Significant degradation of glacial moraines quantified with cosmogenic ^{10}Be, Mono Basin, CA

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Key Points:

- Glacial moraines erode at their crests and accumulate sediment along their flanks at rates of 0.01 – 0.1 mm/yr for the past 10-20,000 years.
- The profile of moraines evolve meters over their lifetimes, suggesting it's best to assign minimum ages to boulders sampled on their crests.
- Significant amounts of 10Be accumulates in sediment as it moves downslope, allowing 10Be to be a tracer for sediment transport rates.

Abstract

We present results that unequivocally demonstrate that glacier moraines erode at their crests and accumulate sediment at their toes, resulting in significant landscape evolution over the lifespan of these landforms. We measured the concentration of cosmogenic ^{10}Be in quartz from ~meter deep soil profiles dug at the crest, flank, and toe of two lateral moraines of different ages in the Mono Basin, CA. The concentrations of ^{10}Be in the profiles show erosion at the moraine crests, and accumulation at their flanks and toes on the order of 0.01 – 0.1 mm/yr for the past 10-20,000 years. Additionally, ^{10}Be concentrations increase downslope significantly. These results are consistent only with sediment transport models that begin with steep and sharp crested moraines that widen and flatten from meters to tens of meters over their lifespans.

Plain Language Summary

Glacial moraines are the most prominent features on land that demonstrate the former size of glaciers during past ice ages. Assigning ages to moraines helps us understand the timing of former ice ages and how glaciers responded to past climate change. As moraines age, they change shape because sediment gets transported downhill. This limits our ability to accurately date them. In this paper, we measured how fast the tops of moraines lower and the sides build up by measuring the concentration of ^{10}Be in quartz sand, which can be used to determine how quickly landscapes change over time. Our computer model and data show that moraines are changing on the order of 0.01 – 0.1 mm/yr for the past 10-20,000 years. This is consistent only with the idea that moraines are initially deposited as steeper and more angular forms that become lower, wider, and more rounded over time.

1 Introduction

Glacial moraines are the most prominent features created by glacier advances, and they are the primary terrestrial landforms used to map the extent and determine the timing of past ice ages. Determining their depositional age is crucial to interpreting glacier moraines as paleoclimate indicators, and a variety of absolute and relative dating methods have been used to establish glacial chronologies (Briner, 2011; Burke & Birkeland, 1979). Recent work has shown that alpine glaciers are a significant water resource and contributor to sea-level rise (Gardner et al., 2013), and this has elevated the importance that we understand the timing and extent of past glaciations in order to establish a baseline for future change. We know that moraines evolve over time, which impacts our ability to accurately date them (Hallet & Putkonen, 1994; Phillips et al., 1990; Phillips et al., 1996; Putkonen et al., 2008; Putkonen & O'Neal, 2006; Putkonen & Swanson, 2003). Yet, there is only one study that has directly quantified moraine degradation rates, and it only measured erosion rates at the moraine crest (Schaller et al., 2009)..

Cosmogenic nuclide exposure dating techniques were first applied to glacial moraines in North America in 1990 (Phillips et al., 1990), and this development allowed for the first time a direct and absolute dating of the mineral matter to provide the depositional age of a moraine. However, if a moraine is continuously eroding, then fresh mineral matter (sand, pebbles, boulders, etc.) would be continuously exhumed and exposed at the surface, resulting in a lower exposure age than the depositional age of the moraine itself. Therefore much of the subsequent exposure age dating of moraines was based on the assumption that erosion is negligible over the lifespan of the moraine (Balco, 2011). On the other hand, evidence based on moraine cross section shape analyses (Putkonen & O'Neal, 2006), exposure age distribution of surface boulders on given moraine surfaces (Hallet & Putkonen, 1994; Putkonen & Swanson, 2003), surface boulder frequencies (Putkonen et al., 2008), lichenometry (Putkonen & O'Neal, 2006), as well as anecdotal observations on fresh and old moraines points to significant amounts degradation of moraines over time. In this paper, we aim to quantify the erosion rate at the crest and the deposition rates along the flanks and toes of two moraines in Mono Basin, CA to improve our understanding of moraine evolution, our interpretation of moraine dating techniques, and our understanding of glacial change.

2 Field Area and Methods

We set out to determine the rate of surface lowering on the same glacial moraines where the original cosmogenic nuclide dating was done in the eastern Sierra Nevada, CA (Phillips et al., 1990) (Figure 1). We surveyed the topography of two moraines with different ages near Bloody Canyon, CA, the older Mono Basin moraine (c. 60-80 kyrs (Gillespie & Zehfuss, 2004)), and the younger Tahoe moraine (c. 42-50 kyrs (Gillespie & Zehfuss, 2004)). On each moraine, we dug soil pits at the crest and along the ice-proximal flanks in a downslope transect (Figures 2 and 3). From each pit, we collected soil samples in vertical profiles at a range of depths down to 60 cm. From these bulk till samples, we isolated quartz sand grains (250 – 500 μm) and analyzed the concentration of *in situ* cosmogenic ^{10}Be in the quartz.

