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Was there a glacial outburst flood in the Torngat Mountains during Marine Isotope Stage 3?

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ABSTRACT

We report previously unpublished evidence for a Marine Isotope Stage 3 (MIS 3; 60-26 ka) glacial outburst flood in the Torngat Mountains (northern Quebec/Labrador, Canada). We present ^{10}Be cosmogenic exposure ages from legacy fieldwork for a glacial lake shoreline with evidence for outburst flooding in the Torngat Mountains, with a minimum age of 36±3 ka (we consider the most likely age, corrected for burial, to be ~56 ±3 ka). This shoreline position and age can potentially constrain the Laurentide Ice Sheet margin in the Torngat Mountains. This region, considered a site of glacial inception, has no published dated geologic constraints for high-elevation MIS 3 ice margins. We estimate the freshwater flux associated with the inferred glacial outburst flood using high-resolution digital elevation maps corrected for glacial isostatic adjustment. Using assumptions about the ice-dammed locations we find that a freshwater flood volume of 1.14x10^{12} m^3 could have entered the Hudson Strait. This glacial outburst flood volume could have contributed to surface ocean freshening to cause a measurable meltwater signal in δ^{18}O records, but would not necessarily have been associated with substantial ice rafted debris.

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Future work is required to refine estimates of the size and timing of such a glacial outburst flood. Nevertheless, we outline testable hypotheses about the Laurentide Ice Sheet and glacial outburst floods, including possible implications for Heinrich events and glacial inception in North America, that can be assessed with additional fieldwork and cosmogenic measurements.

SHORT SUMMARY:

We present data from fieldwork completed in 2002 for a glacial lake in the Torngat Mountains (Northern Quebec and Labrador, Canada). We dated the lake to ~56 ±3 ka and estimated the freshwater volume that may have been released during an outburst flood. The location of this glacial lake is surprising because the Torngat Mountains are considered a site of glacial inception, and this shoreline suggests the region was not ice-covered throughout the North American ice sheet growth phase.

MOTIVATION

MIS 3 Heinrich events, ice sheets, and climate variability

Millennial-scale climate oscillations in the Northern Hemisphere are prominent features of Marine Isotope Stage 3 (MIS 3; 60-26 ka). Abrupt iceberg discharge episodes, known as Heinrich events (Hemming, 2004), passed through the Hudson Strait repeatedly during MIS 3. The cause for Heinrich events remains enigmatic, especially in relation to synchronous temperature changes recorded in Greenland ice cores (Dansgaard-Oeschger events; Bond *et al.*, 1993). These massive ice-rafted debris (IRD) episodes are associated with freshwater anomalies in the North Atlantic, alluding to the potential role of Heinrich events in modulating Atlantic

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53 overturning circulation, and thereby global climate change (Henry et al., 2016; Seidenkrantz et
54 al., 2021) (Figure 1).
55
56 A variety of mechanisms have been proposed to explain Heinrich events, including cycles of
57 large ice sheets reaching an instability (Macayeal, 1993), massive catastrophic outburst floods
58 from a glacially-dammed Hudson Strait (Johnson and Lauritzen, 1995), subglacial lake drainage
59 (Alley et al., 2006), ice shelf instability (Hulbe et al., 2004) or ice shelf collapse in response to
60 warming (Marcott et al., 2011), large tidal forces (Arbic et al., 2008), and ocean forcing (Bassis
61 et al., 2017). Each hypothesis involves MIS 3 North American Ice Sheet dynamics, since ice-
62 rafted debris carried by icebergs is derived from land formerly beneath the Laurentide Ice Sheet
63 (Hemming, 2004); however, the ice sheet's exact relationship to Heinrich events is debated
64 (Rashid and Piper, 2007; Rashid et al., 2019).

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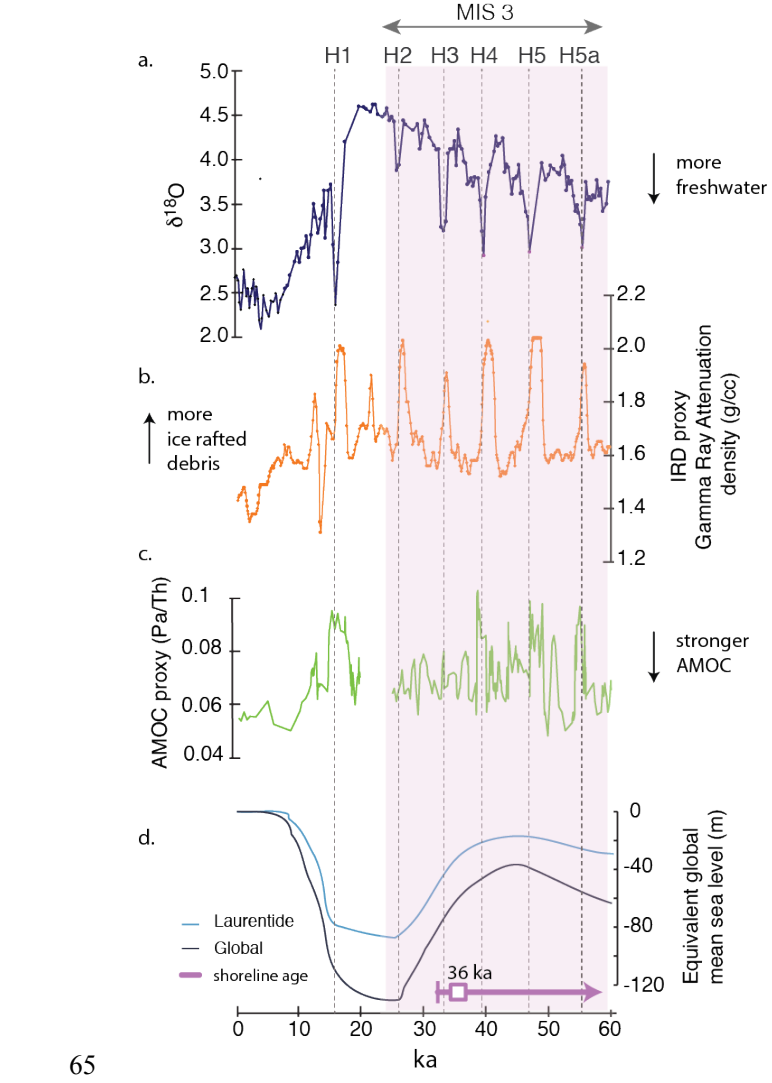

