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Research paper

Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England

Greg Balco[a,*], Joerg M. Schaefer[b]

[a]Quaternary Research Center and Department of Earth and Space Sciences, University of Washington, Mail Stop 351310, Seattle, WA 98195-1310, USA
[b]Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA

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Abstract

We report new cosmogenic-nuclide exposure ages from the Ledyard and Old Saybrook Moraines in eastern Connecticut, summarize previously published exposure ages from elsewhere in southern New England, and compare the resulting deglaciation chronology with that derived from the New England varve chronology. The geomorphic context of southern New England moraine boulders indicates that postdepositional disturbance of boulders, and consequent scatter in boulder exposure ages, should be negligible. Exposure ages of these boulders reinforce this conclusion: the scatter among boulder ages from each moraine is no more than that expected from the measurement uncertainty of the ages. We therefore conclude that geologic uncertainties in the exposure histories of the boulders are relatively unimportant, and that the precision of the exposure-age chronology for deglaciation of southern New England is limited only by the measurement uncertainty of each exposure age and the number of exposure ages. However, exposure ages for deglaciation are nominally at least 1700 yr younger than deglaciation ages inferred from the New England varve chronology and its associated calibration to the absolute calendar year time scale, which is a significant discrepancy relative to the internal precision of each chronology. This discrepancy is similar in size to the uncertainties in the two independently determined parameters that link the two chronologies to the absolute calendar year time scale, that is, the ^{10}Be production rate and the varve year–calendar year offset. Taking into account the uncertainty in these two parameters, the two chronologies essentially agree, and present the opportunity to more accurately determine these parameters by enforcing internal consistency between the two chronologies. The combined deglaciation chronology that results from this exercise indicates that southeastern Connecticut was deglaciated 18,500–19,000 yr BP. It suggests that the varve year–calendar year offset has been overestimated by several hundred years and that the local ^{10}Be production rate has been overestimated by a few percent, and it is consistent with: (a) independent measurements of the varve year–calendar year offset; (b) independent measurements of the ^{10}Be production rate; (c) relevant limiting radiocarbon ages; and (d) the present understanding of the most likely relationship between the exposure age of major moraines and North Atlantic climate changes. The internal consistency of the two chronologies could be further improved by additional exposure dating of ice-marginal landforms that have direct stratigraphic links to the varve chronology. This, in turn, would also result in improved estimates of both the varve year–calendar year offset and cosmogenic-nuclide production rates.

Keywords: Cosmogenic nuclide geochronology; ^{10}Be; New England; Connecticut; Last glacial maximum; Varve chronology; Deglaciation

1. Introduction: the deglaciation of southern New England

The Laurentide Ice Sheet reached its southeastern limit near 24,000 yr ago, during the coldest cold snap evident in records of North Atlantic climate at the last glacial maximum. Despite the fact that the climate did not become appreciably warmer until approximately 15,000 yr BP, this sector of the ice sheet began to shrink rapidly at 19,000 yr BP, and continued to retreat with only minor interruptions until New England was ice-free some 7000 yr later. The rate and timing of ice retreat across the New England landscape is important for two reasons: first, the latter stages of ice retreat coincided with the simultaneous advance of the first human inhabitants (e.g., Ridge, 2003); second, the

*Corresponding author. Tel.: +1 206 221 2579.
E-mail addresses: balcs@u.washington.edu (G. Balco), schaefer@ldeo.columbia.edu (J.M. Schaefer).

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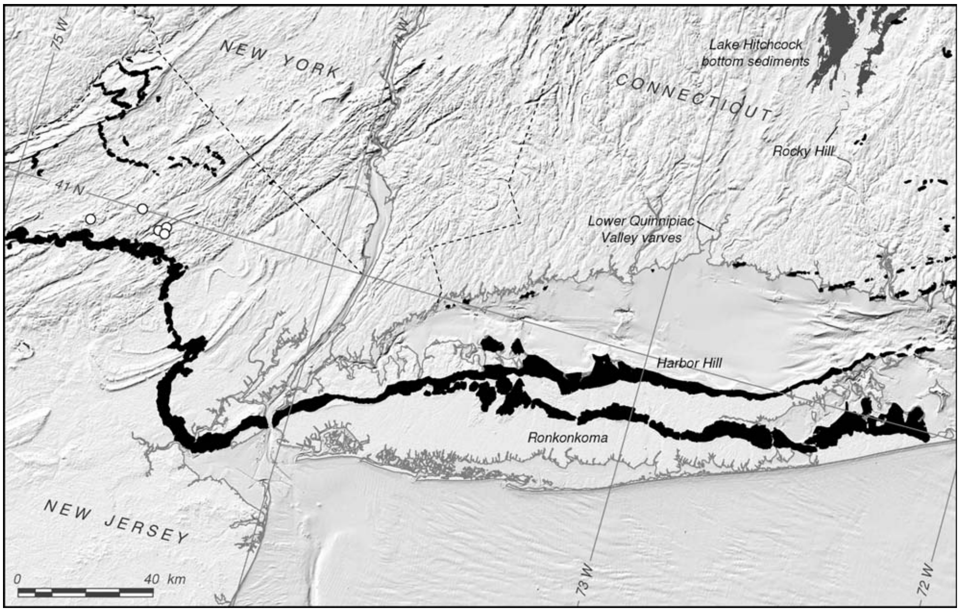

Fig. 1. The end moraines of southern New England. Shaded-relief topography from SRTM90 and NED digital elevation models. Bathymetry and coastlines from the NOAA/NGDC Coastal Relief Model. The labeled dark shaded regions show mapped end moraine systems; the labeled lighter shaded region shows the outcrop area of glaciolacustrine sediment deposited in glacial Lake Hitchcock. Open circles indicate location of previous exposure-dating studies: by Clark et al. (1995) and Larsen (1996) in northern New Jersey, and at the Martha's Vineyard and Buzzards Bay Moraines by Balco et al. (2002). The glacial geology is derived from the digital surficial geologic maps of Connecticut (Stone et al., 1998b), Massachusetts (Office of Geographic and Environmental Information, Commonwealth of Massachusetts: http://www.mass.gov/mgis/sg.htm), Rhode Island (Rhode Island Geographic Information System, University of Rhode Island: http://www.edc.uri.edu/rigis-spf/statewide/state.html), New York (New York State Museum: http://www.nysm.nysed.gov/gis/); and New Jersey (New Jersey Geological Survey Digital Geodata Series DGS96-1: http://www.state.nj.us/dep/njgs/geodata/dgs96-1.htm).

well-studied, well-exposed, and accessible deglaciation record of New England provides us with an extraordinary opportunity to better understand the complicated series of oceanographic, climatic, and glacial events that marked the culmination and end of the last ice age. In this paper, we seek to better establish the chronology of ice retreat in southern New England, so that we may more accurately compare glacial events with coeval climate changes. At present, the deglaciation chronology of southern New England is based on a few limiting radiocarbon dates, cosmogenic-nuclide exposure ages on two major moraines, and a floating varve chronology anchored to the calendar year time scale by radiocarbon dates on plant remains within individual varves. Of these, the varve chronology is by far the most precise and potentially the most accurate, but it relies on only a few radiocarbon dates to link it to the calendar year time scale. The exposure-age chronology in southern New England, as we discuss below, is unusually precise relative to similar chronologies from other locations, but its accuracy depends on independently calibrated production rates for cosmogenic nuclides, which are still the subject of active research. We are particularly interested in the relationship between these two independent deglaciation chronologies, not only because both are necessary if we wish to accurately date the entire history of ice retreat in New England, but because we seek to use the very precise varve chronology as a calibration tool to improve our knowledge of cosmogenic-nuclide production rates (Phillips and CRONUS-Earth participants, 2004). In this paper, we report new cosmogenic-nuclide exposure ages from eastern Connecticut, discuss the discrepancy between cosmogenic-nuclide and varve chronologies that arises from these ages, and seek to resolve it within the present understanding of each method.

