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Opening of glacial Lake Agassiz's eastern outlets by the start of the Younger Dryas cold period

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ABSTRACT

The Younger Dryas (12.9 ± 0.1 to 11.7 ± 0.1 ka) was a return to cold conditions in the Northern Hemisphere during the last deglaciation. This climatic event was hypothesized to have been caused by a change in glacial Lake Agassiz (north-central North America) overflow from its routing to the Gulf of Mexico to an easterly route to the North Atlantic due to Laurentide ice-sheet retreat from the Lake Superior basin, which caused a reduction in Atlantic meridional overturning circulation. Alternative models argue that Lake Agassiz triggered the Younger Dryas via northwestward routing to the Arctic Ocean. We present new ^{10}Be surface exposure ages that directly date ice retreat from eastern Lake Agassiz outlets and show that the area was ice free at the onset of the Younger Dryas. The southernmost eastern channels opened at 14.0 ± 0.4 ka and 13.6 ± 0.2 ka, but an ice-free route through the Lake Superior basin only opened after 13.5 ± 0.5 ka. The main eastern channel to the eastern Great Lakes and North Atlantic opened at 13.0 ± 0.1 ka to 12.7 ± 0.3 ka. This channel opening was concurrent with decreased runoff to the Gulf of Mexico and increased runoff through the lower Great Lakes to the Gulf of St. Lawrence and North Atlantic. Gulf of St. Lawrence runoff records and isostatic-rebound modeling suggest eastern outlet abandonment at ca. 12.2 ka, with possible northwestward routing of runoff. Our results confirm that Lake Agassiz overflow could have been routed eastward to the North Atlantic at the Younger Dryas onset and caused the canonical abrupt climate change event.

INTRODUCTION

Determining the cause of the Younger Dryas, a return to cold conditions in the Northern Hemisphere during the last deglaciation (12.9 ± 0.1 to 11.7 ± 0.1 ka), is critical to understanding Atlantic meridional overturning circulation (AMOC) sensitivity to freshwater discharge as the Younger Dryas is considered the canonical abrupt climate change event (Broecker et al., 1989; Clark et al., 2001). The southern outlet of glacial Lake Agassiz (north-central North America), which routed early overflow to the Gulf of Mexico, was abandoned at the start of the Younger Dryas (Broecker et al., 1989; Wickert et al., 2013) (SO, Fig. 1). Following southern outlet abandonment, Lake Agassiz levels fell to the Moorhead low by ca. 12.4 ka (Fisher et al., 2008), but the routing of Lake Agassiz basin overflow during and after this lake-level fall is unclear.

