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Age of the Berlin moraine complex, New Hampshire, USA, and implications for ice sheet dynamics and climate during Termination 1

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Abstract

At its late Pleistocene maximum, the Laurentide Ice Sheet was the largest ice mass on Earth and a key player in the modulation of global climate and sea level. At the same time, this temperate ice sheet was itself sensitive to climate, and high-magnitude fluctuations in ice extent, reconstructed from relict glacial deposits, reflect past changes in atmospheric temperature. Here, we present a cosmogenic ^{10}Be surface-exposure chronology for the Berlin moraines in the White Mountains of northern New Hampshire, USA, which supports the model that deglaciation of New England was interrupted by a pronounced advance of ice during the Bølling-Allerød. Together with recalculated ^{10}Be ages from the southern New England coast, the expanded White Mountains moraine chronology also brackets the timing of ice sheet retreat in this sector of the Laurentide. In conjunction with existing chronological data, the moraine ages presented here suggest that deglaciation was widespread during Heinrich Stadial 1 event (~18–14.7 ka) despite apparently cold marine conditions in the adjacent North Atlantic. As part of the White Mountains moraine system, the Berlin chronology also places a new terrestrial constraint on the former glacial configuration during the marine incursion of the St. Lawrence River valley north of the White Mountains.

Keywords: Laurentide Ice Sheet; Cosmogenic beryllium-10 surface-exposure dating; Late glacial; New England; Glacial geology

INTRODUCTION

As the planet's largest ice mass during the last glacial maximum (LGM), the Laurentide Ice Sheet is widely evoked as a key player in global climate through Milankovitch forcing (Denton and Hughes, 1983), albedo feedbacks (Broccoli and Manabe, 1987; Weaver et al., 1998; Carlson et al., 2007), and atmospheric interference (Manabe and Broccoli, 1985; Mayewski et al., 1997; Ganopolski et al., 1998; Shuman et al., 2002). On submillennial timescales, whether as a cause or consequence of climate, the Laurentide also was the principal source of ice-rafted debris in North Atlantic marine sediments (Bond et al., 1993; MacAyeal, 1993; Hemming et al., 2000; Hemming, 2004) and thus has a long association with meltwater-induced perturbations of the thermohaline circulation (Broecker et al., 1989; Keigwin et al., 1991; Keigwin and Lehman, 1994; Flower et al., 2004; McManus et al., 2004; Ellison et al., 2006) and abrupt shifts in ocean-atmosphere heat transfer (e.g., Clark et al., 2001), particularly along the ice sheet's marine-terminating North Atlantic margins.

Reconstructing patterns of cryospheric change in the southeastern sector of the Laurentide Ice Sheet is fundamental to establishing the key factors controlling mass balance and, ultimately, for testing the role of North Atlantic Ocean dynamics in regional climate. Here, we build on our previous work (Bromley et al., 2015; Thompson et al., 2017) on the deglacial history of northern New England during the last glacial termination (Termination 1: ~20–11 ka), a period characterized by abrupt shifts in temperature, seasonality, and meltwater flux throughout the circum–North Atlantic (e.g., Denton et al., 2005, 2010) and widespread ice sheet retreat

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in New England. Specifically, we provide new cosmogenic ^{10}Be surface-exposure data from the Berlin moraine complex in northern New Hampshire, part of the White Mountain moraine system (WMMS; Fig. 1; Thompson et al., 2017), which reflects a regional-scale glacial readvance during Termination 1. These new data also help place the deglaciation of New England into a wider climatological context, relative to conditions downwind in the North Atlantic, and provide a new vantage on ice sheet configuration during opening of the Champlain Sea.

THE WHITE MOUNTAINS GLACIAL RECORD

Moraines and glacial deposits associated with the last retreat of the Laurentide Ice Sheet are abundant throughout the White Mountains region of northern New Hampshire and western Maine, where the complex glacial stratigraphy has attracted scientific attention since 1850 (Lyell, 1850; Agassiz, 1870; Thompson, 1999; Balco et al., 2009; Bierman et al., 2015). In their recent study, Thompson et al. (2017) described a series of prominent moraine complexes, collectively termed the WMMS (Fig. 1), which crosses New Hampshire in a roughly east–west direction and represents deposition along the active margin of south-flowing ice approximately 300 km proximal of the Laurentide Ice Sheet's LGM terminus (Goldthwait, 1916; Thompson et al., 1999; Ridge, 2004; Ridge et al., 2012). The historically best-known section of the WMMS is the Littleton-Bethlehem complex, including the Sleeping Astronomer moraine (Fig. 2), which has been correlated with an ice advance recorded in the Connecticut Valley varve record of glacial Lake Hitchcock (Antevs, 1922; Crosby, 1934; Ridge et al., 1999; Thompson et al., 1999). That this event constituted an advance, as opposed to a still stand, is indicated by widespread sedimentologic evidence for the deformation and overriding of proglacial lake sediments by south-flowing ice and incorporation of these sediments in WMMS tills (e.g., Crosby, 1934; Lougee, 1935; Thompson et al., 1999, 2017).

The eastern continuation of the WMMS has been mapped near the towns of Carroll, Randolph, and Berlin (Thompson et al., 1999, 2017), and Bromley et al. (2015) correlated the WMMS with the Androscoggin lateral-terminal moraine complex on the Maine–New Hampshire border (Fig. 2). Between Randolph and the Androscoggin moraines, however, the precise configuration of the ice margin during the advance is unclear, highlighting the problematic nature of reconstructing ice-marginal positions in this densely forested and challenging terrain.

The focus of this article is a set of prominent moraine ridges located west of the town of Berlin (Figs. 2 and 3). The Berlin moraines were described first by Thompson et al. (2007, 2009) and subsequently by Thompson and Svendsen (2015), and they were recently correlated with the nearby Randolph moraines based on the distribution of ice-marginal meltwater channels and former ice-dammed lakes (Thompson et al., 2017). However, although it is tempting to regard the Berlin moraines as a continuation of the WMMS, direct age control for the sequence has been lacking. To provide this constraint, we report seven new cosmogenic ^{10}Be ages from the Berlin moraines that enable us to place the complex firmly in the context of local and regional ice sheet behavior.

