PERGAMON

Quaternary Science Reviews 21 (2002) 2127–2135

QSR RAPID COMMUNICATION

Rapid Communication

Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA

Greg Balco[a,*], John O.H. Stone[a], Stephen C. Porter[a], Marc W. Caffee[b,1]

[a] *Quaternary Research Center and Department of Earth and Space Sciences, University of Washington, Mail Stop 351310, Seattle, WA 98195-1310, USA*

[b] *Center for Accelerator Mass Spectrometry, L-397, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

Received 5 April 2002; accepted 20 June 2002

Abstract

Cosmogenic-nuclide exposure ages for 13 glacially transported boulders atop the Martha's Vineyard moraine, MA, USA, indicate that the southeastern margin of the Laurentide ice sheet reached its maximum extent during the last glaciation 23,200 ± 500 yr ago. Another 10 age determinations from the younger Buzzards Bay moraine near Woods Hole, MA, indicate that this moraine complex was formed 18,800 ± 400 yr ago. These ages correlate approximately with the terminations of cooling cycles recorded in Greenland ice cores and coeval ice-rafting events, suggesting that the marginal position of this sector of the ice sheet was tightly coupled to North Atlantic climate during the last glacial maximum.

1. The coastal end moraines of southern New England

The southern New England coast owes its present form to a series of laterally extensive and well-exposed ice-marginal deposits built during the greatest advances of the Laurentide ice sheet (Fig. 1). These moraines include a variety of ice-contact, stagnant-ice, glaciofluvial, and glaciotectonic deposits, but the most prominent features are large (2–10 km wide; 30–200 km long; 50–100 m high) moraine ridges containing imbricate thrust sheets of displaced older sediments, fronted by wide, shallowly sloping outwash plains. The extent, structure, and stratigraphy of these moraines have been reported in many studies (Hitchcock, 1841; Shaler, 1888; Woodworth et al., 1934; Mather et al., 1940; Kaye, 1964a, b; Oldale, 1982; Oldale and O'Hara, 1984); however, their inferred age was based only on long-distance stratigraphic correlation and a few limiting radiocarbon ages, most of which have uncertain relationships to the moraines. In an effort to better understand the timing of Laurentide ice sheet advances and their relationship to the complicated oceanographic, climatic, and glacial events that marked the culmination and end of the last ice age, we have measured ^{10}Be and ^{26}Al ages for the two outermost moraines in southeastern Massachusetts.

The Martha's Vineyard moraine (Kaye, 1972), which forms the backbone of the island of Martha's Vineyard, is composed of three NE- to SW-trending ridges that are the surface expression of imbricate glaciotectonic thrust sheets. The Buzzards Bay moraine, which forms the Elizabeth Islands and the western margin of Cape Cod, is a single broad ridge formed of one or more similar thrust sheets but largely mantled by kettled outwash (Kaye, 1964a; Oldale and O'Hara, 1984; Fig. 1). The thrust sheets include Cretaceous and Tertiary coastal-plain sediments, shallow-marine deposits, and lignites, as well as Pleistocene tills, outwash, and marine sediments. They are often separated by boulder pavements; and they have been refolded, overturned, and otherwise deformed by repeated glacier advances. Although the size of the Buzzards Bay moraine suggests a significant standstill or possible retreat and readvance, there is no stratigraphic evidence to favor one or the other of these possibilities.

Early attempts to determine the age of these moraines relied on correlation of stratigraphic units with those in

*Corresponding author.
E-mail address: balcs@u.washington.edu (G. Balco).
[1] Present address: PRIME Lab., Purdue University, 1396 Physics Building, West Lafayette, IN 47907-1396, USA.

0277-3791/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S 0 2 7 7 - 3 7 9 1 (0 2) 0 0 0 8 5 - 9

