GSA Data Repository item for Munroe et al., *Geology,* Latest Pleistocene advance of alpine glaciers in the southwestern Uinta Mountains, Utah, USA: Evidence for the influence of local moisture sources; cosmogenic dating methods, Table DR1 (^{10}Be data for Yellowstone canyon moraine boulders), Table DR2 (^{10}Be data for Lake Fork moraine boulders) and Table DR3 (Equilibrium Line Altitude Calculations).

COSMOGENIC DATING METHODS

Field Sampling

Terminal and/or lateral moraines in the Yellowstone and Lake Fork valleys were surveyed to identify 7 to 10 boulders most suitable for cosmogenic-exposure dating. Suitable boulders are those that have been exposed continuously at the moraine surface since they were deposited, with no prior exposure history, and have experienced little or no erosion of their surfaces. Boulders were selected primarily on the basis of position relative to the moraine crest, height, lithology, shape, weathering characteristics, and local geomorphology (e.g., Gosse and Phillips, 2001). For example, the tallest boulders (usually greater than 60 cm high) at the moraine crest composed of silica-cemented sandstone or quartzite with flat or gently rounded surfaces that did not appear to be eroded or mechanically broken were considered suitable (e.g., Gosse and Phillips, 2001). Effects of topographic shielding were considered negligible for all boulders because angles to the horizon were less than 10° in all directions. Boulder locations were determined with a hand-held GPS and the tops of boulders were sampled with a sledge hammer and chisel. Sample thicknesses were reduced prior to processing to 3 cm or less (production rates were later corrected for sample thickness using equations in Gosse and Phillips, 2001).

Laboratory Methods

Laboratory methods used to isolate beryllium and aluminum in boulder samples are from Bierman et al. (2003), as adopted by Kaplan et al. (2004), Douglass et al. (2005), and Laabs (2004) and were undertaken at the UW-Madison Cosmogenic Nuclide Preparation Lab. These procedures are summarized here.

After field collection, samples were reexamined to determine quartz content and to reduce thickness as much as possible. Samples were crushed, pulverized and sieved to separate grains between 420 and 840 μm in diameter. All sample compositions were >95% quartz and all non-quartz phases were easily removed. Quartz grains within the target size were etched in HCl, then in a dilute HNO_3/HF mixture to remove meteoric beryllium from grain surfaces (Kohl and Nishiizumi, 1992). Next, aliquots of the sample were dissolved and tested for purity by inductively-coupled plasma atomic-emission spectrometry (pure samples were identified by beryllium amounts below detection levels). Clean samples were spiked with approximately 500 μg ^{9}Be and dissolved in a concentrated HNO_3/HF mixture and dried to metal fluorides. Flourides were converted to chlorides by dissolving and drying in $HClO_4$ and HCl. Samples were redissolved in HCl to begin separating a variety of cations from the sample, and ultimately beryllium and aluminum. This set of procedures involves the use of ion-exchange chromatography and selective precipitation to remove Fe^{2+}, Ca^{2+}, and Ti^{4+}, and isolate $BeOH_2$ and $AlOH_3$. The final sample of $BeOH_2$ was oxidized, weighed and combined with Niobium binder (5:1 by mass) and sent to the Purdue Rare Isotope Measurement Lab (PRIME Lab) to be analyzed by accelerator mass spectrometry (AMS). This technique is used to measure the extremely low $^{10}Be/^{9}Be$ in boulder samples. Because the amount of ^{9}Be added to each sample is known, the concentration of ^{10}Be (in atoms g^{-1} quartz) can be calculated from this ratio and ultimately used to calculate the boulder-exposure age (see below).

Age Calculations and Uncertainties

Boulder-exposure ages were calculated from measured ^{10}Be concentrations using the age equation from Lal (1991) and scaling equations from Stone (2000). We do not account for erosion of the boulder surface; this effect is assumed to be negligible based on the resistant lithology of boulders and the presence of glacial polish and/or striae on all sampled boulder surfaces. If erosion rates are small (1 to 5 mm/kyr), it can be shown mathematically that this assumption is valid for samples that have been exposed for ~20,000 years (e.g., Bierman et al., 1999).