Because the production of cosmogenic nuclides attenuates with depth, we can follow established methods to calculate the erosion rate, mixing depth, and accumulation rate of ^{10}Be in the soil pits independently of the age of these moraines (Lal & Arnold, 1985; Lal et al., 1987;

Lal, 1991; Lal & Chen, 2005, 2006). The basic concept is that when a surface erodes, the concentration of ^{10}Be should decrease with depth, but when the surface accumulates sediment, the concentration will increase with depth initially but eventually begins to decrease with depth. If the soil is being vertically mixed due to bioturbation or geomorphic processes, then the concentration of ^{10}Be will be mixed as well, and we would expect constant concentrations with depth.

To put the results of the ^{10}Be concentrations in context, we compared these results to the rates of erosion and accumulation predicted by a simple, 1-D, linear diffusion hillslope model. Rather than try to precisely predict the evolution of a moraine through time, the goal of this exercise is to examine whether the measured erosion and accumulation rates indicated by the ^{10}Be concentrations generally match the concept of moraine evolution indicated by this hillslope transport model.

Details on sample preparation, cosmogenic nuclide governing equations, exposure model fitting techniques, and the linear diffusion hillslope evolution model are given in the supplement.

3 Results

The measured topographic profiles (Figures 2 and 3) clearly show that the older Mono Basin moraine has a more relaxed profile that is broader and has gentler slopes (maximum slope = 26°). The younger Tahoe moraine has a narrower profile and steeper slopes (maximum slope = 40°). Figures 2 and 3 also show the results of the linear diffusion model run that begins with a 35° slope for the initial moraine profile and is allowed to run for the minimum age of the moraine. We ran a suite of model runs with different starting angles and over the range of the published moraine ages, and in each run we allowed the diffusivity value, κ, to vary to best fit the observed profile. Model results for the erosion and accumulation rates at the pit sites from the range of model runs we sampled are shown in Table 1.

Measured concentrations of ^{10}Be in these soil pits demonstrate that the crests of the moraines are eroding while the toes are accumulating sediment (Figures 2 and 3, Table 1). On the older Mono Basin moraine, the ^{10}Be concentrations for Pit A at the moraine crest decrease with depth, which is consistent with an eroding pit. If we were to interpret these concentrations as reflecting the depositional age and not include erosion, then the concentrations would reflect exposure ages of only 22-35 kyrs. This is much younger than the age of the moraine, which further supports the interpretation that these concentrations reflect significant erosion and continuous exhumation of previously unexposed mineral matter to the moraine surface. The best-fit model predictions for these measured concentrations are for an erosion rate of 0.14 mm/yr (+0.08/-0.04 mm/yr). This rate is independent of the age of the moraine because ^{10}Be concentrations reach an equilibrium with this erosion rate after about 20,000 years, which is much younger than the age of the moraine. This also indicates that this rate is only for what the moraine has experienced in the past 20,000 years, and is not necessarily the rate since deposition. The inherited nuclide concentration remaining in this till today is 3.6×10^5 at/g_{quartz} ($+4.5 \times 10^4$ / -4.4×10^4 at/g_{quartz}), which is not unexpected given that much of the till in this area is redeposited from previous glacial cycles (Phillips et al., 1990; Phillips et al., 1996).

Further down the flank of this moraine, Pit C was dug just past the transition point from a concave down to a concave up profile (Fig. 2), and the measured concentrations of ^{10}Be increase with depth in the pit, indicating the accumulation of sediment. Measured concentrations of ^{10}Be in Pit C suggest an accumulation rate of 0.078 mm/yr (+0.04/-0.02 mm/yr) for the past 10,000 years. Pit D on this moraine was dug into the toe of the moraine where sediment accumulation is expected to be highest. Measured concentrations of ^{10}Be in this pit are nearly identical with depth, suggesting that either this pit has experienced vertical mixing due to bioturbation, or that the site experienced a geologically recent (in the past 1,000 years) ~meter thick deposit of sediment all at once.

At the crest (Pit E) of the younger Tahoe moraine the pit stratigraphy and ^{10}Be concentrations indicate mixing to a depth of at least 44 cm (the maximum depth at which roots were observed), and the lowest sample is used to constrain the erosion rate. Again, if we were to interpret the concentrations as simple exposure ages, then the moraine concentrations would reflect only 15-22 kyrs of exposure, which is too little for the age of the moraine. We utilize the exposure model of Lal & Chen (2005, 2006) that incorporates mixing, erosion, and exposure age, which yields an erosion rate of 0.066 mm/yr (+0.01/-0.01 mm/yr), a mixing depth of 46 cm (+8.4/-1.9 cm) and an exposure age of 36,000 yrs (+8,300/-5,700 yrs) for the moraine. These results are not well constrained, but are consistent with field observations and overlap with the published age range (Gillespie & Zehfuss, 2004).