2. The coastal end moraines of southern New England

The southern coast of New England owes its present form to two massive end moraine systems built during the greatest advances of the Laurentide Ice Sheet during the last glaciation and very likely during many previous ones. These moraines extend from New Jersey to Nantucket (Fig. 1) and consist of a variety of ice-contact, stagnant-ice, glaciofluvial, and glaciotectonic deposits (Hitchcock, 1841; Schafer and Hartshorn, 1965; Oldale and O'Hara, 1984; Sirkin, 1982). Their most prominent features are large (2–10 km wide, 50–100 m high) ridges containing imbricate thrust sheets of displaced older sediments, fronted by gently sloping plains of sand and gravel outwash. The size and complexity of these moraines appear to be the result of both permafrost conditions at the ice margin that allowed entrainment of huge thrust sheets by advancing ice, and, at least in the case of the outermost moraine, the prolonged residence of the ice margin near its terminal position (Oldale and O'Hara, 1984; Balco et al., 2002; Sirkin, 1982). Ice-marginal positions to the north of these two major moraine complexes are marked by less impressive landforms. In eastern Connecticut and southern Rhode Island,

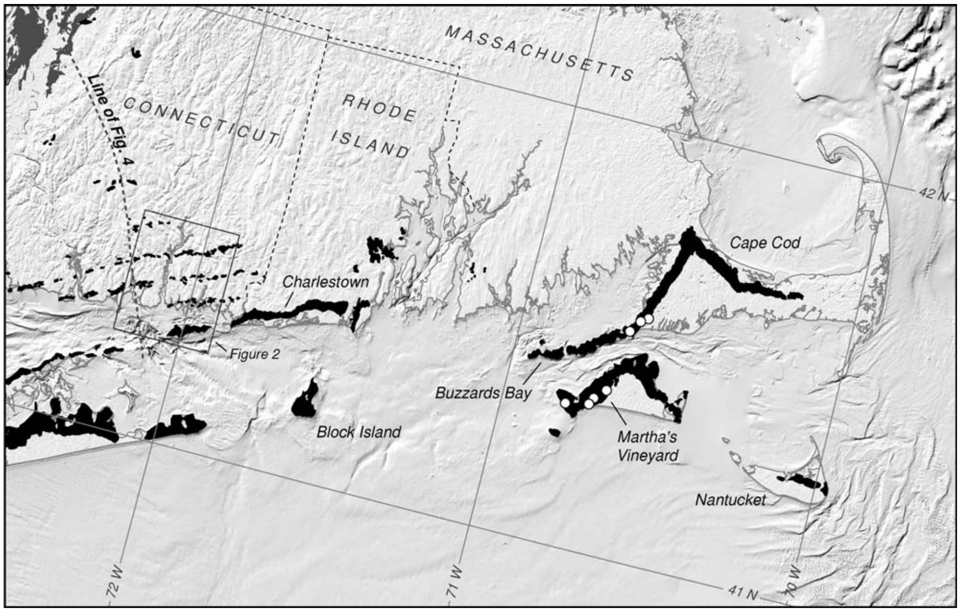

Fig. 1. (*Continued*)

a series of small, discontinuous, and bouldery end moraines (which are the subject of this paper and are described in more detail below) mark several recessional ice-margin positions. Elsewhere in southern New England, the location of the ice margin is best recognized from the location of proglacial lakes, ice-marginal channels, heads of outwash, and 'morphosequences' consisting of coherent assemblages of ice-proximal to -distal landforms and sedimentary facies (Schafer and Hartshorn, 1965; Stone et al., 1998a,b; Koteff and Pessl, 1981).

3. The existing deglaciation chronology

Limiting radiocarbon ages: Early attempts to determine the age of the major coastal moraines relied on correlation of their stratigraphy with glacial stratigraphy in Europe and other parts of North America, as well as observations of weathering characteristics and the condition and frequency of boulders. These studies identified as many as seven glacier advances and at least one major interglaciation, and accordingly correlated various moraines and portions thereof to Illinoian and Wisconsinan drifts elsewhere (Woodworth et al., 1934; Kaye, 1964a,b). Later studies realized that much of this stratigraphic complexity was the result of glaciotectonic deformation, and radiocarbon ages up to 18,500 ^{14}C yr BP (ca. 22,000 cal yr BP) on postglacial sediments north of the coastal moraines and 21,000–34,000 ^{14}C yr BP ($>24,000$ cal yr BP) on preglacial sediments at Boston, Nantucket, and Georges Bank showed that the outermost moraine was most likely entirely Wisconsinan in age, deposited at the last glacial maximum approximately 22,000–25,000 yr BP (Kaye, 1964b; Schafer and Hartshorn, 1965; Stone and Borns, 1986; Boothroyd et al., 1998; Stone et al., 1998a; Tucholke and Hollister, 1973; Oldale, 1982; Cotter, 1984). It has since proved difficult to date either the terminal moraines or early recessional events more accurately by radiocarbon dating, primarily because organic material older than 12,700 ^{14}C yr BP (15,200 cal yr BP) is rare. The climate was cold in coastal New England prior to this time, vegetation was sparse, and, in contrast to regions farther west where organic material of this age is common, only a few plant fragments more than 15,000 yr old have ever been discovered (Kaye, 1964b; Schafer and Hartshorn, 1965; Stone and Borns, 1986; Davis et al., 1980; McWeeney, 1995). The vast majority of basal radiocarbon dates on ponds and peat in southern New England well postdate deglaciation. Instead, they appear to record abrupt North Atlantic climate warming, the establishment of appreciable vegetation cover, and the influx of beavers and consequent expansion of ponds and wetlands (e.g., Kaye, 1962) 15,000 yr ago.

Cosmogenic-nuclide exposure ages: Exposure-age dating, which relies on the measurement of rare nuclides produced in surface rocks by cosmic-ray bombardment, and is widely used to date glacier retreat via the nuclide concentration in glacially transported boulders (e.g., Gosse and Phillips, 2001), offers a means of directly dating ice-marginal deposits in the absence of associated organic remains. Exposure ages from the terminal moraine at Martha's Vineyard, Massachusetts (Fig. 1), have both old (reflecting recycling of previously exposed boulders) and young (reflecting periglacial processes that disturbed boulders after deglaciation) outliers, but cluster between 22,000 and 25,000 yr, with a mean age of $23,200 \pm 500$ yr (Balco et al., 2002). The most extensive ice sheet advance here took place, unsurprisingly, during the coldest period of the LGM, and the exposure ages of these boulders presumably reflect moraine abandonment due to the rapid (although limited) warming thereafter. Boulders from the inner moraine complex, on the Buzzards Bay moraine near Woods Hole, have more tightly grouped exposure ages (reflecting the fact that previously exposed boulders were apparently wiped from the landscape by the first ice sheet advance to the terminal moraine), with a mean age of $18,800 \pm 400$ yr (Balco et al., 2002). Thus, if the physical continuity of the two major moraine systems in fact reflects temporal synchroneity as well, the outer moraine complex (Nantucket, Martha's Vineyard, Block Island, and the Ronkonkoma Moraine on Long Island's South Fork) formed 23,000–24,000 yr ago, and the inner complex (the Buzzards Bay and Charlestown Moraines, Fishers Island, and the Harbor Hill Moraine on the North Fork of Long Island) was emplaced near 19,000 yr ago.