GEOLOGIC SETTING OF THE BERLIN MORAINES

The main part of the Berlin moraine complex comprises five principal northwestern- to southeastern-oriented ridges, locally between 200 and 400 m apart, that are traceable for ∼4 km across the gently undulating Upper Ammonoosuc River valley bottom (Fig. 3). Together with discontinuous moraine sections, the Berlin complex forms a belt as much as 750 m wide (Fig. 3). The sampled moraine and neighboring ridges within the complex are typically 2–10 m tall and composed of bouldery till, with crests mantled by large (>1 m tall) granite boulders, and all are weathered to a similar degree suggesting deposition over a short period. Elevations of the moraine crest at the sample sites are approximately 420 ± 3 m above sea level. The cross-valley configuration of the Berlin moraines indicates deposition along the margin of a south-flowing ice mass in the Androscoggin River valley, which at the time would have blocked the entrance to the Upper Ammonoosuc River valley.

At a distance of 2.0–2.5 km southwest of the Berlin moraines, three similar moraines represent earlier, currently undated ice-margin positions ("Higher moraine" in Fig. 3). Thompson et al. (2017) suggested that when the ice margin stood at this limit, it dammed an early stage of glacial Lake Crescent, an ice-dammed lake located in the highest part of the Upper Ammonoosuc River valley (see fig. 2 of Thompson et al., 2017). However, the position of the sampled moraine indicates it was deposited when the level of the proglacial lake had dropped to ∼430 m (the elevation of a spillway nearby to the east). Further lowering of Lake Crescent occurred very quickly when a few hundred meters of additional ice retreat opened the next spillway at ∼411 m. Thus, we conclude that the moraine complex has been exposed subaerially for virtually all of postglacial time.

Limiting age control for the Berlin moraines is provided by ^{14}C ages on basal lake sediments. Directly proximal to the WMMS, with which the Berlin complex is correlated, macrofossils in basal ages from three lake basins afford the minimum-limiting constraint for the moraines (Table 2): Cherry Pond (13.4–13.8 cal ka BP [11,800 ± 90 ^{14}C yr BP]; Thompson et al., 2017), South Pond (13.6–13.8 cal ka BP [11,825 ± 40 ^{14}C yr BP]; Parris et al., 2010), and Martin Meadow Pond (12.7–13.0 cal ka BP [10,920 ± 80 ^{14}C yr BP]; Thompson et al., 2017) (Fig. 2). All ^{14}C ages discussed here have been calibrated using the IntCal13 curve (Reimer et al., 2013) and OxCal version 4.3 (Ramsey, 2009) and are reported with 1σ uncertainty. The implications of these minimum-limiting radiocarbon data for the deglacial history of the region are explored further in the "Discussion."

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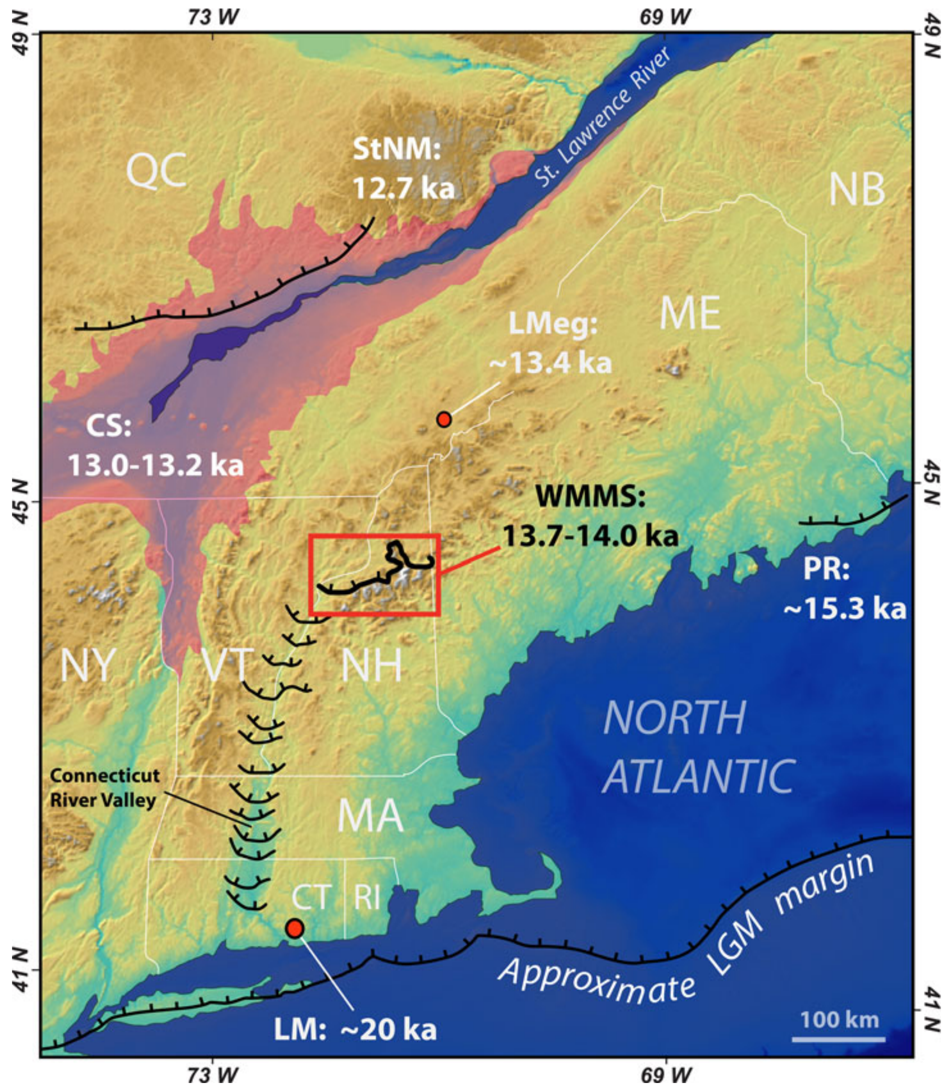

