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Cosmogenic ^{10}Be and ^{36}Cl Ages From Late Pleistocene Terminal Moraine Complexes in the Taylor River Drainage Basin, Central Colorado, U.S.A.

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Abstract

Cosmogenic surface-exposure ages from boulders on a terminal moraine complex establish the timing of the local last glacial maximum (LGM) in the Taylor River drainage basin, central Colorado. Five zero-erosion ^{10}Be ages have a mean of 19.5 ± 1.8 ka while that for three ^{36}Cl ages is 20.7 ± 2.3 ka. Corrections for modest rates (~1 mm ka^{-1}) of boulder surface erosion result in individual and mean ages that are generally within 2% of their zero-erosion values. Both the means and the range in ages of individual boulders are consistent with those reported for late Pleistocene moraines elsewhere in the Southern and Middle Rocky Mountains, and thus suggest local LGM glacier activity was regionally synchronous. Two anomalously young (?) zero-erosion ^{10}Be ages (mean 14.4 ± 0.8 ka) from a second terminal moraine are tentatively attributed to the boulders having been melted out during a late phase of ice stagnation.

1. Introduction

With the development of cosmogenic radionuclide surface-exposure dating, the timing and duration of local last glacial maximums (LGM) in individual ranges of western North America are becoming better understood. However, the range of exposure ages typically obtained from a single moraine complex can and has been interpreted and/or explained in different ways (e.g., Gosse et al., 1995; Phillips et al., 1996; Licciardi et al., 2001; Putkonen and Swanson, 2003; Benson et al., 2005). Such differences in interpretation add to current debates as to whether local LGM glacier advances and retreats were regionally synchronous (cf. Licciardi et al., 2004; Benson at al., 2005). Non-

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synchronous LGM glacier behavior in particular has broader implications for late Pleistocene climate dynamics in western North America, implying that factors other than variations in insolation (i.e. Milankovitch forcing) may have played a role in driving advance and retreat (Clark and Bartlein, 1995; Hostetler and Clark, 1997; Thackray, 2001; Thackray et al., 2004; Licciardi et al. 2004).

This paper presents the results of a pilot study wherein a limited number of ^{10}Be and ^{36}Cl exposure ages were obtained from boulders on two, “Pinedale-age” (sensu lato) terminal moraine complexes, and thus date the local LGM in the Taylor River drainage basin, central Colorado. By increasing the geographic distribution of temporal records of glacial advances, the ages presented here will help resolve the issue of regional synchroneity of late Pleistocene alpine glacial advances and its implications for mechanisms of climate change. Moreover, these ages more precisely constrain the timing of climate change inferred from local LGM equilibrium-line altitudes in the southern Sawatch Range and Elk Mountains (Brugger and Goldstein, 1999; Brugger, 2006).

2. Methods

Rock samples were obtained from atop seven granite boulders on local LGM (known locally as Taylor River-age) terminal moraines in the Taylor River valley proper and Texas Creek (Fig 1). Large boulders (2-4 m in the longest dimension) in excess of ~1 m in height (Table 1) were selected for sampling to minimize potential shielding by snow or sediment cover in the case of post-depositional exhumation (Putkonen and Swanson, 2003). In addition, samples were taken from relatively flat boulder surfaces and away from edges and corners to minimize the effects of boulder geometry on in-situ cosmogenic nuclide production rates and/or neutron-loss effects (cf. Masarik and Weiler, 2003). The moraine in the Taylor River valley was deposited by the largest lobe of a glacier complex that covered about 215 km^2 during its maximum extent (Brugger 2006). The five boulders sampled here are located on relatively flat (therefore presumably stable) individual ridge crests nested within the moraine and far from valley walls. Vegetation at these sites is sparse and consists largely of grass and sagebrush communities; no trees are present. The coarse-grained texture of the granitic lithology makes them susceptible to weathering. This texture also means that boulders did not striate or polish well during transport, and thus precludes using these criteria to evaluate the degree of post-depositional weathering. Care was taken to avoid those surfaces that showed obvious signs of spalling or extensive weathering.