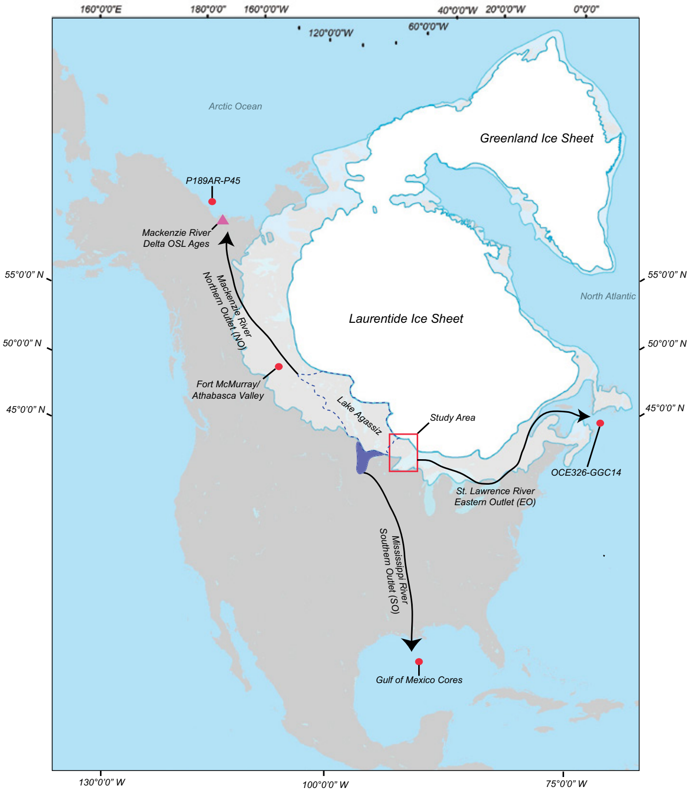

Figure 1. Map of study region. Laurentide ice-sheet extent at ca. 14 ka (outer gray) and ca. 11 ka (inner white) (Dyke, 2004) is shown; study area is noted by red box. Glacial Lake Agassiz runoff routes and locations of records are noted. OSL—optically stimulated luminescence.

The hypothesis of eastward drainage of the Lake Agassiz basin as the cause of the Younger Dryas (Broecker et al., 1989; Clark et al., 2001) has been challenged by arguments that the eastern outlets did not open until after the start of the Younger Dryas, along with the lack of depositional evidence in the eastern outlets, assuming the routing occurred as a flood (Teller et al., 2005; Lowell et al., 2009; Voytek et al., 2012) (EO, Fig. 1). However, a flood would fail to produce a millennia-long reduction in

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AMOC strength and North Atlantic cooling, like the Younger Dryas (Clark et al., 2001; Meissner and Clark, 2006). Evidence for northwestward Lake Agassiz routing at the start of the Younger Dryas is based mainly on optically stimulated luminescence ages from flood deposits at the mouth of the Mackenzie River (Canada) that are interpreted to have been emplaced at the start of the Younger Dryas (Murton et al., 2010) (NO, Fig. 1). However, the gravel sediments at the mouth of the Mackenzie River were likely deposited near the end of the Younger Dryas ca. 11.9 ka based on dates on overlying conformable fluvial sands (Carlson and Clark, 2012). The lack of a direct deglacial chronology for the eastern outlets of Lake Agassiz has thus confounded confirmation of the Younger Dryas forcing mechanism. Here, we use ^{10}Be surface exposure ages from glacial erratic boulders to directly date Laurentide ice-sheet retreat from, and the opening of, the eastern outlets.

METHODS

We collected all samples from boulders on bedrock highs located north of three eastern outlet channels of Lake Agassiz: North Lake (NL), Flatrock Lake (FL), and Lake Kaministiquia (Lake Kam, KM), Canada (Fig. 2) (see methods in the GSA Data Repository[1]). We chose boulders on bedrock highs to reduce the influence of inheritance, boulder exhumation, and snow cover (i.e., windswept areas) on the sample age, as well as avoid remobilization of the boulder by meltwater. We collected multiple samples at each location to identify outliers and reduce the uncertainty in the mean deglacial age. The Steep Rock and Brule moraines, respectively, separate these channels (Fig. 2), with the Marks moraine to the east of Lake Kam channels. The Lake Kam region encompasses multiple overflow channels, consisting of the modern Shebandowan, North, Seine, and Oskondaga Rivers (Fig. 2). We also collected samples from behind the Marks moraine (LN, Fig. 2). Age calculations included corrections for changes in atmospheric depth caused by isostatic rebound and effects of changes in atmospheric pressure are assessed. After excluding six (or seven) outliers due to exhumation (n=4-5) or inheritance (n=2) (Figs. DR1 and DR2 in the Data Repository), we calculated the mean and standard error of the mean (uncertainty is dependent on number of samples measured) for each site (Figs. 2 and 3A) (Tables DR1 and DR2 in the Data Repository).

RESULTS

The southernmost site near the North Lake channel has a mean deglaciation age of 14.0 ± 0.4 ka (n = 3, one outlier). The next site northward, near the Flatrock Lake channel, has a mean deglaciation age of 13.6 ± 0.3 ka (n = 7, two outliers). Farther north, the Lake Kam channels became ice free at 12.7 ± 0.3 ka (n = 4, two outliers), or 13.0 ± 0.1 ka (n = 3, three outliers) if a stricter outlier test is used. The timing of ice-free conditions for these channels is significantly earlier than what has been reconstructed from ^{14}C ages (Teller et al., 2005; Teller and Boyd, 2006; Lowell et al., 2009) (Fig. 3A), reflecting the minimum-limiting nature of deglacial ^{14}C dates (Teller and Boyd, 2006; Carlson and Clark, 2012).

