Geology
August 2022, Volume 50 Issue 8 Pages 934-938
https://doi.org/10.1130/G49956.1
https://archimer.ifremer.fr/doc/00769/88128/

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Extensive evidence for a last interglacial Laurentide outburst (LILO) event

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Abstract :

A catastrophic last interglacial Laurentide outburst (LILO) event approximately 125,000 years ago (125 ka) may have contributed to abrupt climate change during the last interglacial. It has been proposed that this event was an analog of the Holocene 8.2 ka event. We characterize in detail the (1) provenance, (2) timing, and (3) delivery mechanism of a layer of red sediments deposited across much of the northwestern Atlantic Ocean at 125 ka. Our observations provide strong support for the occurrence of a LILO event that was analogous to the 8.2 ka event in all three aspects, and likely surpassed it in magnitude. The freshwater discharge associated with the 125 ka LILO event may explain a series of abrupt global changes, including a reduction of the North Atlantic Deep Water and reinvigoration of the Antarctic Bottom Water. Our findings suggest that the mechanism that triggered the LILO event may be an integral part of the deglacial sequence of events, during which the final collapse of the contiguous Laurentide Ice Sheet took place 3.5–4 k.y. after full interglacial temperature was reached in the middle and high northern latitudes.

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Introduction

Approximately 8200 years ago, large proglacial Lakes Agassiz and Ojibway (central North America) burst through the ice dam formed by the Laurentide Ice Sheet (LIS) remnant and discharged via the Hudson Strait into the North Atlantic Ocean (Barber et al., 1999). The ice dam collapsed because of the marine-terminating outlet and the presence of subglacial till in the Hudson Bay region (Licciardi et al., 1998; Stokes and Tarasov, 2010; Tarasov et al., 2012). The so-called "8.2 ka event" has subsequently been speculated to have been caused by the accelerated melting of the ice dam due to the positive feedback between mass balance and elevation (Carlson et al., 2008; Gregoire et al., 2012). The 8.2 ka event, the largest abrupt climate change during the Holocene, had global climate impacts (Alley and Ágústsdóttir, 2005).

~~Previously, it was~~ Nicholl et al. (2012) suggested that a red layer of sediments with a sharp basal contact in the Labrador Sea might be evidence of an analogous catastrophic event during the last interglacial (LIG). Their seminal finding was important and intriguing, given that a long-noted feature of the 8.2 ka event is the deposition of a red layer around the Hudson Strait (Table S2 in the Supplemental Material[1]). Nicholl et al. (2012) also speculated that the red layer's distribution might be more widespread than documented in their study, inspiring a more extensive survey of evidence for the deposition of the red layer, and better constraints on the age of the LIG red layer and its geographical distribution. We employed physical, chemical, and chronological methods [[analyses?]] on deep-sea sediment cores to document evidence for the counterpart of the 8.2 ka event during the LIG.

METHODS

The identification of the red layer relies on archive core photos and color reflectance data archived in the International Ocean Discovery Program (IODP) Janus database (~~Text S1 in~~ see the Supplemental Material **[[There is no need to number each section in the supplemental text]]**). We examined all **[[all existing? Or all cores from specific studies?]]** drill cores from the western and central North Atlantic Ocean, with the exceptions of those from tropical regions and those without age models, in order to locate the LIG layer.

Core EW9303-37JPC (43.68°N, 46.28°W, 3981 m water depth, International Geo Sample Number [IGSN]: DSR000507; hereafter core EW37JPC) is a jumbo piston core retrieved off the coast of Newfoundland, Canada.**[[Indicate what organization drilled this core, and when.]]** A chronology for this core was previously established by correlating the percentage of foraminifer *Neogloboquadrina pachyderma* to another sea-surface temperature record (Zhou et al., 2021). The chronology indicates that the sedimentation rate at this site is 10 cm/k.y. on average. We identified a red layer in this core at 1220 cm core depth, roughly the interval of the last interglacial. To further constrain the red layer's age, we added new $\delta^{18}O$ measurements from the epifaunal benthic foraminifera species *Cibicidoides wuellerstorfi* to an existing record (McManus et al., 2002) (see the Supplemental Material). Our new data cover the entire Marine Isotope Stage (MIS) 5, and triple the resolution of the previous benthic $\delta^{18}O$ record of McManus et al. (2002). The new age model also increases the number of age-control points during MIS 5 to 140 from the previous 7 of Zhou et al. (2021).