Along the flank and toe of the Tahoe moraine, Pits G and H clearly show the accumulation of sediment in their measured ^{10}Be concentrations because they increase with depth. Pit G, dug just past the transition point from erosion to accumulation, indicates an accumulation rate of 0.059 mm/yr (+0.010/-0.01 mm/yr) for the past 17,000 years. Pit H, dug in the toe of the moraine where sediment buildup should be large, indicates an accumulation rate of 0.095 mm/yr (+0.04/-0.020 mm/yr) for the past 12,000 years. These measurements indicate that the toe of this moraine is accumulating sediment faster than the flank, which is expected for a site further downslope.

4 Discussion

A central question about moraine evolution is whether the two moraines started off with similar topographic profiles and are different because the older moraine has had more time to change, or if they are different because the older moraine started off with a more relaxed profile to begin with. The ^{10}Be concentrations generally match the concept of moraine evolution indicated by the hillslope transport model, which has the moraines starting with the same triangular shape initially. The model results are of the same order of magnitude as the rates measured from the ^{10}Be concentrations, and most of the measured rates fall within the range of the transport model predictions (Table 1). The best-fit values for the diffusivity, κ, range from 0.027 – 0.045 m^2/yr for the Mono Basin moraine, and 0.0002 – 0.0083 m^2/yr for the Tahoe moraine. These values are well within the range of κ values found throughout the globe, which range from 10^{-1} – 10^{-4} m^2/yr (Fernandes & Dietrich, 1997; Heimsath et al., 1997; Oehm & Hallet, 2005; Putkonen & O'Neal, 2006; Roering et al., 1999), and the difference between the two moraines is consistent with the ideas that: 1) due to it being older it has had lower slope angels for the past 10-20 kyrs, than the younger moraine, and 2) the older Mono Basin moraine has experienced different climate regimes over its existence (Madoff & Putkonen, 2016). Our ^{10}Be and hillslope model results for the Sierra Nevada, CA are also consistent with the rates determined from soil pits dug on the crests of moraines in the Rocky Mountains (Schaller et al., 2009).

The ^{10}Be concentrations from the soil profiles capture the rates of degradation of these moraines for the past 10-20 kyrs, but it is important to note that based on the hillslope model, the rate of degradation decreases as the moraine cross-profile relaxes from the sharp crested initial form to a wide and gentle sloped one (Putkonen & Swanson, 2003). Recent research has also shown that as the rate of degradation is dependent on the climate, and the climate in this area has changed drastically over the lifespan of these moraines. The rate of degradation over the recent 15 kyrs has been the lowest that it has been for the past 50 kyrs (Madoff & Putkonen, 2016). Therefore, our results represent the minimum rates over the lifespan of the moraine, and are consistent with the model that predicts rapid initial degradation that slows over time, and underestimate the average rate and total magnitude of degradation over the lifespan of these moraines.

An additional observation from the data that supports the notion that moraines undergo significant post-depositional degradation is that the ^{10}Be concentrations increase on each moraine by 2 – 10 x 10^5 at/g_{qz} of ^{10}Be from the uppermost sample of the pit at the crest, and then down the flanks and to the toes. This result is consistent on both moraine, and cannot be accounted for by inherited nuclides due to previous exposure. If the moraines had not undergone erosion and accumulation, we would expect to find nearly similar concentrations along the profile. This observation cannot be reconciled with a model that presumes moraines start off with rounded crests and broad toes, closely resembling their current forms and experiencing little to no landscape evolution. This result also has broad implications for the method of using detrital quartz in fluvial systems to calculate basin-scale erosion rates (Bierman & Steig, 1996; Granger et al., 1996; Henck et al., 2011). That method assumes negligible ^{10}Be is acquired along hillslopes, but our results show that significant amounts are produced while traveling down slopes of 200-300 meters. This observation also opens up the possibility of using the concentration of ^{10}Be in downslope profiles to quantify sediment transport rates.

5 Conclusions

These results have implications for how to best sample a moraine to determine its depositional age from its exposure age based on samples collected from large boulders. It has been recognized that older moraines have a wider scatter in exposure ages (Balco, 2011; Putkonen & O'Neal, 2006), and our results support the interpretation that this is likely caused by the postdepositional disturbance and exhumation of fresh boulders. Our results clearly indicate that sediment is traveling downslope, during which time it will continue to accumulate more cosmogenic nuclides, and may also cause boulders to roll over, get buried, and exhume fresh boulders at the crest. Our results also suggest that one would get different exposure ages by taking bulk samples from different parts of the moraine toes because it takes sediment significant time to reach these locations. Although moraine crests will erode and exhume fresh boulders, which will yield younger exposure ages than the depositional age, this is a more reliable way to assign a minimum age to a moraine, which is the only limiting age that is supported by our results.