Figure 1 | A. δ^{18}O record from core 303-U1302 B. ice rafted debris (IRD) proxy, Gamma Ray Attenuation density (Channell et al., 2012) C. Atlantic Meridional Overturning Circulation (AMOC) proxy, Pa/Th ratio (Henry et al., 2016; McManus et al., 2004) D. Equivalent global mean sea level associated with the ICE-PC2 ice history (Pico et al., 2017) used to calculate glacial isostatic adjustment correction globally (black) and for the Laurentide Ice Sheet (blue). Purple bar shows shoreline age uncertainty (33-59 ka; minimum age = 36±3 ka, likely age corrected for

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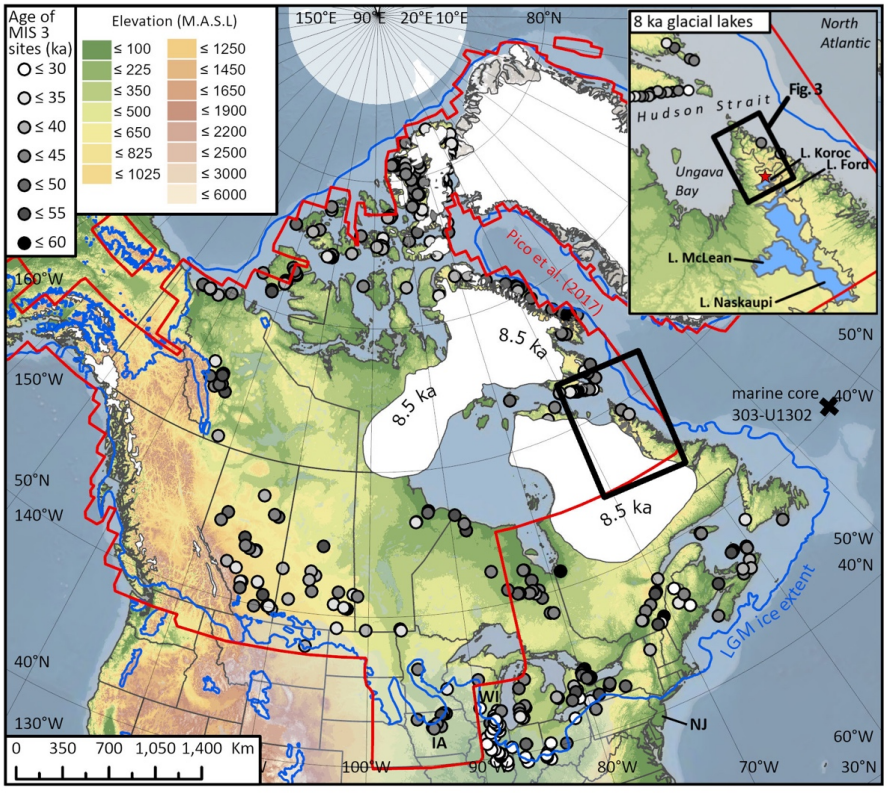
72 burial = 56±3 ka). Shaded purple bar encompasses Marine Isotope 3 (MIS 3; 60-26 ka) and vertical dashed black
73 line note the timing of Heinrich events.



74

75 Figure 2 | Map showing the study area (black rectangle) along with the approximate location of the Laurentide Ice
76 Sheet at ~8.5 ka yr cal. BP, which may serve as an analogue for creating ice-dammed lakes such as the one
77 documented in this study (white; Dalton et al., 2020). The locations of MIS 3 materials spanning 60 ka to 25 ka are
78 also shown (points; Dalton et al., 2019), along with the 44-ka ice margin from Pico et al. (2017). Marine core 303-
79 U1302 location is shown by a black cross (Channell et al., 2012). Elevation data from United States Geological
80 Survey's Center for Earth Resources Observation and Science (EROS 2010) and continental shelf data from
81 http://www. naturalearthdata.com/. NJ= New Jersey, WI= Wisconsin, IA=Iowa. Inset shows the location of
82 deglacial 8 ka glacial lakes in the Torngat Mountains region, including glacial lake Koroc, glacial lake McLean, and