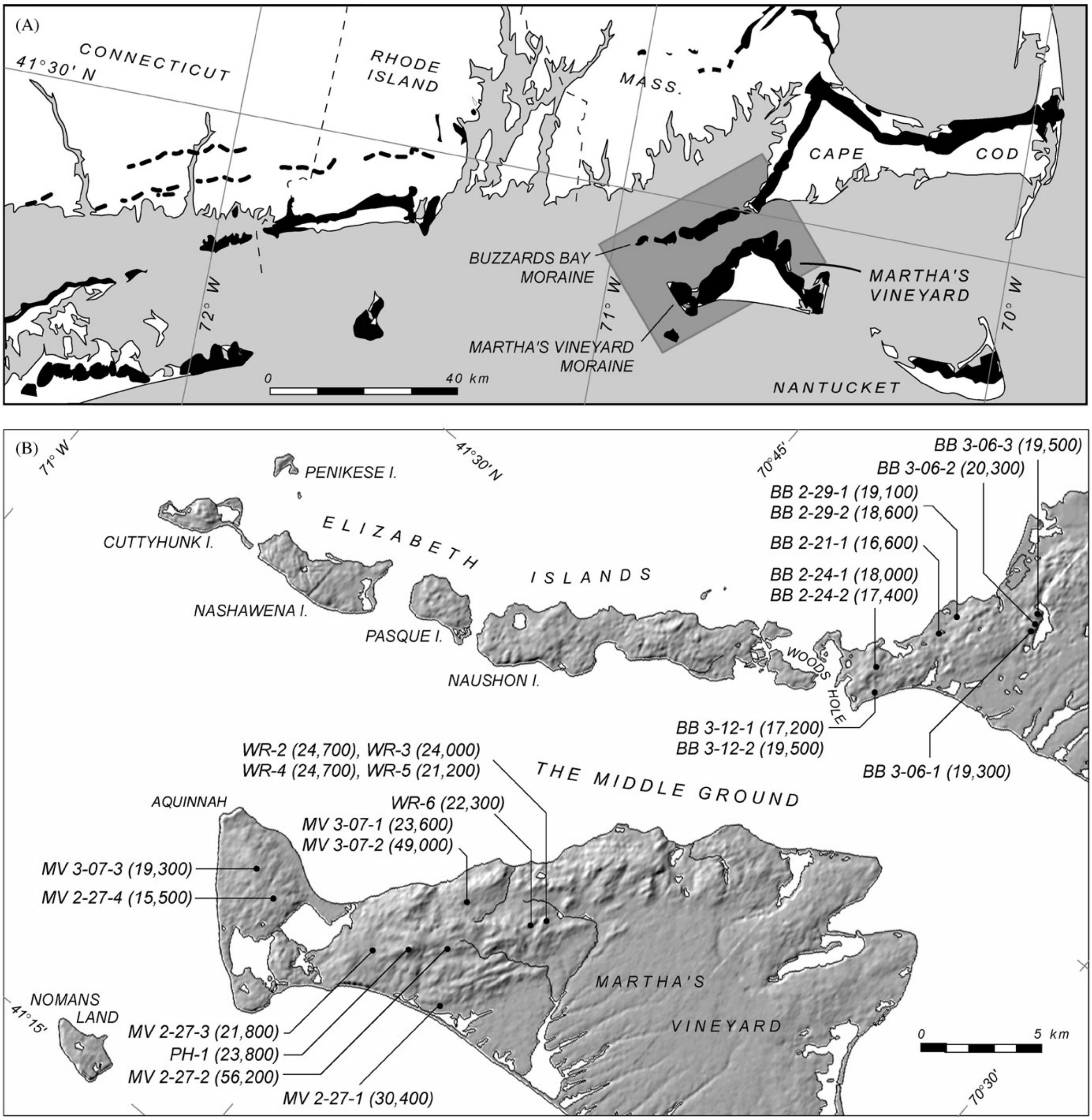

Fig. 1. (A) Map of southeastern New England, adapted from Schafer and Hartshorn (1965). Prominent end moraines are shown in black. (B) Shaded-relief map of portions of Martha's Vineyard, Cape Cod, and the Elizabeth Islands showing the location of exposure-age samples.

other parts of North America, as well as observations of surface topography and the condition and frequency of boulders. Woodworth et al. (1934) and later Kaye (1964a) divided the moraine stratigraphy into deposits of seven glacier advances and one interglaciation, and correlated various portions of the moraine surface with Illinoian, early Wisconsinan, and late Wisconsinan drifts elsewhere. Since that time, radiocarbon ages of 18,000–10,000 ^{14}C yr BP (21,500–11,500 cal yr BP) for postglacial deposits north of the coastal moraine belt (Kaye, 1964b; Schafer and Hartshorn, 1965; Stone and Borns, 1986; Boothroyd et al., 1998; Stone et al., 1998) and 34,000–21,000 ^{14}C yr BP (ca. 35,000–24,000 cal yr BP) for preglacial deposits at Georges Bank, Boston, and Nantucket (Schafer and Hartshorn, 1965; Tucholke and Hollister, 1973; Oldale, 1982), led to more recent conclusions that the outermost moraine was entirely Wisconsinan in age and most likely formed 21,000–18,000 ^{14}C yr BP (24,000–21,500 cal yr BP). The same age constraints apply to the Buzzards Bay moraine. Although basal radiocarbon ages from peat bogs at Martha's Vineyard of 12,700–10,000 ^{14}C yr BP (15,300–11,500 cal yr BP; Ogden, 1959, 1963; Stuiver et al., 1960) are distal to the Buzzards Bay moraine, they are similar to more ice-proximal ages from inland New England and probably reflect the regional onset of organic sedimentation rather than deglaciation.

2. Sampling and methods

Exposure-age dating, which relies on the measurement of rare isotopes produced in near-surface rocks by cosmic-ray bombardment, is widely used to date glacier advance and retreat by measuring the concentration of these isotopes in glacially polished surfaces and erratic boulders (e.g., Gosse and Phillips, 2001). As in comparable studies, we sampled the upper surface of large (>2 m intermediate diameter) boulders whose geomorphic context suggested that they had not moved since deglaciation. All the boulders we sampled are medium- to coarse-grained, often-porphyritic, pink granite derived from plutons in Rhode Island and southeastern Massachusetts (Kaye, 1964b). These boulders are not polished or striated, but have rough surfaces on which resistant quartz grains stand 5–15 mm in relief. However, mineral grains appear fresh, boulder surfaces are minimally flaked and spalled and lack a visible weathering rind, and weathering debris at the base of the boulders is negligible, all suggesting that the amount of postdepositional weathering did not exceed that required to create the present surface roughness.