We used flux fusion measurements of elemental concentrations to calibrate the scanning X-ray fluorescence (XRF) Fe count data from core EW37JPC. The method is described in detail elsewhere (Zhou et al., 2021). We calculated Fe flux by multiplying the bulk sediment mass flux record by the calibrated Fe concentration data.

DISCUSSION

Five cores in the northwestern Atlantic, and possibly a sixth, contain red layers in the LIG sediment (Figs. 1A and 2). Even excluding the sixth, the cores span an astounding linear distance of >3000 km from the Labrador Sea to the subtropical Atlantic. In the sixth core, from Ocean Drilling Program (ODP) Site 1061, we found a red layer, but its ambiguous bottom contact and nominally younger age lowered our confidence in the identification. The presence of the red layer was previously reported in two IODP cores, from Sites U1302 and U1305 (Nicholl et al., 2012).

PROVENANCE

The sediment layer's red color likely comes from the oxidation of iron-rich minerals, likely hematite (Giosan et al., 2002). Red, hematite-rich sediments can be found in the Dubawnt Formation[[**Dubawnt Supergroup, according to Weblex Canada?** **(all instances)**]] in the northern Hudson Bay (Sanford et al., 1979; Shilts, 1980). The Dubawnt Formation red sediments likely spread to Mansel and Coats Islands in the Hudson Bay (Aylsworth and Shilts, 1991) (Fig. 1). In core EW37JPC, the iron-rich composition of the red layer is corroborated by the associated increase in Fe flux data (Fig. 3I).

The provenance of the 125 ka red layer in core EW37JPC may be further narrowed down by Ca/Sr ratios (Nicholl et al., 2012). High Ca/Sr in the North Atlantic has been used as an indicator of detrital carbonates originating through the Hudson Strait (Hodell et al., 2008; Channell et al., 2012b). In core EW37JPC, Ca/Sr within the 125 ka red layer is the highest observed throughout the last glacial cycle (Zhou et al., 2021) (Fig. 3G), similarly suggesting a Hudson Strait–Hudson Bay source.

The spatial distribution of the 125 ka red layer might provide yet another clue to the layer's origin. Four of the six cores where we identified the red layer are adjacent to the meandering ~~of the~~ Northwest Atlantic Mid-Ocean Channel (NAMOC; see the Supplemental Material). The other two cores, from ODP Sites 1063 and 1061, are in the general downstream direction from where mapping of the NAMOC ends. It may be that the unmapped portion of the NAMOC extends further toward the two cores. Submarine density flows have previously been shown to transport sediments hundreds to thousands of kilometers away from their source (Talling et al., 2007). A submarine density flow originating from the Hudson Strait would thus have been capable of spreading the red layer along the NAMOC to ~3000 km away. One core we examined near the eastern edge of the NAMOC, from ODP Site 647, does not appear to contain the red layer. The absence of the red layer at this location may be due to Coriolis deflection of the sediments westward (Chough and Hesse, 1976).

Red-colored sediments deposited during the 8.2 ka event have been noted in 17 cores in and around the Hudson Strait (Fig. 1B). The 8.2 ka red layer is not as extensive as the 125 ka one, but both are likely derived from the Hudson Strait based on their spatial distribution. Peaks of Ca/Sr and Fe flux that fit the timing of the 8.2 ka event are also evident in core EW37JPC (Fig. 3H), consistent with a Hudson Strait origin.

TIMING

In five cores with the red layer, the respective chronologies place the age of the red layer at 125 ± 5 ka (see the Supplemental Material). In the core from ODP Site 1061, the red layer is dated to the early part of MIS 5 (Grützner et al., 2002), although the existing chronology precludes a more precise placement.

Our identification of the red layer's occurrence relative to the core EW37JPC benthic $\delta^{18}O$ record and the alignment of the EW37JPC record to a benthic $\delta^{18}O$ stack offer the most confident stratigraphic and chronological placement of the red layer among the six cores (Fig. S1 in the Supplemental Material). The age model puts the red layer at 125.0 ka with a nominal 2σ uncertainty of 0.5 k.y. (see the Supplemental Material). However, a visual inspection of the $\delta^{18}O$ alignment indicates that this assessment of the age uncertainty is overly optimistic, and we instead use the maximum age uncertainty of the entire record (3 k.y.) as a more robust estimate of the uncertainty associated with the age of the red layer. The 125.0 ka timing of the red layer is 4 k.y. after the onset of LIG warmth, absolutely dated to 129 ± 1 ka (Drysdale et al., 2005). This 4 k.y. interval is similar to the length of time between the 8.2 ka event and the Holocene onset at 11.7 ka (Walker et al., 2009). We suggest that this similarity in timing is not a coincidence. The delivery of the red sediments may result from a coherent deglacial sequence of events that took place near the beginning of both the current and the last interglacial. The implication is that 3.5–4 k.y. after full interglacial temperature is reached, the LIS seems to repeatedly experience instabilities that originate from the Hudson Strait region.