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83 glacial lake Naskaupi from Dube-Loubert et al. (2018). The black rectangle shows study area included in Figure 3
84 and red star is the study site.
85
86 *MIS 3 Laurentide Ice Sheet*
87 The precise configuration of the Laurentide Ice Sheet during the interval leading into the Last
88 Glacial Maximum (LGM) would help to elucidate the origin of Heinrich events and their
89 variability across MIS 3, especially the potential source areas for ice-rafted debris and/or
90 meltwater pulses (Hemming, 2004). Although documenting the growth of the Laurentide Ice
91 Sheet is challenged by the sparsity of preserved records, recent work has refined Laurentide Ice
92 Sheet extent and volume during MIS 3. In particular, there is an increasing number of non-
93 glacial deposits in the Hudson Bay lowlands (Dalton et al., 2016), St. Lawrence lowlands (Parent
94 et al., 2015), Repulse Bay (Mcmartin et al., 2019), New England (Munroe et al., 2016), and
95 Atlantic Canada (Remillard et al., 2017), dated between 60 and 35 ka (Figure 2). This evidence
96 suggests a substantially reduced ice sheet at ~50-35 ka relative to the LGM, with ice possibly
97 restricted to two separate domes over eastern and western Canada at that time (Dalton et al.,
98 2019). However, concerns have been raised about the robustness of these chronologies, in
99 addition to the longstanding assumption that a large ice sheet is necessary to produce Heinrich
100 events (Miller and Andrews, 2019).
101
102 Regardless of the configuration of the Laurentide Ice Sheet between ~50-35 ka, there is
103 evidence for glacial advance towards maximum extent by ~45-35 ka in various locations. Key
104 pieces of evidence come from the dating of moraine deposits in Wisconsin (40-35 ka; Carlson et
105 al., 2018; Ceperley *et al.*, 2019), sub-till organic-bearing deposits in Iowa (45 and 35 ka; Kerr *et*

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106 *al.*, 2021),and evidence for abrupt blockage of northward water drainage in the eastern United
107 States around this time (~38 ka; Karig and Miller, 2013). In combination, these datasets suggest
108 either a rapidly advancing ice sheet from a Hudson Bay ice dome or a substantially revised ice
109 sheet arrangement that entails many separate ice caps.
110
111 Building on this observational evidence, glacial isostatic adjustment (GIA) analysis using
112 anomalously high sea-level markers along the United States mid-Atlantic dated to 50-35 ka
113 supports a late and rapid eastern Laurentide glaciation, suggesting that Laurentide ice volumes
114 increased four-fold from mid-MIS 3 to the LGM (Figure 1D; Pico et al., 2017). GIA analyses
115 based on sea-level records located on the ice sheet's peripheral bulge can determine total ice
116 volume in a given region, but not the precise geographic distribution. For example, although
117 there is evidence for a reduced MIS 3 Laurentide Ice Sheet, it cannot be determined whether
118 the Torngat Mountains, in northern Quebec and Labrador, were glaciated during MIS 3 (Pico et
119 al., 2018). Dynamic ice-sheet modeling studies implicate the Torngat Mountains as a site of
120 glacial inception (Otieno and Bromwich, 2009).
121
122 Following the notion that the Torngat Mountains were a key area of glacial inception through
123 the Quaternary (Koerner, 1980; Ives, 1957) , this region is often depicted as fully glaciated
124 throughout MIS 3 (Batchelor et al., 2019), as well as across the entire interval of the last
125 glaciation phase, even during interstadials such as MIS 5a and 5c (Stokes et al., 2012).
126 Understanding the extent of glaciation in the Torngat Mountains is thus key to developing a
127 unified time-space history of Laurentide Ice Sheet growth because of its critical location as the

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assumed site of inception for the Labrador Dome. However, only two shell ages on the Labrador coastline, dated with conventional radiocarbon methods, exist as MIS 3 ice sheet constraints (Figure 2). At present, no dated geologic constraints on MIS 3 ice sheet cover exist in the high-elevation regions of the Torngat Mountains.

Here we report previously unpublished data from legacy fieldwork suggesting an MIS 3 glacial lake and outburst flood in the Torngat Mountains (pre-LGM glacial lake Koroc, Figure 3). This evidence, including ^{10}Be ages on a wave-cut shoreline, puts forth a series of testable hypotheses about MIS 3 Laurentide configuration and Heinrich events. Did extensive valley glaciers bound this glacial lake during MIS 3? Were high elevation regions of the Torngat Mountains glaciated across MIS 3? Did glacial outburst floods coincide with Heinrich events? How large could glacial outburst floods have been in the Torngat Mountains?

This evidence for glacial lake outburst flooding in the Torngat mountains calls for deeper investigation via additional fieldwork, which could constrain the ice margins and quantify the freshwater flux associated with MIS 3 Torngat outburst floods. The presence of an MIS 3 glacial lake would preclude a full glaciation of the Torngat Mountains and would suggest freshwater from an outburst flood drained into the Hudson Strait, through Ungava Bay. We explore possible implications for MIS 3 Heinrich events by calculating the freshwater flux associated with such a glacial outburst flood using high-resolution digital elevation maps corrected for glacial isostatic adjustment.