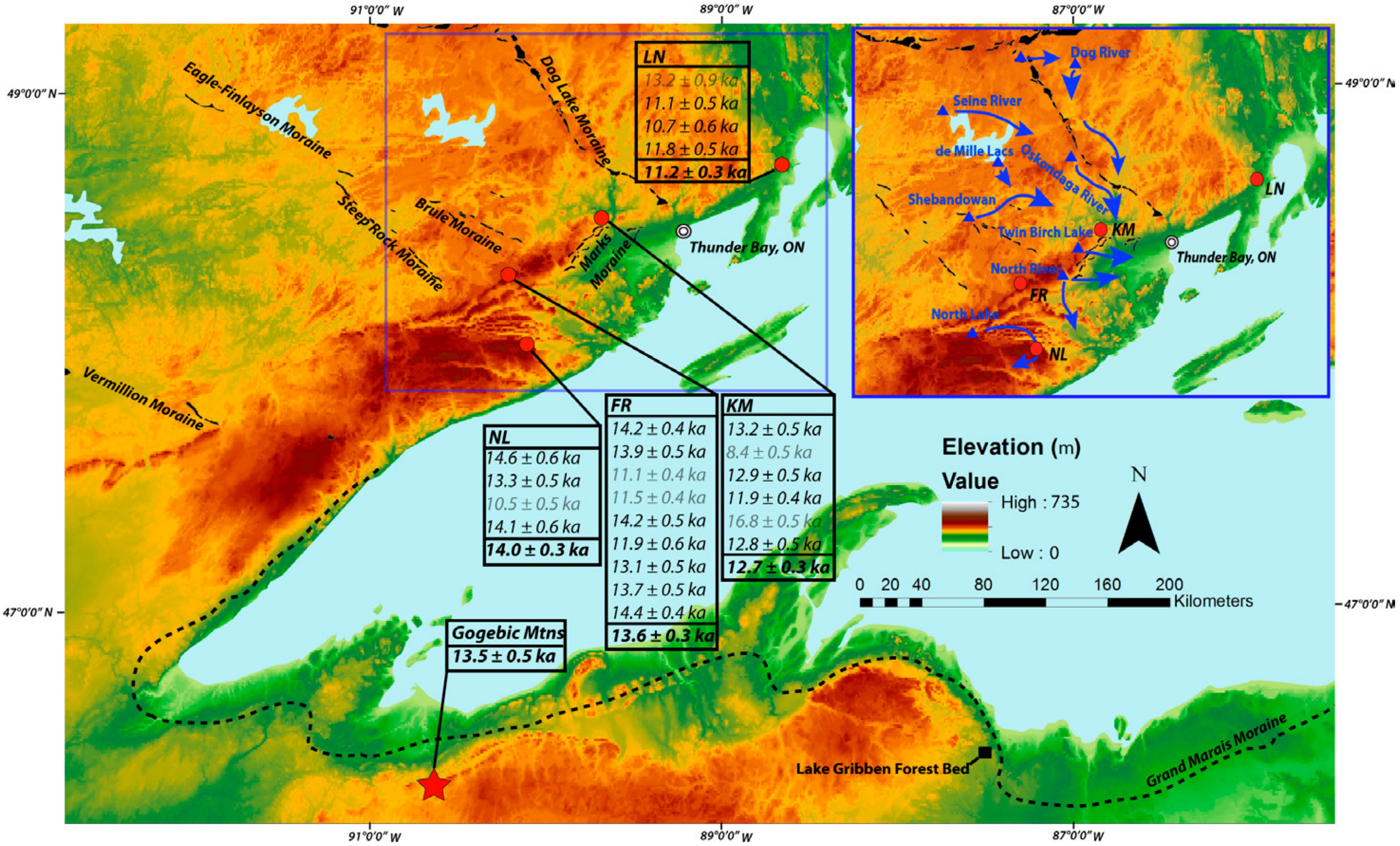

Figure 2. Digital elevation model of western Lake Superior basin, showing moraines (Teller et al., 2005; Lowell et al., 2009; Breckenridge, 2015) and site of dated Lake Gribben forest bed (Lowell et al., 1999), with locations of ^{10}Be sample sites (red dots) near eastern glacial Lake Agassiz outlet channels: NL—North Lake; FR—Flatrock Lake; KM—Lake Kaministiquia; LN—Lake Nipigon. Age of samples and mean age for each site are shown. Outlier ages are in gray. Red star is the mean surface exposure age (n = 7) from Gogebic Mountains (Wisconsin, USA) (Ullman et al., 2015). Dashed line is location of Marquette readvance moraine south of Lake Superior (Lowell et al., 1999). Inset shows heads of eastern outlet channels at edge of Lake Agassiz (blue triangles); runoff paths are blue arrows (Teller et al., 2005; Breckenridge, 2015). ON—Ontario (Canada).

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[1] GSA Data Repository item 2018035, methods, additional figures, and tables, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

Our northernmost site dates Laurentide ice-sheet retreat from the Marks moraine prior to 11.2 ± 0.3 ka (*n* = 3, one outlier).