The two boulders sampled at the Texas Creek location are on the proximal side of a terminal moraine constructed by a large valley glacier (Brugger and Goldstein, 1999). Trees surround both sample localities, but the forest canopy is not very dense. It should be noted that both boulders are some 800-1000 m upvalley from the most distal slope(s) of the moraine (Fig. 1c) and therefore might be associated with the initial retreat of the ice following the local LGM. These boulders also appeared more weathered than those sampled on the moraine in the Taylor valley. Because of the limited number of samples that could be analyzed and the fact that all other large boulders examined on this moraine showed more obvious signs of spalling, fracture, and/or extensive weathering, these were the only samples collected here.

Extraction of quartz for ^{10}Be and various mineral phases (whole rock) for ^{36}Cl and subsequent chemical preparation of the samples were done at the Purdue Rare Isotope Measurement (PRIME) Lab using standard methodology (see for example Gosse and Phillips, 2001, and references therein). Geochemical analyses on those samples used for ^{36}Cl dating (Table 2) were done using X-ray fluorescence for major oxides, inductively coupled plasma mass spectrometry for rare-earth elements, potassium, and calcium, and neutron activation analysis for boron and gadolinium. ^{10}Be/^{9}Be and ^{36}Cl/^{37}Cl ratios (Table 2) were measured using accelerator mass spectrometry (AMS; Muzikar et al., 2003) at PRIME Lab.

^{10}Be exposure ages are determined using a production rate of 5.1 ± 0.3 atoms g^{-1} yr^{-1} at sea level and high latitude (SLHL; Stone, 2000). Production rates for ^{36}Cl are taken as 66.8 ± 10 and 154 ± 20 atoms g^{-1} yr^{-1} (SLHL) from the spallation of Ca and K (Phillips et al., 1996, 2001). The somewhat larger uncertainties assigned to the latter reflect (but certainly do not encompass) the wide range of production rates reported in the literature (cf. Swanson and Caffee, 2001; Gosse and Phillips, 2001 and references therein). SLHL productions rates for ^{10}Be and ^{36}Cl are scaled to altitude and latitude following Stone (2000) and corrected for sample depth following Gosse and Phillips (2001). A neutron attenuation length of 160 ± 10 g cm^{-2} is used and rock density is 2.65 g cm^{-3}. Calculations of ^{36}Cl ages were facilitated using the spreadsheet program CHLOE (Phillips and Plummer, 1996). Changes in production rates due to topographic shielding (Dunne et al., 1999) are negligible (<< 1%) at all sampling sites. Corrections for snow shielding and boulder-surface erosion are discussed subsequently. No corrections are made for potential changes in production rates because of variations in the geomagnetic field through time.

Historical meteorological data, snow course studies, and SNOTEL records from stations 5-10 km away from the sampling locations and at comparable elevations indicate that the modern maximum snowpack thickness is ~0.95 m (the winter mean is 0.36 m with an associated density of 0.24 g cm^{-3}). Pollen and plant macrofossils indicate, however, that modern climate in the region was established by about 2 ka and that slightly wetter conditions and/or higher winter precipitation generally prevailed between ~15 and 4 ka (Fall, 1997). Fall’s (1997) estimates of precipitation during this interval suggest an average roughly 15% greater than modern values. After adjusting snowpack accordingly, shielding corrections are extremely small (0.997 – 1.000) and the resulting cosmogenic ages differ by <1% from their uncorrected values. This implies that such corrections are insignificant even under the assumption of reasonable increases in snowfall for extended periods in the past. Consequently they are not reported here.