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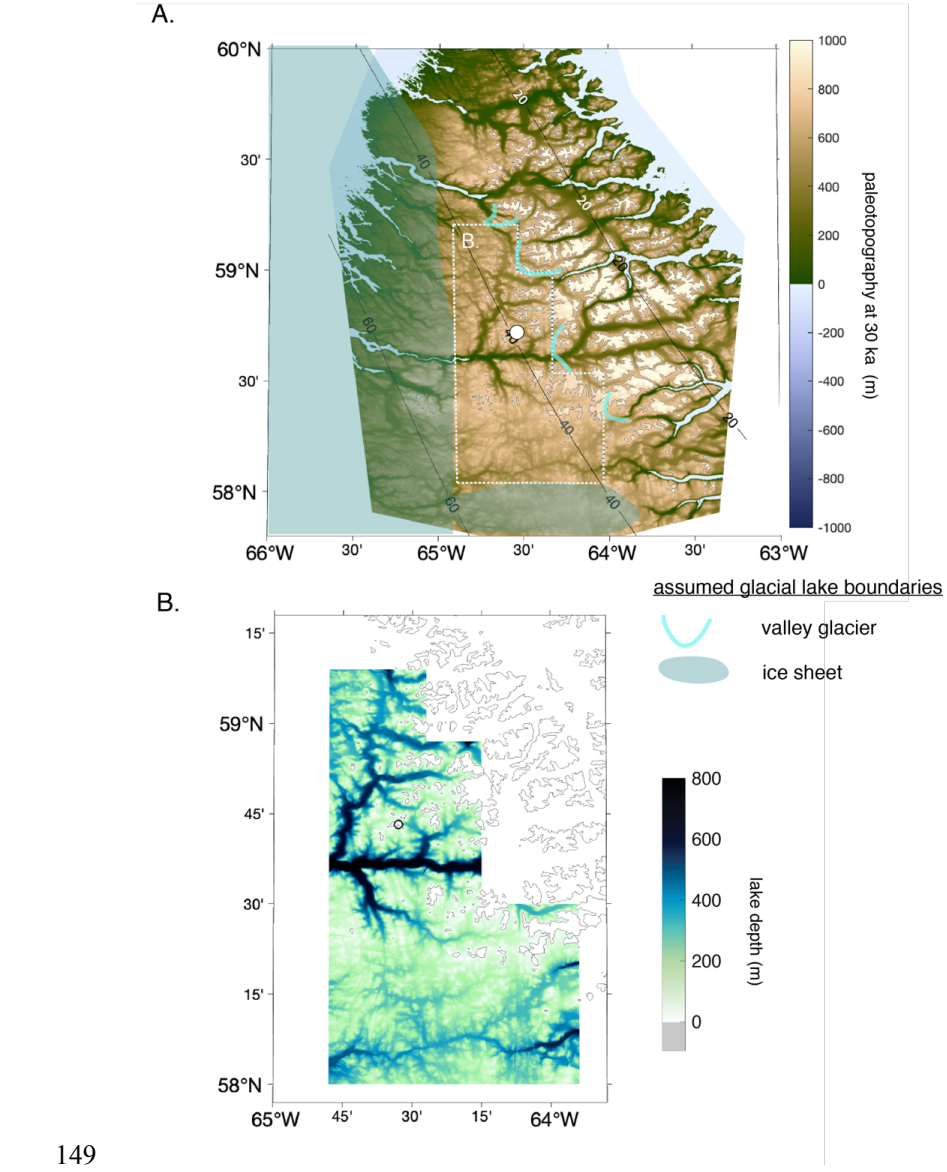

149

150 Figure 3 | A. Paleotopography of study region corrected for glacial isostatic adjustment at 36 ka. Labeled contours
151 note relative sea-level change due to glacial isostatic adjustment (positive values are higher relative sea level, or
152 equivalently lower topography). The assumed glacial lake boundary is shown by a dashed white line, and the shaded
153 region shows the assumed ice sheet location. Blue curves show the assumed location of blockage by valley glaciers.

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B. Calculated lake depth in pre-LGM glacial lake Koroc. White circle shows location age is measured on lake shoreline.

METHODS

Field setting

The Torngat Mountains in north-central Quebec and Labrador form a narrow, north–south-trending, high spine that weaves above a gently westward-dipping (0.8°) subsummit plateau (Figure 3A). East–west trending valleys cut across the plateau, which is currently covered by frost-riven felsenmeer fields and dotted by towering tors. The macroscale features represent a palimpsest landscape with formative valley incision dating to the Mesozoic era (Centeno, 2005), now bearing evidence of modification by Quaternary glaciation.