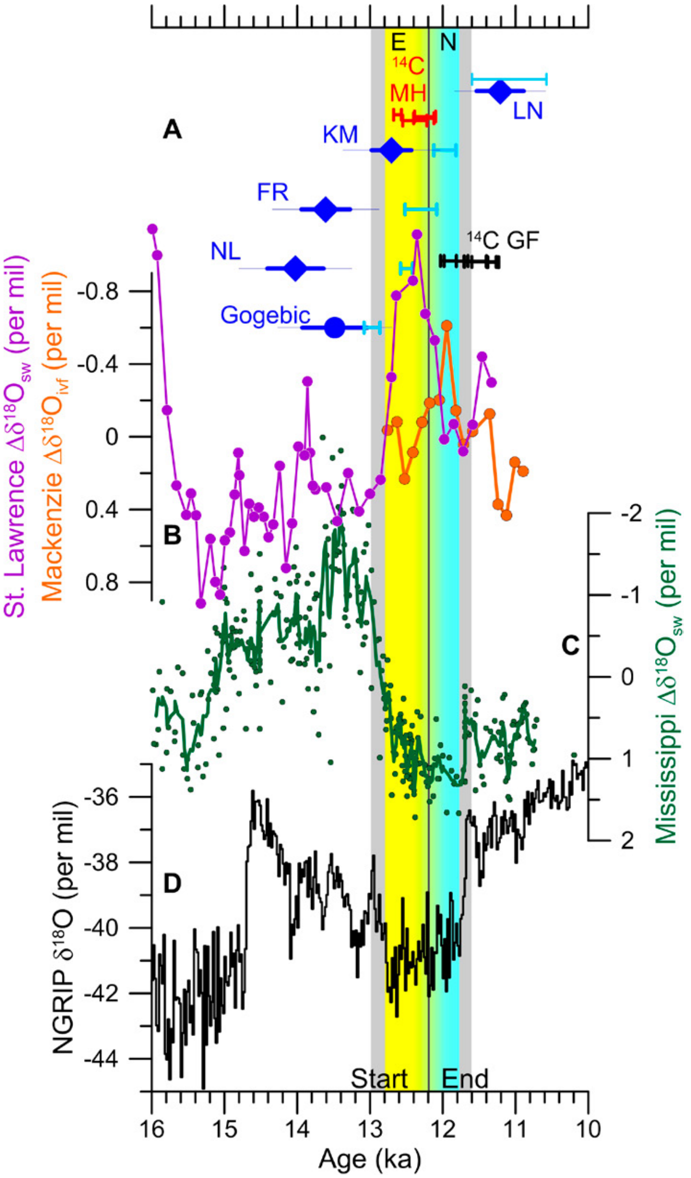

Figure 3. Records of glacial Lake Agassiz basin routing. A: Outlet ages (1σ uncertainty is thick line; thin line is uncertainty including production rate uncertainty). Blue diamonds are new ^{10}Be ages (NL—North Lake; FR—Flatrock Lake; KM—Lake Kaministiquia; LN—Lake Nipigon); blue circle is ^{10}Be age of Gogebic Mountain (Wisconsin, USA) deglaciation (Ullman et al., 2015); red bars are ^{14}C ages from early Moorhead (MH) low (Fisher et al., 2008); light blue bars are minimum-limiting ^{14}C dates for eastern outlet channels (Lowell et al., 2009); black bars are Lake Gribben forest (GF) bed ^{14}C ages (Michigan, USA) (Lowell et al., 1999). B: Seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) from Gulf of St. Lawrence (Canada) (purple) (calculated from Gil et al., 2015) and ice-volume free $\delta^{18}O$ ($\delta^{18}O_{ivf}$) from off of Mackenzie River (Canada) (orange) (Andrews and Dunhill, 2004). C: Gulf of Mexico $\delta^{18}O_{sw}$ (green dots) (Wickert et al., 2013), with five-point running mean (green line). D: North Greenland Ice Core Project (NGRIP) $\delta^{18}O$ (Rasmussen et al., 2006). Gray bars are 1σ uncertainty in Younger Dryas onset and termination. Yellow shading labeled "E" denotes period of eastward Lake Agassiz routing, followed by shift to northwesterly routing (blue shading labeled "N") at ca. 12.2 ka.

DISCUSSION

