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Short Communication

Moraine pebbles and boulders yield indistinguishable ^{10}Be ages: A case study from Colorado, USA

Jason P. Briner*

Department of Geology, University at Buffalo, 411 Cooke Hall, Buffalo, NY 14260, USA

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ABSTRACT

Cosmogenic exposure dating of moraines during the last two decades has vastly improved knowledge on the timing of glaciation worldwide. Due to a variety of geologic complications, such as moraine degradation, snow cover, bedrock erosion and isotopic inheritance, samples from multiple large boulders (>1–2 m) often lead to the most accurate moraine age assignments. However, in many cases, large boulders are not available on moraines of interest. Here, I test the suitability of pebble collections from moraine crest surfaces as a sample type for exposure dating. Twenty-two ^{10}Be ages from two Pleistocene lateral moraine crests in Pine Creek valley in the upper Arkansas River basin, Colorado, were calculated from both pebble and boulder samples. Ten ^{10}Be ages from a single-crested Bull Lake lateral moraine range between 3 and 72 ka, with no statistical difference between pebble ($n = 5$) and boulder ($n = 5$) ages. The lack of a cluster of ^{10}Be ages suggests that moraine degradation has led to anomalously young exposure ages. Twelve ^{10}Be ages from a single-crested Pinedale lateral moraine have a bimodal age distribution; one mode is 22.0 ± 1.4 ka (three boulders, two pebble collections), the other is 15.2 ± 0.9 ka (two boulders, five pebble collections). The interpretation of the two age modes is that two glacier maxima of similar extent were attained during the late Pleistocene. Regardless of moraine age interpretations, that ^{10}Be ages from pebble collections and boulders are indistinguishable on moraines of two different ages, and in two different age modes of the Pinedale moraine, suggests that pebble collections from moraine crests may serve as a suitable sample type in some settings.

1. Introduction

The response of the Earth's cryosphere to climate change is currently of great importance and interest (IPCC, 2007). In particular, alpine glaciers may be the dominant contributor to eustatic sea level rise in the 21st century (Meier et al., 2007). Aspects of the sensitivity of alpine glaciers to climate change, however, remain uncertain (Owen et al., 2008). Numerical models of alpine glacier response to climate change are improving our understanding of alpine glacier behavior, as are contemporary studies of extant glaciers (e.g., MacGregor et al., 2005; Kessler et al., 2006; Laabs et al., 2006). An important approach to improving the understanding of links between alpine glaciers and global and regional climate change also arises from reconstructions of past glacier activity (e.g., Gillespie and Molnar, 1995). Consequently, tremendous effort has been spent on improving the geochronology of glacier deposits (Ehlers and Gibbard, 2004). The development of cosmogenic exposure dating has greatly expanded the number of locations where glacier deposits are suitable for dating (Phillips et al., 1990; Gosse et al., 1995; Balco et al., 2002; Briner et al., 2005; Schaefer et al., 2006; Ivy-Ochs et al., 2007).

The requirements for cosmogenic exposure dating glacial deposits, however, are fairly rigid. For example, large (>1 m) lateral and end moraine boulders are commonly targeted for sampling because their age can provide the timing of maximum glacier extent. Because moraines are steep and high constructional features that degrade, the distribution of cosmogenic exposure ages of moraine boulders consequently is often scattered. Therefore, cosmogenic exposure dating of moraines typically constrains the timing of moraine abandonment and subsequent stabilization (Hallet and Putkonen, 1994; Putkonen and Swanson, 2003; Putkonen and O'Neal, 2006), although inheritance can give rise to boulder ages that pre-date moraine deposition. Thus, moraine chronologies require large boulders that are least likely to be modified by degradation. In addition, the best chronologies arise from young moraines that have degraded little, and from single-crested moraines that likely stabilize quickly rather than

* Tel./fax: +1 716 645 6800x3986.
E-mail address: jbriner@buffalo.edu

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hummocky moraines that may result from ice-stagnation and delayed moraine stabilization. Although other approaches to dating glacier fluctuations, like dating large erratics on flat surfaces (Ward et al., 2007), glacially-eroded bedrock transects (Guido et al., 2007) and depth-profiles in outwash terraces (Anderson et al., 1996) avoid the issue of moraine degradation, moraines are more ubiquitous and thus provide the most common targets for cosmogenic exposure dating.

