



Late glacial fluctuations of the Laurentide Ice Sheet in the White Mountains of Maine and New Hampshire, U.S.A.



Gordon R.M. Bromley^{a,*}, Brenda L. Hall^a, Woodrow B. Thompson^b, Michael R. Kaplan^c,
Juan Luis Garcia^{a,d}, Joerg M. Schaefer^c

^a School of Earth & Climate Sciences and the Climate Change Institute, Edward T. Bryard Global Sciences Center, University of Maine, Orono, ME 04469-5790, USA

^b Maine Geological Survey, 93 State House Station, Augusta, ME 04333-0093, USA

^c Lamont-Doherty Earth Observatory, Geochemistry, Route 9W, Palisades, NY 10964, USA

^d Instituto de Geografía, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna 4860, Santiago 782-0436, Chile

ARTICLE INFO

Article history:

Received 5 November 2014

Available online 19 March 2015

Keywords:

Laurentide Ice Sheet

New England

Deglaciation

Late glacial

Allerød

Readvance

ABSTRACT

Prominent moraines deposited by the Laurentide Ice Sheet in northern New England document readvances, or stillstands, of the ice margin during overall deglaciation. However, until now, the paucity of direct chronologies over much of the region has precluded meaningful assessment of the mechanisms that drove these events, or of the complex relationships between ice-sheet dynamics and climate. As a step towards addressing this problem, we present a cosmogenic ¹⁰Be surface-exposure chronology from the Androscoggin moraine complex, located in the White Mountains of western Maine and northern New Hampshire, as well as four recalculated ages from the nearby Littleton–Bethlehem moraine. Seven internally consistent ¹⁰Be ages from the Androscoggin terminal moraines indicate that advance culminated $\sim 13.2 \pm 0.8$ ka, in close agreement with the mean age of the neighboring Littleton–Bethlehem complex. Together, these two datasets indicate stabilization or advance of the ice-sheet margin in northern New England, at ~ 14 – 13 ka, during the Allerød/Greenland Interstadial I.

© 2015 University of Washington. Published by Elsevier Inc. All rights reserved.

Introduction

During the Last Glacial Maximum (LGM; ~ 26 – 19 ka), the Laurentide Ice Sheet (LIS) constituted the largest ice mass on Earth. With an area of $\sim 13,000,000$ km² and maximum surface elevations of as much as 3000 m (Denton and Hughes, 1981), the LIS exerted a considerable influence on global climate through albedo forcing (e.g., Broccoli and Manabe, 1987), displacement of atmospheric circulation (e.g., Williams et al., 1974; Hostetler and Clark, 1997; Oviatte, 1997; Birkel, 2010), and, particularly along the ice sheet's Atlantic margins, ocean–ice sheet interactions (e.g., Bond et al., 1993; MacAyeal, 1993). Indeed, perturbations of the ice sheet's maritime sectors have been invoked widely as a key component – if not the cause – of Heinrich events (e.g., Hulbe et al., 2004), during which considerable volumes of ice apparently were disgorged into the North Atlantic Ocean with profound consequences for downwind ocean circulation (Broecker, 2003). Concurrently, the temperate nature and relatively low latitude of the ice sheet mean the LIS itself will have been highly sensitive to climate, particularly along southern and eastern margins where deglacial readvances have been correlated with perturbations of North Atlantic

circulation (e.g., Lowell et al., 1999; Dorion et al., 2001; Borns et al., 2004; Kaplan, 2007). Consequently, accurate reconstruction of past ice-sheet behavior provides the means to assess both the role of the LIS in Late Quaternary climate variability and sensitivity of the ice sheet to key events, such as Heinrich stadials and late-glacial climate reversals.

Comprehensive geologic mapping of glacial deposits and features over the past several decades has revealed the overall pattern of ice-sheet behavior in New England during the LGM and subsequent deglaciation. At its maximum extent, the southeastern sector of the LIS terminated at the large moraine systems off the coast of southern New England – Long Island, Martha's Vineyard, and Nantucket Island (Fig. 1; Oldale, 1982; Oldale and O'Hara, 1984; Stone and Borns, 1986; Balco et al., 2002) – while farther east the ice margin lay far offshore at George's Bank in the Gulf of Maine (Fig. 1; Pratt and Schlee, 1969; Stone and Borns, 1986). Inland from these limits, minor moraine belts and landform assemblages in southern New England document the northward retreat of the ice-sheet margin through Connecticut, Massachusetts, and into New Hampshire (Fig. 1; Koteff and Pessl, 1981; Ridge, 2004; Balco and Schaefer, 2006; Balco et al., 2009). In Maine, swarms of minor moraines occur where deglaciation of the coastal lowland was accompanied by marine submergence. The distribution of glacial landforms in these areas indicates that ice-sheet retreat initially was gradual and oscillatory, with frequent stillstands and minor

* Corresponding author. Fax: +1 207 581 1203.

E-mail address: gordon.r.bromley1@maine.edu (G.R.M. Bromley).

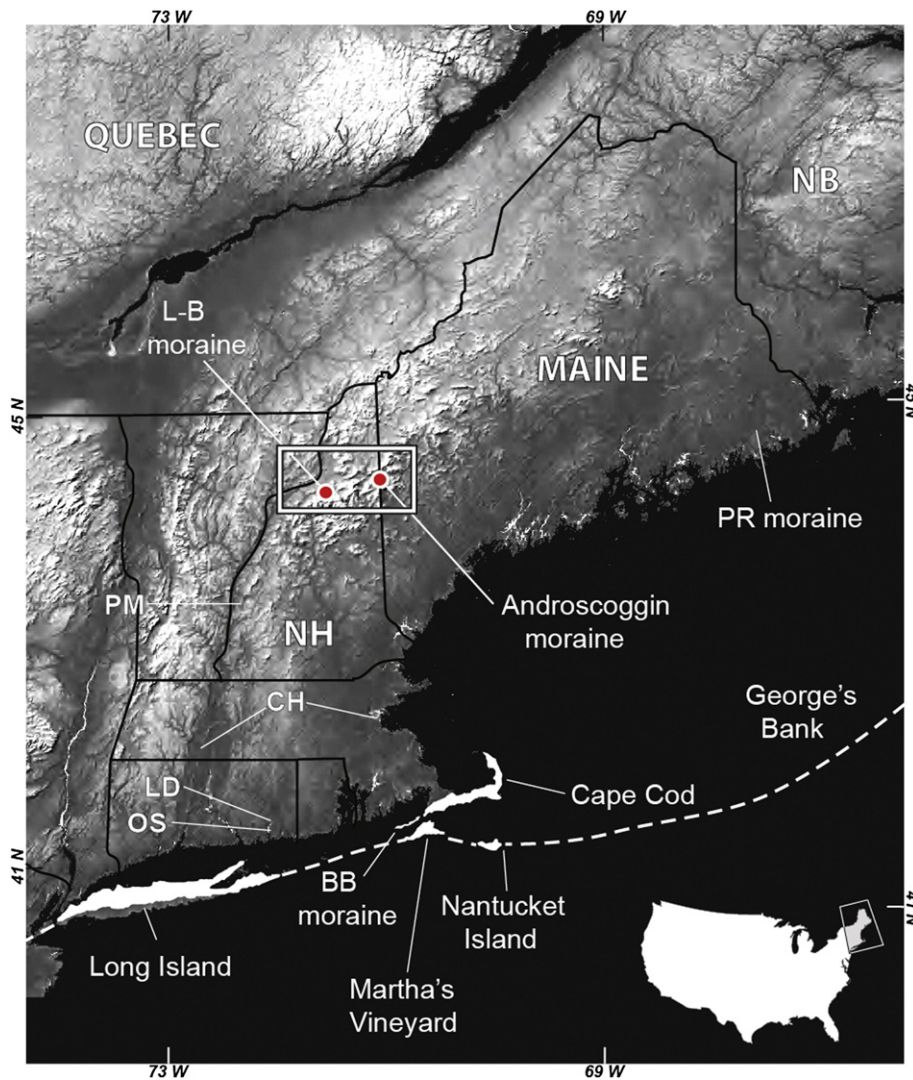


Figure 1. Map of New England and SE Canada showing the maximum extent of the Laurentide Ice Sheet during the LGM (dashed line). Also shown are locations of sites mentioned in the text (L-B moraine – Littleton–Bethlehem moraine; PR moraine – Pineo Ridge moraine; BB moraine – Buzzards Bay moraine; NH – New Hampshire; NB – New Brunswick), as well as prominent moraines corresponding to deglacial ice-marginal positions (CH – Chicopee Readvance moraines: [Ridge, 2004](#); LD – Ledyard moraines; OS – Old Saybrook moraine: [Balco and Schaefer, 2006](#); PM – Perry Mountain moraine: [Balco et al., 2009](#)).

readvances resulting in the extensive (>100 km in length) coastal moraine belt in Maine and New Brunswick ([Borns, 1973, 1980](#); [Borns and Hughes, 1977](#); [Rampton et al., 1984](#); [Thompson and Borns, 1985](#); [Smith and Hunter, 1989](#); [Kaplan, 1999](#); [Borns et al., 2004](#)). In a few places, the advances or stillstands were long enough to build extensive deposits, such as the Pond Ridge moraine and Pineo Ridge moraine complex ([Borns et al., 2004](#); [Fig. 1](#)). The scarcity of moraines and prevalence of eskers proximal to the coastal moraine belt indicates that subsequent deglaciation proceeded rapidly and without major interruption until the ice margin reached the vicinity of the Appalachian Mountains ([Davis and Jacobson, 1985](#)). There, several extensive moraine complexes record fluctuations of this sector of the LIS and are the focus of this study.