Figure 1. Map of New England, northeastern United States, and southeastern Canada, showing the locations and approximate ages of the White Mountain moraine system (WMMS; red square) and other ice-marginal positions relative to the last glacial maximum (LGM) ice sheet limit and the postglacial Champlain Sea (CS: pink shading; see Richard and Occhietti, 2005). Deglacial limits in the Connecticut River valley adapted from Ridge et al. (2012). LMeg, Lac Megantic area (mean of two calibrated basal ^{14}C ages from Lacs Dubuc and Clinton; Elkadi, 2013); PRM, Pineo Ridge moraine (Hall et al., 2017); LM, Ledyard moraine (Balco and Schaefer, 2006); StNM, Sant-Narcisse moraine (Occhietti, 2007). Territorial abbreviations: CT, Connecticut; QC, Québec; MA, Massachusetts; ME, Maine; NB, New Brunswick; NH, New Hampshire; NY, New York; RI, Rhode Island. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Within the Upper Ammonoosuc River valley itself, York Pond (Figs. 2 and 3) is a kettle hole located distal to the Berlin moraines and surrounded by glaciofluvial sands and gravels. Previous work on the lake's sedimentology revealed ∼40 cm of finely laminated sediments, interpreted as varves, overlying till (Thompson et al., 2009). Macrofossils in those varves provided a radiocarbon date of (13.6–14.1 cal ka BP [11,980 ± 90 ^{14}C yr BP]). Ten kilometers south of York Pond, on the western end of the Crescent Range, Pond of Safety also lies distal to the WMMS (Fig. 3) and gives a basal age of (14.2–15.0 cal ka BP [12,450 ± 60 ^{14}C yr BP]; Thompson et al., 2017). Although these data confirm that both York Pond and Pond of Safety were deglaciated by ∼13.8 cal ka, their distal positions mean neither site can provide unequivocal limiting age control for deposition of the adjacent moraines.

Although the age of the Berlin moraine complex has not, until now, been established directly, other sections of the WMMS have been dated using cosmogenic ^{10}Be surface-exposure dating. Four samples from the Sleeping Astronomer and Beech Hill moraines give a mean age of 13.8 ± 0.7 ka (Balco et al., 2009), calculated using the northeastern North America (NENA) production rate and St scaling, as reported in Bromley et al. (2015), which is indistinguishable from subsequent ^{10}Be measurements (Borchers et al., 2016). At its westernmost point, the

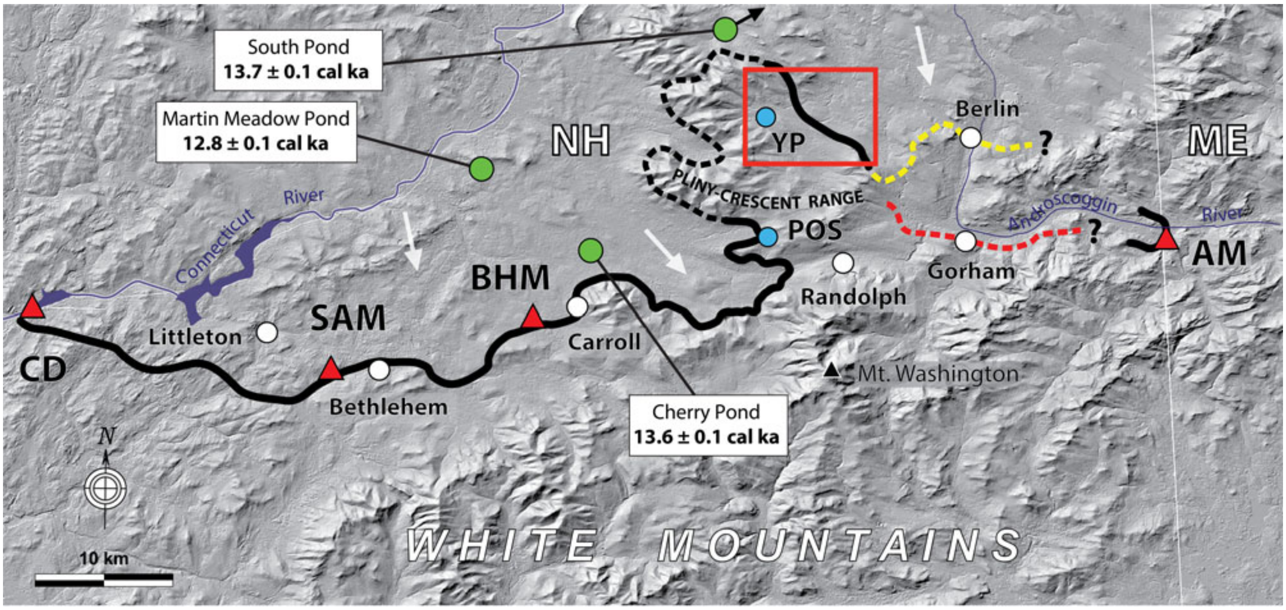

Figure 2. Topographic map of the White Mountains region, showing the mapped (solid black lines) and conjectured (dashed black lines) extent of the White Mountain moraine system (WMMS) and location of the Berlin moraines (red rectangle). Dashed yellow and red lines indicate the conjectured continuation of the former ice margin east of the Berlin moraines according to Thompson et al. (2017) and Bromley et al. (2015), respectively. Proximal lake sites providing minimum-limiting ^{14}C age control for the WMMS are indicated by green circles (note: South Pond is located just off the map in the direction of the black arrow). Distal lake sites (blue circles) mentioned in the text: POS, Pond of Safety; YP, York Pond. Key moraine sites discussed in the text are indicated by red triangles: AM, Androscoggin moraine; BHM, Beech Hill moraine; CD, Comerford Dam; SAM, Sleeping Astronomer moraine. White arrows denote former ice-flow direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