Because the most ideal conditions for cosmogenic exposure dating are not present for all moraines in all valleys, alternative approaches and sample types are sought. Here, I explore the suitability of moraine surface pebbles for cosmogenic exposure dating. Boulders typically have been sampled because it is generally thought that they survive longer on a degrading moraine crest than the finer-grained fraction of till on the moraine surface. If true, then cosmogenic exposure ages of moraine surface pebbles should be systematically younger than cosmogenic exposure ages of boulders. However, if the time it takes for till clasts to be exhumed and subsequently removed from a moraine crest is the same for boulders and pebbles, then cosmogenic exposure ages of each sample type should be similar. In addition, if moraines are relatively pristine and very little moraine degradation has taken place since deposition, then cosmogenic exposure ages of each sample type should also be similar. To test these ideas, I generated ^{10}Be ages from moraine surface pebble amalgamations and moraine boulders from two lateral moraines of different age in the Pine Creek valley, Sawatch Range, central Colorado (Fig. 1).

2. Regional setting

Alpine glaciers in many western U.S. mountain ranges deposited voluminous moraines during the Pleistocene (Porter et al., 1983). Distinct end and lateral moraines common along dozens of range fronts were deposited during the Bull Lake and Pinedale glaciations, which are correlated with marine-isotope-stage 6 (~190–130 ka) and 2 (~30–10 ka), respectively (Martinson et al., 1987; Dahms, 2004; Pierce, 2004). Absolute chronologies of moraines and glacio-fluvial terraces from across the western U.S. have confirmed these correlations (e.g., Phillips et al., 1997; Sharp et al., 2003; Gillespie and Zehfuss, 2004; Pierce, 2004; Licciardi and Pierce, 2008). Along the eastern Sawatch Range, CO, alpine glaciers deposited moraines in numerous valleys tributary to the upper Arkansas River during the Bull Lake and Pinedale glaciations (Richmond, 1986; Nelson and Shroba, 1998).

I collected samples for ^{10}Be dating from moraines in the Pine Creek valley (Fig. 1), which drains granitic terrain of the 1.7 Ga Boulder Creek-Granite-equivalent that contains Laramide (~70–40 Ma) intrusive rocks (Tweto, 1979). Glaciers that flowed down Pine Creek valley and the adjacent Clear Creek valley to the north (Fig. 1) are noteworthy because they crossed the upper Arkansas River valley, damming the river and causing sizeable outburst floods that deposited large boulder bars downstream (Scott, 1984). Sharp-crested, lightly-forested lateral moraines >160 m high that comprise the valley walls of lower Pine Creek valley are most likely of Pinedale age because they are similar in shape and morphostratigraphic position to moraines in adjacent valleys mapped by Nelson and Shroba (1998). The right lateral moraine has ~23–30°

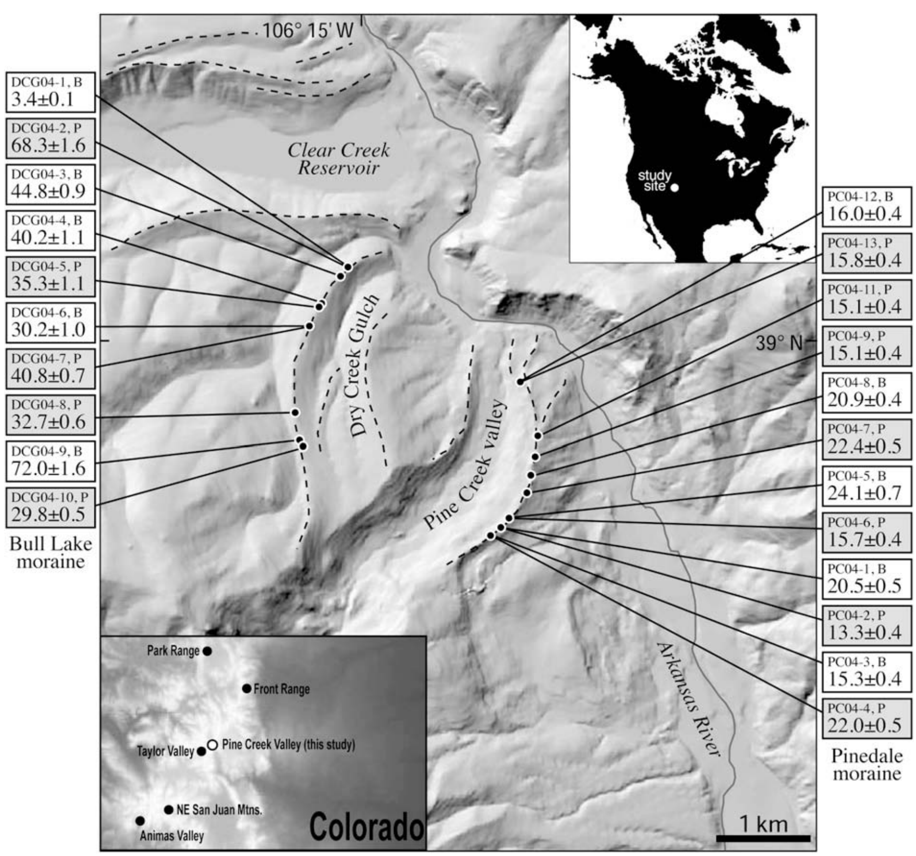

Fig. 1. Shaded relief digital elevation map showing Dry Creek Gulch and lower Pine Creek valley, upper Arkansas River valley, Colorado. Sample locations are shown as black dots, ^{10}Be ages from the left lateral moraine deposited during the Bull Lake glaciation are shown at left, and ^{10}Be ages from the right lateral moraine deposited during the Pinedale glaciation are shown at right (B and P refer to boulder and pebble sample types, respectively). Moraine crests are indicated with dashed black lines. Inset at upper right shows the study site in the context of North America, and the inset at lower left shows localities mentioned in the text; lighter tones are higher in elevation.