Compared to extensive mapping studies, the glacial chronology for this SE sector of the LIS is less complete and, in places, controversial. On the basis of limiting radiocarbon ages and existing ^{10}Be surface-exposure ages, we know that the ice sheet was most extensive during the LGM *sensu stricto* ([Tucholke and Hollister, 1973](#); [Oldale, 1982](#); [Stone and Borns, 1986](#); [Stone et al., 1998](#); [Balco et al., 2002, 2009](#)), consistent with other sectors of the LIS ([Dyke and Prest, 1987](#)). Recalculated ^{10}Be ages from the Buzzards Bay moraine in Massachusetts ([Fig. 1](#))

suggest that the ice margin remained at or near its maximum extent until ~21 ka ([Balco et al., 2009](#)). However, estimates for the onset of deglaciation vary widely, with varve (e.g., [Ridge, 2004](#)) and surface-exposure ([Balco and Schaefer, 2006](#); [Balco et al., 2009](#)) chronologies indicating a significantly earlier (by as much as ~5 ka) retreat of the LIS than that determined by recent terrestrial radiocarbon dating (e.g., [Petee et al., 2012](#)). Nonetheless, radiocarbon ages of mollusk shells from raised marine deposits in eastern Maine indicate that the ice-sheet margin had retreated to the present-day coastline by ~17–15 ka, with the Pineo Ridge moraine complex representing a major stillstand ([Smith and Hunter, 1989](#)) and/or readvance ([Borns and Hughes, 1977](#); [Borns, 1980](#)) of the LIS towards the end of that period (e.g., [Kaplan, 1999](#); [Dorion, 1997](#); [Dorion et al., 2001](#); [Borns et al., 2004](#); [Kaplan, 2007](#)).

Subsequent portions of the deglacial record are problematic. For example, the deglaciation of central and northern Maine is constrained by a relatively sparse coverage of minimum-limiting ^{14}C ages, many of which are based on bulk samples and, in some cases, affected by a marine reservoir effect of uncertain magnitude ([Davis and Jacobson, 1985](#); [Ridge et al., 2001](#); [Borns et al., 2004](#)). In comparison, the varve chronologies constructed for central New England ([Antevs, 1922, 1928](#); [Ridge](#)

et al., 2001; Ridge, 2004) offer a seemingly precise chronology for ice-sheet retreat through that sector. However, as argued by Borns et al. (2004) and later by Peteet et al. (2012), these essentially “floating” chronologies are pinned to the calendar time scale in relatively few locations (see below), raising the possibility of systematic age offsets in the deglacial record. Thus, much of the chronology of ice-sheet retreat in New England is known only on a first-order basis.

Together, the glacial stratigraphy and existing chronology for New England provide some insight into ice-sheet behavior during the last glacial-interglacial transition. However, the temporal resolution is insufficient to reveal the fine structure of deglaciation or to assess the response of the LIS to millennial-scale climate forcing. This is particularly true for the late-glacial period (~15–11.6 ka), during which the climate system underwent high-magnitude, potentially abrupt transitions on both regional and global scales. For example, although several studies have reported evidence for a cryospheric response in New England to such events as the Younger Dryas (YD) stadial (e.g., Lamothe, 1992; Borns et al., 2004) and Heinrich stadials (e.g., Balco et al., 2002; Ridge, 2004; Kaplan, 2007), these correlations have yet to be tested and therefore remain equivocal.

To help develop the deglacial record of New England, specifically after the LIS had retreated inland of the marine limit, we present a ^{10}Be surface-exposure chronology for the Androscoggin moraine complex, located in the White Mountains of western Maine and eastern New Hampshire (Figs. 1, 2). Together with the neighboring Littleton–Bethlehem (L–B) moraine (Figs. 1, 2; Thompson et al., 1996, 1999, 2002), the Androscoggin moraine represents renewed advance – or a stillstand – of the LIS in northern New England during overall deglaciation. However, until now the Androscoggin moraine has not been dated directly. As a result, the significance of these prominent moraines to the deglacial record of the LIS hitherto was poorly understood. In this paper, we discuss the implications of our Androscoggin moraine dataset in conjunction with four recalculated ^{10}Be ages from the L–B moraine.

Geologic setting and methods

The White Mountains of New Hampshire and western Maine contain a rich geologic record of LIS deglaciation that has been studied in detail since the mid-19th century (e.g., Lyell, 1850; Agassiz, 1870; Thompson, 1999, and references therein). The most conspicuous depositional landforms include the L–B moraine system, a broad complex

of ridges in the vicinity of the towns of Littleton and Bethlehem (Fig. 2; Thompson et al., 1999), and a group of prominent lateral and terminal moraines straddling the Maine–New Hampshire border in the Androscoggin River valley (Figs. 2, 3) that are the focus of this paper.

The Androscoggin moraines, comprising approximately twenty sections of lateral and terminal ridges located on both sides of the valley (Fig. 3) (Stone, 1880; Thompson and Fowler, 1989), are some of the most prominent moraines in the White Mountains (Upham, 1904). As detailed by Thompson and Fowler (1989), the arcuate distribution of the moraines defines the former terminus of an ~3 km-wide, east-flowing glacier tongue and its subsequent separation into discrete sub-lobes during initial stages of retreat. The Androscoggin moraines exhibit considerable relief (exceeding 30 m in places) and sharp, well-preserved crests, indicating little post-glacial reworking. Moreover, the crests are mantled with boulders of local and regional provenance (Fig. 4), the majority of which are quartz-bearing and thus ideal for ^{10}Be surface-exposure dating (see below).

Previous work has established the age of the Androscoggin moraine complex only in a broad sense. A basal age of $12,450 \pm 60$ ^{14}C yr BP (OS-7125) (14,985–14,219 cal yr BP (IntCal 13); Thompson et al., 1996) from Pond of Safety (Fig. 2), located approximately 30 km northwest of the moraine in the upper Israel River valley, has been interpreted as a minimum age for the Androscoggin complex (Thompson et al., 1999). However, owing to the challenging terrain and distances involved, the exact correlation between the two sites – and thus the relevance of the basal age to the moraine – has not been established unequivocally.

Age control notwithstanding, Thompson et al. (1999) suggested on the basis of relative position that the Androscoggin moraine might predate the extensive L–B moraine, whereas a subsequent interpretation proposed that the two complexes might correspond to the same advance (Thompson et al., 2007). Because the two moraine systems are not laterally continuous, and owing to heavy forest cover, it is not possible to determine their age relationship from mapping alone.

Compared to the Androscoggin moraine, the age of the L–B complex is better resolved owing to its direct association with the New England varve record at Comerford Dam, on the Vermont–New Hampshire border (Ridge et al., 1996; Fig. 2). Indeed, the correlation of the moraines with a till deposited between varve years 7154 and 7305 (Ridge and Larsen, 1990; Ridge et al., 1999) allowed Balco et al. (2009) to assign a mean age of $13,840 \pm 250$ yr to the complex as part of the north-east North America (NENA) ^{10}Be production-rate calibration