The degree to which glacial moraines change through time has been debated since the 1930s when techniques for establishing relative ages of moraines were developed (Blackwelder, 1931; Matthes, 1940). Here we have presented the first results to directly measure and quantify the amount of erosion and accumulation that moraines are undergoing along a topographic profile, and unequivocally demonstrate their evolution through time. By measuring cosmogenic ^{10}Be concentrations in soil profiles, we demonstrate that moraine crests erode and their flanks and toes accumulate at rates on the order of 0.01 – 0.1 mm/yr, which is consistent only with a landscape evolution model that begins with the moraine crossections as straighter, steeper, and more angular features that degrade through time. At these rates, moraines will evolve on the order of meters per 10,000 years. Because these measurements represent the most recent 10-20 kyrs, they capture only the gentlest moraine slopes and driest climate, which both independently slow down the rate of degradation, and they therefore capture only the minimum rates over the lifespan of these moraines.

In addition to informing how we sample and interpret exposure ages of glacial moraines and illuminating the rates and patterns of landform evolution, these results also have implications for how we utilize cosmogenic nuclides from detrital fluvial sediments to determine basin-scale erosion rates. In both transects, the sample at the top of the pit at the toe of the moraine has 2 – 10 times the concentration of cosmogenic ^{10}Be as does the sample at the top of the crest of the moraine, which means the quartz is accumulating significant amounts of ^{10}Be as it moves downslope. The method of collecting detrital sediment from various points of a watershed and determining the basin-scale erosion rate from the concentration of cosmogenic nuclides from the detrital sands assumes that negligible amounts of cosmogenic nuclides accumulate while the sediment moves downslope. Our samples accumulate significant amounts of ^{10}Be while traveling down steep, loose slopes of only 200-300 meters, which calls into question the validity of this assumption. The increase in the concentration of ^{10}Be downslope also opens up the possibility that *in situ* cosmogenic ^{10}Be could be used as a tracer to determine sediment transport rates.

Acknowledgments, Samples, and Data

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All data referenced in this paper are contained in the tables in the main text and the supplement. They are also available online through the Open Science Framework (links TBD).

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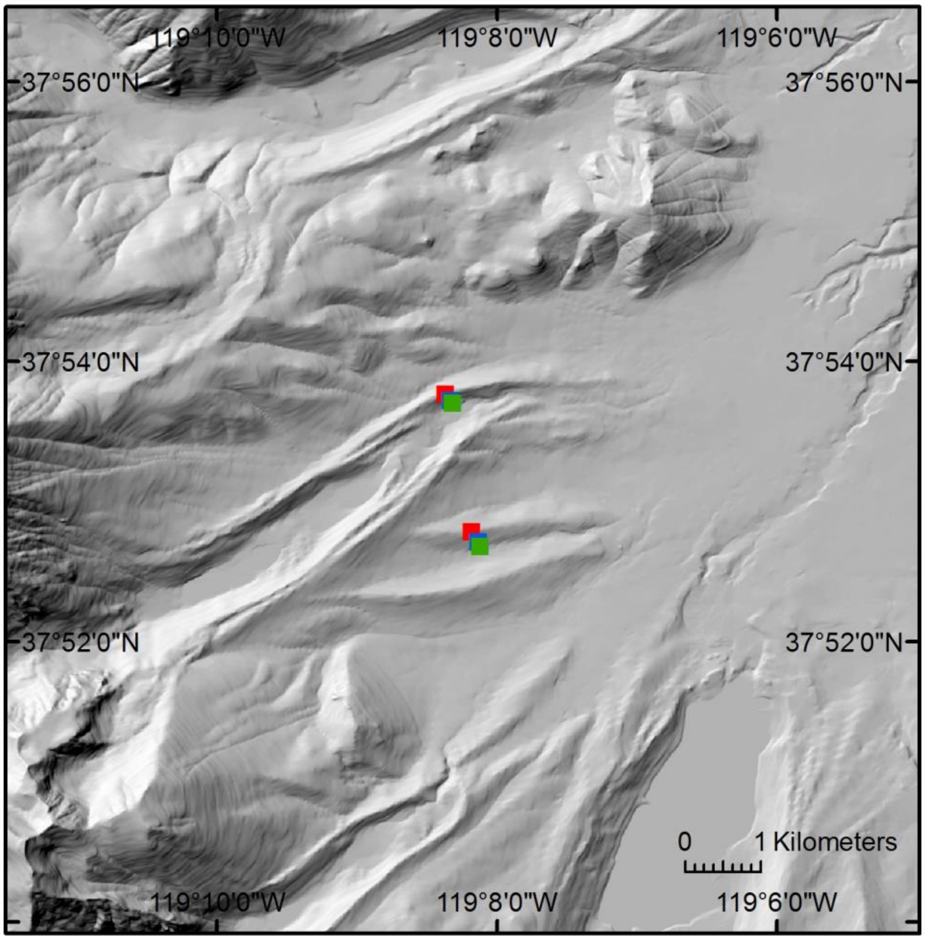


Figure 1. Shaded relief map of the moraines in Bloody Canyon, CA. Colored boxes indicate pit sites in this study, and colors coordinate with Figures 2 and 3.