The New England varve chronology: There are north-draining valleys throughout New England, many south-draining valleys were dammed by glacial sediment during deglaciation, and the entire landscape was glacioisostatically tilted toward the center of the ice sheet to the north. Thus, there were proglacial lakes throughout New England during and well after deglaciation. The largest and longest-lasting of these was glacial Lake Hitchcock, which was initially created by ice retreat from a sediment dam at Rocky Hill, survived several subsequent spillway changes, and continuously occupied at least some part of the Connecticut River Valley for some 6000 yr (Fig. 1). The lake-bottom sediments that record the presence of Lake Hitchcock and many other lakes contain annual laminations, that is, varves, and varved sediment sections throughout New England can be matched to assemble several long sequences that serve as a tool for high-resolution time correlation of late-glacial events. These varve sequences serve as a precise deglaciation chronology as well: not only does the existence of a particular varve at a certain site show that the site must have been ice-free in the year represented by that varve, but many varves can be traced to their northern termination in ice-proximal sediments, thus showing the position of the ice margin in a particular varve year. The bulk of the New England varve chronology was assembled by Antevs (1922, 1928), who developed two floating varve sequences from the lower and upper Connecticut River Valley, reflecting arbitrarily numbered New England varve years 2701–7750 (the numbering scheme runs forward, so that younger varves have higher numbers). Antevs also matched these sequences to other varve sequences in the Hudson, Merrimack, and Winooski Valleys of New York, New Hampshire, and Vermont, respectively. Later work by Ridge and Larsen (1990), Ridge (2003, 2004), Rittenour et al. (2000), Ridge and Toll (1999) extended the NE varve chronology to cover NE varve year 2701–8679, matched it to additional varve sequences in Maine, and correlated it with glaciolacustrine sections in the Champlain Valley via paleomagnetic declination measurements.

The southeasternmost outcrops of varved sediment which match the lower Connecticut Valley varve sequence are several kilometers north of the spillway of Lake Hitchcock (Fig. 1), and are as old as NE varve year 2868. The ice margin must have retreated north of the Lake Hitchcock spillway before they could be deposited. A 500-yr varve sequence in the lower Quinnipiac Valley (Fig. 1) cannot be matched to the Lake Hitchcock chronology, and is therefore presumed to predate it, so this site must have been ice-free before approximately NE varve year 2300. The currently accepted calibration of NE varve years to calendar years BP (Ridge, 2003, 2004, we discuss this in much more detail later) implies deglaciation of the lower Quinnipiac Valley before 18,900 yr BP and the Lake Hitchcock outlet before 18,300 yr BP, respectively.

To summarize, according to the previously published exposure-age chronology, the Buzzards Bay moraine (and by extension the Harbor Hill–Fisher's Island–Charlestown moraine complex) was emplaced 18,800 yr ago. According to the varve chronology, ice retreat had already exposed the Quinnipiac Valley varve sections, some 50 km to the north of this moraine complex, by that time. In this paper we seek to get a better idea of the size and importance of this discrepancy by additional exposure dating of moraines in eastern Connecticut that are intermediate between these two ice-margin positions.

4. ^{10}Be exposure age of the Old Saybrook and Ledyard moraines

The moraines themselves: The eastern Connecticut end moraines consist of five linear, parallel, and evenly spaced belts of scattered moraine segments, the first of which (the Clumps-Avondale moraine) is 1 km north of the Fishers Island–Charlestown moraine complex and is mostly submerged in Long Island Sound. The other four (the Mystic, Old Saybrook, Ledyard, and Madison-Oxoboxo Moraines) lie to the northwest at intervals of 6–8 km (Goldsmith, 1982, 1987; Stone et al., 1998a,b, Fig. 2). The moraine segments consist mostly of bouldery till ridges and, at the Ledyard Moraine in particular, of visually striking piles of massive granite-gneiss boulders (Fig. 3). These boulder accumulations were noted very early as unusual natural features, and many have picturesque names such as Wolf Rocks or the Devil's Den (e.g., Wells, 1890). They are up to 1 km in length, the boulders themselves are 1–6 m in diameter, and the boulders are piled atop one another without interstitial matrix. This unusual grain-size distribution is presumably the result of both the widely spaced joints in the source outcrops, which provided a disproportionate number of large boulders relative to finer material, and of winnowing by meltwater at the ice margin (Goldsmith, 1982, 1987). The boulders that we sampled are potassium-feldspar-rich granite-gneiss and biotite gneiss that outcrop several km to the north of the Ledyard moraine.

Sites and methods: At the Ledyard moraine, we collected samples from large, physically interlocking boulders in and around Glacial Park, in Ledyard, CT (Figs. 2 and 3). The geomorphic situation here is particularly favorable for

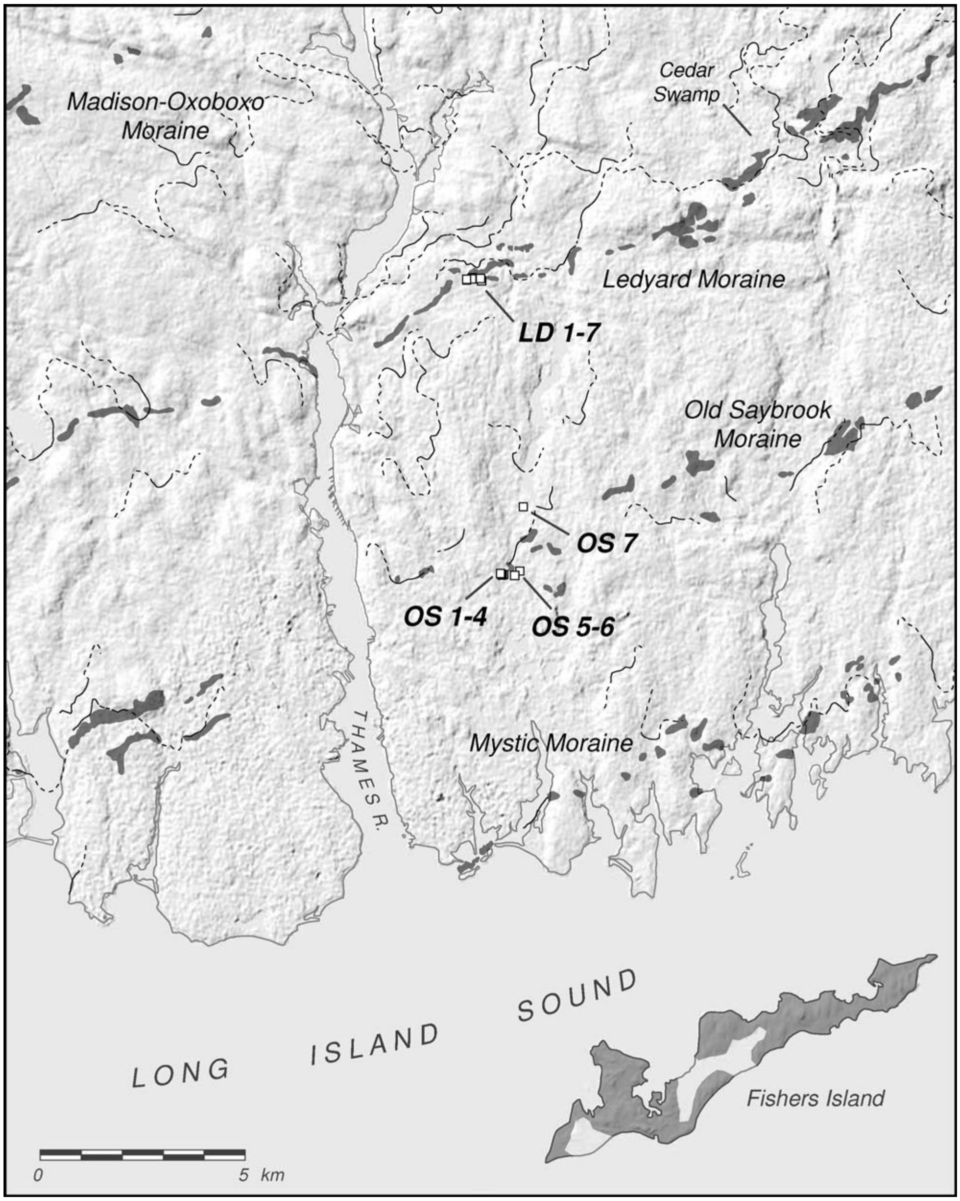

Fig. 2. Location of exposure-dating samples from the Ledyard and Old Saybrook moraines. Shaded-relief topography from SRTM30 digital elevation model. The dark shaded areas are mapped end moraine segments, and the thin black lines are mapped (solid) and inferred (dashed) ice-margin positions, from Stone et al. (1998b). The location of this figure is shown in Fig. 1.

exposure dating, as the interlocking nature of the boulder pile essentially precludes any postdepositional motion of the boulders. At the Old Saybrook moraine, we collected samples from large boulders that were closely spaced (but not physically interlocking) and lay on flat ground, where the geomorphic situation indicated that they had not moved or been covered by soil or sediment since deposition. The boulders are neither polished nor striated, and have rough surfaces with 5–10 mm of relief. Boulder surfaces appear fresh, are neither flaked nor spalled, have no visible weathering rind, and ring when struck with a hammer. We did not observe any accumulation of debris at the base of the boulders. These all suggest that the amount of postdepositional weathering did not exceed that required to create the present surface roughness.

