Glacier readvance during the late glacial (Younger Dryas?) in the Ahklun Mountains, southwestern Alaska

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ABSTRACT

An expansion of alpine glaciers during the latest Pleistocene produced an extraordinarily well defined end moraine system in the Ahklun Mountains, southwestern Alaska. These moraines, deposited during the Mount Waskey advance, are several kilometers beyond modern glacier termini, and ~80 km upvalley of the late Wisconsin Ahklun Mountains ice cap terminal moraine. Eleven cosmogenic ^{10}Be and ^{26}Al exposure ages on moraine boulders, combined with radiocarbon ages from a lake core upvalley of a moraine deposited during the Mount Waskey advance, suggest that the advance culminated between 12.4 and 11.0 ka, sometime during, or shortly following, the Younger Dryas event (ca. 12.9–11.6 ka). We believe that the Mount Waskey advance was a consequence of cooling during the Younger Dryas. These data further strengthen emerging evidence for Younger Dryas–age cooling of the North Pacific region.

Keywords: Alaska, cosmogenic exposure dating, glaciers, Younger Dryas, late glacial.

INTRODUCTION

As the climate changes globally, regional- and synoptic-scale processes modulate the spatial and temporal heterogeneity of its effects. As we strive to predict the local-scale manifestation of global climatic change, we are driven to study the natural experiments afforded by past global changes, particularly those that occurred during the last glacial-interglacial transition. While the climatic changes during this interval have come to light over the past decade, a larger network of well-dated proxy climate records is needed to add to our understanding of these changes. This study contributes to an improved understanding of an interval of rapid global climatic change by documenting a pronounced late glacial readvance of alpine glaciers in southwestern Alaska, and provides the first firm geochronological control for this type of glacier advance recognized throughout Alaska.

The most recent of many climatic fluctuations during the end of the Pleistocene took place during the Younger Dryas (ca. 12.9–11.6 ka; Alley, 2000). Dramatic cooling, which was apparently caused by an abrupt shift in North Atlantic Ocean circulation (e.g., Lehman and Keigwin, 1992), clearly affected the climate of the North Atlantic region (e.g., Alley et al., 1993). Whether global climate responded synchronously to this North Atlantic event has fueled much debate (e.g., Peteet, 1995), but records from widespread locations across the globe (e.g., Porter and Zhisheng, 1995; Steig et al., 1998; Hughen et al., 1998), including the North Pacific (Patterson et al., 1995; Grigg and Whitlock, 1998; Hendy et al., 2002), clearly show climatic fluctuations during the Younger Dryas chronozone.

In Alaska, latest Pleistocene climate fluctuations were likely influenced by a number of competing factors, including an increase in summer insolation, the flooding of the Bering land bridge, and the far-field effects of perturbations in the global climate system such as the Younger Dryas. Numerous paleoclimate proxy records show significant late glacial climatic fluctuations during the Younger Dryas in central Alaska (e.g., Bigelow et al., 1990; Bigelow and Edwards, 2001) and southern Alaska (e.g., Engstrom et al., 1990; Mathewes et al., 1993; Peteet and Mann, 1994; Hu et al., 1995, 2001; Axford, 2000). These records collectively indicate pronounced cool and wet conditions in southeastern Alaska, cool and dry conditions in southwestern Alaska, and a more subtle response in interior Alaska.

While numerous detailed pollen and oceanic sediment records show substantial changes during the Younger Dryas, the record of glacier-margin fluctuations is scanty. The retreat of glaciers from their late Wisconsin maximum positions across Alaska was interrupted by numerous stillstands or readvances (e.g., Kaufman and Hopkins, 1986). However, these glacier records have yet to be dated with enough resolution for millennial-scale correlations. In this study we combine ^{10}Be and ^{26}Al cosmogenic exposure and radiocarbon dating to obtain a precise chronology for a prominent moraine system deposited by alpine glaciers in the Ahklun Mountains, southwestern Alaska.

GEOLOGIC SETTING

The 200-km-long and 150-km-wide Ahklun Mountains (Fig. 1) have been a major center for Pleistocene glaciation. Recent studies have shown that an extensive early Wisconsin ice cap and a relatively restricted late Wisconsin ice cap formed over the range (e.g., Briner and Kaufman, 2000; Kaufman et al., 2001a; Manley et al., 2001). The late Wisconsin ice cap maintained its maximum position from ca. 24 to 22 ka (Kaufman et al., 2001b). Several moraines upvalley from the late Wisconsin terminal moraine, the outermost of which dates to ca. 20 ka (Manley et al., 2001), reveal episodic readvances and stillstands during the waning phase of the ice cap. Cirques in the western part of the range and lake basins in the high, central part of the range were ice free by ca. 16 ka (Hu et al., 1995; Werner et al., 2001; Briner et al., 2001), suggesting regional deglaciation by that time.