3. Results and Discussion

^{10}Be and ^{36}Cl ages are presented in Table 2 and represented schematically in Figure 2. Zero-erosion ^{10}Be ages for moraine boulders on the terminal moraine in the Taylor River valley range between 16.1 ± 1.0 and 20.8 ± 0.8 ka. The uncertainties reported here reflect only those associated with the AMS measurements. The mean, inversely weighted according to the uncertainty in each measurement, suggests an age of 19.5 ± 1.8 ka for this moraine. Zero-erosion ^{36}Cl ages range from 18.2 ± 0.8 to 22.2 ± 1.0 ka, yielding a mean of 20.7 ± 2.3 ka that is in excellent agreement with that for the ^{10}Be ages. Uncertainties in the production rates cited in Section 2 result in zero-erosion ^{10}Be ages that are within ~5% and ^{36}Cl ages within 7-10% of these values. The ^{10}Be and ^{36}Cl ages place the local LGM firmly in marine isotope stage 2 (~12 - 24 ka). The mean ages are also very consistent with those reported[1] for LGM moraines in the San Juan Mountains (18.9 ± 1.6 ^{36}Cl ka) and the Front and Park Ranges (18.4 ± 1.4 ^{36}Cl ka) of Colorado (Benson et al., 2005), and in the Wind River Mountains of Wyoming (20.5 ± 1.8 ^{10}Be ka; Gosse et al., 1995). Similarly the range of cosmogenic ages found on the Taylor River valley moraine corresponds with those found in this broader region (respectively 16.6 – 21.5, 16.5 – 20.9; and 17.5 – 24.0 ka), differences in nuclides notwithstanding.

Cosmogenic ages were also calculated for different assumed rates of surface erosion on the boulders sampled (Table 2; Fig. 2). Rates of continuous erosion are most probably close to 1 mm ka^{-1} based on weathering studies by Benedict (1993) in the nearby Front Range of Colorado where lithologies and climate are similar to those in the study area. An upper limit of 5 mm ka^{-1} is probably reasonable even for instances of episodic fire-induced spalling (Zimmerman et al., 1994). Erosion-corrected mean ^{10}Be ages are ~4 and 9% older than the zero-erosion mean for 1 and 5 mm ka^{-1}, respectively, and mean ^{36}Cl ages younger by 2-3%.

With due consideration of AMS uncertainties, concordance of ^{10}Be and ^{36}Cl ages (Fig. 2b) is reasonably good for two samples (TVP00-1, 3). Concordance is even more reasonable if one considers that the total precision in cosmogenic ages has been estimate to be about ±8% (Gosse and Phillips, 2001) and there remain other, unquantified sources of error. These two samples might also

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[1] Benson et al. (2005) used the same production rates for ^{36}Cl as those used here. ^{10}Be ages for the Wind River Range were recalculated from Gosse et al. (1995) with the parameters (productions rate, attenuation length, scalings, and so forth) used in this study and using the same subset included in Benson et al. (2005). For comparison, Benson et al. (2005) report a mean of 19.6 ^{10}Be ka for the Wind River samples obtained with a production rate of 5.4 atoms g^{-1} yr^{-1}.

suggest that typical rates of boulder weathering are minimal in that concordance is better for low (say ≤ 1-2 mm ka^{-1}) rates of erosion, consistent with Benedict's (1993) work. The discordance between ^{10}Be and ^{36}Cl ages for sample TVP00-4 is difficult to explain in terms of inheritance and/or shielding because its ^{10}Be age is the youngest of the boulders dated on this moraine while the ^{36}Cl age is the oldest. It could be reconciled with a high rate of surface erosion (~11 mm ka^{-1}; Fig. 2b) for which the age becomes 19.1 ka. Such a high rate seems unlikely, however, even for the case fire-induced spalling (Zimmerman et al., 1994). Moreover, field observations indicate that while some spalling is evident at its base, spalling is not unique to this boulder. Nor is there anything peculiar about the geometry and/or surface texture (Birkeland and Noller, 2000) of this or any boulder that might indicate anything other than slower weathering processes (e.g. granular disintegration) dominated on the surfaces sampled. Therefore a more likely explanation is that the magnitude of discordance here is simply an artifact of the production rates used for ^{36}Cl. For example, the values given by Swanson and Caffee (2001) yield a zero-erosion age of 16.0 ka, a 28% reduction in this boulder's apparent age. In view of this and other disadvantages in using ^{36}Cl (Gosse and Phillips, 2001) it seems prudent to assume the ^{10}Be ages presented here are more representative of the true age of this moraine. Finally, because of the uncertainties introduced by hypothetical erosion corrections, the complications of discordance, and the small number of samples, it is not possible to say with certainty whether ages vary systematically across the moraine surface.