slope angles and 5–20 m crest widths (measured according to Kaufman and Calkin, 1988). Dry Creek Gulch, a small north-flowing drainage adjacent to the lower Pine Creek valley (Fig. 1), is bounded by heavily-forested lateral moraines that are more subdued than those along Pine Creek. Moraine slope angles are 11–18°, and the crest widths range from ~20 to ~80 m. These moraines, which were apparently truncated during the deposition of the Pine Creek valley moraines, were assigned to the Bull Lake glaciation by Nelson and Shroba (1998) based on soil properties. The mean annual temperature of towns near the Pine Creek valley (Leadville and Buena Vista) average 1.5 °C, and the mean annual precipitation averages 274 mm, with ~25% falling during winter months (DJFM; www.weather.com).

3. Methods

Rock samples 1–4 cm thick were collected from the upper surface of moraine boulders using a hammer and chisel and ground-surface quartz pebbles were collected near sampled boulders (Fig. 2). Quartz pebbles ranged in size from ~1 to 3 cm in diameter, and 10–25 pebbles were crushed in the lab and amalgamated as a single sample. Five boulders (~0.5–1.0 m high, ~1.5–3.0 m exposed diameter) and five pebble collections were sampled from the left lateral Bull Lake moraine in Dry Creek Gulch, and five boulders (~0.4–2.0 m high, ~1.0–5.0 m exposed diameter) and seven pebble collections were sampled from the right lateral Pinedale moraine in Pine Creek valley (Fig. 1).

Elevations and positions were recorded in the field with a hand-held GPS cross-referenced with 1:24,000 topographic maps. Samples were prepared for ^{10}Be dating at the University at Buffalo cosmogenic isotope laboratory following the procedures outlined in Kohl and Nishiizumi (1992). Sample ratios were measured at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, and normalized to ICN standard KNSTD3110 (^{10}Be/^{9}Be $= 3.11 \times 10^{-12}$). ^{10}Be ages were calculated using the CRONUS-Earth online calculator (Balco et al., 2008; http://hess.ess.washington.edu/math/), and are reported here with internal uncertainty (includes uncertainty in AMS measurement only) and using the constant production rate model and scaling scheme of Lal (1991) and Stone (2000). The version of the calculator employed here uses a ^{10}Be production rate of 4.96 ± 0.43 atoms g^{-1} y^{-1} ($\pm 1\sigma$, at high latitude and at sea level). When calculated with the time-dependent production rate model of Lal (1991) and Stone (2000), the ^{10}Be ages from the Bull Lake moraine become 5.0 to ~8.0% younger, and the ^{10}Be ages from the Pinedale moraine become 1.5–3.5% younger. When calculated with alternate time-dependent scaling schemes listed in Balco et al. (2008), the Bull Lake ^{10}Be ages become 8.7–15.7% younger, and the Pinedale ^{10}Be ages become 4.8–9.7% younger.

The ^{10}Be ages reported below are not corrected for erosion or snow shielding. Because boulders on the Pine Creek valley moraine reveal minimal erosion, and some retain polish, the amount of rock erosion that has taken place since moraine deposition likely has a negligible influence on these ^{10}Be ages. Because the boulders on the Dry Creek Gulch have been exposed longer, erosion has likely influenced their ^{10}Be ages; however, because there is wide scatter in the ^{10}Be ages and no attempt below to interpret the timing of glaciation from the ^{10}Be ages on the Dry Creek Gulch samples, no corrections are made. Accounting for snow cover, which leads to ^{10}Be ages younger than the timing of moraine deposition, is challenging because snowpack data are sparse and many factors contribute to spatially heterogeneous patterns of snowpacks on