Our new chronology indicates that northward Laurentide ice-sheet retreat from the eastern outlets began at ca. 14.0 ka when the North Lake channel opened, followed by opening of the Flatrock Lake channel at ca. 13.6 ka (Fig. 3A). Isostatic-rebound modeling of Lake Agassiz shorelines and paleotopographic reconstructions show that these outlets could have routed Lake Agassiz basin overflow eastward when the lake occupied the high shorelines early in the Younger Dryas (Teller et al., 2005; Breckenridge, 2015). While these two outlet channels were ice free before the onset of the Younger Dryas, ^{10}Be ages from the Gogebic Mountains south of Lake Superior (Wisconsin and Michigan, USA) (Figs. 2 and 3A) indicate that the Laurentide ice sheet extended to southern Lake Superior, blocking eastward Lake Agassiz overflow, until after 13.5 ± 0.5 ka (Ullman et al., 2015). Our Lake Kam ^{10}Be ages indicate that these overflow channels were deglaciated by 13.0 ± 0.1 ka to 12.7 ± 0.3 ka (Fig. 3A), when the Laurentide ice-sheet had retreated from southern Lake Superior (Ullman et al., 2015), allowing Lake Agassiz overflow into the eastern Great Lakes. The Lake Kam overflow channels, along with the North Lake and Flatrock Lake channels, were thus open at the time Lake Agassiz ceased to be routed to the Gulf of Mexico as indicated by increased $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) 13.0–12.7 ka (Wickert et al., 2013) (Fig. 3C) at the start of the Younger Dryas (Fig. 3D). Any one of the Lake Kam channels could have routed Lake Agassiz basin overflow to the lower Great Lakes prior to the Moorhead low lake level and during the early Moorhead low lake level (Teller et al., 2005; Breckenridge, 2015).