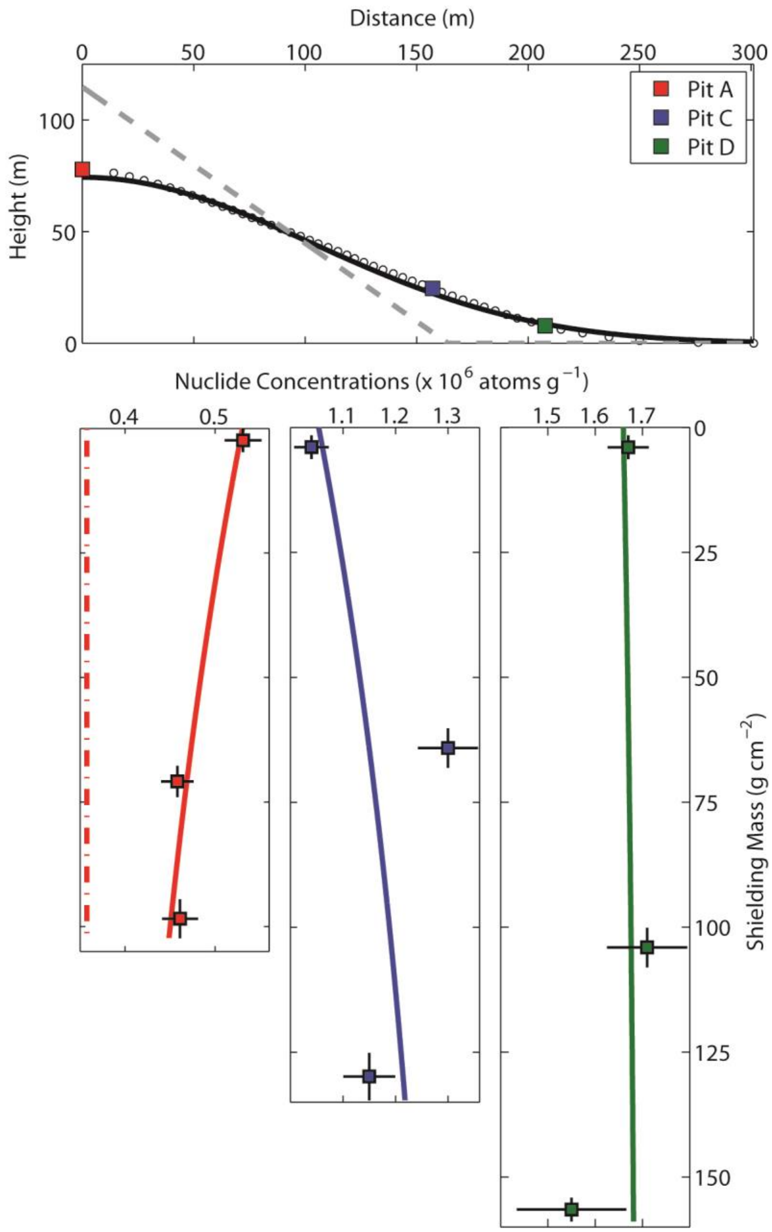


Figure 2. The Mono Basin Moraine. Top: the measured topographic cross section (open circles), the modelled initial profile of the moraine at a slope of 35° (dashed-gray line), and the best-fit model profile (solid-black line). The colored boxes indicate the location of each hand-dug soil pit along the hillslope and correspond to the lines in plots below. Bottom: For each soil pit, the measured concentration of ^{10}Be with shielding mass (depth times density). The boxes show the measured concentration, while horizontal bars show the measurement error and vertical bars demonstrate the thickness of each sample collected. Solid lines indicate the best-fit model result to predict the measured concentrations. Dashed lines indicate any inherited nuclide concentrations remaining in the samples today. Best-fit model results are shown in Table 1.