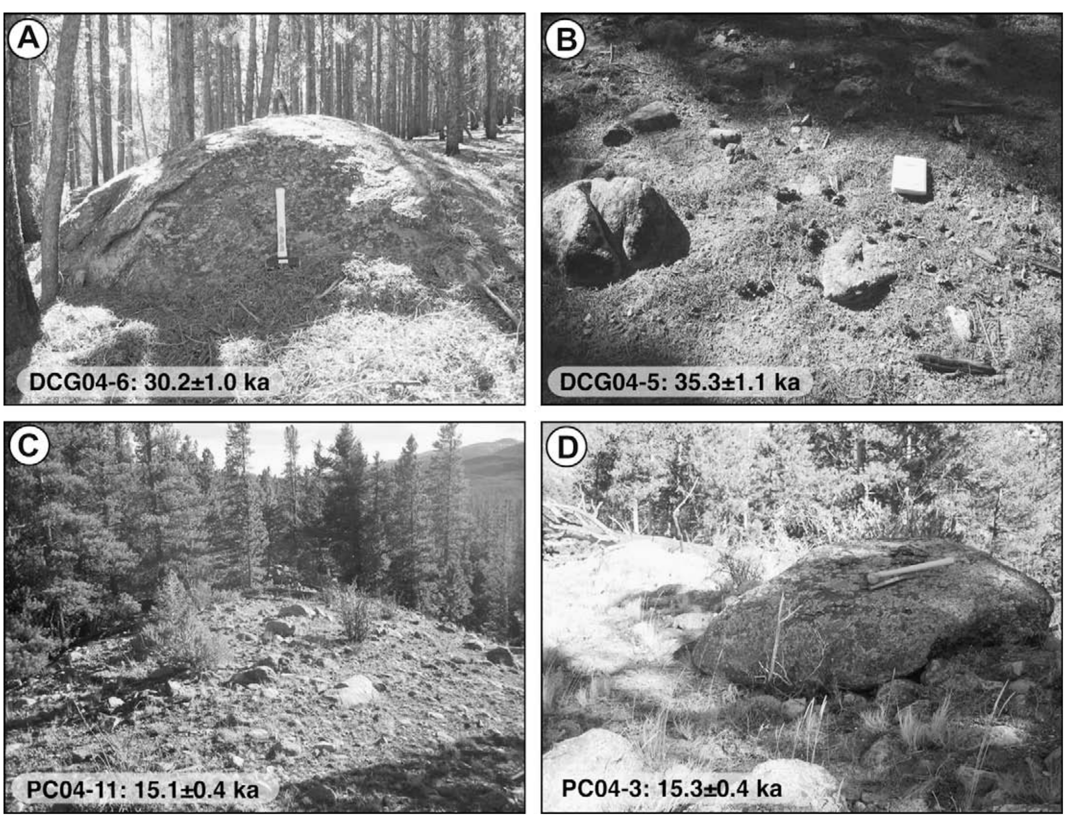

Fig. 2. Photographs taken during sample collection on October 16, 2004. (A) Boulder sample DCG04-6 from Dry Creek Gulch moraine. (B) Surface of Dry Creek Gulch moraine where pebbles were collected for sample DCG04-5. (C) Surface of Pine Creek valley moraine crest where pebbles were collected for sample PC04-11. (D) Boulder sample PC04-3 from Pine Creek valley moraine. Sample localities shown in Fig. 1.

landscapes. However, I attempted to evaluate snow cover by compiling snowpack data from three nearby stations (http://www.co.nrcs.usda.gov/snow/). The three stations are slightly higher in elevation than the sample sites. Snow shielding factors calculated according to Gosse and Phillips (2001) from the three sites are 0.95, 0.98 and 0.97, which yield snowpack-corrected ages that are 2–5% older than reported here. However, I report the ^{10}Be ages below without applying a correction because the Dry Creek Gulch ages are not interpreted as indicators of moraine age, and all samples from the Pine Creek valley moraine are from the top, lightly-forested crest of the moraine, where wind would likely lead to only thin build-up of snow.

4. Results

The 10 ^{10}Be ages from the Bull Lake moraine in Dry Creek Gulch reveal considerable scatter, ranging in age from 72.0 ± 1.6 to 3.4 ± 0.1 ka (Table 1; Fig. 3). The five ^{10}Be ages from boulders range from 72.0 ± 1.6 to 3.4 ± 0.1 ka (average 46.8 ± 17.9 ka) and the five ^{10}Be ages from pebble samples range from 68.3 ± 1.6 to 29.8 ± 0.5 ka (average 41.4 ± 15.6 ka). The 12 ^{10}Be ages from the Pinedale moraine in Pine Creek valley range between 24.1 ± 0.7 and 13.3 ± 0.4 ka (Table 1; Fig. 3). The five ^{10}Be ages from boulders range from 24.1 ± 0.7 to 15.3 ± 0.4 ka (average 19.4 ± 3.7 ka), and the seven ^{10}Be ages from pebble samples range from 22.4 ± 0.5 to 13.3 ± 0.4 ka (average 17.1 ± 3.6 ka). The 12 ^{10}Be ages from the Pinedale moraine are distributed in two distinct modes (Fig. 3). Defined by peaks in the summed probability curve in Fig. 3, one mode ranges between ~16 and 13 ka (two boulders average 15.7 ± 0.5 ka; five pebble samples average 15.0 ± 1.0 ka), and the other ranges between ~24 and 20 ka (three boulders average 21.8 ± 2.0 ka; two pebble samples average 22.2 ± 0.3 ka).