The production rate is perhaps the greatest source of uncertainty in the cosmogenic-exposure age calculations; it increases exponentially with elevation and linearly with geomagnetic latitude (Gosse and Phillips, 2001) and, therefore, must be scaled to the location of each boulder. Many researchers have suggested that the uncertainty of scaled production rates is up to 20% (e.g., Desilets and Zreda, 2001). To minimize this uncertainty, we use a base ^{10}Be production rate of 5.1 ± 0.3 atoms g SiO_2^{-1} yr^{-1} (2σ) determined by Stone (2000) from a calibration site with a similar age (20 ka), latitude and elevation as Smiths Fork-age moraines in the Uinta Mountains. This production rate is the same used by Licciardi et al. (2004), who reviewed the chronology of glacial deposits in the western U.S., many of which are based on ^{10}Be cosmogenic-exposure dating (e.g., Gosse et al., 1995a, b; Licciardi et al., 2001; Benson et al., 2004b). We use scaling factors for elevation and geographic latitude in Stone (2000). For reference, the ^{10}Be production rate in boulders at 2500 m asl and at N40° latitude (the elevation and latitude of most moraine boulders in the southern Uintas) is 30.8 atoms g SiO_2^{-1} yr^{-1}.

Despite the estimated uncertainty of scaled production rates, we consider only the analytical uncertainty of AMS measurements in calculating ^{10}Be exposure-age uncertainties, at least for comparing exposure ages within the Uintas and from elsewhere in the central Rocky Mountains. Samples were measured against standards from NIST SRM 4325 (Sharma et al., 2000), which requires a 14% increase to measured $^{10}Be/^{9}Be$ ratios (Middleton et al., 1993). The ^{10}Be concentration in samples is determined by standard isotope dilution from the amount of spike added to each sample (see Tables DR1 and DR2) and corrected for concentrations of meteoric ^{10}Be in measured blanks. Blank ratios ranged from 4.2 to 23.2 x 10^{-15} for three sample batches, which requires a blank correction of less than 1% for all individual samples. We conclude from this that laboratory contamination from meteoric ^{10}Be is negligible for all samples.

For the Yellowstone and Lake Fork Canyon moraines, we report the 2σ analytical uncertainty of individual boulder-exposure age estimates (Fig. 1, Tables DR1 and DR2) to ensure conservative identification of outliers and for comparison with other reported cosmogenic-age estimates in the Rocky Mountains (e.g., Licciardi et al., 2004; Benson et al., 2004a, b).

Other considerations for boulder-exposure age calculations include the effects of topographic shielding, sample thickness and snow cover on production rate. The former two effects can be easily estimated (Gosse and Phillips, 2001) and are considered constant for the period of boulder exposure (the Uintas have experienced minimal to no tectonic activity during the past ~20 kyr and erosion is considered negligible). Production rates for all boulders were corrected for sample thickness using

$$Q_s = \frac{A_f}{Z_s}\left(1 - \exp\left[-\frac{Z_s}{A_f}\right]\right),$$ Eq. DR1 (Gosse and Phillips, 2001)

where Q_s = production-rate correction factor for sample thickness

A_f = attenuation length of the cosmic-ray flux (159 g cm^{-2})

Z_s = sample thickness

The effect of snow cover is more difficult to accurately estimate, but can be quantified by using

$$S_{snow} = \frac{1}{12}\sum_{i=1}^{i=12} e^{-([H_{snow,i} - H_{rock}]\rho_{snow,i})/A_f}$$, Eq. DR2 (Gosse and Phillips, 2001)

where S_{snow} = shielding factor for snow cover (applied to the production rate)

$H_{snow} - H_{rock}$ = amount of snow on the boulder surface

ρ_{snow} = density of the snowpack

i = month of the year (1 – 12)

Although this procedure is a useful means of estimating the effect of snow thickness on boulder-exposure ages in the western U.S., it may not be appropriate for moraine boulders at the mouths of the Lake Fork and Yellowstone canyons. Boulders on these two moraines are surrounded by minimal vegetation (and were likely surrounded by less vegetation during colder time intervals of the past) and are situated locally at topographic high points; this suggests that moraine crests are wind swept of some portion of their snow cover, leaving the tallest boulders exposed above the snow pack. Furthermore, the lateral and terminal moraines sampled in this study are approximately north-south trending and perpendicular to prevailing wind direction (westerly). Snow could be easily removed from moraine crests by wind and deposited on the leeward slope (in this case, the distal slope of the moraine). Further discussion of the possible effects of snow and sediment cover on ^{10}Be production rates and cosmogenic surface-exposure ages in the Uinta Mountains is available in Laabs (2004).