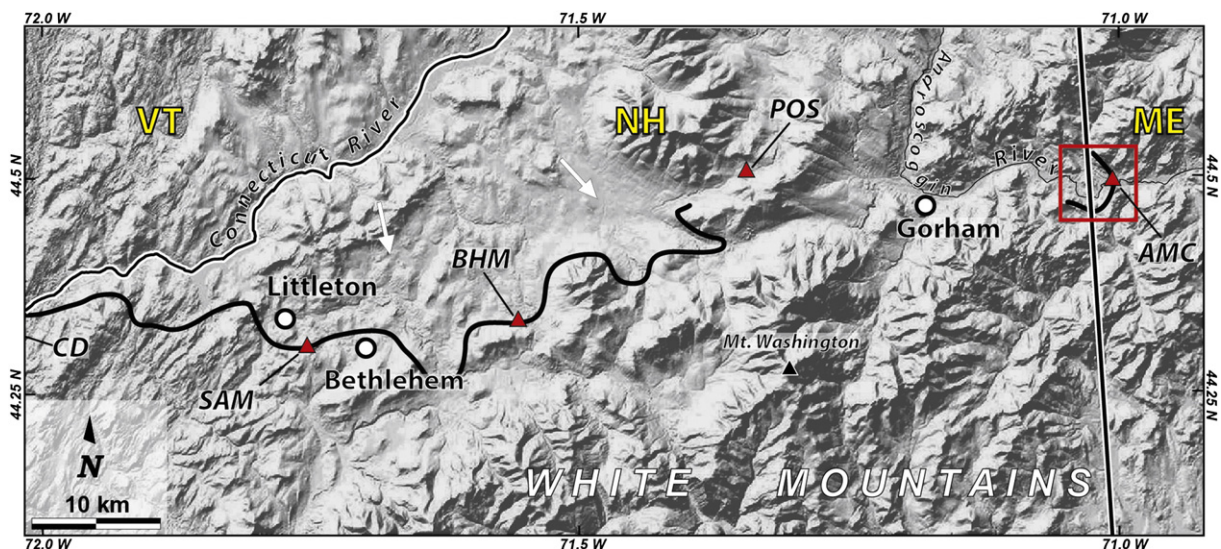


Figure 2. Topographic relief map of central New Hampshire and westernmost Maine showing the location sites discussed in the text. AMC – Androscoggin moraine complex; SAM – Sleeping Astronomer moraine; BHM – Beech Hill moraine; CD – Comerford Dam; POS – Pond of Safety. Thick black line represents the Littleton–Bethlehem moraine complex (adapted from Thompson et al., 1999; for more detailed maps of the BHM and SAM sections, we refer readers to that publication). White arrows indicate the general ice-flow direction. Red square indicates the area depicted in Fig. 3.

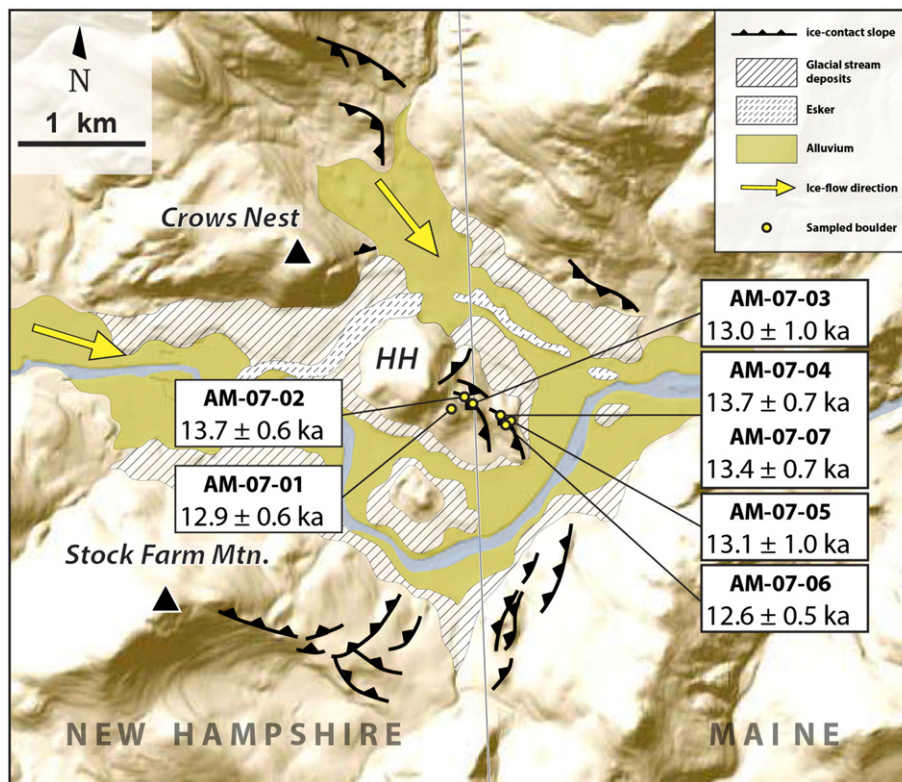


Figure 3. Geomorphic map of the Androskoggin moraine complex, showing the general distribution of surficial deposits (adapted from Thompson and Fowler, 1989), as well as locations and surface-exposure ages of samples from Hark Hill (HH). Non-specified areas comprise till and/or bedrock.

study. Balco et al. (2009) also collected four surface-exposure samples from two sites – the Sleeping Astronomer and Beech Hill moraines (Fig. 2) – located close to the distal edge of the L–B moraine belt. In the current study, we present recalculated ages for those samples using the beryllium concentrations published by Balco et al. (2009).

Our Androskoggin surface-exposure chronology is based on ^{10}Be ages ($n = 7$) from coarse-grained granite boulders, all but one (AM-07-01) of which are located on the crests of two terminal moraines protruding eastward from Hark Hill (Figs. 3, 4). Sample AM-07-01 is located on a bedrock knoll immediately inside the moraine complex (Fig. 3). We targeted these prominent landforms because they represent the closest well-preserved moraines to the maximum terminal position of the Androskoggin glacier. Samples comprise the upper few centimeters (≤ 5 cm) of rock from the boulders' horizontal top surfaces and were collected with a hammer and chisel. Although sampled surfaces exhibited pronounced glacial molding, the absence of striae and polish suggests a minor degree of post-depositional erosion, as reported by Balco et al. (2009) for samples from the L–B moraines. As argued below, however, this process is unlikely to have had a significant effect on exposure age (see Results).

To reduce the likelihood of shielding effects due to snow or vegetation cover, we sampled only boulders greater than 1 m in relief (Table 1). Additionally, we calculated chi-squared (χ^2) values for both the AM and L–B data sets to assess the impact, if any, of post-depositional geological and/or environmental processes on exposure-age distributions (see Results).

Samples were prepared at the University of Maine and Lamont–Doherty Earth Observatory. We separated quartz following established heavy-liquid and HF-leaching procedures, after which beryllium was extracted following the methods described by Schaefer et al. (2009). Beryllium ratios of samples and blanks were measured at the Lawrence–Livermore CAMS facility relative to the 07KNSTD standard [$^{10}\text{Be}/^9\text{Be} = 2.85 \times 10^{-12}$; Nishiizumi et al., 2007] (note: ratios for

the L–B samples were measured relative to the KNSTD standard [$^{10}\text{Be}/^9\text{Be} = 3.15 \times 10^{-12}$]). We calculated surface-exposure ages using the CRONUS-Earth online calculator, version 2.2 (Balco et al., 2008), in conjunction with the NENA ^{10}Be production rate (Balco et al., 2009) and the time-independent “St” scaling (Lal, 1991; Stone, 2000). To provide an independent check of the NENA-derived ages, and to prevent circular reasoning (i.e., the L–B samples are a constituent of the NENA calibration), we also calculated ages using two recent, non-local ^{10}Be production rates, one from north-eastern North America (Young et al., 2013; see Table 3) and one from the Southern Alps of New Zealand ($\sim 44^\circ\text{S}$; Putnam et al., 2010). In calculating moraine mean age, we also propagated analytical uncertainties with a systematic uncertainty (4.8%) associated with the NENA production rate calibration (Table 1). Although inclusion of such a systematic uncertainty is not needed for comparison between the closely located L–B and Androskoggin moraines (e.g., Fig. 5), it is a consideration when comparing to records determined by other chronological methods.

Our choice of St scaling reflects the close match this scheme provides to independent chronological constraints in New England (Balco et al., 2009) and elsewhere (Fenton et al., 2011; Briner et al., 2012; Kelly et al., 2013; Young et al., 2013). However, we stress that our conclusions are independent of our choice of scaling scheme, because at these latitudes and relatively low elevations the respective ages are statistically identical (Table 2). Analytical results and ages are given in Table 1.