The duration of time represented by the deposition of the red layer in core EW37JPC can be estimated by excess ^{230}Th ($^{230}Th_{xs}$) profiling, a technique previously employed to estimate the durations of Heinrich events (Francois and Bacon, 1994), or by our age model (see the Supplemental Material). Using these approaches, we estimate the event that deposited the red layer to be briefer than 126 yr (Fig. S2). This is in line with estimate of 160.5 yr for the duration of the 8.2 ka event based on ice-core data (Thomas et al., 2007).

DELIVERY

The 125 ka red layer in core EW37JPC is characterized by high mass flux and low coarse fraction (Figs. 3A and 3K). Previously, it was suggested that either iceberg calving events or meltwater-induced submarine density flows caused the high mass-flux peaks in EW37JPC (Zhou et al., 2021). The fraction of coarse sediment, defined as the mass >63 μm relative to the whole, can be a differentiating factor between the two potential mechanisms. In this core, each Heinrich event during the last glacial cycle was characterized by increases in both the coarse fraction and mass flux, most likely related to the rapid deposition of ice-rafted debris across the entire grain-size spectrum. On the other hand, a mass-flux increase with a contemporaneous decrease in the relative proportion of coarse sediment implies the rapid deposition of silt and clay alone.

The sediment-transport category of density flow includes turbidity currents that deposit graded sediments and debris flows that deposit poorly sorted fine sediments (Mulder and Alexander, 2001). The essential absence of coarse grains in the core EW37JPC red layer may be the result of a debris flow with a high sediment concentration compared to a turbidity flow (Mulder and Alexander, 2001). Alternatively, the red layer could have been produced by a turbidity flow that deposited its coarse sediments upstream. Both debris flows and turbidity flows can travel as far as 1500 km, and a decelerating turbidity flow can evolve into a debris flow (Talling et al., 2007), although the inferred 3000 km transport of the 125 ka red layer appears unprecedented and deserves more attention.

The delivery of sediments by density flow has been suggested for the 8.2 ka event (St-Onge and Lajeunesse, 2007). In core EW37JPC, the 8.2 ka event, like the 125 ka red layer, is associated with high sedimentary mass flux and low coarse fraction. Density flows may thus have been responsible for both the 8.2 ka and the 125 ka red layers, indicating yet another important similarity between the two events.

LAST INTERGLACIAL LAURENTIDE OUTBURST (LILO) EVENT

We have offered three lines of evidence—provenance, timing, and delivery mechanism—that the 125 ka red layer was caused by a LIG event analogous to the 8.2 ka event. We suggest naming the LIG analog of the 8.2 ka event as the last interglacial Laurentide outburst (LILO) event.

The proposed LILO event coincides with a series of abrupt changes globally during the LIG (Fig. 4). The North Atlantic Deep Water (NADW) underwent rapid reductions (Galaasen et al., 2014) while the Antarctic Bottom Water (AABW) reinvigorated after a stagnation (Hayes et al., 2014). The Antarctic temperature also experienced a small but detectable rise (Jouzel et al., 2007). The North Atlantic's freshening would have increased the buoyancy flux of the surface water and may have slowed down the NADW production (Galaasen et al., 2014) (Fig. 4C). We infer that the LILO event may have seen a higher peak discharge rate than the 8.2 ka event, judging from the far more widespread distribution of the LILO red layer. This difference could explain the more prominent NADW reduction during the LILO event than the 8.2 ka event (Kleiven et al., 2008; Galaasen et al., 2020). The freshening of the North Atlantic combined with the persistence of vertical mixing could have decreased the deep ocean density, presenting a deficit to be filled by the AABW (Broecker, 1998), thus leading to the AABW resumption (Hayes et al., 2014) (Fig. 4B). The NADW reduction may also have curbed the upper branch of the Atlantic Meridional Overturning Circulation. With the associated northward heat transport from the Southern Hemisphere to the Northern Hemisphere diminished, Antarctica temperature rose as a result (Fig. 4A), a process often referred to as the bipolar seesaw[[Cite Broecker, 1998?]].