5. Discussion

5.1. Dry Creek Gulch (Bull Lake) moraine

The ^{10}Be age distributions of boulders and moraine surface pebbles from the Dry Creek Gulch moraine overlap in time with no systematic age difference based on sample type (Fig. 3). The majority of the ages range between ~40 and 30 ka; both pebble and boulder ages are represented in this interval. There are two ages that are significantly older than the others; one ^{10}Be age from a boulder is ~72 ka and one ^{10}Be age from a pebble sample is ~68 ka. One anomalously young ^{10}Be age of ~3 ka is from a boulder.

The ^{10}Be ages from the Dry Creek Gulch moraine are not of Bull Lake age. Either the moraine was deposited sometime following the Bull Lake glaciation, or the ^{10}Be ages do not represent the actual age of moraine deposition. Although there is some evidence for a glacier advance during the early- or middle-Wisconsin in the western U.S. (e.g., Colman and Pierce, 1986), most locations seem to host just Pinedale and Bull Lake moraines (e.g., Pierce, 2004; Dahms, 2004; Licciardi and Pierce, 2008); this is thought to be the case in the upper Arkansas River basin (Nelson and Shroba, 1998). Thus, it is likely that the ^{10}Be ages from the Dry Creek Gulch moraine reflect several processes that yield exposure ages younger than actual moraine age. The most important of these factors is moraine degradation, which exhumes till clasts as the moraine crest lowers and broadens through time (Hallet and Putkonen, 1994; Putkonen and Swanson, 2003). Specific processes that may contribute to the scatter in ^{10}Be ages and to their distribution being younger than the probable Bull Lake age include snow cover, tree throw, tree shielding and forest fire-induced spallation (Zimmerman et al., 1994; Gosse and Phillips, 2001; Plug et al., 2007). Snow shielding may be most influential in forests, where moraine crests are not as wind swept as unforested moraine crests. However, due to relatively dry and thin snowpacks in this continental interior location, snow shielding is not likely the dominant factor. Tree throw would disturb the till matrix along a moraine crest, and thus may influence the exposure of the pebble collections, and perhaps even boulders. The exact processes that led to scattered ^{10}Be ages that are younger than their most likely age of deposition are not known. However, the range of ^{10}Be ages from both pebble and boulder sample types are similar, suggesting that one sample type is not superior to the other on this moraine.

5.2. Pine Creek valley (Pinedale) moraine

The ^{10}Be age distributions of boulders and moraine surface pebbles from the Pine Creek moraine reveal a bimodal age pattern (Fig. 3). The five ^{10}Be ages in the older mode range between ~24 and ~21 ka and average 22.0 ± 1.4 ka. The seven ^{10}Be ages in the younger mode range between ~16 and ~13 ka and average 15.2 ± 0.9 ka; removing the youngest age (13.3 ± 0.4 ka), which lies outside of the 2σ uncertainty range of the others, yields an average of 15.5 ± 0.4 ka. Of all 12 ages, none fall between ~21 and ~16 ka. All of the samples are from the top of the narrow, single-crested lateral moraine ridge, and there is no statistical relationship between sample age and position along moraine or sample height above moraine. Importantly, there is also no relationship between sample age and sample type, indicating that pebbles are not being exhumed and removed from the moraine crest faster than boulders (Fig. 1).

There are several possible interpretations of the distribution of ^{10}Be ages from the Pine Creek valley moraine. The first interpretation involves the moraine being deposited during the Last Glacial Maximum, and abandoned during deglaciation at 22.0 ± 1.4 ka. In this scenario, the samples with ^{10}Be ages that comprise the younger mode were exhumed following deglaciation due to moraine degradation, and thus yield ^{10}Be ages younger than the timing of moraine abandonment and stabilization. A second interpretation involves the moraine being abandoned at the time of the younger mode, and the samples with ^{10}Be ages that pre-date the younger mode are influenced with inherited ^{10}Be from prior exposure. Although both interpretations are possible, neither interpretation seems very likely. The distribution of ^{10}Be ages of samples influenced by moraine degradation more commonly range from the timing of moraine abandonment to the present, where most ages lie near the old end of the range, and progressively fewer ages are spread in the young direction (e.g., Putkonen and Swanson, 2003). In contrast, the ^{10}Be ages from the Pine Creek valley moraine younger than the 22.0 ± 1.4 ka mode fall into a single cluster. Similarly, inheritance typically is represented by anomalously old ages that pre-date the timing of moraine abandonment, not as a single cluster of old ages. In addition, it seems unlikely that the processes leading to moraine degradation and inheritance would affect both boulders and pebbles in the same way. Rather, boulders might be more likely to contain inheritance, whereas pebbles might be more heavily influenced by moraine degradation.