Results

The seven ^{10}Be ages from the Androskoggin moraine – constituting the first surface exposure-dated moraine from the state of Maine – are given in Table 1 and are shown in Figs. 3 and 5. The four recalculated surface-exposure ages from the L–B moraine are given in Table 1 and Fig. 5. Together, the seven Androskoggin ages form an internally consistent grouping, without outliers (i.e., $\pm 1\sigma$), ranging from 13.7 ± 0.6 ka

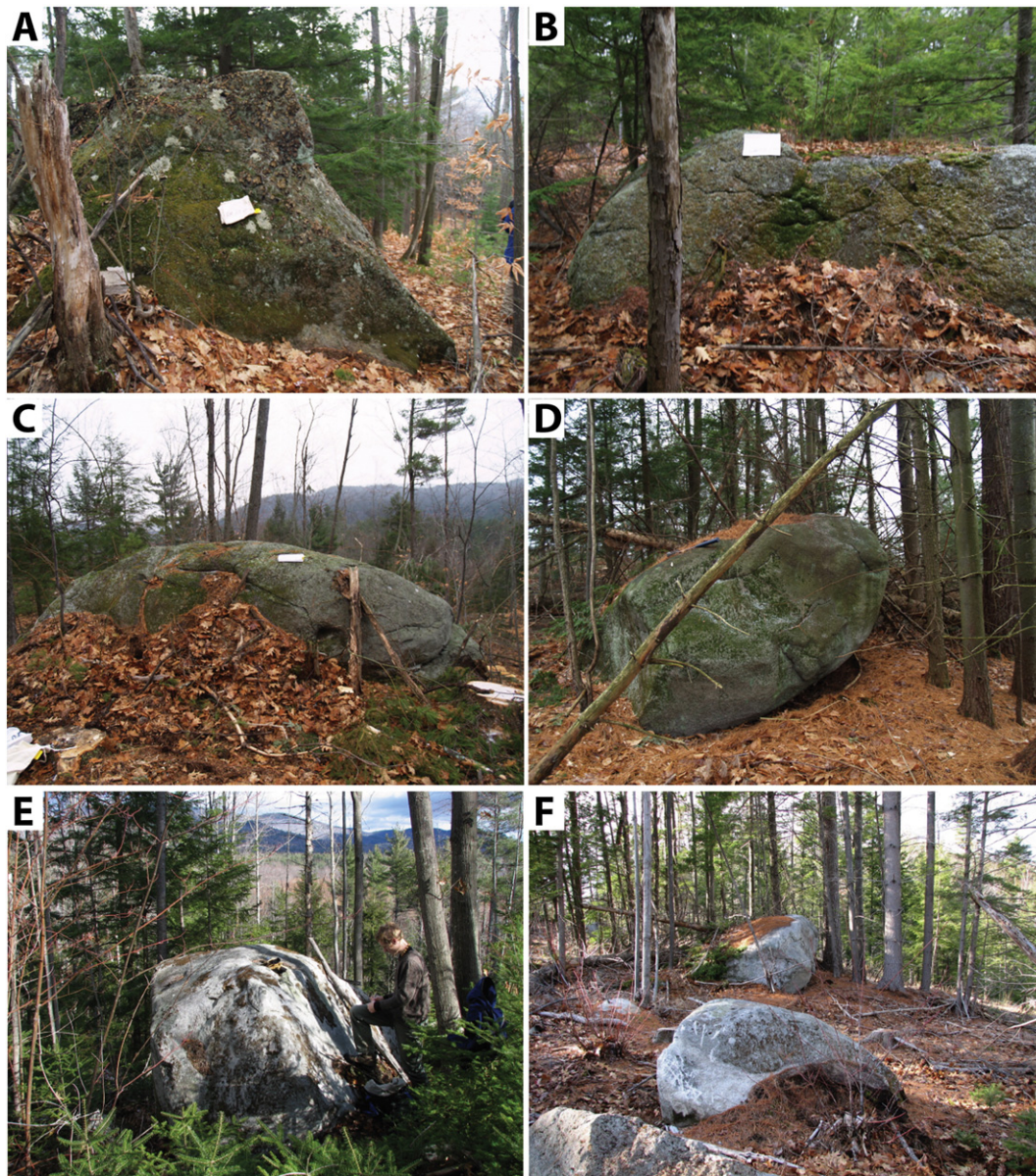


Figure 4. Glacially molded erratics on Hark Hill, Maine. Clockwise from top left: (A) AM-07-01; (B) AM-07-02; (C) AM-07-03; (D) AM-07-04; (E) AM-07-05; and (F) AM-07-07 (foreground) and AM-07-04 (background). With the exception of AM-07-01, which is located on a bedrock knoll inside the moraine complex, all sampled boulders are located on well-defined moraine crests.

to 12.6 ± 0.5 ka, and provide an average moraine age of 13.2 ± 0.4 ka, or 13.2 ± 0.8 ka if an $\sim 5\%$ systematic uncertainty is propagated. Plotted as an age–probability curve, the ages exhibit a normal distribution with a peak age of 13.2 ka (Fig. 5). In comparison, the four samples collected from the L–B moraine by Balco et al. (2009) range from 14.0 ± 0.4 ka to 13.5 ± 0.5 ka, and provide a mean moraine age of 13.8 ± 0.2 ka (or 13.8 ± 0.7 ka with a 5% propagated uncertainty) and a peak age of 13.8 ka (Fig. 5). As the three production rates (Balco et al., 2009; Putnam et al., 2010; Young et al., 2013) are statistically identical, our moraine ages are consistent regardless of which rate is used. Moreover, both of the two more precise rates (Putnam et al., 2010; Young et al., 2013) produce exposure ages for L–B samples that are congruent with that inferred from the New England varve chronology (Ridge et al., 1999; Balco et al., 2009), supporting their use throughout eastern North America. We also point out that the very close agreement between the production rate of Young et al. (2013) and the New England varve chronology implies that our propagation of a 5% systematic uncertainty is conservative.

While we acknowledge the possibility of geologic or environmental processes affecting our Androskoggin ages, several lines of evidence point to these processes having had minimal impact on our age calculations. First, despite the evidence for minor erosion of boulder surfaces, both the glacial molding of selected boulders and the internal consistency of our data set (Figs. 3, 5) suggest that this effect has been minor. Second, comparison of ^{10}Be age versus boulder height shows no significant relationship (Table 1), as would be expected with snow shielding. Third, the Androskoggin moraines are well defined and sharp crested, indicating that post-depositional modification has been negligible. Finally, chi-squared values for both the Androskoggin and L–B data sets are <1 ; values of ~ 1 – 2 indicate that age differences can be explained by analytical uncertainties alone (Bevington and Robinson, 1992). Processes such as snow shielding, substantial boulder erosion, and moraine deflation should cause each boulder to have a different exposure history. Given that our ages are statistically indistinguishable from one another, we conclude that such post-depositional processes have had a negligible effect on our data set.

Table 1

Sample details and ^{10}Be surface-exposure ages for the Androscoggin (AM) and Littleton–Bethlehem (LIT) moraine samples. All exposure ages shown are calculated using the NENA production rate of Balco et al. (2009) and St scaling (Lal, 1991; Stone, 2000). The L–B ages are identical if calculated with either the (independent) rate in Balco et al. (2009) or Young et al. (2013) (see text). Asterisk denotes the average ^{10}Be concentration of two replicates of sample 06-NE-013-LIT (Balco et al., 2009). For mean moraine age (arithmetic), we also present an error that includes propagation of the standard deviation as well as the uncertainty (4.8%) for the NENA production rate calibration. Data for the LIT samples from Balco et al. (2009).

Sample	Latitude	Longitude	Altitude (m)	Boulder height (m)	Thickness (cm)	Horizon correction	Quartz mass (g)	Carrier mass (mg)	$^{10}\text{Be}/^9\text{Be}$ (10^{-14})	^{10}Be conc. (10^3 atoms/g)	Exposure age (yr)
AM-07-01	44.3973	−71.0188	279	2	1.0	0.998	7.3058	0.1798	3.998 ± 0.15	65.37 ± 2.9	$12,890 \pm 570$
AM-07-02	44.3952	−71.0168	288	1.5	2.0	0.999	11.551	0.1797	6.653 ± 0.26	69.57 ± 2.9	$13,700 \pm 580$
AM-07-03	44.3971	−71.0162	283	1.5	2.1	0.999	5.510	0.1798	3.052 ± 0.21	65.54 ± 4.9	$12,980 \pm 970$
AM-07-04	44.3969	−71.0139	273	1.5	0.8	0.999	11.3217	0.1796	6.511 ± 0.30	69.41 ± 3.4	$13,730 \pm 670$
AM-07-05	44.3942	−71.0137	241	1.5	2.1	0.999	8.4227	0.1797	4.468 ± 0.34	63.53 ± 5.0	$13,070 \pm 1040$
AM-07-06	44.3944	−71.0146	244	1.5	2.4	0.999	12.3043	0.1796	6.238 ± 0.23	61.13 ± 2.3	$12,570 \pm 510$
AM-07-07	44.3949	−71.0143	241	1	1.8	0.999	11.8735	0.1796	6.413 ± 0.34	65.17 ± 3.6	$13,380 \pm 740$
										Mean age (s.d.)	$13,190 \pm 430$
										(with PR uncertainty propagated)	$13,190 \pm 770$
06-NE-010-LIT	44.2903	−71.7612	357	1.8	2	0.999	–	–	–	81.80 ± 2.6	$13,730 \pm 450$
06-NE-011-LIT	44.2904	−71.7608	357	1.9	2	0.999	–	–	–	80.60 ± 2.7	$13,530 \pm 450$
06-NE-012-LIT	44.3129	−71.5722	414	1.6	1	0.999	–	–	–	88.30 ± 2.3	$13,970 \pm 360$
06-NE-013-LIT	44.3146	−71.5730	412	1.6	10	0.999	–	–	–	$81.00 \pm 1.8^*$	$13,780 \pm 310$
										Mean age (s.d.)	$13,750 \pm 180$
										(with PR uncertainty propagated)	$13,750 \pm 690$

Note: All AM samples were spiked with a 1024 mg/g ^9Be carrier. Two procedural blanks ($^{10}\text{Be}/^9\text{Be} = (0.491 \text{ and } -1.835 \times 10^{-15})$), consisting of 0.180 ml of ^9Be carrier, were processed identically to the samples. Beryllium ratios of AM samples and blanks were measured relative to the 07KNSTD standard [$^{10}\text{Be}/^9\text{Be} = 2.85 \times 10^{-12}$], while those of L–B samples and blanks were measured relative to the KNSTD standard [$^{10}\text{Be}/^9\text{Be} = 3.15 \times 10^{-12}$]. Ages were calculated using a rock density of 2.65 g/cm 3 and assuming zero erosion.