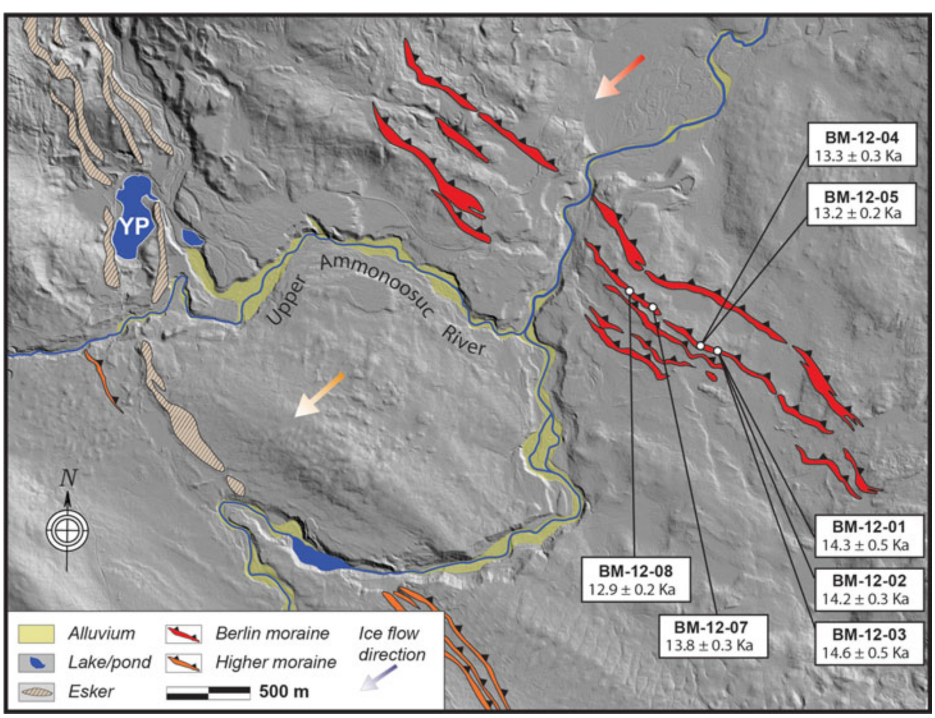

Figure 3. Glacial-geomorphic map of the Upper Ammonoosuc River valley study area. Locations and surface-exposure ages of sampled boulders are shown. Red and orange arrows denote approximate ice-flow direction during deposition of the Berlin and higher moraines, respectively. YP, York Pond. Underlying light detection and ranging (LIDAR) imagery obtained from the GRANIT LIDAR distribution site (http://lidar.unh.edu/map/), University of New Hampshire. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Table 2. Basal radiocarbon and calibrated ages from three distal lake sites providing minimum-limiting control for the White Mountain moraine system (WMMS).

Sample ID	Site name	Material dated	Age (^{14}C yr BP)	Δ^{13}C (‰)	Mean calibrated age (±1σ)	Context	Reference
PL-0000489A	Cherry Pond	Terrestrial plant fragments, insect parts	11,800 ± 80	−22.9	13.6 ± 0.1 cal ka	Minimum	Thompson et al. (2017)
PL-0000889A	Martin Meadow Pond	Terrestrial plant fragments, insect parts	10,920 ± 80	−26.0	12.8 ± 0.1 cal ka	Minimum	Thompson et al. (2017)
90551	South Pond	No details given	11,825 ± 40	NR	13.7 ± 0.1 cal ka	Minimum	Parris et al. (2010)

Littleton-Bethlehem component of the WMMS has also been correlated with a till unit exposed at Comerford Dam (Fig. 2) that, according to the New England varve chronology, was deposited approximately 13.8–14.0 ka (e.g., Ridge et al., 1999, 2012; Balco et al., 2009). Farther east, seven samples from the Androscoggin moraines yielded a mean age of 13.2 ± 0.8 ka (Bromley et al., 2015), which overlaps with the Sleeping Astronomer–Beech Hill mean within analytical uncertainties.

METHODS

To resolve the age of the Berlin moraines, we sampled seven granite boulders (Fig. 4) located on the best-preserved moraine crest of the group, southeast of the Upper Ammonoosuc River (Fig. 3). Samples comprised the upper few centimeters of rock and were collected with a hammer and chisel. Elevations and positions for each sample were obtained from repeated measurements using a handheld GPS, and horizon data were measured with a clinometer. We note that, although they have lost all traces of glacial polish and striae because of post-depositional weathering, the sampled boulders exhibit rounding because of glacial transport (Fig. 4). To minimize the risk of sample shielding because of vegetation and/or seasonal snow cover, we selected prominent boulders of 1–1.5 m relief, and, although this does not preclude some degree of shielding, we note that there is no relationship between boulder age and height.

Samples were prepared for beryllium-10 analysis in the University of Maine cosmogenic isotope laboratory, where we used heavy liquids to separate quartz from the 250–500 μm fraction of the crushed samples and successive leaches in weak (2%) HF to purify the quartz (Kohl and Nishiizumi, 1992). Purity of quartz was assessed using ICP-OES (inductively coupled plasma optical emission spectrometry). Subsequently, beryllium was isolated via ion-exchange chemistry, and cathodes were measured at Lawrence Livermore National Laboratory and normalized to the 07KNSTD standard (^{10}Be/^{9}Be = 2.85 × 10^{-12}; Nishiizumi et al., 2007). We report ages calculated using Version 3 of the online University of Washington cosmogenic calculators (https://hess.ess.washington.edu) in conjunction with the NENA production rate (Balco et al., 2009) and time-invariant Lal (1991)/Stone (2000) "St" scaling, though we stress our interpretations are independent of this choice of scaling scheme (e.g., when calculated using the time-variant "Lm" scheme [Balco et al., 2008], exposure ages are within 0.5% of our St results). Individual and mean-averaged ^{10}Be exposure ages are reported along with 1σ internal (analytical) uncertainties. Analytical results and ages are given in Table 1.

RESULTS

Seven ^{10}Be ages from the sampled moraine fall between 12.9 ± 0.2 and 14.6 ± 0.5 ka (Table 1; Figs. 3 and 5), with an arithmetic mean age of 13.7 ± 0.6 ka. Plotted as an age probability curve, this data set exhibits a bimodal distribution (Fig. 5) representing two statistically distinct age populations: the older population (samples BM-12-1, 2, 3, 7) gives a mean age of 14.2 ± 0.4 ka, and the younger population (samples BM-12-4, 5, 7, 8) an age of 13.3 ± 0.3 ka. We note that sample BM-12-7, which fits equally well within the normal distributions of either population, gives an exposure age (Table 1) that is statistically indistinguishable from the mean and median (13.7 ka) values for the data set as a whole. Together, the seven ages confirm the late-glacial age of the Berlin moraines; the bimodal distribution, however, poses a challenge to establishing the most representative age for moraine formation, leading us to present three possible scenarios that are discussed in the following section: (1) Moraine deposition is represented by the older population, but subsequent erosion has lowered the apparent ages of the younger samples (43% of the data set) by varying degrees. (2) Moraine deposition is represented by the younger population, but the landform includes boulders (again, 43% of the data set) reworked from a prior period of exposure. (3) Ice occupied the Berlin moraines at 14.2 ± 0.4 ka and again at 13.3 ± 0.3 ka.