A third interpretation is that following initial deglaciation from the Pine Creek valley moraine ~22.0 ± 1.4 ka, there was a period of glacier recession followed by a younger advance, culminating ~15.5 ± 0.4 ka, that briefly attained a similar extent to the advance during the Last Glacial Maximum. According to this scenario, a thin veneer of till was deposited on the same single moraine crest that was abandoned ~5–10 k.y. earlier. Thus, ^{10}Be ages from boulders and pebbles from the moraine surface reflect both periods of till deposition. Although this interpretation seems unlikely, it is more consistent with the ^{10}Be age distribution than the first two possible

Table 1
Cosmogenic ^{10}Be data from samples collected in the Pine Creek valley, upper Arkansas River basin, Colorado.

Sample	Lat. (N)	Long. (W)	Elevation (m asl)	Sample type	Thickness (cm)	Thickness Correction	Mass quartz (g)	[^{10}Be] (10^5 atoms g^{-1})	Site Production Rate (at g^{-1} y^{-1})	^{10}Be age (ka)
Pinedale-aged left lateral moraine crest, Pine Creek valley										
PC04-1	38° 58.847	106° 13.947	2992	Boulder	3.0	0.9756	31.4326	8.285 ± 0.194	40.62	20.5 ± 0.5
PC04-2	38° 58.847	106° 13.947	2992	Pebbles	1.0	0.9918	40.6550	5.457 ± 0.159	41.28	13.3 ± 0.4
PC04-3	38° 58.812	106° 14.043	2911	Boulder	1.0	0.9918	35.2152	5.992 ± 0.159	39.32	15.3 ± 0.4
PC04-4	38° 58.812	106° 14.043	2911	Pebbles	1.0	0.9918	40.2864	8.587 ± 0.200	39.32	22.0 ± 0.5
PC04-5	38° 58.908	106° 13.899	2893	Boulder	3.0	0.9756	31.9476	8.903 ± 0.260	37.16	24.1 ± 0.7
PC04-6	38° 58.847	106° 13.947	2893	Pebbles	1.0	0.9918	40.1704	6.103 ± 0.144	38.89	15.7 ± 0.4
PC04-7	38° 59.187	106° 13.664	2877	Pebbles	1.0	0.9918	40.3870	8.582 ± 0.202	38.52	22.4 ± 0.5
PC04-8	38° 59.333	106° 13.635	2851	Boulder	3.0	0.9918	31.7452	7.887 ± 0.154	37.91	20.9 ± 0.4
PC04-9	38° 58.403	106° 13.617	2837	Pebbles	1.0	0.9918	40.0701	5.661 ± 0.134	37.58	15.1 ± 0.4
PC04-11	38° 59.500	106° 13.636	2835	Pebbles	1.0	0.9918	40.1715	5.637 ± 0.133	37.54	15.1 ± 0.4
PC04-12	38° 59.882	106° 13.718	2739	Boulder	1.5	0.9877	40.0041	5.605 ± 0.135	35.24	16.0 ± 0.4
PC04-13	38° 59.882	106° 13.718	2739	Pebbles	1.0	0.9918	40.2064	5.578 ± 0.134	35.38	15.8 ± 0.4
Bull Lake-aged right lateral moraine crest, Dry Creek Gulch										
DCG04-1	39° 00.450	106° 15.135	2845	Boulder	2.5	0.9796	26.5661	1.255 ± 0.397	37.31	3.4 ± 0.1
DCG04-2	39° 00.450	106° 15.135	2845	Pebbles	1.0	0.9918	40.0360	25.435 ± 0.586	37.77	68.3 ± 1.6
DCG04-3	39° 00.438	106° 15.151	2860	Boulder	4.0	0.9676	31.3030	16.510 ± 0.322	37.20	44.8 ± 0.9
DCG04-4	39° 00.214	106° 15.343	2903	Boulder	2.5	0.9597	30.3068	15.110 ± 0.397	37.87	40.2 ± 1.1
DCG04-5	39° 00.214	106° 15.343	2903	Pebbles	1.0	0.9918	40.0585	13.724 ± 0.439	39.13	35.3 ± 1.1
DCG04-6	39° 00.125	106° 15.403	2924	Boulder	2.0	0.9796	30.1709	11.605 ± 0.368	38.65	30.2 ± 1.0
DCG04-7	39° 00.125	106° 15.403	2924	Pebbles	1.0	0.9918	40.6015	16.027 ± 0.273	39.63	40.8 ± 0.7
DCG04-8	38° 59.545	106° 15.497	2967	Pebbles	1.0	0.9918	40.1879	13.229 ± 0.227	40.67	32.7 ± 0.6
DCG04-9	38° 59.327	106° 15.406	2991	Boulder	1.0	0.9918	21.9367	29.179 ± 0.649	41.26	72.0 ± 1.6
DCG04-10	38° 59.327	106° 15.406	2991	Pebbles	1.0	0.9918	40.1837	12.232 ± 0.210	41.26	29.8 ± 0.5