Discussion

The prominent nature of the Androscoggin moraines suggests that this complex, like the L–B moraine belt (Thompson et al., 1999), represents an advance or stillstand of the LIS during overall retreat. However, owing to dense forest cover and challenging terrain, the exact relationship between the two complexes has remained ambiguous. Our new ages for the Androscoggin moraine and recalculated ages for the L–B moraine provide important insight into the deglaciation of northern New England. As noted above, we discuss the data as calculated using the local NENA production rate, but stress that our interpretations would remain unchanged using other recently published, indistinguishable production rates (see Table 3). Indeed, it is noteworthy that these three production rates produce results that are indistinguishable statistically despite having been calibrated in starkly different geographic and environmental contexts (i.e., New England, Arctic, Southern Alps).

Although the peak ages of the two moraine complexes differ by ~600 yr, their respective mean ages overlap within 1 σ uncertainty and thus the datasets are indistinguishable statistically. Therefore, we suggest that the Androscoggin and L–B moraine systems represent the same late-glacial advance/stillstand of the LIS, as hypothesized originally by Thompson et al. (2007). Viewed in greater detail, the small discrepancy in peak age potentially reflects differences in the distribution of moraines and sampled boulders between the two sites. For instance, the sprawling geographic distribution of the L–B complex (Upham, 1904; Thompson et al., 1999) indicates that this moraine belt was deposited over a considerable period, while the four existing L–B ^{10}Be ages, from the Sleeping Astronomer and Beech Hill moraines, constrain the age of only the most distal parts of the complex. In contrast, the Androscoggin moraines, which are primarily composite landforms, exhibit a more compact spatial distribution. Our seven samples, collected from the crests of those composite moraines, thus represent the most recent period of deposition. Therefore, it is conceivable that the marginally younger peak age of the Androscoggin moraines correlates with the more proximal, as yet undated deposits in the L–B complex. Nonetheless, given the statistically indistinguishable ages of the two moraine complexes, we acknowledge that we are unable to test this model with the existing dataset.

We also note that our surface-exposure data conflict with the original interpretation of the Pond of Safety radiocarbon chronology. By that model, the ^{14}C date from the basal sediments of the pond constitutes a minimum-limiting age for the Androscoggin moraines but a maximum-limiting age for the L–B complex, moraines of which are located proximal (relative to ice-flow direction) to the pond (Thompson et al., 1996, 1999). However, our data suggest that the Androscoggin moraines postdate the onset of sedimentation in – and thus deglaciation of – the pond, and therefore must be younger. This conflict is resolved by our interpretation of the Androscoggin and L–B moraines as representing the same advance. Because Thompson et al. (1996, 1999) have established that Pond of Safety represents a maximum-limiting age for the L–B complex, it follows that this basal date must also constitute a maximum age for the Androscoggin moraines.

Together, our tightly grouped ages from the Androscoggin River valley and the recalculated ages from Balco et al. (2009) show that the ice-sheet margin advanced during the Allerød (GI-1a-c; Lowe et al., 2008), resulting in formation of the Androscoggin and L–B moraine complexes. This interpretation is reinforced by the maximum-limiting basal radiocarbon age (14,985–14,219 cal yr BP) from Pond of Safety, located distal to the L–B complex in the upper Israel River valley. Moreover, as surface-exposure ages typically represent the culmination of a glacial advance close to the onset of retreat, our Androscoggin chronology also might suggest that this sector of the LIS retreated during the subsequent YD stadial. This interpretation is supported by the absence of nearby moraines up-valley from the Androscoggin terminus (Borns et al., 2004).

At first glance, this disparity between glacial activity in northern New England and the widely accepted late-glacial temperature record for the North Atlantic region represents an ostensible paradox, in terms of the assumed climatic conditions during the YD stadial. Indeed, within New England, organic-poor, minerogenic sediments dating to the late glacial have been documented at several sites in Maine and the White Mountains and are interpreted as a return to stadial conditions during the YD (e.g., Dorion, 1997; Borns et al., 2004; Dieffenbacher-Krall and Nurse, 2006). Nonetheless, we note that this pattern of Allerød advance–YD retreat has been documented elsewhere in the Northern Hemisphere, including at sites immediately adjacent to the North Atlantic Ocean where YD cooling apparently was greatest

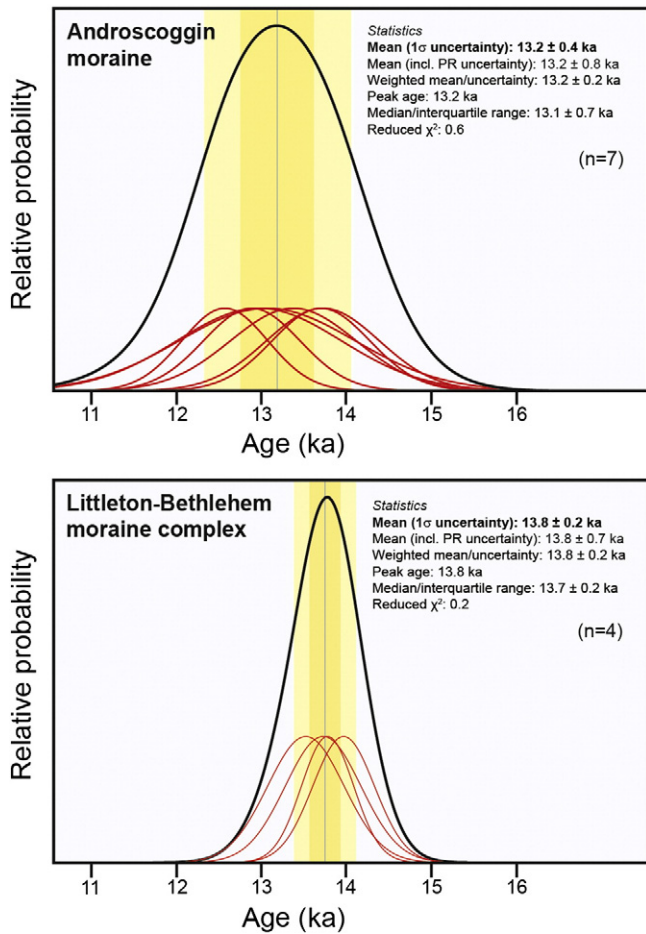


Figure 5. Age probability curves for the Androskoggin moraine and Littleton–Bethlehem moraine complex, showing mean and peak ages calculated using the NENA production rate (Balco et al., 2009) and time-independent St scaling (Lal, 1991; Stone, 2000). Vertical yellow bands depict the 1σ (dark yellow) and 2σ (light yellow) ranges of uncertainty for the mean ages. Reduced χ^2 (χ^2) values of <1 – 2 reflect that age differences can be explained by analytical uncertainties alone (Bevington and Robinson, 1992).

(Bowen, 1999; Lohne et al., 2007; Bromley et al., 2014). Moreover, our New England record is in accordance with evidence for mild YD summertime temperatures in Greenland (Björck et al., 2002) and with the absence of YD moraines (e.g., Mangerud and Landvik, 2007; Hall et al.,

Table 2

Comparison of ^{10}Be surface-exposure ages for the Androskoggin and Littleton–Bethlehem moraine samples generated using the NENA production rate and various scaling schemes: St – time-independent (Lal, 1991/Stone, 2000); Lm – time dependent (Lal, 1991/Stone, 2000); De (Desilets et al., 2006); Du (Dunai, 2001); and Li (Lifton et al., 2005). All ages were calculated using the CRONUS-Earth online calculator, version 2.2 (Balco et al., 2008).