In summary, we avoid the considerable uncertainty of accounting for possible effects of snow (or sediment cover) on production rate, and consider the inverse-variance weighted-mean of individual boulder-exposure ages from each moraine to represent the time of terminal-moraine abandonment. The robust set of cosmogenic ^{10}Be surface-exposure ages from the Lake Fork moraines (Fig. 2, Table DR2) provides the chronological framework for the discussion in this paper.

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Table DR1. ^{10}Be Data and Boulder-Exposure Ages on the Yellowstone Canyon Moraine. Munroe et al., *Geology*

Sample	Lithology*	Elevation (m asl)	Latitude (°N)	Longitude (°W)	Boulder height (m)	^{9}Be spike added (μg)	^{10}Be/^{9}Be (10^{-15})	2σ error	^{10}Be ± 2σ (10^4 atoms g SiO_2^{-1})	Sample thickness (cm)	Scaling factor†	Age ± 2σ§ (ka)
YS-11	qtzite	2512	40.5208	110.3271	0.35	512	349.98	20	35.0 ± 2.8	9.0	6.17	12.0 ± 1.0**
YS-6	wm ss	2540	40.5291	110.3262	0.50	510	459.42	26	40.0 ± 3.2	2.5	6.28	13.3 ± 1.1**
YS-7	qtzite	2531	40.5282	110.3262	0.55	510	491.34	28	46.1 ± 3.8	2.5	6.24	15.1 ± 1.3**
YS-9	qtzite	2514	40.5207	110.3272	1.00	511	557.46	34	53.6 ± 4.6	2.5	6.17	17.4 ± 1.5
YS-3	wm ss	2561	40.5324	110.3256	1.20	503	582.54	40	55.3 ± 5.0	2.5	6.36	17.4 ± 1.6
YS-10	wm ss	2554	40.5317	110.3258	0.65	509	639.54	38	56.3 ± 4.6	2.5	6.33	17.9 ± 1.5
YS-8	wm ss	2517	40.5223	110.3270	0.80	512	665.76	32	58.6 ± 4.5	2.5	6.19	19.0 ± 1.5
								weighted mean (n = 7; 95% confidence) =				15.2 ± 2.6
										MSWD (n = 7) =		18

*wm ss = weakly metamorphosed sandstone, qtzite = orthoquartzite.

†Computed using equations in Stone (2000).

§Ages are corrected for sample thickness. Analytical uncertainty is reported.

Table DR2. ^{10}Be Data and Boulder-Exposure Ages on the Lake Fork Moraines. Munroe et al., *Geology*

Moraine*	Sample†	Elevation (m asl)	Latitude (°N)	Longitude (°W)	Boulder height (m)	^{9}Be spike added (μg)	^{10}Be/^{9}Be (10^{-15})	2σ error	^{10}Be ± 2σ (10^4 atoms g SiO_2^{-1})	Sample thickness (cm)	Scaling factor§	Age ± 2σ# (ka)
LF1	LF04-3	2543	40.5144	110.4584	0.35	506	520	42	34.0 ± 3.4	3.0	6.29	11.5 ± 1.2**
LF1	LF04-1	2561	40.5166	110.4615	0.64	505	702	48	51.6 ± 4.6	5.0	6.36	16.7 ± 1.5
LF1	LF04-2	2560	40.5176	110.4627	1.20	505	785	46	53.7 ± 4.6	6.0	6.36	17.7 ± 1.5
LF1	LF04-5B	2553	40.5190	110.4623	0.56	506	621	42	55.4 ± 8.2	4.0	6.33	17.8 ± 1.6
LF1	LF04-5A	2553	40.5190	110.4623	0.48	505	642	40	55.4 ± 7.6	8.0	6.33	18.4 ± 1.6
LF1	LFRK-5	2551	40.5172	110.4603	0.50	512	547	60	60.3 ± 7.4	2.5	6.32	19.2 ± 2.4
LF1	LF04-4	2555	40.5181	110.4608	0.47	507	636	52	60.4 ± 10.6	7.0	6.34	19.9 ± 2.0
							weighted mean (n = 6; 95% confidence; MSWD = 1.6)					18.0 ± 1.1
LF2	LFR-6	2438	40.5098	110.4509	0.61	504	589	52	47.0 ± 5.0	7.0	5.88	16.1 ± 1.5
LF2	LFR-9	2499	40.5167	110.4572	0.65	505	641	52	50.5 ± 5.0	2.5	6.11	16.6 ± 1.4
LF2	LFR-4	2450	40.5105	110.4515	0.51	505	728	62	48.7 ± 5.0	2.0	5.92	16.6 ± 1.5
LF2	LFR-7	2490	40.5157	110.4560	0.70	504	661	50	50.7 ± 5.0	2.5	6.08	16.7 ± 1.4
LF2	LFR-5	2439	40.5103	110.4511	0.65	505	595	100	46.9 ± 8.4	8.0	5.88	16.7 ± 2.9
LF2	LFR-1	2464	40.5131	110.4533	0.68	506	622	40	50.9 ± 4.4	1.0	5.98	16.9 ± 1.2
LF2	LFR-3	2451	40.5112	110.4519	0.71	506	698	70	53.4 ± 6.2	2.0	5.93	18.0 ± 1.9
							weighted mean (n = 7; 95% confidence; MSWD = 0.36)					16.8 ± 0.7