We separated quartz from rock samples and then extracted and purified Al and Be according to Stone (2001), then measured isotope ratios by AMS at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory (Table 1). We calculated ages from measured isotope abundances using production rates of 5.1 ± 0.3 atoms/g/yr for ^{10}Be and 31.1 ± 1.8 atoms/g/yr for ^{26}Al (Stone, 2000). We made production-rate corrections for latitude, altitude, and magnetic field variation using geomagnetic scaling factors from Stone (2000), the ICAO standard atmosphere, paleomagnetic intensity records from Guyodo and Valet (1996) and McElhinny and Senanayake (1982), Holocene magnetic pole positions from Ohno and Hamano (1992), and the formula for paleomagnetic correction from Nishiizumi et al. (1989). We corrected for sample thickness assuming a rock density of 2.7 g/cm^3 and for assumed steady surface erosion of 0.8 μm/yr (i.e., 2 cm in the last 25,000 yr). Topographic shielding was negligible ($<10^{-3}$) for all samples. Samples in which we analyzed both isotopes had ^{26}Al/^{10}Be ratios indistinguishable from the production ratio of 6.1, providing no evidence of complex exposure histories. Thus, we report the weighted mean of ^{26}Al and ^{10}Be ages as the best estimate of the true exposure age of each sample.

3. Results, discussion, and conclusions

Boulder ages from Martha's Vineyard cluster between 25,000 and 22,000 yr, with three samples significantly older and two somewhat younger than the main age cluster (Fig. 2). The older outliers likely reflect recycling of previously exposed boulders incorporated during the initial advance of the ice sheet to its maximum position. Both younger outliers are from Aquinnah in the westernmost part of the island, but are younger than ice-proximal ages from the Buzzards Bay moraine. They could be explained by 20–60 cm of flaking or spalling of the boulder surface, late exposure from beneath an eroding sediment cover, or late exposure due to melting of buried stagnant ice that may have persisted for several thousand years after deglaciation of southern New England (e.g., Boothroyd et al., 1998; Stone et al., 1998). As there is no field evidence for severe postglacial weathering of boulders, the sample sites are flat and unlikely to have experienced meters of postglacial soil erosion, and kame-and-kettle topography prevails in this region of the island, the latter explanation seems most likely. The spread of ages, even within the central age distribution, is greater than expected from analytical error alone. This has two possible explanations: first, some samples may contain small amounts of inherited ^{10}Be and ^{26}Al, in which case the true age of the moraine would be near 22,000 yr. Second, the spread of ages combined with the complex moraine stratigraphy that reflects multiple ice advances may indicate that the ice margin remained near its maximum position with only small fluctuations for 2000–3000 yr. In the absence of evidence that would distinguish these two possibilities, we believe the best estimate for the true age of the moraine is the error-weighted mean of the central age cluster, $23{,}200 \pm 500$ yr. This agrees very well with the limiting radiocarbon ages discussed in the previous section.

Ten boulder ages from the Buzzards Bay moraine are clustered around an error-weighted mean of $18{,}600 \pm 400$ yr. The presence of old outliers in the Martha's Vineyard moraine but not in the Buzzards Bay moraine suggests that boulders present at the surface before the initial advance of the ice sheet were transported to the terminal moraine, and that only fresh subglacial erratics were available to be deposited in younger moraines.

These data allow us to place the prominent but previously poorly dated moraines of the New England