Sample	Exposure age: St (ka)	Exposure age: Lm (ka)	Exposure age: De (ka)	Exposure age: Du (ka)	Exposure age: Li (ka)
AM-07-01	12.9 ± 0.6	12.9 ± 0.6	13.0 ± 0.6	13.0 ± 0.6	13.0 ± 0.6
AM-07-02	13.7 ± 0.6	13.7 ± 0.6	13.8 ± 0.6	13.8 ± 0.6	13.8 ± 0.6
AM-07-03	13.0 ± 1.0	13.0 ± 1.0	13.0 ± 1.0	13.1 ± 1.0	13.1 ± 1.0
AM-07-04	13.7 ± 0.7	13.7 ± 0.7	13.8 ± 0.7	13.8 ± 0.7	13.8 ± 0.7
AM-07-05	13.1 ± 1.1	13.1 ± 1.1	13.1 ± 1.1	13.2 ± 1.1	13.2 ± 1.1
AM-07-06	12.6 ± 0.5	12.6 ± 0.5	12.6 ± 0.5	12.7 ± 0.5	12.7 ± 0.5
AM-07-07	13.4 ± 0.8	13.4 ± 0.8	13.4 ± 0.8	13.5 ± 0.8	13.5 ± 0.8
06-NE-010-LIT	13.7 ± 0.4	13.7 ± 0.5	13.8 ± 0.5	13.8 ± 0.5	13.8 ± 0.5
06-NE-011-LIT	13.5 ± 0.5	13.5 ± 0.5	13.6 ± 0.5	13.6 ± 0.5	13.6 ± 0.5
06-NE-012-LIT	14.0 ± 0.4	13.9 ± 0.4	14.0 ± 0.4	14.1 ± 0.4	14.0 ± 0.4
06-NE-013-LIT	13.8 ± 0.3	13.8 ± 0.3	13.8 ± 0.3	13.9 ± 0.3	13.9 ± 0.3

Table 3

Comparison of ^{10}Be surface-exposure ages for the Androskoggin and Littleton–Bethlehem moraine samples generated using several recent production rates: NENA (Balco et al., 2009); Arctic (Young et al., 2013); and New Zealand (Putnam et al., 2010). All ages were calculated using the CRONUS-Earth online calculator, version 2.2 (Balco et al., 2008), and St scaling (Lal, 1991; Stone, 2000).

Sample	Exposure age: NENA (ka)	Exposure age: NZ (ka)	Exposure age: Arctic (ka)
AM-07-01	12.9 ± 0.6	13.2 ± 0.6	12.9 ± 0.6
AM-07-02	13.7 ± 0.6	14.0 ± 0.6	13.7 ± 0.6
AM-07-03	13.0 ± 1.0	13.3 ± 1.0	13.0 ± 1.0
AM-07-04	13.7 ± 0.7	14.0 ± 0.7	13.7 ± 0.7
AM-07-05	13.1 ± 1.0	13.4 ± 1.1	13.1 ± 1.0
AM-07-06	12.6 ± 0.5	12.9 ± 0.5	12.6 ± 0.5
AM-07-07	13.4 ± 0.7	13.7 ± 0.8	13.4 ± 0.7
06-NE-010-LIT	13.7 ± 0.4	14.1 ± 0.5	13.7 ± 0.4
06-NE-011-LIT	13.5 ± 0.5	13.8 ± 0.5	13.5 ± 0.4
06-NE-012-LIT	14.0 ± 0.4	14.3 ± 0.4	14.0 ± 0.4
06-NE-013-LIT	13.8 ± 0.3	14.1 ± 0.3	13.8 ± 0.3

2008; Kelly et al., 2008; Briner et al., 2009) or stratigraphy (e.g., Wolfe, 1996) at many northern high-latitude sites. Such late-glacial behavior potentially points to the effects of extreme seasonality adjacent the North Atlantic during the YD (Denton et al., 2005), with warm summers driving glacial recession and very cold winters causing the depressed mean-annual temperatures recorded by ice-core proxies. If true, the sedimentologic signature of the YD recorded in New England lakes potentially reflects periglacial remobilization of slope deposits rather than year-round cooling (Putnam and Putnam, 2009).

Finally, our new chronology supports the findings of Richard and Occhietti (2005) that late-glacial marine transgression of the St. Lawrence lowlands occurred later than indicated by basal radiocarbon ages from the former Champlain Sea (Rodrigues, 1992). Construction of the L–B and Androskoggin moraines would have required the persistence of a robust ice-sheet margin in northern New England at least as late as ~ 13.2 ka, a scenario that is supported by terrestrial radiocarbon data from elsewhere in this region (see Thompson et al., 1999; Borns et al., 2004) but which may be incompatible with ice-free conditions in the St. Lawrence River valley immediately north of New Hampshire as early as ~ 14 ka (Parent and Occhietti, 1988). This discrepancy is removed, however, if the radiocarbon dates upon which the age of the Champlain Sea is based incorporate a considerable reservoir effect, as suggested by Rodrigues (1992) and demonstrated by Richard and Occhietti (2005). Thompson et al. (2011) found evidence of a 1000-yr reservoir at a site with juxtaposed marine and terrestrial organics, located in Portland, Maine.

Conclusions

Our cosmogenic ^{10}Be surface-exposure chronology from the Androskoggin moraine, coupled with four recalculated ages from the L–B complex, affords robust and directly dated evidence for a major late-glacial fluctuation of the LIS in northern New England. Retreat of the ice sheet north of the White Mountains was interrupted by at least one advance during the Allerød, resulting in deposition of the prominent L–B and Androskoggin complexes. Seven ages from the terminal moraines of the Androskoggin complex indicate deposition $\sim 13.2 \pm 0.8$ ka, broadly coincident with the emplacement of the Sleeping Astronomer and Beech Hill moraines in the L–B complex, leading us to conclude that the two moraine belts represent the same late-glacial climate reversal. Ultimately, our chronology indicates that the LIS in northern New England underwent readvance, or stillstand, during the Allerød. These findings have important implications for our understanding both of ice-sheet behavior in New England during the last glacial termination and the terrestrial impact of deglacial climate changes, including cold stadials, in the North Atlantic region.

Acknowledgments

We thank Pike Industries, Inc., and the University of Maine for funding this research, as well as the various landowners in the Androscoggin River valley for allowing access to the field sites. We are particularly grateful to Roseanne Schwartz for lab assistance, Aaron Putnam and Toby Koffman for constructive discussions and comments, and Peter Strand and Sean Birkel for assisting with figures. Finally, we thank Ari Matmon and Lewis Owen for providing detailed and constructive reviews of an earlier version of the manuscript. This is LDEO contribution 7882.