We separated quartz from rock samples by crushing, heavy liquid separation, and repeated etching in dilute HF, then extracted and purified Be according to Stone (2004). We measured Be isotope ratios by AMS at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, against LLNL internal ^{10}Be standards. Combined carrier and process blanks run simultaneously with samples had 6000 ± 3000 atoms ^{10}Be. We computed the nominal exposure ages in Table 1 from measured ^{10}Be abundances using the reference ^{10}Be production rate (5.1 atoms g^{-1} yr^{-1}) and latitude/altitude scaling factors from Stone (2000). We corrected for sample thickness using an effective attenuation length for nuclide production of 160 g cm^{-2} and the measured rock density of 2.6 g cm^{-3}, and for assumed steady surface erosion of

0.6 μm yr^{-1} (e.g., 1 cm in the past 18,000 yr). We made no correction for paleomagnetic variation, primarily because we suggest later that the disagreement between exposure-age and varve chronologies is in part the result of an inaccurate estimate of the local ^{10}Be production rate. For the purpose of this discussion, the uncertainty in the ^{10}Be production rate derived from improperly accounting for magnetic field variations is indistinguishable from other production rate uncertainties. Thus, the exposure ages we report in this paper do not take account of past magnetic field changes.

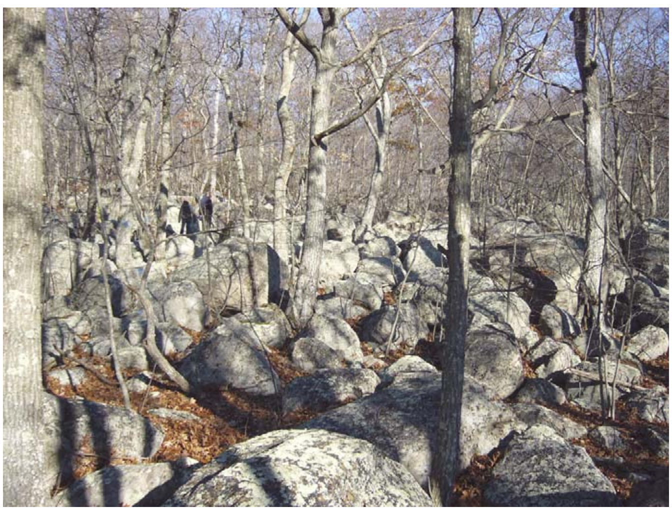

Fig. 3. The Ledyard moraine at Glacial Park, Ledyard, CT.

Results: Seven exposure ages from the Ledyard moraine varied between 17,200 and 19,000 yr; an additional seven from the Old Saybrook moraine varied between 17,200 and 19,100 yr (Table 1). In both cases, the scatter in the individual ages is symmetric and has the magnitude expected from analytical uncertainties alone.

In general, scatter in the exposure ages of multiple boulders on the same moraine has two major sources: analytical uncertainty in the ^{10}Be measurements, and 'geomorphogenic' errors caused by our incomplete knowledge of the precise history of each boulder, and the possibilities that it was exposed to the cosmic-ray flux before glaciation, or that it was moved, eroded, or covered by soil or sediment after deposition. Recent model studies of the secondary particle flux within irradiated boulders suggest a third possible source of scatter at the level of several percent, that is, the failure to properly account for secondary particle leakage in irregularly shaped boulders that differ from the infinite flat surface usually assumed in production rate calculations (e.g., Masarik and Wieler, 2003).

The goal in collecting the samples is to minimize the geomorphogenic scatter, by selecting samples that appear to have been undisturbed since emplacement. We can test whether we have achieved this by comparing the observed scatter in exposure ages with that expected from analytical uncertainty alone. For example, the reduced chi-squared (χ^2_R) statistic of a set of measurements and associated uncertainties (e.g., Bevington and Robinson, 1992) is a simple means of evaluating this: χ^2_R values of order 1 indicate that the scatter in the measurements is adequately

Table 1
^{10}Be concentrations and exposure ages, Ledyard and Old Saybrook moraines

Sample name	Latitude (DD)	Longitude (DD)	Elevation (m)	Thickness (cm)	Shielding correction[a]	Geographic scaling factor[b]	[^{10}Be] (10^3 atoms g^{-1})	Exposure age (yr)[c]	Exposure age (yr)[d]
Ledyard moraine									
LD-1	41.4428	−72.0452	79	5	1	1.022	90.5 ± 2.6	18300 ± 500	19100 ± 600
LD-2	41.4433	−72.0455	82	3	1	1.025	88.6 ± 2.5	17600 ± 500	18300 ± 500
LD-3	41.4434	−72.0470	79	1.5	1	1.022	96.8 ± 3.0	19000 ± 600	19800 ± 600
LD-4	41.4436	−72.0480	76	2.5	0.999	1.019	89.8 ± 2.2	17900 ± 500	18600 ± 500
LD-5	41.4433	−72.0481	73	5	1	1.016	88.2 ± 3.1	17900 ± 600	18700 ± 700
LD-6	41.4430	−72.0496	63	3.5	1	1.007	84.8 ± 2.3	17200 ± 500	17900 ± 500
LD-7	41.4432	−72.0496	63	1.5	1	1.007	93.6 ± 2.9	18700 ± 600	19500 ± 600
Old Saybrook moraine									
OS-1	41.3782	−72.0418	27	3	0.9999	0.973	88.4 ± 2.5	18500 ± 500	19300 ± 500
OS-2	41.3781	−72.0422	24	3.5	1	0.97	85.0 ± 2.5	17900 ± 500	18600 ± 500
OS-3	41.3783	−72.0424	24	4	1	0.97	81.5 ± 3.1	17200 ± 700	17900 ± 700
OS-4	41.3784	−72.0427	27	3.5	1	0.973	80.9 ± 2.1	17000 ± 400	17700 ± 500
OS-5	41.3788	−72.0371	17	3	1	0.963	90.5 ± 2.4	19100 ± 500	19900 ± 500
OS-6	41.3779	−72.0385	15	3	1	0.961	84.4 ± 2.0	17800 ± 400	18600 ± 500
OS-7	41.3929	−72.0354	33	4.5	1	0.978	89.2 ± 2.3	18800 ± 500	19600 ± 500

[a]Ratio of the production rate at the shielded site to that for a 2π surface at the same location.
[b]According to Stone (2000).
[c]Nominal exposure age calculated using the commonly accepted reference ^{10}Be production rate of 5.1 atoms g^{-1} yr^{-1} from Stone (2000). Additional details of the calculation appear in Section 4. The quoted uncertainty is the 1-σ internal error, which reflects measurement uncertainty only.
[d]Exposure age calculated using the reference ^{10}Be production rate of 4.9 atoms g^{-1} yr^{-1} that is required to obtain an internally consistent deglaciation chronology.