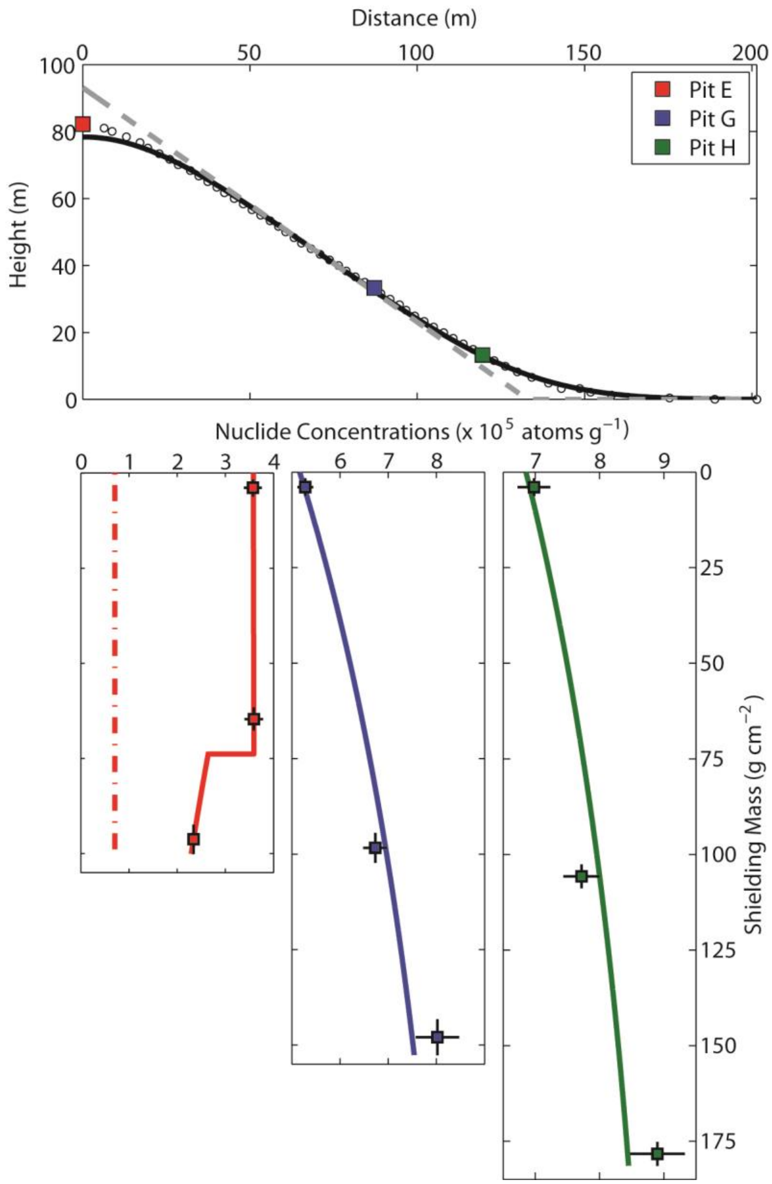


Figure 3. The Tahoe Moraine. Symbols and colors are the same as indicated in Figure 2.

Table 1. Erosion and accumulation rates indicated by the ^{10}Be concentrations and the linear diffusion model predictions. Fit refers to the error-weighted chi-square fit as the metric between the measured and modeled concentrations.

		^{10}Be Results (mm/yr)					Model results (mm/yr)		
Site	**Pit location**	**^{10}Be Profile**	**Rate**	**Error +**	**Error -**	**χ^2 Fit**	**Model prediction**	**Minimum**	**Maximum**
Mono Basin moraine	Pit A - Crest	Erosion	0.14	0.08	0.04	0.62	Erosion	0.19	0.31
	Pit C - Flank	Accumulation	0.078	0.04	0.02	9.0	Accumulation	0.08	0.14
	Pit D - Toe	Mixed		Mixed		1.3	Accumulation	0.09	0.14
Tahoe moraine	Pit E - Crest	Mixed with erosion	0.066	0.01	0.01	0.10	Erosion	0.02	0.18
	Pit G - Flank	Accumulation	0.059	0.01	0.01	2.1	Accumulation	0.00	0.02
	Pit H - Toe	Accumulation	0.095	0.04	0.02	2.2	Accumulation	0.00	0.60

Figure 1.