Our direct ^{10}Be chronology indicates deglaciation of the eastern Lake Agassiz outlet channels by the onset of the Younger Dryas. The lower Great Lakes (Lewis and Anderson, 1989; Colman et al., 1994; Hladyniuk and Longstaffe, 2016) and the St. Lawrence lowlands (Brand and McCarthy, 2005; Rayburn et al., 2011; Cronin et al., 2012) were ice free by the Younger Dryas (Dyke, 2004) and provide evidence for increased meltwater discharge at the start of the Younger Dryas. Strontium isotopic data indicate that the enhanced runoff originated from the Lake Agassiz basin (Brand and McCarthy, 2005). Freshening of the Gulf of St. Lawrence is evident in a planktonic $\delta^{18}O$ decrease at the start of the Younger Dryas, which is further decreased when accounting for effects of contemporaneous cooling (Keigwin and Jones, 1995; de Vernal et al., 1996; Gil et al., 2015; Levac et al., 2015) on $\delta^{18}O$ of calcite (i.e., $\delta^{18}O_{sw}$) (Carlson et al., 2007; Carlson and Clark, 2012; Gil et al., 2015) (Fig. 3B). The micropaleontology of the Gulf of St. Lawrence also indicates decreased salinity at the Younger Dryas onset (Levac et al., 2015). Planktonic foraminifera Sr isotopes, U/Ca, and Mg/Ca trace the increased runoff to the Lake Agassiz basin (Carlson et al., 2007). Thus, there is clear evidence that the eastern outlets of Lake Agassiz were open at the start of the Younger Dryas, with its runoff routed to the North Atlantic where it could cause the AMOC reduction and the Younger Dryas. While others have argued for minimal evidence of Gulf of St. Lawrence freshening at the start of the Younger Dryas (Keigwin and Jones, 1995; de Vernal et al., 1996), these studies did not account for the effect of Younger Dryas cooling on their calcite proxies (Clark et al., 2001; Carlson et al., 2007; Carlson and Clark, 2012) or utilized proxies that are not sensitive to salinity changes (Telford, 2006).

The late Moorhead lake level projects below the Lake Kam channels, which would have prevented eastward routing of Lake Agassiz overflow due to isostatic rebound of the eastern outlets (Teller et al., 2005; Breckenridge, 2015). Gulf of St. Lawrence records show decreased meltwater discharge at ca. 12.2 ka (Carlson et al., 2007; Gil et al., 2015) (Fig. 3B), in agreement with rebound-estimated eastern-outlet abandonment at ca. 12.2 ka (Breckenridge, 2015). The only viable outlet for late-Moorhead overflow from Lake Agassiz is the northwestern outlet (Teller et al., 2005; Breckenridge, 2015). The northwestern outlet was deglaciated before ca. 11.0 ka according to minimum-limiting ^{14}C dates (Murton et al., 2010) (Fig. 1). Optically stimulated luminescence ages on fluvial sands conformable with an underlying gravel deposit from the mouth of the Mackenzie River date that a discharge event ended at ca. 11.9 ka (Murton et al., 2010; Carlson and Clark, 2012) (Fig. 1), with an adjacent record in the Arctic

Ocean showing decreased planktonic $\delta^{18}O$ at ca. 12.2–11.9 ka (Andrews and Dunhill, 2004) (Figs. 1 and 3B). These records could suggest that Lake Agassiz basin overflow was rerouted to the Arctic Ocean after ca. 12.2 ka; further research is needed to link northwestward Lake Agassiz overflow to the Arctic Ocean.

Abandonment of the northwestern outlet at the end of the Younger Dryas (Andrews and Dunhill, 2004; Murton et al., 2010; Carlson and Clark, 2012) raises the question as to where Lake Agassiz overflow was subsequently routed. ^{14}C dates from the Lake Gribben forest bed on the southern side of the Superior basin (Michigan, USA) (Fig. 2) document a Laurentide ice-sheet readvance across the Lake Superior basin at the end of the Younger Dryas (Lowell et al., 1999) (Fig. 3A), consistent with our ^{10}Be ages from within the Marks moraine (LN, Fig. 2) that date Laurentide ice-sheet retreat from this moraine prior to ca. 11.2 ka (Fig. 3A). Consequently, Lake Agassiz basin runoff could not then have been rerouted through the eastern outlets at the end of the Younger Dryas. ^{14}C ages in southern outlet gravel deposits (Fisher, 2003) and decreased $\delta^{18}O_{sw}$ in the Gulf of Mexico (Fig. 3C) (Wickert et al., 2013) could suggest reoccupation of the southern outlet at the end of the Younger Dryas.

In conclusion, our ^{10}Be chronology for deglaciation of Lake Agassiz's eastern outlets by the start of the Younger Dryas supports eastward routing of lake-basin overflow to the North Atlantic as the cause of the canonical abrupt cold event. Potential northwestward routing of Lake Agassiz overflow halfway through the Younger Dryas may have allowed the cold event to persist another few centuries.

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