Table 1
Sample information and analytical data

Sample[a]	N latitude (DD)	W longitude (DD)	Elevation (m)	Thickness (cm)	$[^{10}Be]$[b] (10^4 atoms/g)	^{10}Be age (yr)[c] and 1σ error	$[^{26}Al]$[b] (10^4 atoms/g)	^{26}Al age (yr)[c] and 1σ error	$^{26}Al/^{10}Be$ ratio	Mean of Al and Be ages (yr) and 1σ error
Martha's Vineyard moraine										
PH-1	41.3567	70.7348	91	4.5	12.35±0.37	24,400±1700	71.24±3.12	23,400±1800	5.8±0.3	24,000±1200
WR-2	41.3937	70.6992	54	2	12.29±0.36	24,700±1700	74.91±4.22	25,000±2100	6.1±0.4	24,800±1300
WR-3	41.3922	70.6995	54	1.5	12.28±0.47	24,500±1800	60.44±17.58	20,100±6100	4.9±1.4	24,200±1700
WR-4	41.3939	70.6972	30	3	12.18±0.35	25,300±1700	70.7±2.96	24,400±1800	5.8±0.3	24,900±1200
WR-5	41.3920	70.6983	51	6	10.29±0.3	21,500±1400	61.19±2.95	21,200±1700	5.9±0.3	21,400±1100
WR-6	41.3897	70.7017	51	4	11.06±0.42	22,700±1600	65.12±2.56	22,200±1600	5.9±0.3	22,400±1100
MV 2-27-1	41.3483	70.7063	9	2	14.05±0.36	29,400±1900	92.55±3.71	32,300±2400	6.6±0.3	30,600±1500
MV 2-27-2	41.3633	70.7258	69	2.5	28.25±0.7	56,900±3800	162.78±14.06	55,200±6200	5.8±0.5	56,400±3200
MV 2-27-3	41.3483	70.7482	30	2	10.68±0.28	22,100±1500	63.61±4.08	21,800±1900	6±0.4	22,000±1200
MV 2-27-4	41.3350	70.7977	33	2	7.55±0.32	15,700±1100	45.77±2.27	15,700±1200	6.1±0.4	15,700±800
MV 3-07-1	41.3758	70.7320	51	2.5	n.m.		70.72±2.43	23,800±1700		23,800±1700
MV 3-07-2	41.3758	70.7320	54	2	24.6±0.61	49,700±3300	143.29±7.6	48,600±4100	5.8±0.3	49,200±2600
MV 3-07-3	41.3417	70.8143	51	2.5	9.71±0.36	19,800±1400	56.41±3.35	19,100±1600	5.8±0.4	19,500±1100
Buzzards Bay moraine										
BB 2-21-1	41.5500	70.6495	12	1.0	7.98±0.33	16,700±1200	48.39±2.98	16,800±1500	6.1±0.4	16,700±900
BB 2-24-1	41.5317	70.6588	24	2.0	8.82±0.31	18,400±1300	52.6±2.33	18,100±1400	6±0.3	18,200±900
BB 2-24-2	41.5317	70.6597	24	2.0	8.45±0.34	17,600±1300	54.13±2.48	18,600±1400	6.4±0.4	18,100±900
BB 2-29-1	41.5567	70.6458	24	2.0	9.29±0.41	19,300±1400	57.01±2.05	19,600±1400	6.1±0.3	19,500±1000
BB 2-29-2	41.5567	70.6458	24	2.5	8.83±0.62	18,400±1700	59.23±11.31	20,400±4200	6.7±1.4	18,700±1600
BB 3-06-1	41.5750	70.6178	24	2.5	8.92±0.29	18,600±1300	66.16±5.8	22,800±2500	7.4±0.7	19,500±1100
BB 3-06-2	41.5783	70.6192	21	2.5	9.46±0.32	19,800±1400	62.25±3.25	21,600±1700	6.6±0.4	20,500±1100
BB 3-06-3	41.5817	70.6217	21	2.5	9.21±0.4	19,300±1400	59.7±4.98	20,700±2200	6.5±0.6	19,700±1200
BB 3-12-1	41.5250	70.6532	9	1.5	8.25±0.41	17,400±1400	53.08±3.71	18,500±1700	6.4±0.6	17,800±1100
BB 3-12-2	41.5242	70.6528	18	2.0	9.38±0.46	19,600±1500	60.08±2.28	20,800±1500	6.4±0.4	20,200±1100

[a] Topographic shielding was $<10^{-3}$ for all samples.
[b] Measured relative to LLNL internal standards. Procedural blanks contained $2.4\pm1.8\times10^4$ atoms ^{10}Be and $<10^5$ atoms ^{26}Al. Uncertainties propagated at $\pm1\ \sigma$ including all known sources of analytical error.
[c] Ages calculated using production rates of 5.1 ± 0.3 (^{10}Be) and 31.1 ± 0.8 (^{26}Al) at/g SiO_2/yr at 1013.25 mb and latitude $>60°$. Ages include a correction for paleomagnetic variation as described in the text. The scaling factors used are tabulated in Tables 2 and 3.