DISCUSSION

Age of the Berlin moraines

For boulders sampled on the Littleton-Bethlehem moraines, under similar climatic conditions to the Berlin site, Balco

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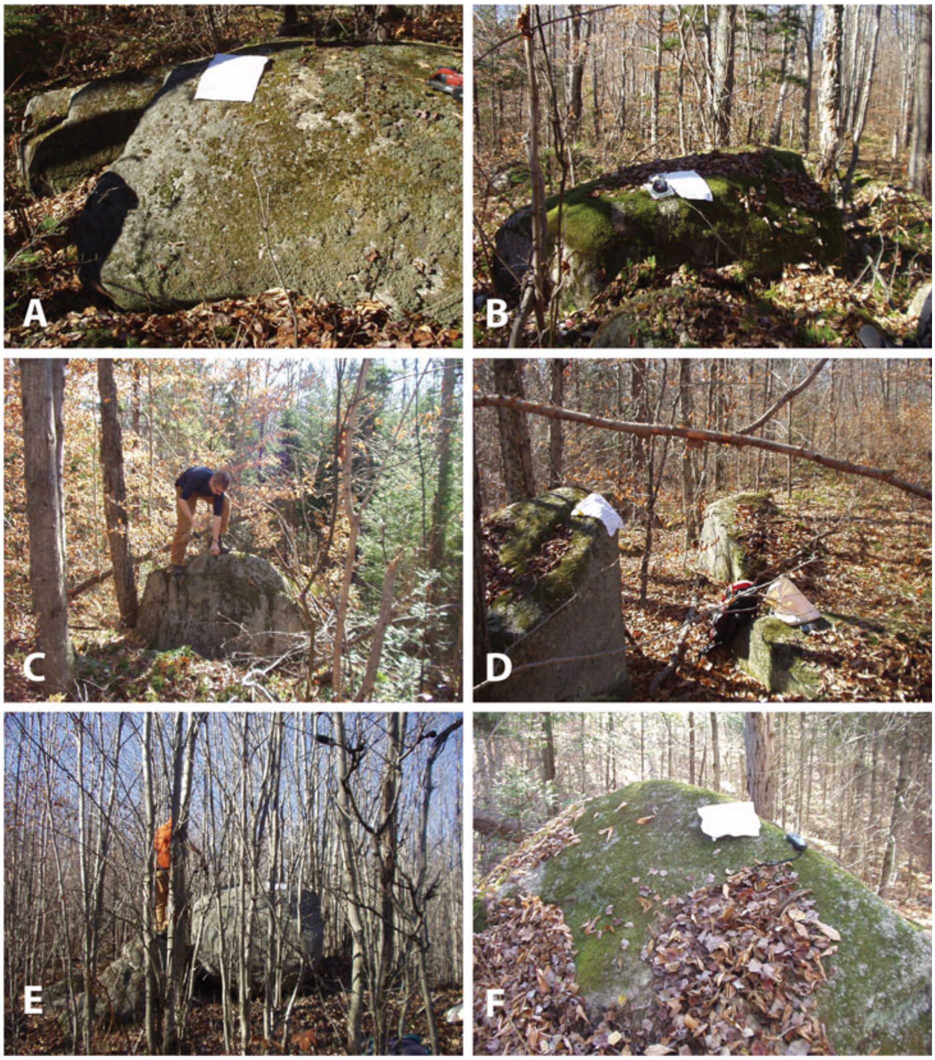

Figure 4. (color online) Sampled glacially molded boulders on the Berlin moraines: BM-12-01 (A); BM-12-02 (B); BM-12-03 (C); BM-12-04 (left) and BM-12-05 (right) (D); BM-12-07 (E); and BM-12-08 (F).

et al. (2009) estimated the magnitude of postdepositional surface erosion to be approximately <1.5 cm. Nonetheless, it is plausible that the nonnormal distribution of our ages simply reflects minor variations in weathering rate among the seven boulders (scenario 1), potentially accentuated by their minor lithologic differences. Furthermore, whereas erosion might cause larger data sets to exhibit a distribution with a young "tail," the relatively small size of our sample set (n = 7) means such a feature is unlikely to be apparent.

Under scenario 2, almost half of the sampled boulders would contain concentrations of inherited ^{10}Be, reflecting the incomplete removal of nuclide-bearing material by glacial erosion. This process typically results in age distributions with old "tails" or conspicuous old outliers. Yet the older population in our data set forms an internally consistent grouping of at least three ages (Fig. 5), thus suggesting a process other than the random incorporation of incompletely reset surfaces.

The remaining scenario (scenario 3), in which the ice margin advanced to the same moraine limit on two separate occasions, cannot be tested quantitatively within the bounds of the existing data set, nor stratigraphically, because all seven ages are from boulders located on the moraine crest and there is no field evidence for multiple periods of glacial occupation.

Therefore, we propose that the most straightforward interpretation from the beryllium data alone is that the Berlin moraines represent deposition along an active ice margin at some point between 14.2 ± 0.4 ka and 13.3 ± 0.3 ka and centered around a mean age encompassing both populations of 13.7 ± 0.6 ka. This model is supported by the minimum-limiting basal ^{14}C data from the three proximal lakes described previously (Figs. 2 and 5; Table 2). Using the NENA production rate, the probability distributions of the ^{10}Be and radiocarbon data overlap (Fig. 5). However, the radiocarbon distribution (oldest peak of 13.6 ± 0.1 cal ka BP) indicates that the actual age of the moraine is represented by the older population of the total ^{10}Be age range and is unlikely to be much younger than 13.7 ka. Use of a more recent Northern Hemisphere ^{10}Be production rate

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Table 1. Sample details and ^{10}Be surface-exposure ages for the Berlin moraine samples. All exposure ages and 1σ uncertainties shown are calculated using the northeastern North America (NENA) production rate (Balco et al., 2009) and St scaling (Lal, 1991; Stone, 2000). Mean ages are reported along with the standard error of the mean.