Although not heavily glaciated today, the Ahklun Mountains sup-

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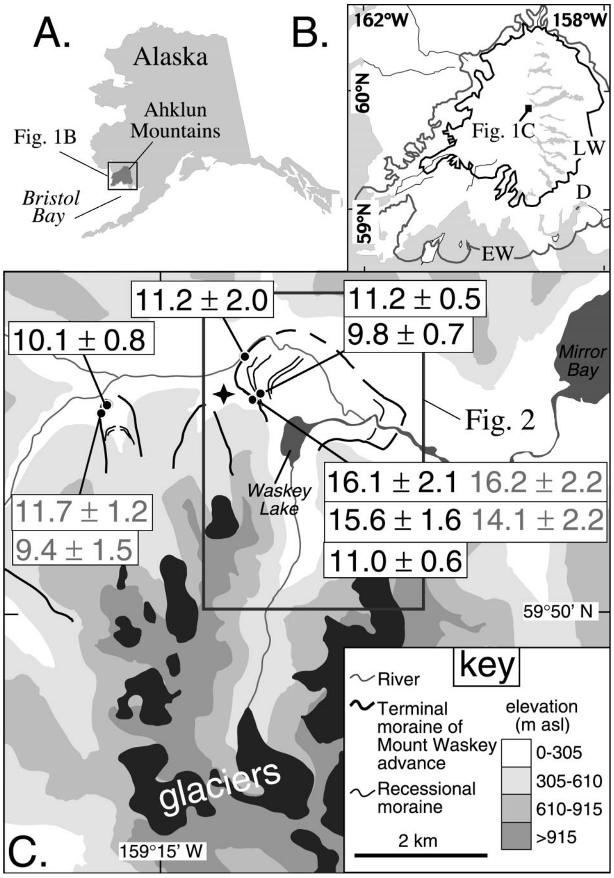

Figure 1. A: Map of Alaska showing Ahklun Mountains. B: Ice caps that existed over Ahklun Mountains during early Wisconsin (EW) and late Wisconsin (LW). In eastern part of range, LW drift impounds series of lakes (gray). D is Dillingham. C: Mount Waskey massif and moraines of Mount Waskey advance. ^{10}Be (black) and ^{26}Al (gray) exposure ages (1 standard deviation uncertainty) assume no boulder surface erosion or snow shielding (Tables 1 and 2 [see text footnote 1]). Star is location of ice-marginal lake delta (see text); asl is above sea level.

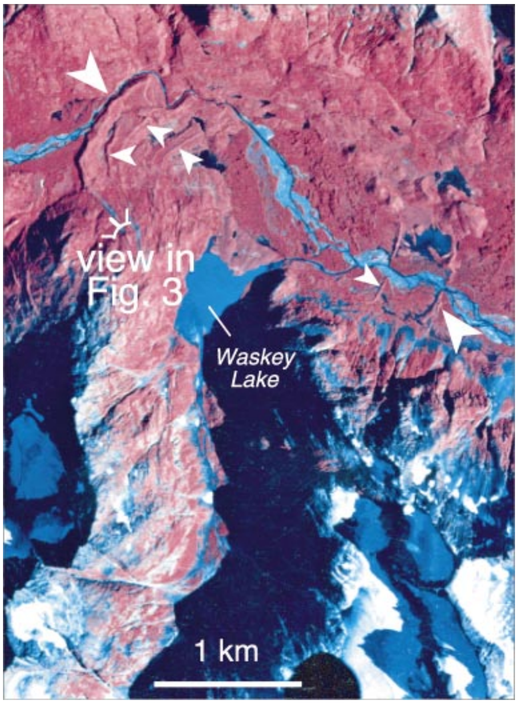

Figure 2. Vertical air photograph of Waskey Lake and moraines deposited during Mount Waskey advance in northeasternmost valley of Mount Waskey massif. See Figure 1C for location. Large arrows point to terminal moraine; smaller arrows point to recessional moraines.