explained by their individual uncertainties; larger values indicate that another source of dispersion must be present. Most published sets of exposure ages from moraine boulders, in large part from alpine glacial moraines, scatter many times more than expected from the analytical uncertainties and have χ^2_R values of 10–500 (Putkonen and Swanson, 2003, unpublished compilation by Balco). The sets of exposure ages from the Ledyard and Old Saybrook moraines, in contrast, have $\chi^2_R = 1.5$ and 2.5, respectively, indicating that the analytical uncertainty alone adequately explains the scatter of the ages, and geomorphogenic uncertainty is unimportant by comparison. This is also true at the Buzzards Bay moraine ($\chi^2_R = 2$; Balco et al., 2002). In principle it might be possible for geomorphogenic factors to systematically affect each individual exposure age equally, thus changing the mean exposure age of the moraine without affecting the degree of scatter among the measurements. In this case the degree of scatter might not be a good indication of the importance of geomorphogenic uncertainty. This situation is implausible for most sources of disturbance of the boulders—for example, it is difficult to envision boulders of different heights emerging simultaneously from overlying sediment that might have existed in the past—and, in fact, both models of moraine degradation and age distributions from moraine sequences suggest that differences between the measured and actual exposure ages of a moraine that arise from boulder disturbance are always accompanied by an increase in the scatter among the individual ages (Putkonen and Swanson, 2003; Hallet and Putkonen, 1994, unpublished compilation by Balco). The main possible exception to this is the process of boulder surface erosion, which might have identical effects on boulders of like lithology, and our use of a single surface erosion rate in calculating all the boulder exposure ages implicitly recognizes this possibility. We emphasize that we are making two separate judgements about the relative importance of the various sources of error here. Both the geomorphic context of the boulders and the statistics ofthe measured age distribution lead us to the conclusion that the observed scatter largely reflects measurement uncertainties and not geomorphogenic uncertainties. However, the statistical analysis does not allow us to completely exclude the possibility that some geomorphic process has affected all the boulder ages equally, without increasing their scatter: we rely on our field observations and our understanding of the processes involved to ensure that we have adequately accounted for this possibility.

We conclude, both from geomorphic observations and from the data here and in Balco et al. (2002) that erratic boulders in the recessional deposits of southern New England are particularly well suited to precise exposure dating. First, no nunataks existed upstream of the sample sites at the time they were deglaciated, so boulders must have originated from subglacial erosion and should not carry any inherited nuclide inventory; and, in fact, we have not yet found any pre-exposed boulders in recessional deposits. This supports our previous conclusion that essentially all preglacially exposed boulders were swept from the New England landscape by the initial ice sheet advance to its terminal position (Balco et al., 2002). Second, in contrast to alpine glacial situations where moraines are steep, poorly consolidated, and erode rapidly, the moraines of southern New England are broad, gently sloping, and marked by large accumulations of boulders in particularly stable landscape positions; and this is manifested in the tightly grouped boulder age distributions that we observe.

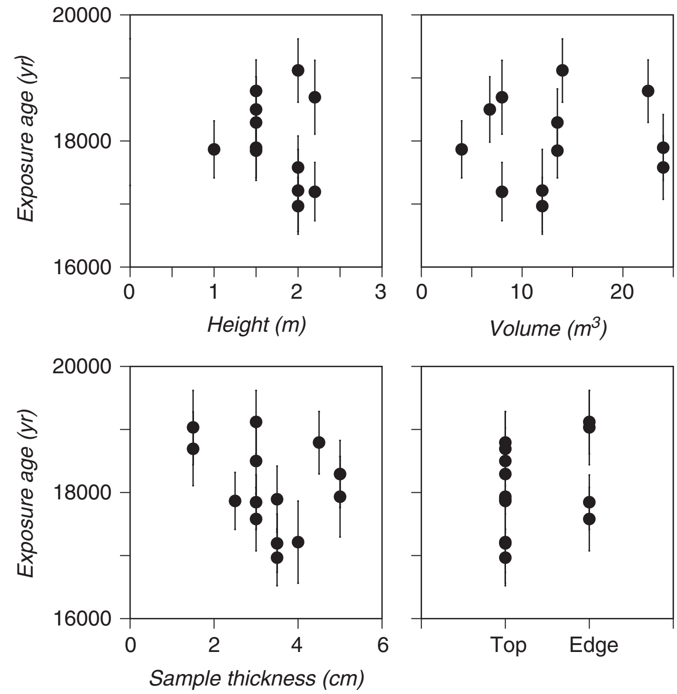

Fig. 4. Relationship of boulder geometry to boulder exposure age at the Ledyard and Old Saybrook moraines. As the mean exposure ages of the two moraines are statistically indistinguishable, we have plotted all the measurements from both moraines together. The boulders had irregular surfaces, so we estimated their average height above ground to the nearest 0.25 m. Boulder volume is approximate, calculated as the product of the length, width, and height. The error bars show the 1-σ internal uncertainty in the exposure ages. Numerical models of particle transport within boulders (Masarik and Wieler, 2003) predict a systematic relationship between nuclide concentration (here expressed as the exposure age to remove the elevation dependence of the production rate) and the size of the boulder as well as the position of the sample at the edge or center of the boulder surface. Also, numerical models of particle transport in the top few centimeters of rock surfaces (Masarik and Reedy, 1995) suggest that correcting for sample thickness on the basis of a production rate that exponentially decreases with depth, as we have done, should result in a spurious correlation between exposure age and sample thickness. We observe no such correlations.

Finally, we can test whether failure to account for secondary particle leakage could account for some of the scatter in our exposure ages by seeking a correlation between the size and geometry of the boulders and samples, and the exposure age that we calculated from the measured nuclide concentrations as described above (Fig. 4). There is no correlation between exposure age and boulder size,

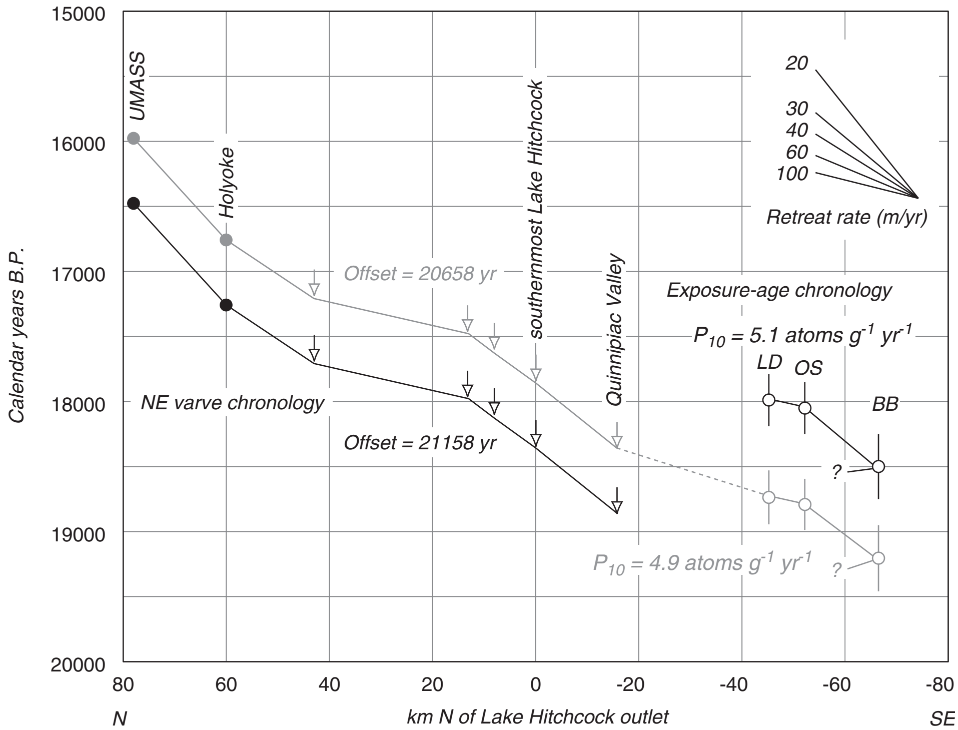

Fig. 5. Time–distance diagram for ice recession in eastern Connecticut. Line of projection shown in Fig. 1. Filled circles denote northern terminations of basal varves (which pinpoint the ice-margin location in a certain varve year). Arrows denote the oldest varve found at a particular site, which provides an upper limiting age for ice retreat past that site. Open circles with 1-σ error bars (taking account of measurement uncertainty only) show exposure ages on moraines. The dark symbols and lines show the mismatch between ice recession histories derived from the currently accepted values of the varve year–calendar year offset and the ^{10}Be production rate. The light symbols and lines show the internally consistent ice-recession history that results from adjusting these two parameters as described in the text. The varve chronology is adapted from Fig. 3 of Ridge (2003). The exposure age for the Buzzards Bay moraine shown here differs slightly from that in Balco et al. (2002) because we have not included the ^{26}Al ages reported therein (for consistency with the ages from the Connecticut moraines, where we only measured ^{10}Be). The idea that the Buzzards Bay and Charlestown–Fishers Island moraines are coeval is implicit in this diagram.

sample thickness, or the position of the samples on the boulder (e.g., center or edge). This suggests that the effect of variable secondary particle leakage is significantly less important than the analytical uncertainty.

