilodeau, G. & Wu, G. Isotope stratigraphy, sedimentation rates, deep circulation, and carbonate events in the Labrador Sea during the last ∼200 ka. *Can. J. Earth Sci.* **31,** 63–89 (1994).
22. Stoner, J. S., Channell, J. E. T. & Hillaire-Marcel, C. The magnetic signature of rapidly deposited detrital layers from the deep Labrador Sea: Relationship to North Atlantic Heinrich layers. *Paleoceanography* **11,** 309–325 (1996).
23. Kerwin, M. W. A regional stratigraphic isochron (ca . 8000 14C yr B.P.) from final deglaciation of Hudson Strait. *Quat. Res.* **46,** 89–98 (1996).
24. St-Onge, G. & Lajeunesse, P. Flood-induced turbidites from northern Hudson Bay and western Hudson Strait: A two-pulse record of Lake Agassiz final outburst flood? *Submar. Mass Mov. Consequences* **27,** 129–137 (2007).
25. Lajeunesse, P. & St-Onge, G. The subglacial origin of the Lake Agassiz–Ojibway final outburst flood. *Nature Geosci.* **1,** 184–188 (2008).
26. Carlson, A. E. Why there was not a Younger Dryas-like event during the penultimate deglaciation. *Quat. Sci. Rev.* **27,** 882–887 (2008).
27. Shilts, W. W. in *Glaciation of the Hudson Bay region.* (ed. Martini, I. P.) 55–78 (Canadian Inland Seas, Elsevier Oceanography Series, 1986).
28. Alley, R. B. *et al.* Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology* **25,** 483–486 (1997).
29. Barber, D. C. *et al.* Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* **400,** 344–348 (1999).
30. Clark, P. U. *et al.* Freshwater forcing of abrupt climate change during the last glaciation. *Science* **293,** 283–7 (2001).

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Author contributions

J.A.L.N. and D.A.H. conceived the project, collected and interpreted the data, and drafted the paper. J.E.T.C. and D.A.H. identified site locations and collected the cores during IODP Expedition 303. B.D.A.N. performed the biomarker analysis and interpreted the data. C.H-M. produced the oxygen isotope stratigraphies. All authors contributed to data interpretation and the writing of the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.