The Torngat's U-shaped valleys are rife with flutes, moraines, roches moutoneés, striations and other indicators of the glacial and deglacial history. These attracted exploration and research from various landscape historians (Ives, 1958; Ives et al., 1978; Clark, 1987; Clark et al., 2000; Jansson, 2003; Jansson and Kleman, 2004; Barnett and Peterson, 1964; Staiger et al., 2005; Dube-Loubert et al., 2018; Andrews, 1973; Gray et al., 1993; Marquette et al., 2004). Ives (1958; 1978) interpreted the "weathering zones" above the valleys as trimlines of older, more voluminous glaciations. Later, Marquette et al.(2004) and Staiger et al.(2005) documented the presence of LGM-aged erratic boulders perched on older, angular felsenmeer slabs at high elevations, indicating that all but perhaps the highest few peaks >1800m were ice-covered. This observation was corroborated using cosmogenic burial dating of the plateau surfaces that indicate

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177 a complex burial history consistent with several phases of waxing and waning ice domes – the
178 last of which included a dome of the LIS likely centered on Ungava Bay (Staiger et al., 2005).
179
180 In the most recent deglaciation, the retreating margin dammed meltwater from flowing to the
181 ocean, forming large glacial lakes with shorelines around 500 m asl at its fullest extent in more
182 extensive lakes to the south in the George River valley, including Lake Naskaupi and Lake
183 McLean (Jansson, 2003; Allard et al., 1989; Jansson and Kleman, 2004; Rice et al., 2019).
184 Shorelines associated with Glacial Lake Naskaupi have been well-mapped and were dated to 8.3
185 ka using cosmogenic nuclide exposure dating (Dube-Loubert et al., 2018; Dube-Loubert and
186 Roy, 2017). Subsequently, these low-elevation lakes drained when the ice thinned enough to
187 allow them to release meltwater into Ungava Bay. Draining of Glacial Lake Koroc, Glacial Lake
188 Naskaupi, and other nearby glacial lakes into Ungava Bay (in addition to drainage of Glacial
189 Lake Agassiz and Ojibway into the Hudson Bay (Barber et al., 1999), has been invoked as
190 potential meltwater sources to trigger the 8.2 ka cold episode recorded in Greenland ice cores
191 (Jansson and Kleman, 2004).
192
193 The “intermediate zone” - between the high elevation peaks/plateau and the glacial valleys -
194 contain incipient felsenmeer, lacustrine beach sediments, and glacial drift covering bedrock with
195 scant evidence of glacial erosion. To our knowledge, indicators of high elevation lakes in the
196 Torngat Mountains have not been previously documented in the literature. This study considers
197 the outlines of an individual glacial lake in the “intermediate zone” at 890 m elevation in
198 Labrador-Ungava, Canada in the present-day Kuururjuaq National Park in Québec, Canada. This

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199 glacial lake was identified based on geomorphological mapping of shorelines, spillways, and
200 drainage channels containing rounded cobbles and gravel entering the lake at high elevation.
201
202 *Cosmogenic dating*
203 During a 2002 field campaign, two locations were sampled to determine ^{10}Be ages on bedrock
204 surfaces from a well-developed shoreline at 890 m elevation (Figure 3; white circle). The
205 shoreline is an erosional feature, and there is a small inlet channel at this elevation with rounded,
206 imbricated cobbles, suggestive of outburst flooding (Figure 4).
207

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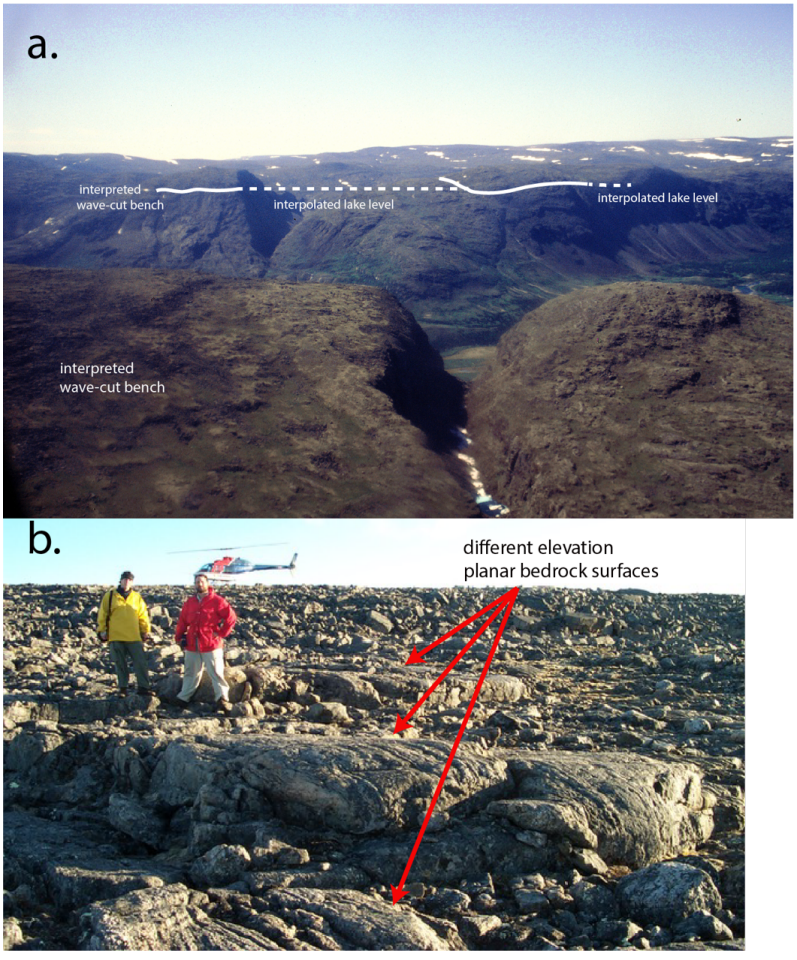

Figure 4 | A. Photograph of view above interpreted wave-cut bench shoreline with high elevation shoreline visible across the valley. B. Photograph of planar bedrock surfaces with people for scale. Photographs courtesy of J. Willenbring and J. Gray.