References

- Agassiz, L., 1870. On the former existence of local glaciers in the White Mountains. *American Association for the Advancement of Science, Proceedings* 19, 161–167.
- Antevs, E., 1922. The recession of the last ice sheet in New England. *American Geographical Society, Research Series* 11.
- Antevs, E., 1928. The Last Glaciation With Special Reference to the Ice Sheet in North America: Research Series No. 17. American Geographical Society.
- Balco, G., Schaefer, J., 2006. Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England. *Quaternary Geochronology* 1, 15–28.
- Balco, G., Stone, J., Porter, S., Caffee, M., 2002. Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA. *Quaternary Science Reviews* 21, 2127–2135.
- Balco, G., Stone, J., Lifton, N., Dunai, T., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology* 3, 174–195.
- Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M., 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Geochronology* 4, 93–107.
- Bevington, P., Robinson, D., 1992. *Data Reduction and Error Analysis for the Physical Sciences*. WCB McGraw-Hill, New York (320 pp.).
- Birkel, S.D., 2010. *Climate Investigations Using Ice Sheet and Mass Balance Models With Emphasis on North American Glaciation*. (Ph.D. dissertation). University of Maine, Orono, Maine, USA.
- Björck, S., Bennike, O., Rosén, P., Andresen, C.S., Bohncke, S., Kaas, E., Conley, D., 2002. Anomalous mild Younger Dryas summer conditions in southern Greenland. *Geology* 30, 427–430.
- Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., Bonani, G., 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature* 365, 143–147.
- Borns Jr., H.W., 1973. Late-Wisconsinan fluctuations of the Laurentide Ice Sheet in southern and eastern New England. In: Black, R.F., Goldthwait, R., Willman, H.B. (Eds.), *The Wisconsin Stage*. Geological Society of America, Memoir 136, pp. 37–45.
- Borns Jr., H.W., 1980. Glaciomarine geology of the eastern Coastal Zone, in American Quaternary Association, Field Trip A and D, Field Trip Guide: Orono, Maine. American Quaternary Association 18 pp.
- Borns Jr., H.W., Hughes, T.J., 1977. The implications of the Pineo Ridge readvance in Maine. *Géographie Physique et Quaternaire* 31, 203–206.
- Borns, H.W., Doner, L.A., Dorion, C.C., Jacobson Jr., G.L., Kaplan, M.R., Kreutz, K.J., Lowell, T.V., Thompson, W.B., Weddle, T.K., 2004. The deglaciation of Maine, U.S.A. In: Ehlers, J., Gibbard, P. (Eds.), *Quaternary Glaciations – Extent and Chronology, Volume 2, Part II*. Elsevier, pp. 89–110.
- Bowen, D.Q., 1999. Only four major 100-ka glaciations during the Brunhes Chron? *International Journal of Earth Sciences* 88, 276–284.
- Briner, J.P., Davis, P.T., Miller, G.H., 2009. Latest Pleistocene and Holocene glaciation of Baffin Island, Arctic Canada: key patterns and chronologies. *Quaternary Science Reviews* 28, 2075–2087.
- Briner, J.P., Young, N.E., Goehring, B.M., Schaefer, J.M., 2012. Constraining Holocene ^{10}Be production rates in Greenland. *Journal of Quaternary Science* 27, 2–6.
- Broccoli, A.J., Manabe, S., 1987. The influence of continental ice, atmospheric CO_2 , and land albedo on the climate of the last glacial maximum. *Climate Dynamics* 1, 87–99.
- Broecker, W.S., 2003. Does the trigger for abrupt climate change reside in the ocean or the atmosphere? *Science* 300, 1519–1522.
- Bromley, G.R.M., Putnam, A.E., Rademaker, K.M., Lowell, T.V., Schaefer, J.M., Hall, B.L., Winckler, G., Birkel, S.D., Borns, H.W., 2014. Younger Dryas deglaciation of Scotland driven by warming summers. *Proceedings of the National Academy of Science* 111, 6215–6219.
- Davis, R.B., Jacobson Jr., G.L., 1985. Late glacial and early Holocene landscapes in northern New England and adjacent areas of Canada. *Quaternary Research* 23, 341–368.
- Denton, G.H., Hughes, T.J., 1981. *The Last Great Ice Sheets*. John Wiley, New York.
- Denton, G.H., Alley, R.B., Comer, G.C., Broecker, W.S., 2005. The role of seasonality in abrupt climate change. *Quaternary Science Reviews* 24, 1159–1182.
- Desilets, D., Zreda, M., Prabu, T., 2006. Extended scaling factors for in situ cosmogenic nuclides: new measurements at low latitude. *Earth and Planetary Science Letters* 246, 265–276.
- Diefenbacher-Krall, A.C., Nurse, A.M., 2006. Late-glacial and Holocene record of lake levels of Matthews Pond and Whitehead Lake, Northern Maine, USA. *Journal of Paleolimnology* 34, 283–309.
- Dorion, C.C., 1997. An Updated High Resolution Chronology of Deglaciation and Accompanying Marine Transgression in Maine. University of Maine, Orono (M.S. thesis).
- Dorion, C.C., Balco, G.A., Kaplan, M.R., Kreutz, K.J., Wright, J.D., Borns Jr., H.W., 2001. Stratigraphy, paleoceanography, chronology, and environment during deglaciation of eastern Maine. In: Weddle, T.K., Retelle, M.J. (Eds.), *Deglacial History and Relative Sea-level Changes, Northern New England and Adjacent Canada*: Boulder, Colorado. Geological Society of America Special Paper 351, pp. 215–242.
- Dunai, T., 2001. Influence of secular variation of the magnetic field on production rates of in situ produced cosmogenic nuclides. *Earth and Planetary Science Letters* 193, 197–212.
- Dyke, A.S., Prest, V.K., 1987. Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. *Géographie Physique et Quaternaire* 41, 237–263.
- Fenton, C.R., Hermanns, R.L., Blikra, L.H., Kubik, P.W., Bryant, C., Niedermann, S., Meixner, A., Goethals, M.M., 2011. Regional ^{10}Be production rate calibration for the past 12 ka deduced from the radiocarbon-dated Grøtlandsura and Russenes rock avalanches at 69° N, Norway. *Quaternary Geochronology* 6, 437–452.
- Hall, B., Baroni, C., Denton, G., Kelly, M., Lowell, T., 2008. Relative sea-level change, Kjøve Land, Scoresby Sund, East Greenland: implications for seasonality in Younger Dryas. *Quaternary Science Reviews* 27, 2283–2291.
- Hostetler, S.W., Clark, P.U., 1997. Climatic controls of western U.S. glaciers at the last glacial maximum. *Quaternary Science Reviews* 16, 505–511.
- Hulbe, C.L., MacAyeal, D.R., Denton, G.H., Klemm, J., Lowell, T.V., 2004. Catastrophic ice shelf breakup as the source of Heinrich event icebergs. *Paleoceanography* 19. <http://dx.doi.org/10.1029/2003PA000890>.
- Kaplan, M.R., 1999. Retreat of a tidewater margin of the Laurentide ice sheet in eastern coastal Maine ca. 14 to 13,000 ^{14}C yrs BP. *Geological Society of America Bulletin* 111, 620–633.
- Kaplan, M.R., 2007. Major ice sheet response in eastern New England to a cold North Atlantic region, ca. 16–15 cal ka BP. *Quaternary Research* 68, 280–283.
- Kelly, M.A., Lowell, T.V., Hall, B.L., Finkel, R.C., Schaefer, J.M., Goehring, B.M., Alley, R.B., Denton, G.H., 2008. A ^{10}Be chronology of late-glacial and Holocene mountain glaciation in the Scoresby Sund region, east Greenland: implications for seasonality during late-glacial time. *Quaternary Science Reviews* 27, 2273–2282.
- Kelly, M.A., Lowell, T.V., Applegate, P.J., Phillips, F.M., Schaefer, J.M., Smith, C.A., Kim, H., Leonard, K.C., Hudson, A.M., 2013. A locally calibrated, late glacial ^{10}Be production rate from a low-latitude, high-altitude site in the Peruvian Andes. *Quaternary Geochronology*. <http://dx.doi.org/10.1016/j.quageo.2013.10.007>.
- Koteff, C., Pessl, F., 1981. Systematic ice retreat in New England. *United States Geological Survey Professional Paper* 1179 (20 pp.).
- Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters* 104, 424–439.
- Lamothe, M., 1992. Pleistocene stratigraphy and till geochemistry of the Miramichi Zone, New Brunswick. *Geological Survey of Canada, Bulletin* 433.
- Lifton, N., Bieber, J., Clem, J., Duldig, M., Evenson, P., Humble, J., Pyle, R., 2005. Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays for in situ cosmogenic nuclide applications. *Earth and Planetary Science Letters* 239, 140–161.
- Lohne, O.S., Bondevik, S., Mangerud, J., Svendsen, J.I., 2007. Sea-level fluctuations imply that the Younger Dryas ice-sheet expansion in western Norway commenced during the Allerød. *Quaternary Science Reviews* 26, 2128–2151.
- Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z.C., the INTIMATE group, 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quaternary Science Reviews* 27, 6–17.
- Lowell, T.V., Hayward, R.K., Denton, G.H., 1999. Role of climate oscillations in determining ice-margin position: hypothesis, examples, and implications. In: Mickelson, D.M., Attig, J.W. (Eds.), *Glacial Processes Past and Present*: Geological Society of America Special Paper 337. Geological Society of America, Boulder, CO, pp. 193–203.
- Lyell, C., 1850. *A Second Visit to the United States of North America*. 2nd ed. John Murray, London.
- MacAyeal, D.R., 1993. Binge/purge oscillations of the Laurentide Ice Sheet as a cause of the North Atlantic's Heinrich events. *Paleoceanography* 8, 775–784.
- Mangerud, J., Landvik, J.Y., 2007. Younger Dryas cirque glaciers in western Spitsbergen: smaller than during the Little Ice Age. *Boreas* 36, 278–285.
- Nishiizumi, K., Imamura, M., Caffee, M.W., Southon, J.R., Finkel, R.C., McAninch, J., 2007. Absolute calibration of ^{10}Be AMS standards. *Nuclear Instruments and Methods in Physics Research B* 258, 403–413.
- Oldale, R.N., 1982. Pleistocene stratigraphy of Nantucket, Martha's Vineyard, the Elizabeth Islands, and Cape Cod, Massachusetts. In: Larson, G.J., Stone, B.D. (Eds.), *Late Wisconsinan Glaciation of New England: Proceedings of the Symposium*. Kendall/Hunt, Dubuque, IA, pp. 1–34.
- Oldale, R.N., O'Hara, C.J., 1984. Glaciotectonic origin of the Massachusetts coastal end moraines and a fluctuating late Wisconsinan ice margin. *GSA Bulletin* 95, 61–74.
- Oviatte, C.G., 1997. Lake Bonneville fluctuations and global climate change. *Geology* 25, 155–158.
- Parent, M., Occhietti, S., 1988. Late Wisconsinan deglaciation and Champlain Sea invasion in the St. Lawrence Valley, Québec. *Géographie Physique et Quaternaire* 42, 215–246.
- Peteet, D.M., Beh, M., Orr, C., Kurdyla, D., Nichols, J., Guilderson, T., 2012. Delayed deglaciation or extreme Arctic conditions 21–16 ca. ka at southeastern Laurentide Ice Sheet margin? *Geophysical Research Letters* 39, L11706. <http://dx.doi.org/10.1029/2012GL051884>.
- Pratt, R.M., Schlee, J., 1969. Glaciation on the continental margin off New England. *Geological Society of America Bulletin* 80, 2335–2342.
- Putnam, A.E., Putnam, D.E., 2009. Inactive and relict rock glaciers of the Deboullie Lakes Ecological Reserve, northern Maine, USA. *Journal of Quaternary Science* 24, 773–784.
- Putnam, A.E., Schaefer, J.M., Barrell, D.J.A., Vandergoes, M., Denton, G.H., Kaplan, M.J., Finkel, R.C., Schwartz, R., Goehring, B.M., Kelley, S.M., 2010. In situ cosmogenic