To summarize, the scatter in the sets of exposure ages can be adequately explained by analytical uncertainty alone, so we take the error-weighted mean of each set of ages to be the best estimate of the age of each moraine. According to the currently accepted ^{10}Be production rate and considering measurement uncertainties only (we discuss the production rate uncertainty at length below), the Ledyard moraine was deposited $17,990 \pm 200$ yr ago, and the Old Saybrook moraine was deposited $18,050 \pm 190$ yr ago. Although these ages differ in the correct sense (the Ledyard moraine is stratigraphically and numerically younger), they are statistically distinguishable only at 60% confidence.

5. Discussion I. Cosmogenic-nuclide vs. varve chronologies

Having argued that the geomorphic situation in southern New England lends itself to exposure-dating with high precision, we now turn to the question of its accuracy. According to the nominal exposure ages, the Ledyard and Old Saybrook moraines were deposited near 18,000 yr ago. According to the New England varve chronology and associated calibration to calendar years, the southern Quinnipiac Valley was ice-free much earlier, prior to 18,900 yr BP. The eastward extension of this ice-marginal position (Stone et al., 1998b) lies 25 km up-ice of the Ledyard moraine (Figs. 1 and 5). Both the varve chronology in southern Massachusetts and comparison of exposure ages from the Buzzards Bay moraine (which is presumed correlative with the Charlestown–Fishers Island moraine) with those from Ledyard and Old Saybrook suggest that the ice margin was retreating at approximately 30 m yr^{-1} at this time. If this rate was more or less constant during deglaciation of all of these features, then the varve and exposure-age chronologies differ by at least 1700 yr, an amount which is well in excess of the internal uncertainty in the exposure ages (Fig. 5).

To summarize, the new exposure ages from eastern Connecticut are consistent with our previously reported exposure ages from the Buzzards Bay moraine, but almost 10% younger than permitted by the currently accepted calibration of the varve chronology. This difference is relatively small in light of the fact that the two chronologies are based on entirely independent techniques and assumptions, which suggests the possibility of improving the accuracy of both chronologies by exploring what modifications are required to bring them into line with each other. In the rest of this paper, we examine whether or not the difference can be accommodated within the uncertainties of the calibration of each of these chronologies to true calendar years, or if it indicates a serious problem with the geological assumptions that go into both chronologies. In the former case, then there are two possible reasons for the mismatch: first, the currently accepted offset between varve years and calendar years may be incorrect; and second, the ^{10}Be production rate that we used to compute the exposure ages could be wrong. We now consider both of these possibilities.

6. Discussion II. The varve year to calendar year calibration could be wrong

The calendar year calibration of the New England varve chronology (Ridge, 2003, 2004) is accomplished by radiocarbon-dating plant remains associated with a particular varve, calibrating the radiocarbon age to a calendar age, and then differencing calendar year and varve year to compute an offset between the two. Taking calendar years BP to be negative, the offset is simply the difference between the numerical New England varve year and the calendar age associated with the radiocarbon date. To determine the calendar age of a particular varve, one takes its assigned varve year and subtracts the offset. The currently accepted varve year–calendar year offset takes NE varve year 5858 to be 15,300 cal yr BP, that is, the value of the offset is 21,158 yr (Ridge, 2003, 2004). Here we discuss this value for the offset in light of a newly available radiocarbon year–calendar year calibration (INTCAL04, Reimer et al., 2004). In this section we rely heavily on data and discussion from Ridge (2003, 2004), and on more recent discussions with Ridge.

Both the measurement of ^{14}C abundance itself and the calibration between radiocarbon and calendar years have some uncertainty, so the calibrated calendar age of a radiocarbon-dated sample is more properly thought of not as an individual year, but as a probability density function (PDF) over a range of years. The radiocarbon age–calendar age calibration curve is irregular and contains plateaux and breaks in slope, so the PDF of the calendar age of a particular sample is often fairly complicated, and not easily approximated by an ideal PDF. If the sample is associated with a particular NE varve year, the PDF of calendar age can be transformed into a PDF for the value of the offset simply by subtracting the calendar years in question from the NE varve year. If there are multiple radiocarbon dates on different varves, and if we believe each radiocarbon date equally, we may sum the PDFs for the offset implied by each radiocarbon date to arrive at a summary PDF for the value of the offset (Fig. 6). It is not clear how to choose the best value of the offset from this summary PDF—for example, as we discuss below, plant

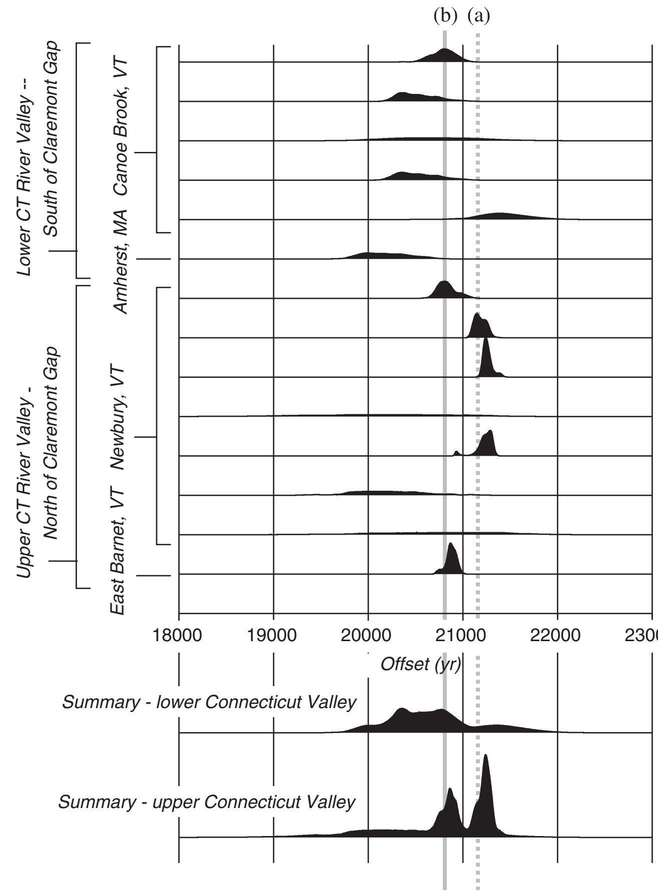

Fig. 6. Probability distributions for varve year–calendar year offsets derived from radiocarbon-dated plant remains on particular varves from the NE varve chronology, according to the INTCAL04 radiocarbon calibration and CALIB 5 (Reimer et al., 2004). The raw ages are listed in Table 1 of Ridge (2004). Each individual probability distribution is normalized to the same total area; the summary distributions are not renormalized and thus have area proportional to the number of individual distributions that were summed. The dotted line marked (a) shows the currently accepted value of the offset, which is based on the radiocarbon dates from this data set that are deemed the most reliable (see Ridge, 2003, 2004 for discussion). The solid line marked (b) shows the value of the offset for the lower Connecticut Valley varve chronology implied by the same selection of radiocarbon dates but updated to the INTCAL04 calibration.

remains in a particular varve may be older than the varve itself, indicating that simply taking the modal value might be misleading—but this representation provides a compact way of summarizing how consistent the present set of radiocarbon dates is, and thus gives a sense of the uncertainty in the value of the offset.