Ages calculated using the CRONUS-Earth online ^{10}Be exposure age calculator (http://hess.ess.washington.edu/math/) with the Lal (1991)/Stone (2000) scaling scheme and a constant production rate model (Balco et al., 2008). A rock density of 2.65 g cm^{-3} was used. No corrections for topographic shielding or sample geometry were required. Process blanks are $2.64 \pm 0.14 \times 10^{-14}$ (samples PC04-2, -3, -4, -5; DCG04-2, -4, -5, -7, -8, -9, -10), $1.95 \pm 0.13 \times 10^{-14}$ (samples PC04-1, -6, -7, -11, -13; DCG04-1, -3, -6), $2.47 \pm 0.13 \times 10^{-14}$ (samples PC04-8, -9), and $2.43 \pm 0.12 \times 10^{-14}$ (sample PC04-12).

interpretations. Furthermore, the reoccupation of a single-crested lateral moraine has been described elsewhere. Licciardi et al. (2004) obtained two coherent clusters of ^{10}Be ages from a single moraine crest at Willowa Lake in the Willowa Mountains, Oregon. If the Pine Creek valley moraine was indeed reoccupied ~15.5 ± 0.4 ka, following original moraine abandonment ~22.0 ± 1.4 ka, the tight clusters of ^{10}Be ages from both boulders and surface pebbles demonstrate remarkable stability of the moraine. However, this is not surprising given the relatively pristine morphology of the moraine crest.

The interpretation that glacier advances culminated in the Pine Creek valley at ~22.0 ± 1.4 ka and ~15.5 ± 0.4 ka is evaluated by comparing these ^{10}Be ages to glacial chronologies elsewhere in the Rocky Mountains (all further discussion involves published ages with no corrections for erosion or snow shielding, and all ^{10}Be ages reported in this section have been recalculated using the CRONUS-Earth online calculator). Brugger (2007) dated two Pinedale moraines on the west side of the Sawatch Range, just ~30 km from the Pine Creek valley (Fig. 1). Five ^{10}Be ages from boulders on the Pinedale terminal moraine in the Taylor River valley average 19.1 ± 1.9 ka. Two boulders from the Pinedale terminal moraine in the adjacent Texas Creek valley, however, average 14.8 ± 0.8 ka. Although the boulders from the Taylor River valley moraine lie along the outer margin of the terminal moraine, the boulders in the Texas Creek valley lie ~1 km upvalley from the terminal limit (Brugger, 2007). Thus, it is possible that glacier maxima of similar extent were reached at ~19 and ~15 ka, and boulders from the older event were sampled in the Taylor River valley and boulders from the younger event were sampled in the Texas Creek valley. Alternatively, the boulders in the Texas Creek valley were exhumed several thousand years after deglaciation.

In southwestern Colorado, Guido et al. (2007) dated glacier retreat in the Animas River valley in the San Juan Mountains (Fig. 1). Abandonment of the Pinedale outwash terrace occurred ~19.4 ± 1.5 ka, and following a period of slow retreat, most of the length of the Animas River valley became quickly deglaciated ~14.6 ± 0.5 ka (Guido et al., 2007). Pinedale terminal moraines dated in two valleys in the northeastern San Juan Mountains (Fig. 1) are between 21 and 20 ka based on moraine boulder ^{36}Cl ages reported in Benson et al. (2005). Farther north in the Front Range, Ward et al. (in press) combined four boulder ages that average 20.6 ± 1.2 ka for the Pinedale terminal moraine in the middle Boulder Creek valley. The Pinedale terminal moraine in the adjacent North St. Vrain Creek valley has a single ^{10}Be age of 22.0 ± 1.0 ka (Benson et al., 2005). Finally, in the Park Range, north-central Colorado (Fig. 1), Benson et al. (2004, 2005) reported ^{10}Be ages from three boulders on the terminal Pinedale moraine in the Roaring Fork Creek valley that average 22.7 ± 2.9 ka. Thus, there seems to be a strong mode of Pinedale terminal moraine ages throughout Colorado at ~22–20 ka, and at least some evidence suggesting that glaciers may have remained relatively extensive until 15–14 ka.