port ~100 small glaciers in the highest cirques. Several valleys around the Mount Waskey massif contain moraines deposited during a prominent readvance of alpine glaciers, herein termed the Mount Waskey advance (Fig. 1). The moraines are ~80 km upvalley from the late Wisconsin maximum position and 2–6 km downvalley from modern glacier termini. They consist of a prominent bouldery terminal moraine ridge, and numerous (in some places more than five) recessional ridge crests (Figs. 2 and 3). Three of these moraines protrude from prominent north-south–trending valleys that drain the north side of the Mount Waskey massif and crosscut ice-flow features in an east-west–trending trunk valley, suggesting that the moraines represent glacier readvances. A delta in the trunk valley with a surface elevation of ~10 m above the current valley bottom, ~300 m upvalley from the largest (easternmost) moraine (Figs. 1 and 2), indicates that the Mount Waskey advance dammed the trunk valley and created an ice-marginal lake. This same moraine currently impounds Waskey Lake (informal name; Figs. 1 and 2) and provides an opportunity to combine exposure dating of moraine boulders with a radiocarbon chronology from lake sediment cores.

CHRONOLOGY

A 6.5-m-long sediment core recovered from Waskey Lake (Fig. 1) delimits the age of the Mount Waskey advance. A collection of handpicked terrestrial macrofossils obtained 3 cm above the core base yielded a calibrated age of 11.0 ± 0.2 ka (9700 ± 900 ^{14}C yr B.P.; NSRL-11058; Levy, 2002). Eight stratigraphically consistent radiocarbon dates throughout the core reaffirm the basal age (Levy, 2002); the entirely granitic drainage basin (Hoare and Coonrad, 1961) reduces the possibility of a hardwater dating effect.

Seven ^{10}Be and four ^{26}Al cosmogenic exposure ages were determined for nine large (1–3 m high) plutonic boulders deposited during

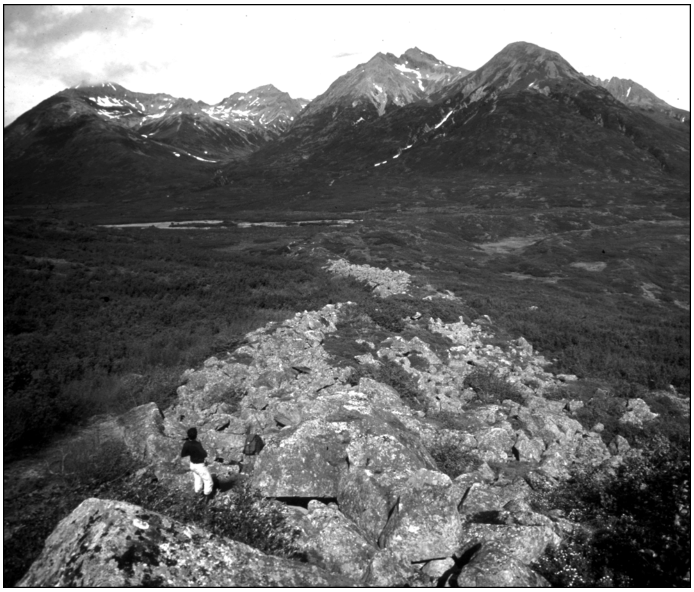

Figure 3. Photograph showing bouldery left-lateral terminal moraine deposited during Mount Waskey advance. Person for scale at lower left is 1.8 m tall. Vantage point is shown in Figure 2.

the Mount Waskey advance in two different valleys (Fig. 1; Table 1[1]; see Gosse and Phillips [2001] for an up-to-date summary of cosmogenic exposure dating). The samples were processed following the method of Kohl and Nishiizumi (1992) at the University of Colorado Cosmogenic Isotope Laboratory. Isotopic ratios were measured by accelerator mass spectrometry at the Lawrence Livermore National Laboratory.

The accuracy of cosmogenic exposure dating is limited by knowledge of the sample's isotopic production rates and exposure history. Published ^{10}Be production rates range from 4.7 to 6.0 (all production rates are reported as atoms per gram of quartz per year for $\geq 60°$ latitude at sea level). However, recent work has greatly reduced the uncertainty in ^{10}Be production rates and settled on a value of 5.1 ± 0.3 (Stone, 2000; Gosse and Stone, 2001). In addition to improving isotope production rates, recent research has focused on latitudinal and altitudinal production-rate scaling (e.g., Stone, 2000). Here we use production rates of 5.1 and 31.1 for ^{10}Be and ^{26}Al, respectively (Gosse and Stone, 2001), and latitudinal and altitudinal scaling factors from Stone (2000).