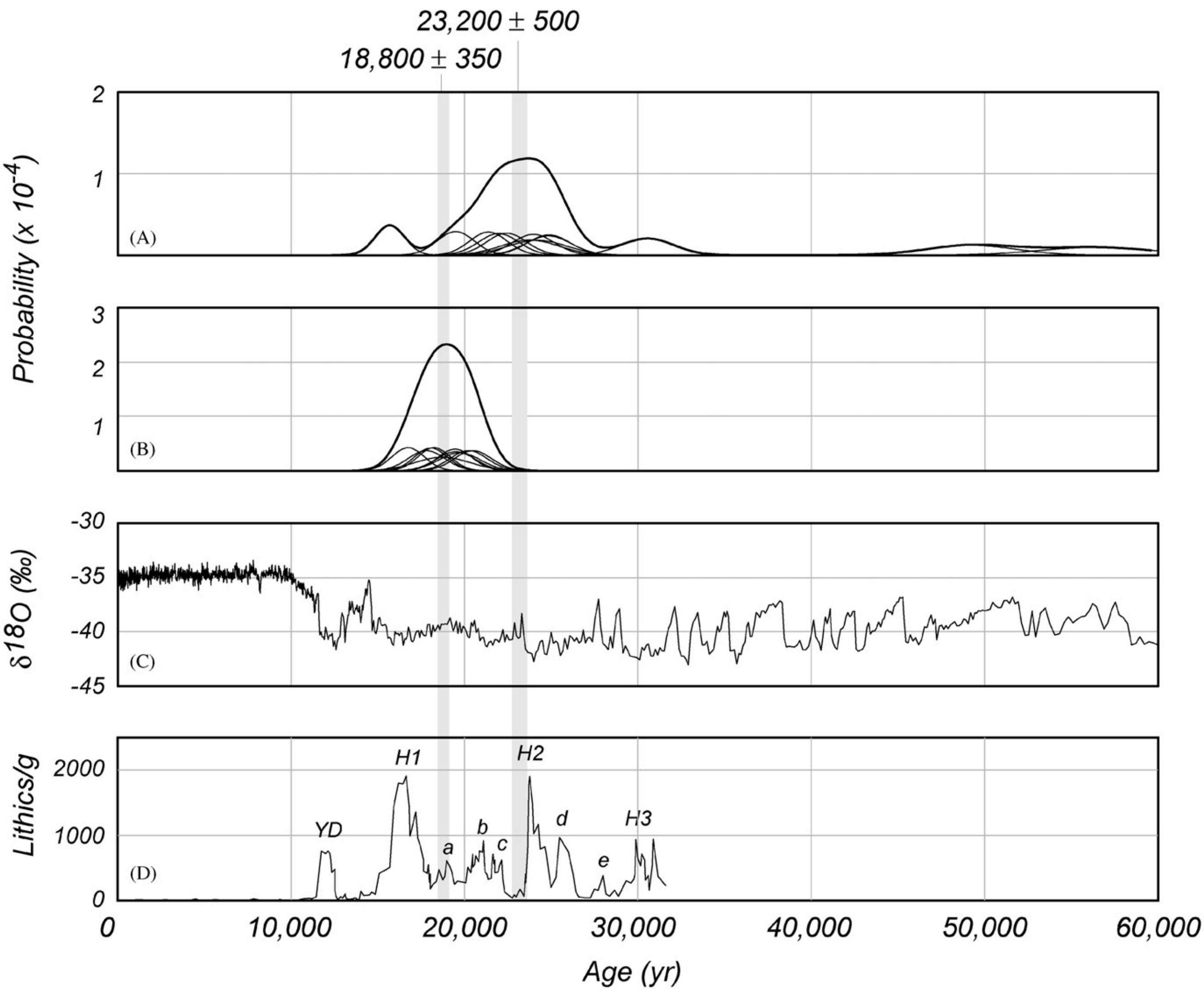

Fig. 2. Relationship of exposure ages in this study to North Atlantic paleoclimate records. (A) and (B), probability diagrams (e.g., Lowell, 1995) representing sets of exposure ages from the Martha's Vineyard and Buzzards Bay moraines, respectively. Multiple light lines are Gaussian probability distributions representing the weighted mean of ^{10}Be and ^{26}Al ages for individual samples. Probability values are normalized so that each individual probability distribution has unit area. Heavier lines are the sum of probability distributions for all samples. Gray bands show $1-\sigma$ range around weighted means, calculated as described in text, (C) δ^{18}O record from the GISP2 ice core (Grootes and Stuiver, 1997) and (D) record of ice-rafted debris from marine core V29-191 (Bond et al., 1997).

coast in the context of other glacial-geological and climate records from New England and the North Atlantic region. Our data combined with radiocarbon dates from pre-glacial lake sediments in Maine (C.C. Dorion, unpublished data) indicate that the ice margin advanced across northern New England between 31,000 and 27,000 yr ago, perhaps approaching its maximum extent at Martha's Vineyard at the beginning of the sustained cold period recorded in North Atlantic climate records near 25,000 yr ago (Fig. 2). Our best estimate of the age of the Martha's Vineyard moraine, which presumably records the time of moraine abandonment and ice retreat, agrees remarkably well with the end of the coldest period of the last glacial maximum recorded in Greenland ice cores and with the termination of Heinrich Event 2 (Bond et al., 1997). It is also nearly identical to the age of the Hartwell and Cuba moraines in Ohio (23,180 ± 41 and 24,080 ± 97 cal yr BP, respectively), which also mark the farthest Wisconsinan advance of Laurentide ice (Lowell et al., 1999). Our age estimate for the Buzzards Bay moraine is also correlative with a minor ice-rafting event (event "a" of Bond et al., 1997), although the Greenland ice core record lacks a major warm event at this time.

Although the uncertainties in our data are too large to support detailed correlation with high-resolution climate records, it nevertheless appears that both moraines are associated with the peaks of cooling cycles and coeval ice-rafting episodes known from many North Atlantic records (Bond et al., 1992, 1997). Lowell et al. (1999) pointed out a close correspondence between moraine ages in the Great Lakes region and the terminations of such cooling cycles, and argued that changes in surface temperature, and consequent changes in ablation rate, explained the pattern of ice margin advance and retreat. Our data are consistent with this idea. Thus, it seems likely that the greatest ice advance of the last ice age in this region occurred during the coldest period of the last glacial maximum, that the Martha's Vineyard moraine records the onset of ice sheet contraction due to the rapid warming recorded in Greenland ice cores at 23,700 yr BP, and that the Buzzards Bay moraine records a similar climate event near 18,500 yr BP. We speculate that an intermediate moraine, which we did not date because it is not exposed above sea level (the Middle Ground shoal; Fig. 1), is probably associated with an intermediate warming event near 21,000 yr BP (Fig. 2). Thus, we conclude that the marginal position of this sector of the Laurentide Ice Sheet was tightly coupled to North Atlantic climate during the last glacial maximum.

Acknowledgements

Adam Moore of the Martha's Vineyard Land Bank Commission graciously allowed GB to collect samples on Land Bank properties. Lloyd Keigwin at the Woods Hole Oceanographic Institution kindly provided office space for SCP during the period when he collected samples for this study. GB was supported by a Hertz Foundation Graduate Fellowship during the period of this stucy. Paul Bierman and Joe Licciardi provided helpful and constructive reviews.