Before the ice dam between the Keewatin and Labrador ice domes collapsed during the 8.2 ka event, the LIS was about the same size as, or slightly larger than, the Greenland Ice Sheet (Dyke et al., 2003) (Fig. 1B). Likewise, before and after the LILO event took place, the LIS may have been in a similar configuration as [[during? or before and after?]] the 8.2 ka event, and the existing sea-level data do not preclude that possibility (see the Supplemental Material). We suggest that the ice dam's collapse that broke up the contiguous LIS into smaller ice domes is an integral part of the deglacial sequence of events, taking place 3.5–4 k.y. after full interglacial temperature is achieved. In this framework, the 8.2 ka and LILO events [[each?]] represent the "last gasp" of the LIS before its summary demise.

CONCLUSIONS

Our study lays out three lines of evidence that a red layer of sediment was deposited at 125 ka throughout the northwest Atlantic Ocean by a LIG analog of the 8.2 ka event:

(1) Similar to the 8.2 ka red layer, the 125 ka red layer likely originated from the Hudson Strait given its high Ca/Sr, red color, high Fe flux, and occurrence along the NAMOC.

(2) The 8.2 ka and LILO events both occurred 3.5–4 k.y. after the onset of the full warming associated with their respective interglacial intervals.

(3) In core EW37JPC, the 125 ka red layer was deposited rapidly and with mostly fine sediments. This, together with the red layer's occurrence along the NAMOC, suggests that a density flow triggered by an 8.2 ka–style glacial outburst or accelerated melting likely delivered the red sediments.

~~We suggest naming the LIG analog of the 8.2 ka event the LILO event.~~ **[[Already stated on line 167, and the acronym is used previous to this sentence in this Conclusions section.]]** The proposed LILO event can explain a series of abrupt global climate changes, including a reduction of the North Atlantic Deep Water and reinvigoration of the Antarctic Bottom Water. The existence of the LILO event suggests that the same mechanism that triggered the 8.2 ka event may be an integral part of the deglacial sequence of events, wherein the breakdown of the contiguous LIS takes place 3.5–4 k.y. after full interglacial temperature is established.

ACKNOWLEDGMENTS

We thank Julia Gottschalk and Sid Hemming for discussions that led to this project. We thank Kassandra M. Costa for sharing the core EW37JPC XRF data, and James E.T. Channell for sharing data from Ocean Drilling Program Site 1063. This research used samples and/or data provided by the International Ocean Discovery Program (IODP). Y. Zhou acknowledges the support from the IODP Schlanger Fellowship. This research was funded in part by U.S. National Science Foundation grant AGS 16-35019 to J. McManus, with additional support from the Gary Comer Family Foundation (Chicago, Illinois, USA) Abrupt Climate Change Fellowship, and the

Columbia University Climate Center (New York, USA). We thank Lev Tarasov and an anonymous reviewer for comments that greatly improved the manuscript.

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FIGURE CAPTIONS

Figure 1. Extent of red sediment layers during the 125 ka and 8.2 ka events. (A) Red circles are core locations [[**correct?**]] with a red layer present during the last interglacial. White circles indicate the layer is not present. Black line is the Northwest Atlantic Mid-Ocean Channel (NAMOC). LILO—last interglacial Laurentide outburst. Core EW9303-37JPC is marked as EW37JPC. Also marked are the distribution of Dubawnt Group[[**See query in the text regarding Dubawnt Formation versus Supergroup**]] red beds including sedimentary and volcanogenic rock (Aylsworth and Shilts, 1991) as well as limestone and dolomite bedrock (Bond et al., 1992). (B) Red diamonds indicate core locations with a red layer during the 8.2 ka event. Details on the cores can be found in Tables S1 and S2 (see footnote 1). Blue and white polygons are the lake and ice extents,

respectively, at 8.45 ka B.P.[[Change to either “kyr B.P.” or “ka”, just prior to 8.2 ka event (Dyke et al., 2003).