The two samples from the terminal moraine in Texas Creek have a mean ^{10}Be zero-erosion age of 14.4 ± 0.8 ka. In view of the ages obtained in the Taylor River valley and within the region (e.g. Benson et al., 2004, 2005) these appear to be rather young. Shielding by either snow and/or sediment is not thought to be a factor for these samples. Modest rates of surface erosion of 1 and 5 mm ka^{-1} increase the mean age to 14.5 ± 0.7 and 15.3 ± 0.8 respectively. As noted previously, however, the probability of spalling on these boulders is high and therefore a more rapid rate of erosion could be considered. For example, using the rate (11 mm ka^{-1}) required for concordance of ^{10}Be and ^{36}Cl ages for TVP00-4 the mean age could be as old as 16.6 ± 0.9 ka. Alternatively, given the locations of the boulders sampled their young ages might document a sustained interval of moraine construction. More likely these ages reflect the slow down-wasting and late melt-out of debris from a stagnating ice margin. Brugger et al. (1988) suggested the latter scenario based on the abundance of ice disintegration features on this particular moraine and low driving stresses over the lower reach of a reconstruction of the Texas Creek glacier. Ultimately these ambiguities need to be resolved before the validity and meaning of these ages can be assessed, but at present they can be taken as minimums for ice retreat in this valley.

4. Conclusions

Cosmogenic ^{10}Be and ^{36}Cl ages for boulders on the terminal moraine complex in the Taylor River valley demonstrate that the local LGM occurred between 16.1 and 20.8 ka, and possibly as early as 22.2 ka if the oldest ^{36}Cl age is included. If this range represents an interval of moraine construction (e.g., Gosse et al. 1995), then its correspondence (within given uncertainties) with those found elsewhere in the Rocky Mountains of Colorado and Wyoming (Benson et al., 2005) suggest regional synchroneity of LGM glacial advances and/or retreats. Barring the effects of shielding, the ages of the two youngest boulders (16.1 and 17.8 ^{10}Be ka, zero erosion) at the very least corroborate the conclusion reached by Benson et al. (2005) that regional deglaciation occurred at ~16.8 ka (cf. Licciardi et al., 2004).

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Table 1
Sample locations and height with respect to moraine surface

Sample	Latitude (° N)	Longitude (° W)	Elevation* (m)	Height** over moraine surface (m)	Sample thickness (cm)
Taylor River valley LGM terminal moraine					
TVP00-1	38.9126	106.5947	2950	1.75	2.0
TVP00-2	38.9138	106.5940	2950	0.90	2.5
TVP00-3	38.9171	106.5901	2960	1.75	2.0
TVP00-4	38.9170	106.5913	2955	1.50	2.0
TVP00-5	38.9157	106.5952	2955	2.00	1.75
Texas Creek LGM terminal moraine					
TCP00-1	38.8515	106.5488	2925	1.50	1.75
TCP00-2	38.8530	106.5507	2940	0.85	2.5

* Elevation given to the nearest 5 m with a presumed accuracy of ±10 m

** Value given is to the nearest 0.05 m

Table 2

Isotope ratios, pertinent whole rock geochemistry (where appropriate), and ^{10}Be and ^{36}Cl ages for the moraine boulders sampled