Appendix

Tables 2 and 3 provide comprehensive data related to our study of the Martha's Vineyard and Buzzard's Bay moraines.

Table 2 gives the precise locations of the sample sites, and sample thicknesses.

Table 3 gives details of the isotopic measurements and correction factors we used to arrive at the exposure ages given in the paper. These data can be used to reconstruct our calculations, or recompute exposure ages if the production rates and correction factors used in this study are revised in future.

Table 2
Site information

Sample[a]	N latitude (DD)	W longitude (DD)	Elevation (m)	Thickness (cm)	Thickness correction[b]
PH-1	41.3567	70.7348	91	4.5	0.963
WR-2	41.3937	70.6992	54	2	0.9833
WR-3	41.3922	70.6995	54	1.5	0.9874
WR-4	41.3939	70.6972	30	3	0.9751
WR-5	41.3920	70.6983	51	6	0.951
WR-6	41.3897	70.7017	51	4	0.967
MV 2-27-1	41.3483	70.7063	9	2	0.9833
MV 2-27-2	41.3633	70.7258	69	2.5	0.9792
MV 2-27-3	41.3483	70.7482	30	2	0.9833
MV 2-27-4	41.3350	70.7977	33	2	0.9833
MV 3-07-1	41.3758	70.7320	51	2.5	0.9792
MV 3-07-2	41.3758	70.7320	54	2	0.9833
MV 3-07-3	41.3417	70.8143	51	2.5	0.9792
BB 2-21-1	41.5500	70.6495	12	1.0	0.9916
BB 2-24-1	41.5317	70.6588	24	2.0	0.9833
BB 2-24-2	41.5317	70.6597	24	2.0	0.9833
BB 2-29-1	41.5567	70.6458	24	2.0	0.9833
BB 2-29-2	41.5567	70.6458	24	2.5	0.9792
BB 3-06-1	41.5750	70.6178	24	2.5	0.9792
BB 3-06-2	41.5783	70.6192	21	2.5	0.9792
BB 3-06-3	41.5817	70.6217	21	2.5	0.9792
BB 3-12-1	41.5250	70.6532	9	1.5	0.9874
BB 3-12-2	41.5242	70.6528	18	2.0	0.9833

[a] Topographic shielding was $<10^{-3}$ for all samples.
[b] Assuming rock density of $2.7\,g/cm^3$.

Table 3
Age calculations

Sample	$[^{10}Be]$[a] (10^4 atoms/g)	Location scaling factors[b] (at modern geographic latitude)			Simple ^{10}Be age (yr)[c] and 1σ error	Location scaling factors[d] (accounting for paleomagnetic variation)			^{10}Be age (yr) and 1σ error[c] (accounting for paleomagnetic variation)
		Spallation	μ-capture	Total[e]		Spallation	μ-capture	Total[e]	
^{10}Be ages									
PH-1	12.35±0.37	1.035	0.986	1.034	24,900±1700	1.053	0.999	1.052	24,400±1700
WR-2	12.29±0.36	0.998	0.967	0.997	25,100±1700	1.015	0.981	1.014	24,700±1700
WR-3	12.28±0.47	1.000	0.968	0.999	25,000±1800	1.016	0.982	1.016	24,500±1800
WR-4	12.18±0.35	0.975	0.956	0.975	25,700±1700	0.992	0.970	0.991	25,300±1700
WR-5	10.29±0.30	0.997	0.967	0.996	21,700±1500	1.007	0.975	1.006	21,500±1400
WR-6	11.06±0.42	0.997	0.967	0.996	23,000±1600	1.010	0.977	1.009	22,700±1600
MV 2-27-1	14.05±0.36	0.957	0.947	0.957	30,100±2000	0.978	0.965	0.978	29,400±1900
MV 2-27-2	28.25±0.70	1.014	0.975	1.013	58,900±4000	1.047	1.001	1.046	56,900±3800
MV 2-27-3	10.68±0.28	0.975	0.956	0.974	22,300±1500	0.986	0.965	0.985	22,100±1500
MV 2-27-4	7.55±0.32	0.980	0.958	0.980	15,600±1100	0.975	0.954	0.975	15,700±1200
MV 3-07-1	n.m.								
MV 3-07-2	24.60±0.61	0.999	0.968	0.999	51,400±3400	1.034	0.996	1.033	49,700±3300
MV 3-07-3	9.71±0.36	0.994	0.966	0.994	19,900±1400	1.001	0.971	1.000	19,800±1400
BB 2-21-1	7.98±0.33	0.959	0.949	0.959	16,700±1200	0.958	0.947	0.958	16,700±1200
BB 2-24-1	8.82±0.31	0.972	0.955	0.972	18,400±1300	0.975	0.957	0.975	18,400±1300
BB 2-24-2	8.45±0.34	0.972	0.955	0.972	17,600±1300	0.973	0.956	0.973	17,600±1300
BB 2-29-1	9.29±0.41	0.973	0.955	0.972	19,400±1400	0.977	0.959	0.977	19,300±1400
BB 2-29-2	8.83±0.62	0.973	0.955	0.972	18,500±1700	0.976	0.958	0.975	18,400±1700
BB 3-06-1	8.92±0.29	0.973	0.955	0.972	18,700±1300	0.976	0.958	0.976	18,600±1300
BB 3-06-2	9.46±0.32	0.968	0.953	0.968	19,900±1400	0.974	0.958	0.974	19,800±1400
BB 3-06-3	9.21±0.40	0.969	0.954	0.969	19,400±1400	0.974	0.958	0.973	19,300±1400
BB 3-12-1	8.25±0.41	0.957	0.947	0.957	17,400±1400	0.958	0.948	0.957	17,400±1400
BB 3-12-2	9.38±0.46	0.965	0.951	0.964	19,700±1500	0.970	0.956	0.970	19,600±1500