[[In the figure, replace the hyphen with a space in “125 ka” and “8.2 ka”]]

Figure 2. North Atlantic sediment core images that show red layers. The red layer can be found at International Ocean Discovery Program (IODP) Expedition 303 Site U1305 (IODP 303–1305), red layer C4H2, 30 cm[[Specify what parameter this value refers to (core depth? measurement from top of the core segment? thickness of the red layer?)]]; Ocean Drilling Program (ODP) Leg 105 Site 646 (ODP 105–646), red layer B2H5, 20 cm; IODP Expedition 303 Site U1302 (IODP 303–1302), red layer C2H6, 100 cm; [[Indicate what organization drilled this core]]core EW9303-37JPC (EW37JPC), 1220 cm; ODP Leg 172 Site 1063 (ODP 172–1063), red layer B4H5, 25 cm; and ODP Leg 172 Site 1061 (ODP 172–1061), red layer D4H7, 45 cm. Age of the red layer is interpolated from published age models for IODP 303–1305 (Nicholl et al., 2012), ODP 105–646 (Aksu and Hillaire-Marcel, 1989), IODP 303–1302 (Channell et al., 2012b), EW37JPC (this study), ODP 172–1063 (Channell et al., 2012a), and ODP 172–1061 (Grützner et al., 2002). Color reflectance (a*) data or red/green ratios (R/G) from digital-image RGB channels are overlain on the images. No color data are available from ODP 105–646. MIS—Marine Isotope Stage.

[[In the figure, change instances of “~” to “ca.” followed by a space; in the “a*” axis descriptions, include units of measure in parentheses]]

Figure 3. Sedimentary proxy measurements from North Atlantic sediment core EW9303-37JPC. (A,B) Coarse fraction (>63 µm) (Zhou et al., 2021). (C,D) Benthic $\delta^{18}O$ measurements on *Cibicidoides wuellerstorfi* (this study; McManus et al., 2002). Black line in C is Prob-stack**[[Cite Ahn et al., 2017?]]** (see the Supplemental Material [see footnote 1]). (E,F) Planktic $\delta^{18}O$ measurements on *Neogloboquadrina pachyderma* (Zhou et al., 2021). (G,H) Ca/Sr (Zhou et al., 2021). (I,J) Fe flux (this study). (K,L) Mass flux based on excess ^{230}Th ($^{230}Th_{xs}$) (Zhou et al., 2021). Pink shadings are last interglacial Laurentide outburst (LILO) and 8.2 ka events; gray shadings mark warm Marine Isotope Stages (MISs) 5e, 5c, and 5a and the Holocene; blue shadings denote Heinrich 11 event (H11) and the Younger Dryas (YD).

[[In the figure, change instances of “yrs BP” to “yr B.P.”; remove all italics from all vertical-axis descriptions; insert a space in instances of “63 µm”; replace hyphen with a space in “8.2 ka”; change instances of “kyr” to “k.y.” preceded by a space (for time spans “4 k.y.” and “3.5 k.y.”) or a slash (in units of measure in vertical-axis descriptions for panels I, J, K, and L)]]

Figure 4. Last interglacial Laurentide outburst (LILO) event’s relation to other last interglacial abrupt changes. MIS—Marine Isotope Stage; H11—Heinrich 11 event. (A) Antarctic ice core δD from Dome C (core EDC) (Jouzel et al., 2007).**[[Explain the difference between the two lines (thin versus thick)]]** (B) Antarctic South Atlantic authigenic uranium mass-accumulation rate (aU MAR) from Ocean Drilling Program Site 1094 (Hayes et al., 2014). (C) North Atlantic benthic $\delta^{13}C$ from core MD03-2664 (IMAGES P.I.C.A.S.S.O cruise on the R/V *Marion Dufresne*; Galaasen et al.,

2014).**[[Explain the difference between the two lines (thin versus thick)]]** (D,E) Ca/Sr and mass flux from core EW9303-37JPC (same as Figs. 3G and 3I**[[3K? (3I shows Fe flux, not mass flux)]]**).

[[In the figure, change “yrs BP” to “yr B.P.”; remove all italics from all vertical-axis descriptions; change instances of “kyr” to “k.y.”; in units of measure, use slashes instead of negative exponents for consistency with the rest of the paper (e.g., change “µg cm^{-2} k.y.$^{-1}$” to “µg/cm^{2}/k.y.”); in panel B, change “Southern Ocean” to “South Atlantic” for consistency with the caption (or vice versa)]]

[1] Supplemental Material. **[[Please provide a brief caption here]]**. Please visit https://doi.org/10.1130/XXXX to access the supplemental material, and contact editing@geosociety.org with any questions.