Factors that control sample exposure history, including paleo–snow cover and postglacial boulder surface erosion, must also be considered. For this study, we chose to model 1 m of snow (0.2 g cm^{-3}) covering the sampled boulders for 4 months per year (equating to an age increase of 4%) and a boulder surface erosion rate of 3 mm $k.y.^{-1}$ (equating to an age increase of 4%). Both values were chosen to estimate a maximum reasonable effect on the ages (extreme values could increase the ages by ~20%; see Tables 1 and 2 [footnote 1] for a more detailed justification of chosen parameters).

There are two populations of exposure ages (Table 1 [see footnote 1]; Fig. 4). Seven cluster between 11.7 and 9.4 ka, and two samples (MB1-99-2 and MB1-99-3) have considerably older ages, between 16.2 and 14.9 ka. The older ages suggest an exposure history similar to boulders on moraines formed during the late Wisconsin (Briner et al., 2001). We therefore attribute these two anomalously old ages to inherited nuclides, a common finding among moraine dating studies, where as much as 10%–20% of boulders contain inherited nuclides (e.g., Briner et al., 2001; Gosse and Phillips, 2001).

The weighted mean ages, excluding samples MB1-99-2 and MB1-99-3, range from 11.5 ± 0.9 (assuming maximum snow cover and boulder surface erosion) to 10.7 ± 0.8 ka (assuming no snow and no erosion; Table 2 [see footnote 1]). Based on the cosmogenic results, the 1 standard deviation range of 12.4–9.9 ka is our favored exposure duration for the boulders deposited during the Mount Waskey advance. However, because this range overlaps with the calibrated radiocarbon age of 11.0 ± 0.2 ka from Waskey Lake, we can use this minimum age to further define the age of the advance. Thus, our best age estimate for the culmination of the Mount Waskey advance and the stabilization of the moraines is between 12.4 and 11.0 ka.

DISCUSSION

Our cosmogenic isotope and radiocarbon chronology indicates that the Mount Waskey advance culminated during, or soon after, the Younger Dryas, and thus it may have been a response to global cooling during the Younger Dryas. Reconstructed equilibrium-line altitudes (ELAs) for the Mount Waskey advance (using an accumulation area ratio of 0.6) are 80 ± 30 m ($n = 3$) lower than modern values. The ELA lowering is 25%–40% of the full glacial ELA depression, reconstructed to be only 200–300 m below modern values in the central Ahklun Mountains (Manley and Kaufman, 1999).

[1]GSA Data Repository item 2002080, Table 1, Sample location information and cosmogenic exposure ages, and Table 2, Weighted mean moraine stabilization ages, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

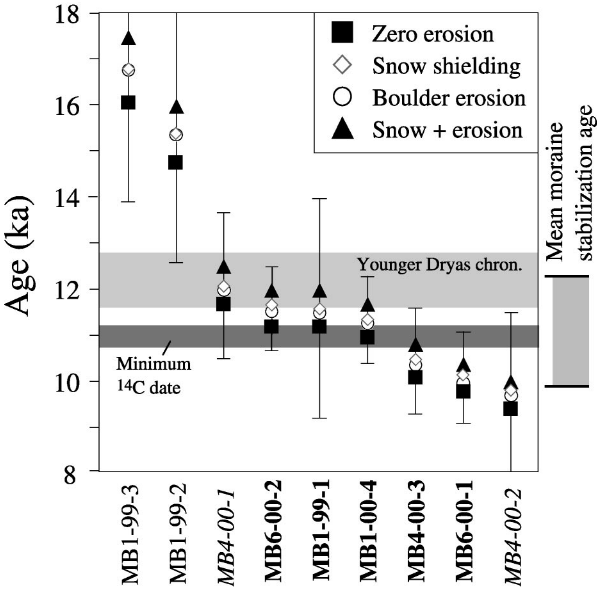

Figure 4. Cosmogenic exposure ages of moraine boulders deposited during Mount Waskey advance. See text and Tables 1 and 2 (see text footnote 1) for information regarding variables that affect exposure ages. Error bars span upper limit of 1 standard deviation range of ages calculated using maximum estimates of snow cover and surface erosion, and lower limit of 1 standard deviation range using zero erosion and snow cover. Plain text sample designations represent average exposure age for samples that have both ^{10}Be and ^{26}Al ages; bold designations are ^{10}Be ages, and italicized designations are ^{26}Al ages. Also shown are Younger Dryas chronozone (12.9–11.6 ka; Alley, 2000), calibrated radiocarbon age (2 standard deviation range) from Waskey Lake (minimum-limiting age for Mount Waskey advance), and maximum 1 standard deviation weighted mean moraine stabilization age range.