5.3. Why do moraine surface pebbles and boulders have indistinguishable ^{10}Be ages?

This dataset incites the above question. Some research suggests that the fine-grained component of moraines is exhumed and transported off the moraine crest faster than the coarse-grained component, and thus leaves moraine crests with a lag of boulders (e.g., Putkonen et al., 2008). However, the similar distribution of ^{10}Be ages on pebble and boulder samples reported here, and on the degraded Dry Creek Gulch moraine in particular, suggests that pebbles and boulders are being exhumed and removed at similar rates, rather than boulders residing unaltered as the moraine crest lowers. Because the Pine Creek moraine is relatively pristine, it is perhaps less surprising that the different sample types have similar ages. It is somewhat surprising that bioturbation and depth-distributed soil creep apparently have not systematically reduced pebble-based ^{10}Be ages with respect to boulder-based ^{10}Be ages.

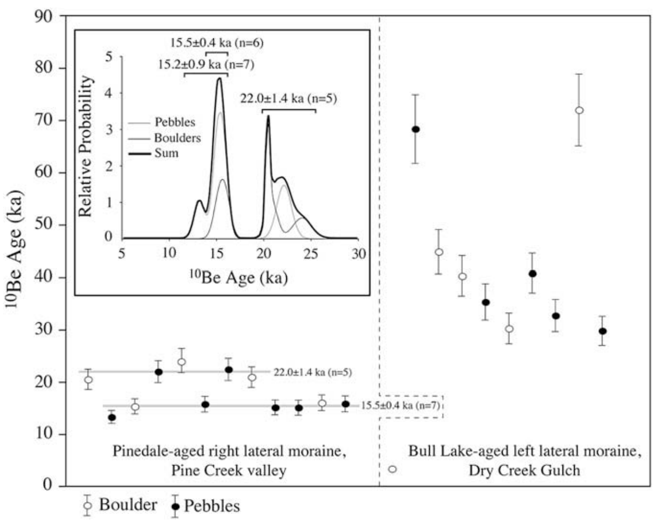

Fig. 3. ^{10}Be ages from Pine Creek and Dry Creek Gulch moraines. Error bars are one σ uncertainty of ^{10}Be AMS measurements. Inset graph shows probability distribution function of Pine Creek valley moraine ages.

One possibility is that the pebbles on the moraine crests sampled here are derived from the physical weathering of boulders. However, this is unlikely for two reasons. First, the pebbles on the moraine surfaces are rounded with smooth surfaces and edges, and are larger than the common grain size of quartz in moraine boulders observed in the study area. Second, pebbles were never collected from the base of boulders, were collected from at least some areas that are not down-slope of boulders, and were collected in some locations of the moraine where boulders were absent. Thus, the pebbles are most likely derived from the moraine matrix and are not byproducts of physical weathering of boulders on the moraine surfaces. Future studies on the processes of moraine degradation may better elucidate why moraine surface pebbles and boulders can yield indistinguishable exposure ages.

6. Conclusions

The ^{10}Be ages from the Dry Creek Gulch (Bull Lake) and Pine Creek valley (Pinedale) moraines reveal that collections of moraine surface pebbles and boulders can yield indistinguishable ^{10}Be ages. Despite the wide distribution of ^{10}Be ages on the Dry Creek Gulch moraine that may significantly post-date the age of the moraine itself, ^{10}Be ages of pebbles are not statistically different than ^{10}Be ages of boulders. If the Dry Creek Gulch moraine was indeed deposited during the Bull Lake glaciation, then these ^{10}Be ages weaken the notion that moraine boulders exposed upon deglaciation survive on the surface of significantly degraded moraines. On the other hand, the morphology of the much younger sharp-crested Pine Creek valley moraine indicates that it has not significantly degraded since deposition. The ^{10}Be ages of both boulders and pebbles support this observation. Again, ^{10}Be ages of boulder and pebble samples overlap in both age modes on the Pine Creek valley moraine. The results suggest that boulders do not survive longer on these moraines crests than finer-grained till matrix, and that where boulders are lacking, moraine surface pebbles may provide suitable sample types for exposure dating of relatively pristine moraines.

The two age modes of the single-crested Pine Creek valley moraine at 22.0 ± 1.4 and 15.5 ± 0.4 ka are difficult to interpret. The interpretation most consistent with the ^{10}Be ages is that following deglaciation from the Pinedale terminal moraine $\sim$22 ka, a second advance $\sim$15.5 ka briefly reached the moraine and deposited a thin veneer of till. The finding of bimodal ages from single-crested Pinedale moraines is not unique to the Pine Creek valley, nor is the finding that glacier snouts remained near their Pinedale terminal positions so late in the deglacial period. The interpretation that the Pine Creek valley glacier remained near its Pinedale terminus until $\sim$15.5 ka can be tested by dating valley-bottom bedrock surfaces farther upvalley, additional moraines in adjacent valleys in the Sawatch Range, and by dating glacial-outburst flood boulders in the upper Arkansas River valley.

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