Sample	Latitude	Longitude	Altitude (m)	Boulder height (m)	Thickness (cm)	Horizon correction	Quartz mass (g)	Carrier mass (g)	$^{10}Be/^{9}Be$ (10^{-14})	^{10}Be concentration (10^3 atoms/g)	Exposure age (yr)
BM-12-01	44.49693	−71.2918	430	>1	1.8	0.999	8.1362	0.5317	4.045 ± 0.15	82.76 ± 2.9	14,325 ± 504
BM-12-02	44.49693	−71.2920	430	>1	1.5	0.999	19.353	0.2339	9.914 ± 0.19	81.65 ± 1.6	14,169 ± 262
BM-12-03	44.49688	−71.2919	430	>1	2.0	0.999	6.4029	0.5332	3.263 ± 0.11	84.27 ± 2.9	14,610 ± 510
BM-12-04	44.49708	−71.2931	436	>1	1.9	0.999	17.007	0.5273	7.892 ± 0.15	77.27 ± 1.5	13,311 ± 266
BM-12-05	44.49708	−71.2931	436	>1	1.5	0.999	17.455	0.5266	8.065 ± 0.13	76.85 ± 1.3	13,199 ± 219
BM-12-07	44.49930	−71.2971	421	>1	1.5	0.999	13.322	0.5315	6.291 ± 0.14	78.88 ± 1.8	13,758 ± 319
BM-12-08	44.50012	−71.2988	418	>1	1.6	0.999	15.459	0.5275	6.897 ± 0.12	74.22 ± 1.2	12,948 ± 215
									Mean age (n = 7)		13,739 ± 630

Notes: All samples were collected in 2012. All BM samples were spiked with a 477 μg/g ^{9}Be carrier, with the exception of BM-12-02, which was spiked with a 1029 μg/g carrier. Three procedural blanks, $^{10}Be/^{9}Be$ = (7.2×10^{-16} to 9.0×10^{-16}), were processed identically to the samples. Beryllium ratios of BM samples and blanks were measured relative to the 07KNSTD standard [$^{10}Be/^{9}Be = 2.85 \times 10^{-12}$]. Ages were calculated using a rock density of 2.7 g/cm^3 and assuming zero erosion.

(Putnam et al., 2019) produces a slightly (3%) older age for the Berlin moraines and improves the fit with the minimum-limiting radiocarbon data.

Finally, acknowledging that our samples were taken from one of five main moraines and therefore cannot document specifically the full age range of the complex, the regular spacing and uniform morphology and weathering appearance of the ridges nonetheless suggests that deposition of the Berlin complex occurred over a relatively short period centered around ~13.7 ka.

Implications for the timing of deglaciation in the White Mountains region

Comparison of our Berlin ^{10}Be data with previously published ages from the Littleton-Bethlehem (Balco et al., 2009) and Androscoggin (Bromley et al., 2015) complexes shows that the three data sets, which have been calculated here in an identical manner, exhibit considerable statistical overlap (respective mean ages agree within 1σ) and thus are close in age (Fig. 5). The most straightforward interpretation of this pattern is that the three moraine complexes constitute different sections of the WMMS and were deposited more or less contemporaneously during an advance of south-flowing ice. By that model, the moraine chronology for the WMMS prescribes an ice margin that was oriented roughly east–west across western and central portions of northern New Hampshire, but which formed a northern loop around the Pliny–Crescent Range (Fig. 2) before terminating in the Androscoggin River valley on the Maine–New Hampshire border (red dashed line in Fig. 2).

We acknowledge, however, that this interpretation conflicts with the recent suggestion by Thompson et al. (2017), based on stratigraphic relationships between moraines and former ice-dammed lakes, that the Androscoggin moraines predate the WMMS and the continuation of the ice margin east of the Berlin moraines lay north of the Androscoggin River valley (yellow dashed line in Fig. 2). To reconcile that model with the overlapping ^{10}Be ages, Thompson et al. (2017) concluded that both the Androscoggin moraines and the WMMS were deposited within ~200 yr, potentially as different episodes in a broader period of regional ice sheet fluctuation. Although the mean age of the Androscoggin moraines aligns with those of both the Berlin and Littleton-Bethlehem moraines (Fig. 5), the relatively broad age distribution and analytical uncertainty for the former permit the Androscoggin event to have occurred slightly prior to construction of the main WMMS, as envisaged by Thompson et al. (2017). Confirmation of either scenario (i.e., the Androscoggin moraines being part of or predating the WMMS) will require detailed mapping of former glacial limits between the Berlin and Androscoggin complexes.

Implications for the deglacial configuration of the Laurentide Ice Sheet

Regardless of whether the WMMS ultimately includes the Androscoggin complex, the Berlin and Littleton-Bethlehem