Sample	Sample weight (g)	^{10}Be/^{9}Be* (10^{-15})	^{36}Cl/^{35}Cl* (10^{-15})	^{35}Cl/^{37}Cl (10^{-15})	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O (wt. %)	Fe_2O_3	MnO	TiO_2	P_2O_5	Sum
TVP00-1	30.82	611 ± 24	718 ± 30	4.21 ± 0.07	62.72	16.22	2.59	1.44	2.94	5.25	5.67	0.10	1.02	0.53	98.48
TVP00-2	30.72	559 ± 46													
TVP00-3	30.40	581 ± 27	632 ± 26	4.29 ± 0.05	66.32	15.96	2.58	0.91	3.07	4.96	3.50	0.07	0.72	0.20	98.29
TVP00-4	32.56	518 ± 33	636 ± 27	3.76 ± 0.06	69.35	15.22	1.79	0.77	3.27	5.21	2.23	0.11	0.34	0.10	98.38
TVP00-5	32.59	524 ± 80													
TCP00-1	59.61	907 ± 31													
TCP00-2	58.33	932 ± 29													

*Blank corrected values; blank ratios as follows: ^{10}Be/^{9}Be for TVP00 samples, 0.0 ± 2.6 x 10^{-15} (below detection); ^{10}Be/^{9}Be for TCP00 samples, 1.8 ± 1.5 x 10^{-15}; ^{36}Cl/^{35}Cl for TVP00 samples, 2.4 ± 3.5 x 10^{-15}.

Sample	Cl (ppm)	B (ppm)	Gd (ppm)	Carrier weights (mg)		Zero-erosion age		1 mm ka^{-1} erosion age		5 mm ka^{-1} erosion age	
				^{10}Be	^{36}Cl	^{10}Be	^{36}Cl	^{10}Be	^{36}Cl	^{10}Be	^{36}Cl
TVP00-1	128	9	9	0.639	1.042	20.8 ± 0.8	22.0 ± 0.5	21.2 ± 0.9	21.6 ± 0.9	22.9 ± 1.0	21.0 ± 1.0
TVP00-2				0.630		18.9 ± 1.6		19.2 ± 1.6		20.6 ± 1.9	
TVP00-3	124	<3	5	0.636	1.065	19.9 ± 0.9	18.2 ± 0.8	20.2 ± 1.0	17.8 ±0.8	21.7 ± 1.1	17.1 ± 0.7
TVP00-4	214	9	4	0.618	1.072	16.1 ± 1.0	22.2 ± 1.0	16.3 ± 1.0	21.4 ± 1.0	17.3 ± 1.2	19.8 ± 0.9
TVP00-5				0.625		17.8 ± 2.7		18.1 ± 2.8		19.3 ± 3.2	
Weighed means						**19.5 ± 1.8**	**20.7 ± 2.3**	**19.8 ± 1.9**	**20.2 ± 2.1**	**21.3 ± 2.2**	**20.1 ± 2.0**
TCP00-1				0.548		13.8 ± 0.5		14.0 ± 0.5		14.7 ± 0.5	
TCP00-2				0.557		14.9 ± 0.5		15.0 ± 0.5		15.8 ± 0.5	
Weighed means						**14.4 ± 0.8**		**14.5 ± 0.7**		**15.3 ± 0.8**	

Figure Captions

(Authors Note – The figures here should be of sufficient quality for review purposes. The maps in Figures 1b and c will be reproduced at a higher resolution. Both are sized in accordance with journal standards.)

Figure 1. (a) Map of the Taylor River drainage basin showing its location in central Colorado and the mapped LGM extent of glaciers. Locations of boulders sampled on the terminal moraine complex in (b) the Taylor River valley and (c) Texas Creek.

Figure 2. (a) Schematic representation of cosmogenic ^{10}Be and ^{36}Cl ages showing the effects of different rates of boulder surface erosion. (b) Concordance diagram for the three samples from which ^{10}Be and ^{36}Cl ages were obtained. Dashed diagonal line represents complete concordance. Erosion "trajectory" (arrows) shows the age relationships as a function of increasing boulder surface erosion. Bold numbers are the value of erosion required for concordance. Error bars reflect only uncertainties in the AMS analyses. Extended error bars shown in gray for zero-erosion ages assume a *total precision* of 8%.