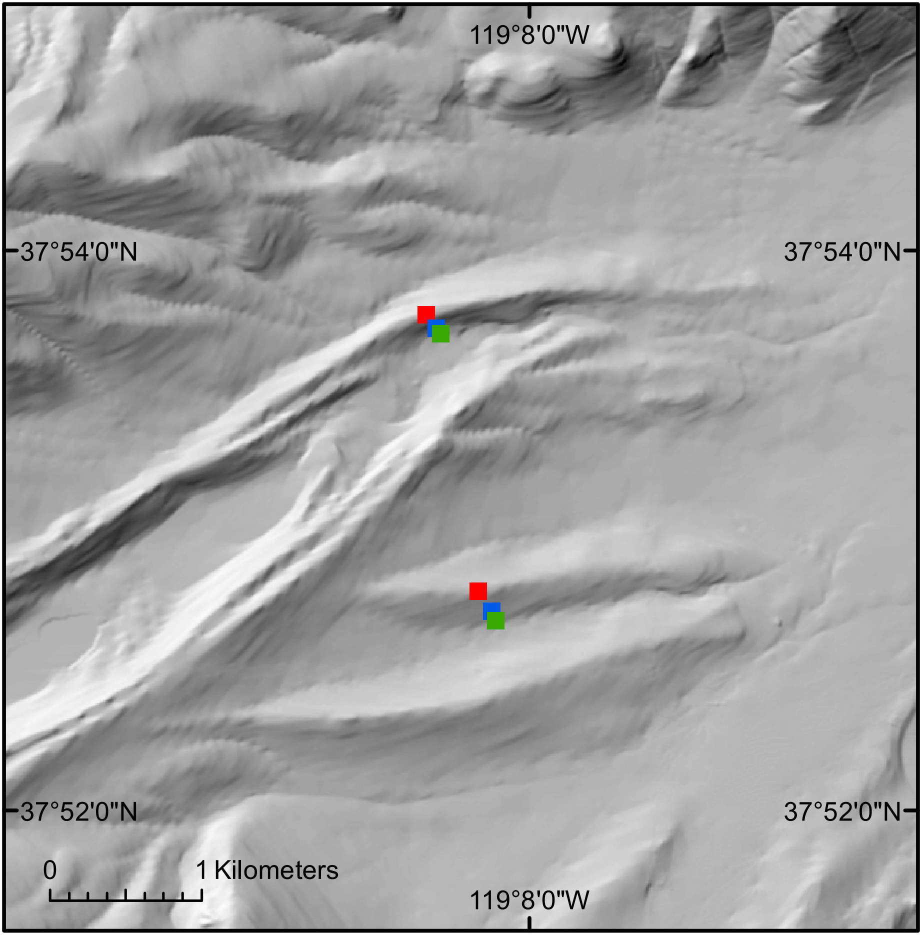
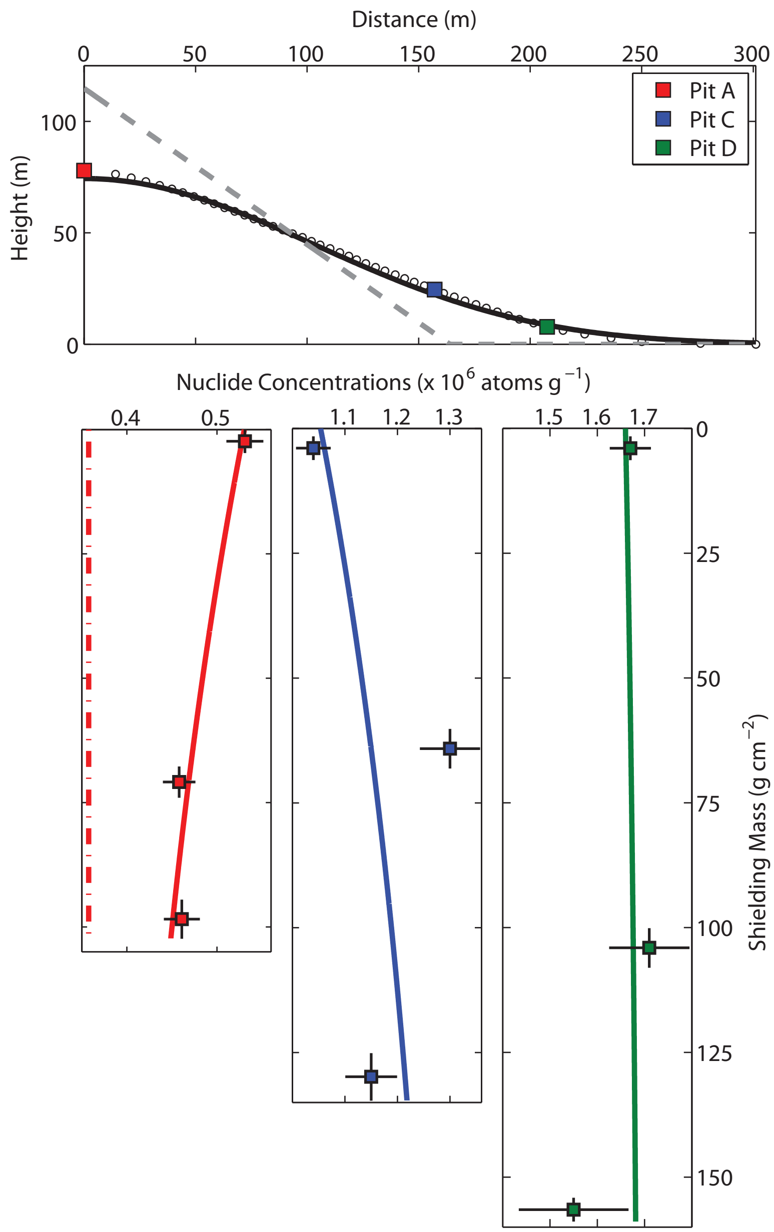
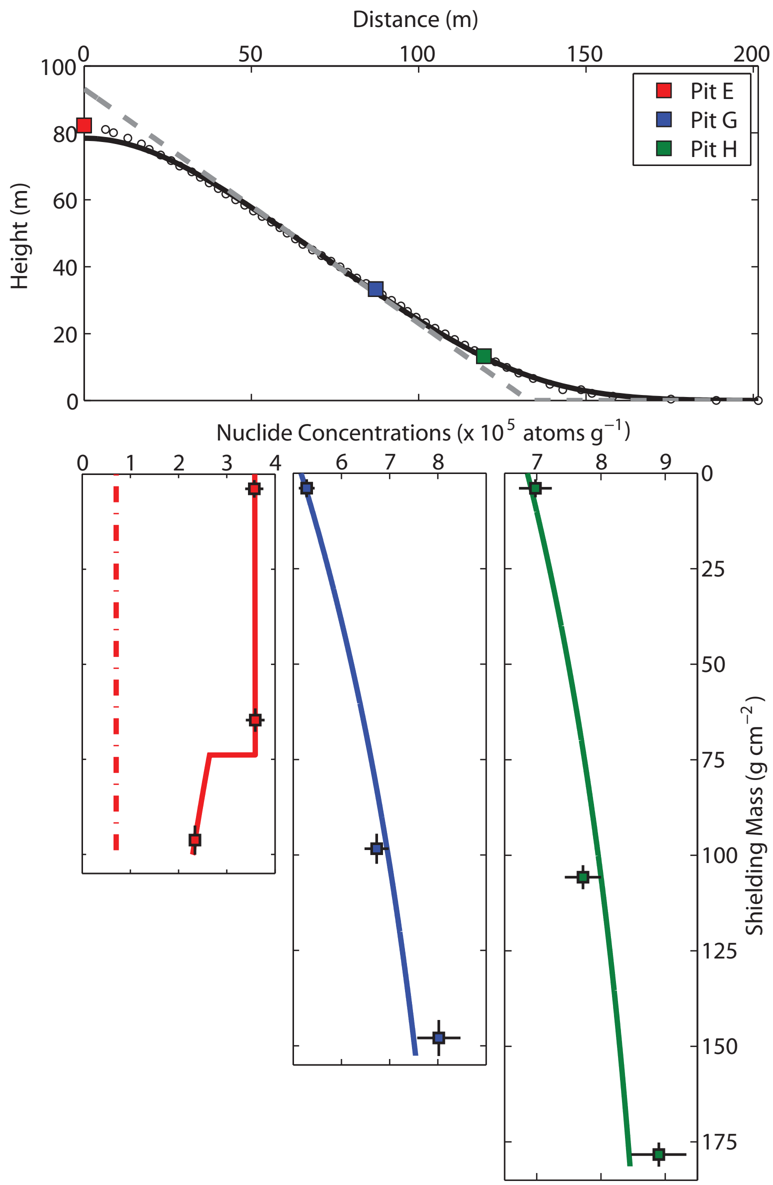