Samples were collected from the gneissic bedrock wave-cut bench, whose surface did not appear highly weathered, using a hammer and chisel. The highest level of the lake was ~3m above the sample location. The lowest wave-cut bench level at this elevation was chosen in order to sample deeper into the cosmogenic nuclide production zone, thus minimizing inherited ^{10}Be in the bedrock in this area (Staiger et al., 2005). Samples were collected in 2002, as part of the field

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campaign reported in Staiger et al. (2005). Sample preparation and quartz separation were carried out according to standard laboratory protocols developed at the Dalhousie Cosmogenic Dating Laboratory (Willenbring Staiger, 2005). The $^{10}Be/^{9}Be$ ratios were measured at Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory (California, USA). Ages were calculated with version 3 of the online calculator (http://hess.ess.washington.edu/) Uncertainties reflect 2σ analytical uncertainties (external uncertainties) in the AMS analyses. Be carrier is from a shielded beryl, prepared by J. Klein. Chemical blanks from the lab at that time ranged from 1.9 × 10 to 3.9 × 10 Be atoms. AMS was completed at the at Lawrence Livermore National Laboratory (LLNL). AMS targets were prepared at Dalhousie University. Concentrations were normalized to SLHL production rate in order to compare samples from differing locations.

The reported ages assume no erosion or ice cover. Many processes control cosmogenic nuclide production including erosion, burial by snow or vegetation, and changing atmospheric concentrations(Gosse and Phillips, 2001). Although the history of ice burial and erosion is unknown, based on prior regional studies, the apparent exposure age at our site's elevation of 890 m is likely less than 20 ky (Staiger et al., 2005). We considered the impact of GIA-induced subsidence on our age calculation(Jones et al., 2019). Nevertheless, this correction is small (~100s years) compared to age uncertainty related to ice cover or erosion, and thus we did not quantify an age correction for GIA.

Glacial isostatic adjustment simulations

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To reconstruct paleotopography during MIS 3 we simulate sea-level (or equivalently topographic) change using gravitationally self-consistent glacial isostatic adjustment modeling. Our calculations are based on the theory and pseudo-spectral algorithm described by Kendall et al. (2005) with a spherical harmonic truncation at degree and order 256. These calculations include the impact of load-induced Earth rotation changes on sea level (Milne & Mitrovica, 1996), evolving shorelines and the migration of grounded, marine-based ice (Johnston, 1993; Milne et al., 1999; Lambeck et al., 2003; Kendall et al., 2005). Our predictions require models for Earth's viscoelastic structure and the history of global ice cover. We adopt the viscosity profile VM2, and ice history ICE-PC2, which is characterized by a rapid growth of the eastern Laurentide Ice Sheet from 44 to 26 ka (Pico et al., 2017). We calculate paleotopography at 36 ka and 56 ka by subtracting the simulated sea-level change from the present-day regional digital elevation model.

Glacial lake volume calculation

We extracted a 0.75 arc second resolution digital elevation model from the Canadian Digital Elevation Model project (https://maps.canada.ca/czs/index-en.html) of the region shown in Figure 3. The glacial lake shoreline feature was measured at 890 m elevation. Lake extent was delineated by assuming an ice margin to the southwest similar to where the 8 ka Glacial lake Koroc shorelines are inferred (Figure 2 inset; Figure 3A; shaded blue). Because this lake is at high elevation, it is not presently bounded to the east by higher topography. We assumed that valley glaciers (long-recognized to have existed regionally during glaciations; Ives, 1958), descended from these high elevation regions, and this glacial ice would have bounded this

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glacial lake during MIS 3 (Figure 3A; blue lines). Pre-LGM glacial Lake Koroc is defined by rectangular bounds in our study for simplicity (Figure 3; dashed white line), given that MIS 3 ice-dam locations are unknown. We reconstructed paleotopography at 36 ka by correcting for sea-level (or equivalently topographic) change using gravitationally self-consistent glacial isostatic adjustment modeling (contours; Figure 3A). We calculated the lake volume by summing the area multiplied by the water depth in each grid cell.

RESULTS & DISCUSSION

Glacial lake shoreline age

An age of 36±3 ka is calculated assuming a continuous exposure with no erosion or burial (Supplementary Table 1), and therefore may be considered a minimum exposure duration. Erosion of exposed surfaces removes built-up cosmogenic nuclides, and ice cover reduces cosmic ray exposure. Fully accounting for these processes is not possible, but would lead to older exposure ages (Jones et al., 2019). Similar elevation sites nearby in the Torngat Mountains studies have a maximum apparent exposure age (combined history of erosion and ice cover) of 20 ky (Staiger et al., 2005).