Sample	$[^{26}Al]$[f] (10^4 atoms/g)	Location scaling factors[b] (at modern geographic latitude)			Simple ^{26}Al age (yr)[g] and 1σ error	Location scaling factors[d] (accounting for paleomagnetic variation)			^{26}Al age (yr) and 1σ error[g] (accounting for paleomagnetic variation)
		Spallation	μ-capture	Total[h]		Spallation	μ-capture	Total[h]	
^{26}Al ages									
PH-1	71.24±3.12	1.035	0.986	1.034	23,700±1800	1.044	0.993	1.043	23,400±1800
WR-2	74.91±4.22	0.998	0.967	0.997	25,300±2100	1.008	0.976	1.008	25,000±2100
WR-3	60.44±17.58	1.000	0.968	0.999	20,200±6100	1.001	0.970	1.001	20,100±6100
WR-4	70.70±2.96	0.975	0.956	0.974	24,600±1800	0.984	0.963	0.983	24,400±1800
WR-5	61.19±2.95	0.997	0.967	0.996	21,300±1600	1.001	0.970	1.000	21,200±1700
WR-6	65.12±2.56	0.997	0.967	0.996	22,300±1600	1.003	0.972	1.002	22,200±1600
MV 2-27-1	92.55±3.71	0.957	0.947	0.957	32,900±2400	0.973	0.960	0.972	32,300±2400
MV 2-27-2	162.78±14.06	1.014	0.975	1.013	56,300±6300	1.033	0.990	1.032	55,200±6200
MV 2-27-3	63.61±4.08	0.975	0.956	0.974	21,900±1900	0.979	0.959	0.979	21,800±2000

Table 3 (*continued*)

Sample	$[^{26}Al]$[f] (10^4 atoms/g)	Location scaling factors[b] (at modern geographic latitude)			Simple ^{26}Al age (yr)[g] and 1σ error	Location scaling factors[d] (accounting for paleomagnetic variation)			^{26}Al age (yr) and 1σ error[g] (accounting for paleomagnetic variation)
		Spallation	μ-capture	Total[h]		Spallation	μ-capture	Total[h]	
MV 2-27-4	45.77±2.27	0.980	0.958	0.980	15,600±1200	0.971	0.951	0.971	15,700±1200
MV 3-07-1	70.72±2.43	0.997	0.967	0.996	24,000±1700	1.005	0.974	1.004	23,800±1700
MV 3-07-2	143.29±7.60	0.999	0.968	0.999	49,700±4100	1.021	0.985	1.020	48,600±4100
MV 3-07-3	56.41±3.35	0.994	0.966	0.994	19,100±1600	0.994	0.965	0.993	19,100±1600
BB 2-21-1	48.39±2.98	0.959	0.949	0.959	16,700±1400	0.954	0.944	0.954	16,800±1500
BB 2-24-1	52.60±2.33	0.972	0.955	0.972	18,100±1300	0.970	0.953	0.970	18,100±1400
BB 2-24-2	54.13±2.48	0.972	0.955	0.972	18,600±1400	0.971	0.954	0.971	18,600±1400
BB 2-29-1	57.01±2.05	0.973	0.955	0.972	19,600±1400	0.973	0.956	0.973	19,600±1400
BB 2-29-2	59.23±11.31	0.973	0.955	0.972	20,500±4200	0.975	0.957	0.974	20,400±4200
BB 3-06-1	66.16±5.80	0.973	0.955	0.972	23,000±2500	0.979	0.961	0.979	22,800±2500
BB 3-06-2	62.25±3.25	0.968	0.953	0.968	21,700±1700	0.972	0.956	0.972	21,600±1700
BB 3-06-3	59.70±4.98	0.969	0.954	0.969	20,700±2200	0.971	0.956	0.971	20,700±2200
BB 3-12-1	53.08±3.71	0.957	0.947	0.957	18,500±1700	0.956	0.946	0.955	18,500±1700
BB 3-12-2	60.08±2.28	0.965	0.951	0.964	20,900±1500	0.967	0.953	0.967	20,800±1500

[a] Measured relative to LLNL working ^{10}Be standards, traceable to ICN standard. Uncertainties propagated at $\pm 1\sigma$ level including all known sources of analytical error. Procedural blanks contained $2.4 \pm 1.8 \times 10^4$ atoms ^{10}Be.

[b] Calculated according to Stone (2000).

[c] Calculated using a ^{10}Be production rate of 5.1 ± 0.3 atoms/g SiO_2/yr at 1013.25 mb and latitude $>60°$.