Note: weighted-mean age is considered the age of moraine abandonment (see text for explanation).

*See Figure 1.

†All samples are composed of weakly-metamorphosed sandstone.

§Computed using equations in Stone (2000).

#Ages are corrected for sample thickness. Analytical uncertainty is reported.

**Age is a statistical outlier at 2σ.

Table DR3. Equilibrium Line Altitude Calculations. Munroe et al., *Geology*

Glacier	AAR 0.65 m	THAR 0.40 m	L. Moraine m	Weighted ELA m	Easting km
Pinon Canyon	2621	2610	2568	2609	0.9
Swifts Canyon	2682	2520	2506	2599	1.8
Bear Basin	2524	2524	2573	2532	2.9
White Pine	2667	2570	2658	2633	4.4
South Fork	2774	2610	2463	2668	6.5
Nobletts Creek	2646	2680	2682	2663	7.7
Shingle Mill	2743	2670	2699	2711	8.7
Shingle Mill east	2633	2700	2560	2643	9.6
Bear Trap north	2768	2770	2682	2754	9.9
Smith & Morehouse	2880	2710	2963	2837	12.7
Slader Ridge west	2719	2700	2682	2707	13.3
Slader Creek	2728	2770	2850	2762	15.4
Main Weber	2972	2780	2743	2870	21.5
West Fork Bear	2880	2788	2849	2844	23.6
Gold Hill	2840	2888	2939	2873	27.7
Duchesne	3005	2719	2987	2907	29.8
Hayden Fork Bear River	3025	2948	3188	3027	32.3
East Fork Bear	3035	2988	3188	3045	39.2
Log Hollow	3008	2904	2859	2949	42.0
Rock Creek	3132	2733	3109	2995	49.1
Little West Fork Blacks	2990	2952	2970	2974	49.9
Blacks Fork	3020	3036	3212	3057	51.9
Lake Fork	3170	2881	2926	3033	60.5
West Fork Smiths	3110	3136	3120	3120	61.8
Smiths Fork	3045	3080	3103	3066	67.7
Yellowstone	3185	2811	3094	3045	73.7
Henrys Fork	3130	3112	3280	3149	73.7
West Fork Beaver Creek	3230	3156	3212	3202	79.4
Crow Canyon	3078	3075	2987	3062	80.0
Heller Lake	3011	3019	3011	3014	83.2
Middle Fork Beaver Creek	3210	3168	3225	3199	84.0
Thompson Creek	3125	3084	3139	3114	90.5
Uinta	3286	2853	3018	3097	91.3
Burnt Fork	3210	3048	3160	3148	94.9
Upper Rock Lake	3089	2980	3078	3051	99.5
Middle Fork Sheep Creek*	3130	3128	3055	3117	102.4
Whiterocks	3267	2755	3170	3080	104.6
South Fork Sheep Creek*	3170	3068	3080	3121	107.1
West Fork Carter Creek*	3140	3068	3130	3114	111.3
Dry Fork	3093	2897	3158	3039	114.8
East Fork Carter Creek*	3060	3048	3121	3066	115.3
North Fork Ashley	3160	3136	3078	3138	119.6
Chimney Rock Lake	3097	3116	3121	3107	120.9
South Fork Ashley*	3100	3040	3150	3088	122.9
Mean	2986	2892	2962	2951	

* Piedmont glacier, AAR of 0.50