Although the duration of ice cover at this site is unknown, there is evidence for ice cover at the LGM (Staiger et al., 2005), and this region likely deglaciated between 11 and 8 ka (Dalton et al., 2020). The age correction for ice burial depends on the timing of glaciation, which occurred after the existence of pre-LGM glacial lake Koroc. For example, if ice advanced over our site at 30 ka and the entire area was glaciated until 10 ka, then there would have been 20 ky of ice cover,

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286 which would shift the age to 56 ka. We therefore consider 36±3 ka to represent a minimum age,
287 and 56 ±3 ka a likely age for the identified pre-LGM glacial lake Koroc. Future work could
288 include measuring the ratio of two cosmogenic nuclides, such as paired $^{26}Al/^{10}Be$ isotope data.
289 Such paired isotope data would improve our understanding of ice burial and erosional history at
290 this site, better constraining the chronology of this wave-cut shoreline feature and granting
291 insight into the longer-term exposure history.
292
293 How would this glacial lake shoreline feature have been preserved? The presence of non-erosive
294 cold-based ice could have allowed the preservation of this wave-cut bench and small channel
295 with imbricated rounded cobbles. Felsenmeer has been documented at this elevation range in the
296 Torngat Mountains, which suggests the presence of a cold-based ice sheet (Staiger et al., 2005).
297 Future fieldwork could include mapping of shoreline features across this valley, and other
298 valleys within the Koroc River area. Other glacial lake outlets likely existed, and mapping these
299 features would better quantify the history of flood routing.
300
301 *Glacial lake outburst volume estimate*
302 We calculated the possible freshwater volume associated with an outburst flood event from the
303 pre-LGM glacial lake Koroc based on an 890 m elevation glacial lake shoreline (white circle;
304 Figure 3) and assumed ice-dammed locations (dashed white line; Figure 3). A shoreline elevation
305 of 851 m at 36 ka was determined by subtracting 39 m, the magnitude of topographic change at
306 36 ka due to glacial isostatic adjustment at this site (Figure 3A; contours).
307

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Figure 3B shows the lake depth associated with the reconstructed extent of the pre-LGM glacial lake. This calculation results in a glacial lake water volume of 1.14×10^{12} m^3. If a glacial lake outburst flood of this magnitude lasted three days (within the range of typical glacial outburst flood (jokulhaup) duration; Bjornsson, 2010), a freshwater flux of 0.004 Sv (1 Sv = 10^6 m^3/s) would drain to the Hudson Strait. Nevertheless, the duration of such an outburst flood could vary substantially from present-day typical durations depending on the size of the drained lake. We also calculated lake volume using GIA-corrected topography at 56 ka, to account for age uncertainty, which results in an equivalent value of 1.14×10^{12} m^3. Calculating the lake volume without accounting for GIA resulted in a 7% smaller volume, with a value of 1.13×10^{12} m^3.

We used an 890 m contour on present-day topography to determine lake extent and simplified assumptions about ice-dammed locations. However, lake extent is uncertain as ice sheet margins for this time interval are unknown. Nevertheless, ice thickness must have been over 1.1 times the lake depth to be grounded and dam the glacial lake (Weertman, 1974; Schoof, 2007). Although the presence of a glacial lake during MIS 3 suggests smaller ice sheet heights than previously assumed in the Torngat Mountains, ice must have been sufficiently thick to create a glacially-dammed lake. Could alpine glaciers be sufficiently thick to block such a lake? How thick would the eastern ice margin need to be to block this lake? Future work, including mapping the full extent of this glacial lake, could help answer these questions. In particular, it may be possible to determine the minimum required ice thickness necessary to dam measured lake depths, as determined by topography at shoreline locations.

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Another uncertainty in our analysis is that we do not consider how topography may have changed due to erosion. For example, there is evidence for at least 2.5 m of erosion in the valley bottoms of the Torngat Mountain region over a single glacial cycle (Staiger et al., 2005), and glacial outburst floods can cause substantial incision (Keisling et al., 2020; Larsen and Lamb, 2016). Future work aimed at reconstructing topography prior to landscape erosion may also improve estimates of glacial lake volume.

Heinrich events

A freshwater volume of 1.14×10^{12} m^3 , associated with the glacial lake outburst described in this study, could contribute to the large $\delta^{18}O$ recorded for MIS 3 Heinrich events (minimum volume required = 1.4×10^{13} -2.3 $\times 10^{14}$ m^3 ; Hemming, 2004). Outburst flooding from the ice-dammed lake identified in this study would have drained westward through Ungava Bay into the Hudson Strait and released a substantial volume of freshwater into the North Atlantic, likely carrying ice-rafted debris.

Our estimated freshwater volume may represent a minimum bound. Glacial lakes in the Koroc Valley existed during the Holocene, concurrent with larger lakes, including Lake Naskaupi and Lake McLean, to the south, which have been dated to 8 ka (Dube-Loubert et al., 2018) (Figure 2; inset). Thus, other pre-LGM glacial lakes likely existed to the south of the identified pre-LGM glacial lake Koroc, similar to during the Holocene (Dube-Loubert et al., 2018), and could have released their freshwater at a similar time during MIS 3. Each of these glacial lakes, including glacial Lake Koroc, may have flooded repeatedly depending on the timescale of meltwater refilling and ice dam lifting.

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353

354 The age uncertainty of this glacial lake shoreline (33-59 ka), and its associated outburst flood,
355 spans the time period of multiple Heinrich events (Figure 1). As opposed to an ice discharge
356 event, floodwaters would introduce substantial freshwater but not carry ice rafted debris as far.
357 However, given age uncertainty, it is also possible this outburst flooding coincided with times
358 that are not associated with Heinrich events.