[d] Calculated using the paleomagnetic intensity records of Guyodo and Valet (1996), McElhinny and Senanayake (1982), the paleo-pole positions of Ohno and Hamano (1992), the paleomagnetic correction procedure of Nishiizumi et al. (1989), and latitude/altitude scaling factors from Stone (2000).

[e] 2.2% of surface production assigned to muons (Stone, 2000).

[f] Measured relative to LLNL working ^{26}Al standards. Uncertainties propagated at $\pm 1\sigma$ level including all known sources of analytical error. Procedural blanks contained $<10^5$ atoms ^{26}Al.

[g] Calculated using a ^{26}Al production rate of 31.1 ± 1.8 atoms/g SiO_2/yr at 1013.25 mb and latitude $>60°$.

[h] 2.6% of surface production assigned to muons (Stone, 2000).

References

Bond, G.C., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J.T., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., Ivy, S., 1992. Evidence for massive discharges of icebergs into the North Atlantic Ocean during the last glacial period. Nature 360, 245–249.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millenial-scale cycle in North Atlantic holocene and glacial climates. Science 278, 1257–1266.

Boothroyd, J.C., Freedman, J.H., Brenner, H.B., Stone, J.R., 1998. The glacial geology of southern Rhode Island. 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.

Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Science Reviews 20, 1475–1560.

Grootes, P.M., Stuiver, M., 1997. Oxygen 18/16 variability in Greenland snow and ice with 10^3 to 10^5-year time resolution. Journal of Geophysical Research 102, 26455–26470.

Guyodo, Y., Valet, J.P., 1996. Relative variations in geomagnetic intensity from sedimentary records: the past 200,000 years. Earth and Planetary Science Letters 143, 23–36.

Hitchcock, E., 1841. Final Report on the Geology of Massachusetts. J.S. and C. Adams, Amherst.

Kaye, C.A., 1964a. Illinoian and early Wisconsinan moraines of Martha's Vineyard, Massachusetts. US Geological Survey Professional Paper 501-C. US Geological Survey, Washington, DC, pp. C140–C143.

Kaye, C.A., 1964b. Outline of pleistocene geology of Martha's Vineyard, Massachusetts. US Geological Survey Professional Paper 501-C. US Geological Survey, Washington, DC, pp. C134–C139.

Kaye, C.A., 1972. Preliminary surficial map of Martha's Vineyard, Nomans Land, and parts of Naushon and Pasque Islands, Massachusetts. US Geological Survey Open-File Report 72-205. US Geological Survey, Washington, DC.

Lowell, T.V., 1995. The application of radiocarbon age estimates to the dating of glacial sequences: an example from the Miami Sublobe, Ohio, USA. Quaternary Science Reviews 14, 85–99.

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.

Mather, K.F., Goldthwait, R.P., Theismeyer, L.R., 1940. Preliminary report on the geology of western Cape Cod, Massachusetts. Massachusetts Department of Public Works Bulletin 2.

McElhinny, M.W., Senanayake, W.E., 1982. Variations in the geomagnetic dipole I: the past 50,000 years. Journal of Geomagnetism and Geoelectricity 34, 39–51.

Nishiizumi, K., Winterer, E.L., Kohl, C.P., Klein, J., Middleton, R., Lal, D., Arnold, J.R., 1989. Cosmic ray production rates of 10Be and 26Al in quartz from glacially polished rocks. Journal of Geophysical Research 94, 17907–17915.

Ogden III, J.G., 1959. A late-glacial pollen sequence from Martha's Vineyard, Massachusetts. American Journal of Science 257, 366–381.

Ogden III, J.G., 1963. The Squibnocket cliff peat: radiocarbon dates and pollen stratigraphy. American Journal of Science 261, 344–353.

Ohno, M., Hamano, Y., 1992. Geomagnetic poles over the past 10,000 years. Geophysical Research Letters 19, 1715–1718.

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.

Schafer, J.P., Hartshorn, J.H., 1965. The Quaternary of New England. In: Wright Jr., H.E., Frey, D.G. (Eds.), The Quaternary of the United States. Princeton University Press, Princeton, NJ, pp. 113–127.

Shaler, N.S., 1888. Report on the Geology of Martha's Vineyard, Massachusetts. US Geological Survey Annual Report 7. US Geological Survey, Washington, DC, pp. 297–363.

Stone, J.O.H., 2000. Air pressure and cosmogenic isotope production. Journal of Geophysical Research 105, 23753–23759.

Stone, J.O.H. 2001. Extraction of Al and Be from quartz for isotopic analysis. http://depts.washington.edu/cosmolab/chem.html.

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, pp. B7-1–B7-20.

Stuiver, M., Deevey, E.S., Gralenski, J.L., 1960. Yale natural radiocarbon measurements V. Radiocarbon 2 (Supple.), 49–61.

Tucholke, B.E., Hollister, C.D., 1973. Late Wisconsin glaciation of the southwestern Gulf of Maine: new evidence from the marine environment. GSA Bulletin 84, 3279–3296.

Woodworth, J.B., Wigglesworth, E., Berry, E.W., Bryan, K., Hollick, C.A., Stephenson, L.W., 1934. Geography and geology of the region including Cape Cod, the Elizabeth Islands, Nantucket, Martha's Vineyard, and Block Island. Harvard University, Museum of Comparative Zoology, Cambridge, MA.