The currently accepted offset for the NE varve chronology is based on 14 radiocarbon dates on identifiable plant fragments found within individual varves or sets of a few adjacent varves (Ridge, 2003, 2004). The NE varve chronology actually consists of two separate varve sequences which are separated by a time gap of unknown duration (the 'Claremont Gap,' for the town of Claremont, NH which separates the outcrop areas of the two sequences), so we must consider the radiocarbon ages on the upper (that is, north of and younger than the Claremont Gap; 8 ages) and the lower (south of and older than the Claremont Gap; 6 ages) sequences separately (Fig. 6). The offsets for the two sequences then tell us the correct calendar year assignments for both sequences, and this in turn tells us the length of the Claremont Gap. Thus, the fact that both upper and lower sequences are assigned to the same numerical sequence of NE varve years implies a particular length for the Claremont Gap, which means that the currently accepted numbering system implicitly contains some of the calibration measurements. Here, however, we are mainly interested in the offset for the lower varve sequence.

We draw two important observations from this exercise (Fig. 6). First, the previously published offset for the lower varve sequence, which was based on the single radiocarbon date from Canoe Brook deemed to be most reliable (the uppermost PDF in Fig. 6), is revised downward 350 yr by the more recent radiocarbon age–calendar age calibration. Second, if we consider the distribution of radiocarbon dates for the lower varve sequence alone, it suggests that the offset for the lower varve sequence could be as low as 20,300 yr, that is, 800 yr less than the previously accepted value. This would have the effect of making the calendar ages of events that are dated by association with the varve chronology younger: the southern Quinnipiac Valley would have deglaciated before 18,100 yr BP, and the southern end of Lake Hitchcock before 17,500 yr BP.

There are a few flaws in this argument. The main difficulty is that the distribution of radiocarbon dates for the upper varve sequence is not compatible with a reduction in the offset for the upper varve sequence of more than the 350 yr implied by the INTCAL04 radiocarbon calibration. Thus, reducing the offset for the lower varve sequence by more than this amount would require a reduction in the length of the Claremont Gap. The currently accepted length of the Claremont Gap is only 350 yr, so if we were to believe that the offset for the lower Connecticut Valley varve chronology could be as much as 800 yr lower than the currently accepted value, we would also have to conclude that the two halves of the varve sequence could overlap. While this has been proposed in the past (Ridge et al., 1996), the recent discovery by Ridge (2003, 2004) of short varve sequences near Claremont that do not match either half of the existing chronology essentially precludes any overlap. Taking all this information into account, it appears that the offset for the lower sequence is unlikely to be more than approximately 500 yr less than the currently accepted value, that is, a 350 yr reduction to reflect the INTCAL05 calibration and no more than a 150 yr reduction in the length of the Claremont Gap. A secondary difficulty is that plant fragments within a particular varve may be older than that varve, either because of the transport time from landscape to lake bottom or because of recycling of previously deposited lake sediment (Ridge, 2003, 2004). If this were true, the radiocarbon dates would overestimate the value for the offset. We have no way to critically evaluate this possibility, but it would work in our favor in the present study: if we believed that we had overestimated the value of the offset for this reason, it would reduce the discrepancy between varve and exposure-age chronologies. Taking all these things into consideration, it appears that no more than 500 yr of the 1700-yr discrepancy between the exposure-age and varve chronologies for the deglaciation of southeastern Connecticut can be accommodated within the uncertainty of the varve year–calendar year offset (Figs. 5 and 6).

7. Discussion III. The ^{10}Be production rate could be wrong

Calculating exposure ages from ^{10}Be concentrations requires knowing the production rate of ^{10}Be at the sample sites. We determine this production rate independently by measuring the ^{10}Be concentration in surfaces of known age at a variety of sites; several such calibrations exist at present (e.g., Gosse and Phillips, 2001). We then use a scaling scheme that describes the variation of the cosmic ray flux with time, position, and elevation to scale the set of calibration measurements to a reference value (usually taken to be the modern value at sea level and high geomagnetic latitude), and then scale this reference value again to compute the local production rate at the site we wish to date. Thus, we could obtain the wrong results if: (a) we used an incorrect reference value; (b) we used an inaccurate scaling scheme; or (c) we used an accurate scaling scheme with incorrect information, that is, if we made wrong assumptions about the geomagnetic field or atmospheric pressure at our site in the past. We present no information here that would allow us to distinguish among these possible errors, so we assume, for the sake of argument, that the scaling scheme we used (Stone, 2000) is correct, and we ask what reference production rate would be needed to bring the exposure-age chronology for southern New England into line with the varve chronology. If we assume that the ice margin retreated at a more or less constant rate, and we adjust the value of the varve year–calendar year offset downwards by 500 yr, we need to lower the reference ^{10}Be production rate by at least 4% from the currently accepted value, that is, to lower than 4.9 atoms g^{-1} yr^{-1}, to maintain a plausibly internally consistent deglaciation history (Fig. 5).

The next question that we should ask, as we did above for our proposed adjustment to the varve year–calendar year offset, is whether or not the size of the proposed adjustment, that is, a 4% reduction in the ^{10}Be production rate, violates other important constraints. First, with regard to the precision of the independent production rate calibrations, the stated uncertainty in the reference production rate for ^{10}Be (5.1 atoms g^{-1} yr^{-1}) is 6% (Stone, 2000; Stone, unpublished calculations). No one has attempted to quantitatively estimate the uncertainty in the commonly used geographic scaling factors, but it is thought to be as much as 10% for certain regions (Lal, 1991). Thus, a production rate in southern New England that is 4% lower that the commonly accepted value is easily accommodated within either of these uncertainties. In addition, Clark et al. (1995) sought to determine the ^{10}Be production rate by measuring ^{10}Be concentrations in ice-polished bedrock and erratic boulders from northern New Jersey (Fig. 1), whose true exposure age is constrained by radiocarbon dates on postglacial pond sediment to be near 18,400 ^{14}C yr BP (22,100 cal yr BP). When made consistent with the scaling factors that we use here, their measurements imply a reference ^{10}Be production rate of 4.7 ± 0.5 atoms g^{-1} yr^{-1}. This agrees with our observation that the exposure-age and varve chronologies can only be consistent if the reference ^{10}Be production rate is taken to be less than 4.9 atoms g^{-1} yr^{-1}.

Second, lowering the ^{10}Be production rate to make exposure ages for the Ledyard and Old Saybrook moraines consistent with the varve chronology also results in changes to previously published exposure ages for the Martha's Vineyard and Buzzards Bay moraines, so we can ask whether these adjustments create new conflicts with other age constraints. The effect of lowering the production rate is to increase the exposure age for all moraines, increasing the mean ^{10}Be ages for the Ledyard and Old Saybrook moraines to 18,700 and 18,800 yr, and for the Martha's Vineyard and Buzzards Bay moraines to 24,000 and 19,200 yr, respectively.

The oldest radiocarbon date on postglacial sediment in eastern Connecticut is a basal radiocarbon date of 15,200 ^{14}C yr BP (18,560–18,710 cal yr BP) from Cedar Swamp, which is immediately north of the Ledyard moraine (Fig. 2, McWeeney, 1995; Stone et al., 1998b). The fact that the Ledyard moraine must predate this deposit also requires a 4% reduction in the ^{10}Be production rate, the same amount that we infer from the exercise of making the exposure age and varve chronologies consistent. In fact, this relationship is a strong constraint on the local ^{10}Be production rate. The youngest preglacial deposit yet discovered in New England is a bison horn from eastern Massachusetts dated at $21,200 \pm 1000$ ^{14}C yr BP (22,500–24,100 cal yr BP) (Schafer and Hartshorn, 1965), and the exposure age of the Martha's Vineyard moraine is now close to this age, but the two ages are still consistent in light of the large uncertainty in the radiocarbon date. Furthermore, the most likely relationship between the major coastal moraines, whose exposure ages record the time of moraine abandonment after a readvance or prolonged stillstand, and past climate changes is that moraine abandonment should occur during rapid warmings at the end of prolonged cold periods (Balco et al., 2002; Lowell et al., 1999). It would be impossible to conclusively prove this hypothesis without the ability to correlate exposure ages and ice-core records at the decadal level, which, as the foregoing discussion suggests, is not immediately forthcoming. We previously argued that the exposure ages from the major moraines at Martha's Vineyard and Buzzards Bay were consistent with the hypothesis (Balco et al., 2002); if the production rate were 4% lower, this would still be the case, and, in fact, the mean exposure ages of both major moraines would come into closer agreement with the terminations of cooling cycles and coeval ice-rafting episodes evident in North Atlantic climate records at 24,000 yr BP (Heinrich event 2) and 19,000 yr BP (event 'a' of Bond et al., 1997; Fig. 7). The Ledyard and Old Saybrook moraines do not correlate with any particular event evident in North Atlantic paleoclimate records (Fig. 7). However, these moraines are small and reflect only minor interruptions in a steady ice margin