This well-dated pronounced glacier advance adds to a growing database of late glacial climate change across the North Pacific and around the globe. The synchroneity of submillennial-scale climate events between the Santa Barbara Basin and the North Atlantic (Hendy et al., 2002) leaves little doubt that the climate of the North Pacific is tightly linked with that of the North Atlantic. The dominant atmospheric feature of the North Pacific, the Aleutian Low pressure system, is in turn tightly linked with several main surface ocean currents, including the California Current (which affects the Santa Barbara Basin), and its north-flowing corollary, the Alaska Stream (e.g., Davis, 1976). Mikolajewicz et al. (1997) modeled a cooler North Pacific Ocean and an eastward-displaced Aleutian Low during the Younger Dryas, providing a potential forcing for observed Younger Dryas–age oscillations in the Santa Barbara Basin and northward, where the local climate is strongly moderated by the Pacific Ocean.

Other possible climate forcings need to be considered. The most obvious local influence on the late glacial climate of western Alaska was the approach of the Bering Sea shoreline due to eustatic sea-level rise. The current age estimates suggest that the flooding of the Bering Shelf occurred sometime after ca. 12 ka (Elias et al., 1996). Thus, the Bering Sea transgression provided a closer source of moisture to nourish Ahklun Mountain glaciers, and is an alternative forcing mechanism for the Mount Waskey advance. However, available pollen records show that dry conditions prevailed in the Ahklun Mountains during the Younger Dryas (Hu et al., 1995, 2001; Axford, 2000). The effect of rising sea level on the climate of western Alaska will remain uncertain until the age and geography of the transgression are better defined.

CONCLUSION

Our evidence for a late glacial glacier readvance, the first well-dated late glacial moraines in Alaska, reinforces other southern Alaska records indicating pronounced cooling during the Younger Dryas. The degree to which this advance was fueled by local factors, such as increased winter precipitation associated with the transgression of the Bering Sea, is not clear. Nonetheless, pronounced paleoecological changes documented at coastal sites across southern Alaska and the Pacific Northwest combined with our results indicate that the far-field response to Younger Dryas–age cooling in the North Atlantic was possibly strong enough to cause glaciers to readvance in Alaskan mountain ranges.

ACKNOWLEDGMENTS

We thank Jay Austin and Daniel Goldstein for assistance in the University of Colorado cosmogenic isotope preparation laboratory; Fred Luiszer and John Drexler for assistance with inductively coupled plasma measurements; Gifford Miller for his encouragement of this research; Yarrow Axford, Ali Feinberg, and Benjamin Laabs for assistance in the field; Yarrow Axford for enlightening discussions of the data and helpful comments on the manuscript; and the personnel of the Togiak National Wildlife Refuge for providing logistical support. Cosmogenic isotope measurements were performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract W-7405-Eng-48. This research was supported by the National Science Foundation (grants EAR-9808593, OPP-9977972, and OPP-9977974).

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Manuscript received January 16, 2002
Revised manuscript received April 11, 2002
Manuscript accepted April 16, 2002

Printed in USA

GSA Data Repository Item 2002080, Table DR1, Sample location information and cosmogenic exposure ages, and Table DR2, Weighted mean moraine stabilization ages

Table DR2. Weighted mean moraine stabilization ages. Because the cosmic-ray flux is attenuated by the atmosphere, local atmospheric pressure anomalies may alter local production rates (Stone, 2000). Due to the proximity of the Ahklun Mountains to the Aleutian Low pressure system, the local production rate may have at times been as much as 5% higher (Table 2).

Factors that control sample exposure history, including paleo-snow cover and post-glacial boulder surface erosion, must also be considered. Both of these factors are difficult to quantify for the Ahklun Mountains because there are no nearby climate stations to provide snow data and because quantifying bedrock erosion has not been attempted in this region. Fortunately, Mt. Waskey moraine boulders are high enough to be mostly windswept and probably only minimally covered by snow for a few months per winter. The nearest snow data are from Dillingham (at sea level ~90 km away; Fig. 1), where the historic average snow depth is ~25 cm for six months per year. Because all sampled boulders are situated on moraine crests and are themselves 1-3 m high, we chose to model 1 m of snow (0.2 g cm^{-3}) covering the sampled boulders for four months per year as a maximum estimate. As an extreme, denser (0.3 g cm^{-3}) and thicker snow (2 m thick atop sampled boulders) could increase the ages by 11%.