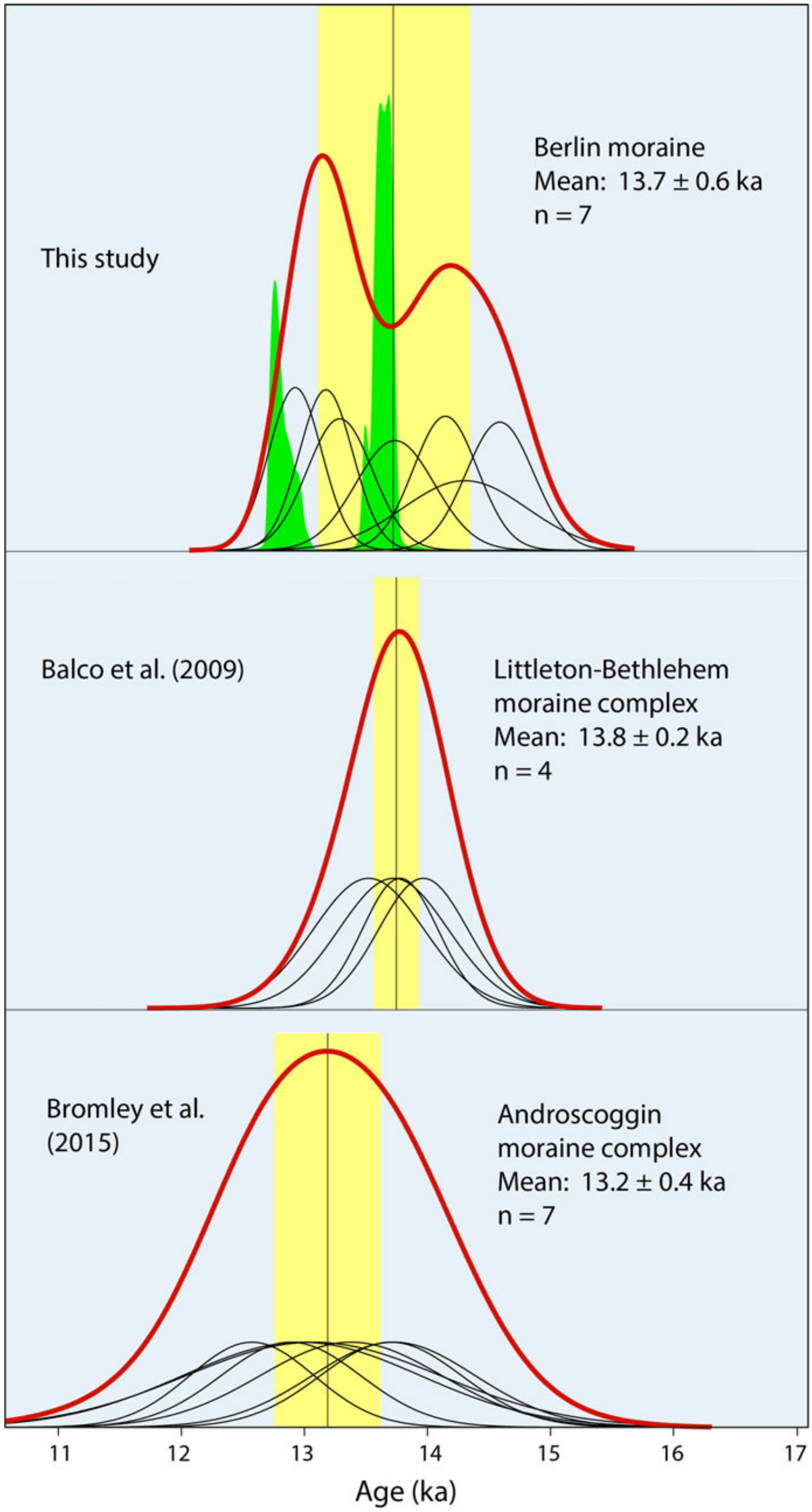

Figure 5. Stacked age probability curves for the Berlin, Littleton-Bethlehem, and Androscoggin moraines (individual and summed probability curves denoted by black and red lines, respectively), relative to the minimum-limiting ^{14}C age data (shown in green as a summed probability curve) discussed in the text. Exposure ages calculated using the NENA (northeastern North America) production rate and time-independent St scaling. Vertical yellow bands depict the standard deviation of the mean ^{10}Be ages (vertical black lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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sites together constrain the position of an active ice margin in northern New Hampshire. The dated Berlin moraine ridge, which represents one of the inner moraines of the WMMS, dates to approximately 13.7 ± 0.6 ka (and must be >13.6 ± 0.1 ka, according to minimum-limiting ^{14}C control). This date is similar to the mean age of ^{10}Be samples from the Littleton-Bethlehem moraines (13.8 ± 0.2; Balco et al., 2009) and to the age derived for the western end of the Littleton-Bethlehem moraines from varves (13.8–14.0 ka; Balco et al., 2009, after Ridge et al., 1999). Altogether, these ages point to a prominent late-glacial moraine-building event at ∼13.7–14.0 ka. Such geochronological constraint is central to testing conceptual models of ice sheet recession during the termination. According to the current paradigm, this sector of the Laurentide Ice Sheet retreated progressively northward and northwestward from its LGM termini in southern New England and the Gulf of Maine, respectively (e.g., Ridge, 2004), eventually vacating the St. Lawrence River valley and enabling formation of the Champlain Sea (Fig. 1; Occhietti and Richard, 2003; Richard and Occhietti, 2005).

Constraining the first part of that model, ^{10}Be data from southern (Balco et al., 2002; Balco and Schaefer, 2006: recalculated here using the same production rate and scaling as our data) and northern (Balco et al., 2009; Bromley et al., 2015; this study) New England depict ice-marginal retreat of >300 km between ∼20 ka (recalculated mean age of the Ledyard moraine near the Connecticut coast [Fig. 1]) and ∼13.7–14.0 ka, when the WMMS was being deposited by a reinvigorated ice margin. North of the WMMS, the timing of deglaciation and the St. Lawrence River marine transgression in adjacent Québec has been investigated extensively for almost half a century using radiocarbon dating (see Cronin, 1979; Parent and Occhietti, 1988; Occhietti and Richard, 2003; Occhietti, 2007; Occhietti et al., 2011). Existing ^{14}C dates are based primarily on marine fauna and, once adjusted for a reservoir effect of as much as 1700 ^{14}C yr (Occhietti and Richard, 2003), place formation of the Champlain Sea at ∼13.0–13.2 ka (see Richard and Occhietti, 2005). The lower St. Lawrence River Estuary to the northeast presumably deglaciated earlier. Radiocarbon dates near the Maine-Quebec border place deglaciation there by ∼13.4–13.5 ka, based on dates of the lowest organic materials in lake cores (Thompson et al., 1996, 1999; Elkadi, 2013). However, configuration of the remaining ice mass south of the St. Lawrence in Maine and Quebec and how that might relate to the WMMS and the chronology presented here remain uncertain.

Assuming that the Champlain Sea chronology is correct, construction of the WMMS at ∼13.7–14.0 ka (Ridge et al., 1999; Balco et al., 2009; Bromley et al., 2015; this study) presents a potential wrinkle in the current understanding of Laurentide deglaciation in northern New Hampshire and adjacent southern Québec. For one, our results, in conjunction with previous work farther west on the WMMS, suggest the Berlin moraines represent deposition along the margin of a late glacial ice mass sufficiently robust not only to advance but also to maintain a semistable position in the northeastern White Mountains long enough to build the extensive and high-relief moraine system. The currently accepted model holds that this ice mass was the south-flowing Laurentide Ice Sheet (e.g., Thompson et al., 2017). Yet, according to the marine chronology, within a few centuries of ice recession from the Berlin moraines, an open seaway filled the St. Lawrence River valley and by about 12.7 ka the Laurentide Ice Sheet's southern margin lay nearly 300 km north of the White Mountains at the Saint-Narcisse moraine (Fig. 1; Occhietti and Richard, 2003; Occhietti, 2007; Occhietti et al., 2011). Although the deglaciation of the St. Lawrence Estuary is beyond the scope of this article, the close timing between moraine and marine chronologies raises questions about ice sheet dynamics and configuration of ice masses in New England and southeastern Canada during opening of the Champlain Sea, such as how rapidly a calving embayment could evacuate the >600 km length of the estuary and what impact this approaching marine margin would have had on the configuration and retreat rates of adjacent terrestrial ice masses.

Implications for late glacial climate and ocean–cryosphere interactions

Both the new and existing ^{10}Be data support previous findings that (1) deglaciation of the White Mountains was interrupted at least once during the late glacial period (Thompson et al., 1996, 1999, 2017) and (2) this advance was of sufficient magnitude and duration to build a conspicuous >90-km-long moraine belt, arguably the most prominent formed since the LGM. Although we do not yet know definitively the cause (s) of this advance, the ^{10}Be-dated Berlin moraine in the eastern part of the WMMS provides two critical pieces of climatic information for northeastern North America.