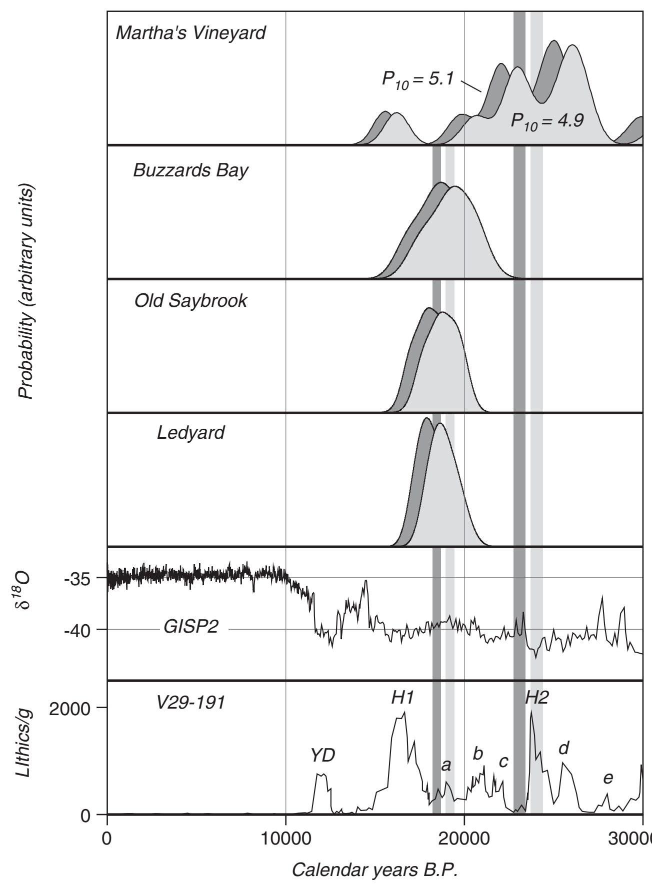

Fig. 7. Relationship of exposure ages of New England moraines to North Atlantic paleoclimate records. The four camel diagrams at top show summary probability distributions for sets of ^{10}Be ages from the Martha's Vineyard ($n = 12$, although old outliers are not shown on these axes), Buzzards Bay ($n = 10$), Old Saybrook ($n = 7$), and Ledyard ($n = 7$) moraines. The first two sets of ages have been previously published in Balco et al. (2002). The probability distributions are normalized to have total area proportional to the number of samples included. The dark gray probability distributions use the reference ^{10}Be production rate of 5.1 atoms g^{-1} yr^{-1} from Stone (2000); the light gray ones use the value of 4.9 atoms g^{-1} yr^{-1} needed for consistency between exposure-age and varve chronologies, as described in the text. The corresponding light and dark bands in the background show the weighted means of ages from the Martha's Vineyard and Buzzards Bay moraines. The probability distributions and means for these two moraines differ from those in Balco et al. (2002) because we have not included the ^{26}Al ages reported therein (for consistency with the ages from the Connecticut moraines, where we only measured ^{10}Be). The δ^{18}O record from GISP2 is from Grootes et al. (1993); the record of ice-rafted debris in core V29-191 is from Bond et al. (1997).

retreat, so we expect no such correlation. This argument is circular from the point of view of climate reconstruction and thus does not serve to independently establish coincidence between warming events and the emplacement of major moraines, but it serves to show that the production rate revision, needed to make exposure-age and varve chronologies consistent, does not require any changes in our present understanding of the climate significance of these moraines.

We conclude that the ^{10}Be production rate in southern New England is several percent less than that inferred from commonly accepted reference production rates and scaling schemes. Once again, however, we have no information as to whether the reference production rate, the geographic scaling scheme, or our assumptions about past magnetic field or atmospheric pressure changes, are in error.

8. Conclusions

Precision of exposure dating in New England: The glacial erratics of New England are exceptionally well-suited to precise exposure dating. Boulders with a nuclide inventory inherited from preglacial exposure only occur in the terminal moraine. Boulders are commonly in stable landscape positions, and the tight distribution of exposure ages of boulders on the same moraine indicate that geomorphogenic uncertainties in the exposure history of the boulders are less important than the measurement uncertainty of the exposure ages. Given boulders enough and time, it is possible to exposure-date late-glacial ice-margin positions in New England with a precision of a few hundred years, which is encouraging in light of our goal of correlating glacial events with other paleoclimate records. The main obstacle to achieving this goal is now the need to improve the accuracy of the ages by better establishing the ^{10}Be production rate.

Exposure-age and varve chronologies for deglaciation: The New England varve chronology and the exposure-age chronology for the southern New England moraines nominally disagree by some 1700 yr, a significant difference given the internal precision of the two chronologies. However, this discrepancy is similar in size to the uncertainties in the two independently determined parameters that link the two chronologies to the absolute calendar year time scale, that is, the ^{10}Be production rate and the varve year–calendar year offset. Considering the uncertainty in these two parameters, the two chronologies essentially agree, and present the opportunity to more accurately determine these parameters by enforcing internal consistency between the two chronologies. The combined deglaciation chronology that results from this exercise indicates that retreat from the terminal moraine at Martha's Vineyard started near 24,000 yr BP, the Buzzards Bay moraine was emplaced near 19,200 yr BP, and southeastern Connecticut was deglaciated 18,500–19,000 yr BP. It suggests that the varve year–calendar year offset has been overestimated by several hundred years and that the local ^{10}Be production rate has been overestimated by a few percent, and it is consistent with: (a) independent measurements of the varve year–calendar year offset; (b) independent measurements of the ^{10}Be production rate; (c) relevant limiting radiocarbon ages; and (d) the present understanding of the most likely relationship between the exposure age of major moraines and North Atlantic climate changes. As the exposure-age and varve chronologies are based on entirely independent evidence and assumptions, their good agreement within their respective calibration uncertainties shows that the geological assumptions that go into each one are well founded. Determining whether our adjustments to both calibration parameters are in fact justified, and thus whether our combined chronology is in fact correct, requires three research tasks: one, improving the independent calibration of the production rate; two, better establishing the offset via additional radiocarbon dating; and three, measuring the exposure age of erratic boulders at an ice margin that is stratigraphically connected to the varve chronology, for example, at sites farther north in the Connecticut River Valley where recessional moraines and ice-proximal varves occur together.

The varve chronology as a calibration tool for determining cosmogenic-nuclide production rates: The New England landscape appears particularly well-suited to precise exposure dating, and ice-marginal positions in central and northern New England can be closely linked to the very precise and potentially very accurate varve chronology. If we can improve the internal consistency of the two chronologies by measuring the exposure ages of ice-marginal landforms with direct stratigraphic links to the varve chronology, then we can use measurements of the varve year–calendar year offset to determine cosmogenic-nuclide production rates, and vice versa. Not only does the combined varve and exposure-age chronology provide a potentially very accurate means of dating late-glacial events, but the new constraint of internal consistency between the two chronologies provides a means of improving the accuracy of the separate dating techniques as well. The requirement that varve and exposure-age chronologies must yield the same results for the entire 6000-yr duration of the varve chronology is a particularly stringent test for any production-rate scaling scheme. Once again, the main obstacles here that require additional research are the need for additional radiocarbon dates to better establish the varve year–calendar year offset, and the need to locate new sites for exposure dating farther to the north, where ice-marginal landforms are more closely tied to the varve chronology.

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