359

360 Previously proposed hypotheses for Heinrich events (ice-sheet instability/tides/jokulhaups)
361 invoke specific assumptions about Laurentide ice sheet dynamics or configurations. However,
362 to-date, evidence on land beneath the former ice sheet could not sufficiently support or refute
363 these ideas. We present the first direct evidence on land for an MIS 3 jokulhaup. The shoreline
364 age uncertainty in our study encompasses multiple Heinrich events, and suggests the possibility
365 of outburst flooding as a mechanism for one of these climatic events. This early dataset
366 motivates future fieldwork that could test the hypothesis that a jokulhaup in the Torngat
367 Mountains coincided with a Heinrich event. Further investigation mapping glacial lake extent
368 would better quantify the volume associated with such a glacial outburst flood.

369

370 *Ice sheet constraints*

371 The pre-LGM glacial lake Koroc shoreline, with a minimum age of 36±3 ka, is the first evidence
372 to suggest that the Torngat Mountains were not fully glaciated across MIS 3, and has the
373 potential to grant insight into MIS 3 Laurentide ice margins as well as the mechanisms
374 underlying glacial inception in North America. Although we cannot infer the precise locations
375 where ice dammed this lake, we know that, during the Holocene, glacial lakes existed in the

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lower elevation Koroc River valley in addition to farther south, such as Lake Naskaupi (Dube-Loubert et al., 2018) (Figure 2; inset). These 8 ka glacial lakes, surrounding the retreating remainder of the Laurentide Ice Sheet, occurred at a time when the Laurentide Ice Sheet held 4 m of equivalent global mean sea level (Ullman et al., 2016), a fraction of the ~80 m global mean sea level equivalent the Laurentide Ice Sheet held at the LGM (Figure 1d). Despite similar glacial lake locations, however, mid-MIS 3 ice margins were not necessarily the same as at 8 ka, and caution is required in interpreting ice volumes associated with an ice margin proximal to pre-LGM glacial lake Koroc. Higher water levels in the pre-LGM glacial lake Koroc (890 m compared to ~500 m at 8 ka) suggest greater ice thickness at the margin. Therefore, although the mid-MIS 3 ice sheet margin may have been close to the 8-ka margin near the Torngat Mountains, the ice cap may have been more extensive to the west at the time of this MIS 3 glacial lake than it was at 8 ka.

Nonetheless, our study suggests that the Torngat Mountains were not fully glaciated across MIS 3. This finding is in contrast to numerical ice sheet modeling studies and other ice sheet reconstructions, which predict that this region is one of the first to glaciate (Otieno and Bromwich, 2009) and would have remained glaciated through the Last Glacial Maximum (Stokes et al., 2012). Assumptions about glacial climate used in dynamic ice-sheet simulations based on global circulation models may require revision to fit constraints for a reduced mid-MIS 3 Laurentide Ice Sheet, and an unglaciated sector (of at least part) of the Torngat Mountains at MIS 3.

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398 The location of pre-LGM glacial lake Koroc in the Torngat Mountains supports a rapidly-
399 growing ice sheet, given that maximum ice sheet extent was reached on the United States east
400 coast by 27-25 ka (Corbett et al., 2017) and the United States Midwest by 45-35 ka (Carlson et
401 al., 2018; Kerr, 2018; Ceperley *et al.*, 2019). This finding would support a dynamic Laurentide
402 Ice Sheet in the period leading to the Last Glacial Maximum. Rather than a single growing mass,
403 this ice sheet may have encompassed a series of temporally variable ice caps in various centers
404 such as the Appalachians, Mid-Quebec, as well as the lager domes in Keewatin and Labrador.
405
406 **CONCLUSION**
407 In this study we provide the first direct on-land evidence for an MIS 3 glacial outburst flood. We
408 present cosmogenic exposure ages from legacy fieldwork for a glacial lake shoreline with
409 evidence for outburst flooding, with a minimum age of 36 ± 3 ka in the Torngat Mountains. This
410 previously unpublished dataset weighs into debates about the Laurentide Ice Sheet and Heinrich
411 events during MIS 3.
412
413 We suggest a series of hypotheses based on these observations: Were high elevation regions of
414 the Torngat Mountains, at least partially, deglaciated during MIS 3? Could glacial outburst
415 floods in the Torngat Mountains have coincided with Heinrich events in the North Atlantic? How
416 large and how frequent were Torngat Mountain glacial outburst floods? Future work, including
417 thorough mapping of MIS 3 glacial lake shorelines in the Torngat Mountains and an improved
418 burial history from paired cosmogenic isotopes can begin to answer these questions.
419 Furthermore, tracking pre-LGM glacial lake shorelines and documenting glacial lake tilts, in

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420 combination with glacial isostatic adjustment modeling, can begin to tease out ice sheet
421 dynamics during the glaciation phase of North America.
422
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429
430 **Author contribution & Competing Interests**:
431
432 T.P performed glacial isostatic adjustment modeling and lake volume calculation. T.P prepared
433 the manuscript with contributions from all coauthors. J.K.W. carried out fieldwork, sample
434 collection, and cosmogenic nuclide laboratory work and analysis. All coauthors contributed
435 conceptually to the development of this manuscript. The authors declare that they have no
436 conflict of interest.
437
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