First, along with the aforementioned moraine chronologies from southern New England (Balco et al., 2002; Balco and Schaefer, 2006), the WMMS brackets a period of net deglaciation (∼20–14 ka) during which the southern margin of the ice sheet retreated several hundred kilometers inland. Although this process was interrupted by brief pauses and/or reversals (e.g., the Rocky Hill readvance [Ridge and Larsen, 1990], Chicopee readvance [Larsen, 1982], and Charlestown readvance [Ridge et al., 2012]), we interpret the overall pattern of ice retreat prior to deposition of the WMMS as reflecting increased summertime melting (Oerlemans, 2005; Zemp et al., 2015). Moreover, we note that this pattern broadly mirrors moraine and deglacial transect records from other well-dated sections of the Laurentide Ice Sheet (Mooers and Lehr, 1997; Glover et al., 2011; Hall et al., 2017; Barth et al., 2019) and European ice masses—including the Alps (Suter, 1981; Lister, 1988; Schlücter, 1988; Ammann and Lotter, 1989; Ravazzi et al., 2014), Scandinavia (Andersen, 1981; Rinterknecht et al., 2005, 2006; Lüthgens et al., 2011; when ^{10}Be exposure ages are recalculated using a more up-to-date production rate, such as those of Putnam et al. [2010, 2019], Fenton et al. [2011], Kaplan et al. [2011], Briner et al. [2012], Young et al. [2013], and Borchers et al. [2016]), and the British Isles (Ballantyne et al., 2013;

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Small et al., 2017)—and aligns with marine evidence for enhanced meltwater discharge into the North Atlantic Ocean during Heinrich stadial 1 event (~18–14.7 ka; Toucanne et al., 2015).

We note, however, that this emerging picture of widespread terrestrial deglaciation driven by summertime melting conflicts with classic North Atlantic marine (e.g., Bard et al., 2000; McManus et al., 2004) and Greenland ice core data (Dansgaard et al., 1993; Grootes and Stuiver, 1997), which have been interpreted as reflecting extremely cold conditions at least during the ~3000-yr duration of the Heinrich stadial 1 event. One potential mechanism by which the two scenarios might be reconciled is enhanced seasonality (Denton et al., 2005), whereby stadial winters in the circum–North Atlantic were characterized by severe cooling because of the anomalous expansion of sea ice, yet summers were relatively warm and/or warming because of such factors as rising summer insolation and greenhouse gas concentrations (Marcott et al., 2014) and/or increased poleward atmospheric heat transport (McGee et al., 2014).

A second climatic implication of the Berlin ^{10}Be chronology concerns the close agreement between this and similar glacial advances reported from a growing number of sites worldwide, and in both ice sheet and alpine glacier settings. Thompson et al. (2017) discussed similarities between the western and central parts of the WMMS and synchronous glacial still stands/readvances recorded by investigators in Maritime Canada (Nova Scotia), Norway, Sweden, Scotland, and Austria. Along the southern margin of the Laurentide Ice Sheet, for instance, Lowell et al. (1999, and references therein) summarized an advance (Two Rivers advance) of the Lake Superior Lobe that was underway by 13.8 ka, broadly coincident with the Middlesex readvance in central Vermont (≤13.8 ka: Larsen, 2001). On the opposite side of the Atlantic, Andersen et al. (1995) reported numerous moraine systems in Norway that, within the ^{14}C uncertainties, document advances that culminated during the Allerød interstade (~13.9–12.9 ka) and earliest Younger Dryas stade, a pattern that has also been reported from the British Isles (Bromley et al., 2018; Putnam et al., 2019). Beyond the Northern Hemispheric ice sheets, alpine glacier systems in the tropics (Rodbell and Seltzer, 2000; Bromley et al., 2011; Jomelli et al., 2014; Rademaker et al., 2014; Stansell et al., 2015) and southern middle latitudes (Kaplan et al., 2010, 2013; Putnam et al., 2010; Strelin et al., 2011; Garcia et al., 2012; Menounos et al., 2013) underwent widespread advance between ~14.5 and 13.0 ka. Rather than constituting mere fluctuations of retreating ice margins, these events are reported as having been the most prominent late-glacial advances in their respective regions.

Acknowledging that temporal coincidence is not proof of common causality, and that individual ice masses may respond differently to a uniform forcing, the broad alignment of these geographically disparate moraine records nonetheless raises the possibility that, collectively, they represent a short-lived yet globally extensive synchronous cooling event. Further high-resolution, directly dated late glacial moraine records will be key to exploring this hypothesis further.

CONCLUSIONS

Our new ^{10}Be data set from the Berlin moraines constrains a glacial advance in northern New Hampshire that culminated at 13.7 ± 0.6 ka. When combined with minimum-limiting radiocarbon data, the age of the Berlin moraine complex must be $>13.6 \pm 0.1$ ka. Chronologically, this landform is statistically indistinguishable from the Littleton-Bethlehem moraines farther west, with which the Berlin moraines are correlated stratigraphically, leading us to conclude that both complexes represent contemporaneous or at least overlapping sections of the WMMS. ^{10}Be ages also raise the possibility that the WMMS is coeval with the Androscoggin complex on the Maine–New Hampshire border.

Coupled with existing (recalculated) surface-exposure data from the southern New England coast, the WMMS ^{10}Be chronology brackets a period of pronounced active recession, punctuated by readvances/still stands, during which the southeastern margin of the Laurentide Ice Sheet retreated >300 km from near its full LGM limits to the northern White Mountains. Much of this deglaciation, and thus atmospheric warming, occurred during Heinrich stadial 1 event (~18–14.7 ka), a period traditionally associated with annually cold conditions. Therefore, our interpretation of the New England deglacial record supports the hypothesis of extreme seasonality (warmer summers and much colder winters) during North Atlantic stadial events relative to nonstadial conditions.

Within their respective uncertainties, the ages of the Berlin moraines and broader WMMS (~13.7–14.0 ka) are in close agreement with robustly dated late glacial advances documented along other sections of the Laurentide ice margin, as well as with events farther afield in Europe, the tropics, and southern middle latitudes. Although any correlations among the data sets are at this stage speculative, the alignment nonetheless raises the possibility of a climate anomaly of potentially global scale that interrupted warming during the last glacial termination.

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