FIGURE 1

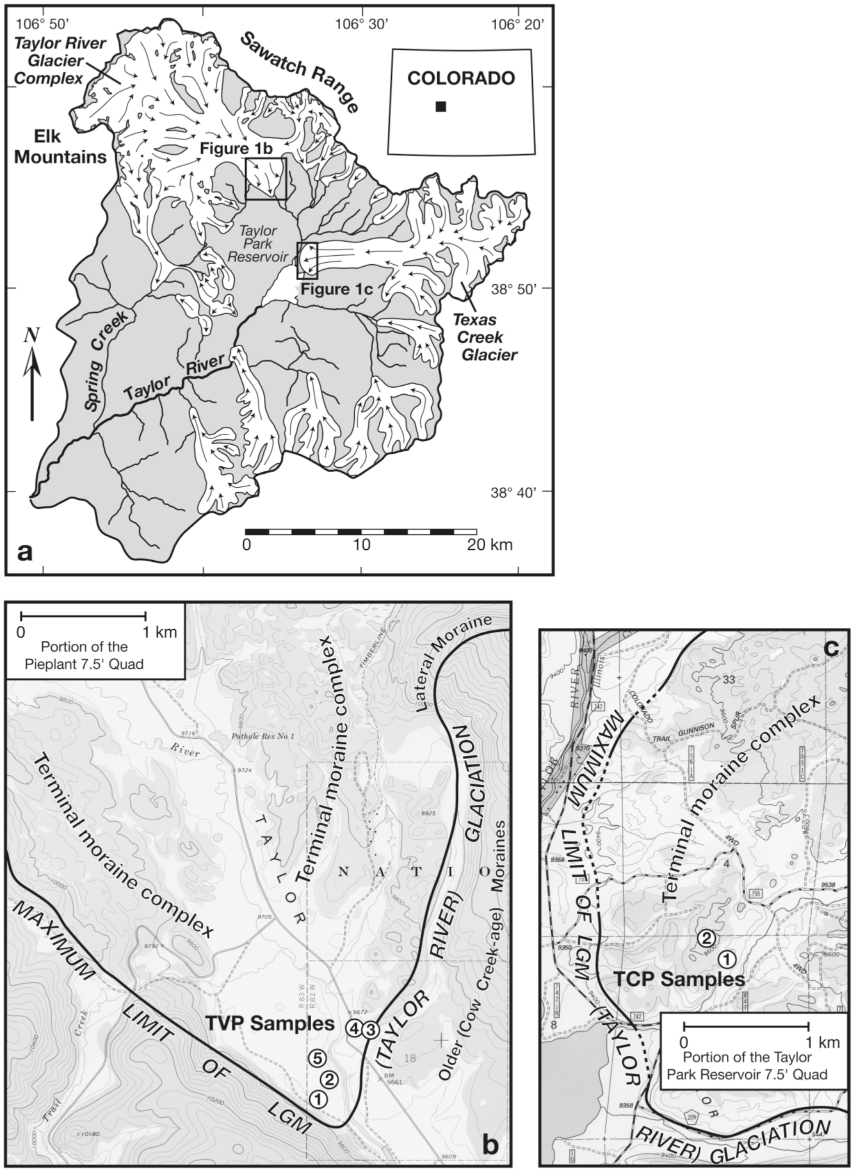
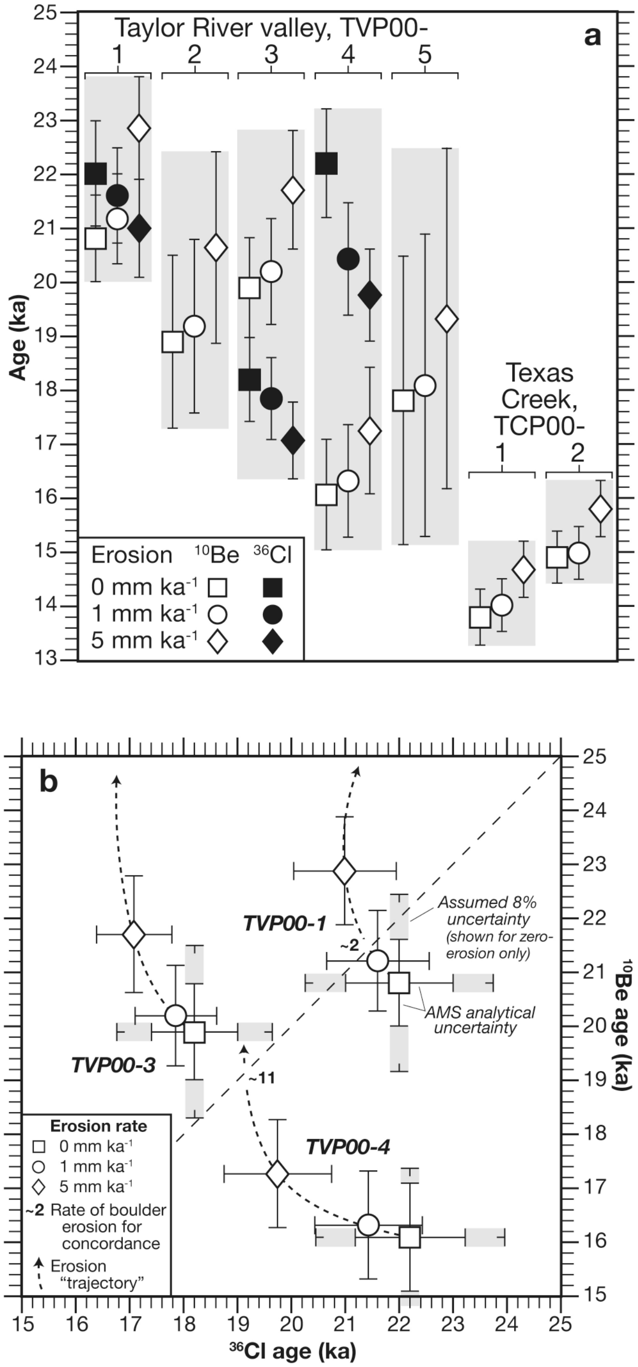