119°8'0"W
37°54'0"N
37°54'0"N
37°52'0"N
37°52'0"N
0
1 Kilometers
119°8'0"W

Figure 2.



Distance (m)
0
50
100
150
200
250
300
Height (m)
100
50
0
Pit A
Pit C
Pit D
Nuclide Concentrations (x 10^6 atoms g^−1)
0.4
0.5
1.1
1.2
1.3
1.5
1.6
1.7
Shielding Mass (g cm^−2)
0
25
50
75
100
125
150

Figure 3.



Distance (m)
0
50
100
150
200
100
80
60
40
20
0
Height (m)
Pit E
Pit G
Pit H
Nuclide Concentrations (x 10^5 atoms g^-1)
0
1
2
3
4
6
7
8
7
8
9
0
25
50
75
100
125
150
175
Shielding Mass (g cm^-2)

Table 1. Erosion and accumulation rates indicated by the 10Be concentrations and the linear diffusion model predictions. Fit refers to the error-weighted chi-square fit as the metric between the measured and modeled concentrations.

		^{10}Be Results (mm/yr)					Model results (mm/yr)		
Site	**Pit location**	**^{10}Be Profile**	**Rate**	**Error +**	**Error -**	**χ^2 Fit**	**Model prediction**	**Minimum**	**Maximum**
Mono Basin moraine	Pit A - Crest	Erosion	0.14	0.08	0.04	0.62	Erosion	0.19	0.31
	Pit C - Flank	Accumulation	0.078	0.04	0.02	9.0	Accumulation	0.08	0.14
	Pit D - Toe	Mixed		Mixed		1.3	Accumulation	0.09	0.14
Tahoe moraine	Pit E - Crest	Erosion with mixed zone	0.066	0.01	0.01	0.10	Erosion	0.02	0.18
	Pit G - Flank	Accumulation	0.059	0.01	0.01	2.1	Accumulation	0.00	0.02
	Pit H - Toe	Accumulation	0.095	0.04	0.02	2.2	Accumulation	0.00	0.60