Bierman et al. (1999) estimated a maximum erosion rate of 1.1 mm $k.y.^{-1}$ for the eastern Canadian Arctic, and Gosse et al. (1995) reported a similar value of 1.3 mm $k.y.^{-1}$ for western North America. Other studies have yielded rates as high as ~10 mm $k.y.^{-1}$ for mid-latitude mountain summits (e.g., Small and Anderson, 1998). The boulders on moraines of the Mt. Waskey advance lack striae, but are generally smooth and show little grain-to-grain relief.

Because of the lack of advanced weathering features, we have modeled the exposure ages with 3 mm $k.y.^{-1}$ of erosion, and as with our model of snow cover, we believe that these estimates result in a reasonable maximum effect on the ages (an extreme value of 1 cm k.y.-1 would increase the ages by 9.5%).

In addition, all samples were corrected for topographic shielding and sample thickness (maximum corrections of 1% and 4%, respectively).

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TABLE DR1. SAMPLE LOCATION INFORMATION AND COSMOGENIC EXPOSURE AGES

Sample	Lat. (N)	Long. (W)	Elevation (m asl)	^{10}Be (10^5 atoms g^{-1})	^{26}Al (10^5 atoms g^{-1})	^{10}Be age* (ka)	^{26}Al age† (ka)
MB1-99-1	56° 52' 12"	159° 13' 20"	240	0.70 ± 0.12		11.2 ± 2.0	
MB1-99-2	56° 52' 14"	159° 13' 25"	236	0.96 ± 0.10	5.32 ± 0.83	15.6 ± 1.6	14.1 ± 2.2
MB1-99-3	56° 52' 23"	159° 13' 38"	200	0.97 ± 0.13	6.06 ± 0.83	16.1 ± 2.1	16.2 ± 2.2
MB1-00-4	56° 52' 03"	159° 13' 11"	276	0.71 ± 0.04		11.0 ± 0.6	
MB4-00-1	56° 52' 10"	159° 16' 34"	274		4.59 ± 0.45		11.7± 1.2
MB4-00-2	56° 52' 10"	159° 16' 35"	273		3.72 ± 0.60		9.4 ± 1.5
MB4-00-3	56° 52' 13"	159° 16' 14"	274	0.65 ± 0.05		10.1 ± 0.8	
MB6-00-1	56° 52' 04"	159° 13' 00"	270	0.63 ± 0.04		9.8 ± 0.7	
MB6-00-2	56° 52' 06"	159° 13' 06"	273	0.72 ± 0.03		11.2 ± 0.5	

NOTE: The ages reported here do not account for erosion or paleo-snow cover.

*^{10}Be ages include isotope ratio measurement uncertainty (1 S.D.).

†^{26}Al ages include both isotopic ratio and total Al measurement uncertainties (1 S.D.).

TABLE DR2. WEIGHTED MEAN MORAINE STABILIZATION AGES

Sample groups	No corrections	Corrections		
		Erosion*	Snow†	Erosion and snow
No correction for atm pressure anomaly (^{10}Be P=5.1; ^{26}Al P=31.1)				
all ages	10.9 ± 2.3	11.2 ± 2.4	11.3 ± 2.4	11.6 ± 2.5
excluding outliers§	10.7 ± 0.8	11.0 ± 0.9	11.2 ± 0.9	11.5 ± 0.9
Correction for atm pressure anomaly (^{10}Be P=5.4; ^{26}Al P=32.7)#				
all ages	10.4 ± 2.2	10.6 ± 2.3	10.8 ± 2.3	11.1 ± 2.4
excluding outliers§	10.2 ± 0.8	10.5 ± 0.8	10.6 ± 0.8	10.9 ± 0.9

NOTE: Includes the average ^{10}Be and ^{26}Al age for samples MB1-99-2 and MB1-99-3.

*3 mm k.y.-1 (see text).

†4 months of 1 m of snow cover (0.2 g cm^{3}).

§Excludes MB1-99-2 and MB1-99-3 (see text).

#Production rates increase by ~5% for local atmospheric pressure anomaly (Stone, 2000).