106° 50'
106° 30'
106° 20'
Taylor River Glacier Complex
Sawatch Range
COLORADO
Elk Mountains
Figure 1b
Taylor Park Reservoir
Figure 1c
38° 50'
Texas Creek Glacier
N
Spring Creek
Taylor River
38° 40'
0
10
20 km
a
0
1 km
Portion of the Pieplant 7.5' Quad
Terminal moraine complex
Terminal moraine complex
Lateral Moraine
MAXIMUM LIMIT OF LGM
(TAYLOR RIVER) GLACIATION
Older (Cow Creek-age) Moraines
TVP Samples
④③
⑤
②
①
b
c
MAXIMUM LIMIT OF LGM (TAYLOR RIVER) GLACIATION
Terminal moraine complex
②
①
TCP Samples
0
1 km
Portion of the Taylor Park Reservoir 7.5' Quad

FIGURE 2


a
Taylor River valley, TVP00-
1
2
3
4
5
Texas Creek, TCP00-
1
2
Age (ka)
13
14
15
16
17
18
19
20
21
22
23
24
25
Erosion ¹⁰Be ³⁶Cl
0 mm ka⁻¹ □ ■
1 mm ka⁻¹ ○ ●
5 mm ka⁻¹ ◇ ◆
b
TVP00-1
TVP00-3
TVP00-4
~2
~11
Assumed 8% uncertainty (shown for zero-erosion only)
AMS analytical uncertainty
Erosion rate
□ 0 mm ka⁻¹
○ 1 mm ka⁻¹
◇ 5 mm ka⁻¹
~2 Rate of boulder erosion for concordance
Erosion "trajectory"
¹⁰Be age (ka)
³⁶Cl age (ka)
15
16
17
18
19
20
21
22
23
24
25