- ^{10}Be production-rate calibration from the Southern Alps, New Zealand. *Quaternary Geochronology* 5, 392–409.
- Rampton, N., Gauthier, R.C., Thibault, J., Seaman, A.A., 1984. Quaternary geology of New Brunswick. *Memoirs. Geological Survey of Canada* 416.
- Richard, P.J.H., Occhietti, S., 2005. ^{14}C chronology for ice retreat and inception of Champlain Sea in the St. Lawrence Lowlands, Canada. *Quaternary Research* 63, 353–358.
- Ridge, J., 2004. The Quaternary glaciation of western New England with correlations to surrounding areas. In: Ehlers, J., Gibbard, P. (Eds.), *Quaternary Glaciations – Extent and Chronology*. Elsevier, pp. 169–199.
- Ridge, J., Larsen, F., 1990. Reevaluation of Antevs' New England varve chronology and new radiocarbon dates of sediments from glacial Lake Hitchcock. *Geological Society of America Bulletin* 102, 889–899.
- Ridge, J., Thompson, W., Brochu, M., Brown, S., Fowler, B., 1996. Glacial geology of the upper Connecticut Valley in the vicinity of the lower Ammonoosuc and Passumpsic Valleys of New Hampshire and Vermont. In: Van Baalen, M. (Ed.), *Guidebook to Field Trips in Northern New Hampshire and Adjacent Regions of Maine and Vermont: New England Intercollegiate Geologic Conference, 88th Annual Meeting*, pp. 309–340.
- Ridge, J.C., Benson, M.R., Brochu, M., Brown, S.L., Callahan, J.W., Cook, G.J., Nicholson, R.S., Toll, N.J., 1999. Varve, palaeomagnetic and ^{14}C chronologies for Late Pleistocene events in New Hampshire and Vermont. In: Thompson, W.B., Fowler, B.K., Davis, T. (Eds.), *Late Quaternary History of the White Mountains, New Hampshire and Adjacent South-eastern Québec*. *Géographie physique et Quaternaire* 53, pp. 79–106.
- Ridge, J., Canwell, B., Kelly, M., Kelley, S., 2001. Atmospheric ^{14}C chronology for late Wisconsinan deglaciation and sea-level change in eastern New England using varve and paleomagnetic records. In: Weddle, T., Retelle, M. (Eds.), *Deglacial History and Relative Sea-level Changes, Northern New England and Adjacent Canada*. *Geological Society of America Special Paper* 351, pp. 173–191.
- Rodrigues, C.G., 1992. Successions of invertebrate microfossils and the late Quaternary deglaciation of the central St. Lawrence Lowland, Canada and United States. *Quaternary Science Reviews* 11, 503–534.
- Schaefer, J.M., Denton, G.H., Kaplan, M., Putnam, A., Finkel, R.C., Barrell, D.J.A., Andersen, B.G., Schwartz, R., Mackintosh, A., Chinn, T., Schlucter, C., 2009. High-frequency Holocene glacier fluctuations in New Zealand differ from the northern signature. *Science* 324, 622–625.
- Smith, G.W., Hunter, L.E., 1989. Deglaciation of coastal Maine. Tucker, R.D., Marvinney, R.G. (Eds.), *Studies in Maine Geology*. Quaternary geology: Augusta Maine Geological Survey 6, 13–32.
- Stone, G.H., 1880. Note on the Androscoggin glacier. *American Naturalist* 14, 299–302.
- Stone, J.O.H., 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research* 105, 23753–23759.
- Stone, B.D., Borns, H.W., 1986. Pleistocene glacial and interglacial stratigraphy of New England, Long Island, and adjacent Georges Bank and Gulf of Maine. In: Sibrava, V., Bowen, D.Q., Richmond, G.M. (Eds.), *Quaternary Glaciations in the Northern Hemisphere*. Pergamon Press, Oxford, pp. 39–52.
- Stone, J.R., DiGiacomo-Cohen, M., Lewis, R.S., Goldsmith, R., 1998. Recessional moraines and the associated deglacial record of southeastern Connecticut and Long Island Sound. In: Murray, D.P. (Ed.), *Guidebook to Field Trips in Rhode Island and Adjacent Regions of Connecticut and Massachusetts: New England Intercollegiate Geologic Conference, 90th Annual Meeting*, Kingston, Rhode Island, p. B7-1-B7-20.
- Thompson, W.B., 1999. History of research on glaciation in the White Mountains, New Hampshire (U.S.A.). *Géographie Physique et Quaternaire* 53, 7–24.
- Thompson, W. B., Borns, H. W., Jr., 1985. Surficial geologic map of Maine. Maine Geological Survey, 1:500,000-scale map.
- Thompson, W.B., Fowler, B.K., 1989. Deglaciation of the upper Androscoggin River valley and northeastern White Mountains, Maine and New Hampshire. In: Tucker, R.D., Marvinney, R.G. (Eds.), *Studies in Maine Geology—Volume 6: Quaternary Geology*. Maine Geological Survey, Augusta.
- Thompson, W.B., Fowler, B.K., Flanagan, S.M., Dorion, C.C., 1996. Recession of the Late Wisconsinan ice sheet from the northwestern White Mountains, New Hampshire. In: Van Baalen, M.R. (Ed.), *Guidebook to Field Trips in Northern New Hampshire and Adjacent Regions of Maine and Vermont*. Harvard University Department of Earth & Planetary Sciences, Cambridge, Mass.
- Thompson, W.B., Fowler, B.K., Dorion, C.C., 1999. Deglaciation of the northwestern White Mountains, New Hampshire. *Géographie Physique et Quaternaire* 53, 59–77.
- Thompson, W., Hildreth, C., Boisvert, R., Dorion, C., Fowler, B., 2002. Glacial geology and archaeology of the northern White Mountains, New Hampshire. *Guidebook for the 65th Annual Reunion of the Northeastern Friends of the Pleistocene*.
- Thompson, W.B., Borns Jr., H.W., Hall, B., 2007. Extrapolation of the Littleton–Bethlehem (Older Dryas) and Pineo Ridge moraine systems across New Hampshire and Maine. *Geological Society of America Abstracts with Programs* 39, 55.
- Thompson, W.B., Griggs, C.B., Miller, N.C., Nelson, R.E., Weddle, T.K., Kilian, T.M., 2011. Associated terrestrial and marine fossils in the late-glacial Presumpscot Formation, southern Maine, USA, and the marine reservoir effect on radiocarbon ages. *Quaternary Research* 75, 552–565.
- Tucholke, B.E., Hollister, C.D., 1973. Late Wisconsinan glaciation of the southwestern Gulf of Maine: new evidence from the marine environment. *GSA Bulletin* 84, 3279–3296.
- Upham, W., 1904. Moraines and eskers of the last glaciation in the White Mountains. *The American Geologist* 33, 7–14.
- Williams, J., Barry, R.G., Washington, W.M., 1974. Simulation of the atmospheric circulation using the NCAR Global Circulation Model with ice age boundary conditions. *Journal of Applied Meteorology* 13, 305–317.
- Wolfe, A.P., 1996. A high-resolution late-glacial and early Holocene diatom record from Baffin Island, eastern Canadian Arctic. *Canadian Journal of Earth Sciences* 33, 928–937.
- Young, N.E., Schaefer, J.M., Briner, J.P., Goehring, B.M., 2013. A ^{10}Be production-rate calibration for the Arctic. *Journal of Quaternary Science* 28, 515–526.