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Slow regolith degradation without creep determined by cosmogenic nuclide measurements in Arena Valley, Antarctica

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Abstract

Estimates of regolith degradation in the McMurdo Dry Valleys of Antarctica are currently based on indirect evidence and ancient ashes at or near the soil surface that suggest excellent preservation of surfaces. On the other hand, the existing cosmogenic-nuclide surface exposure ages from many parts of the Dry Valleys are younger than the age of surface deposits inferred from stratigraphic relations. This suggests some combination of surface erosion or past ice cover, both of which would reduce the apparent exposure age. This paper quantifies the regolith degradation and/or past ice cover by measuring ^{10}Be and ^{26}Al from a landslide deposit that contains 11.3 Ma volcanic ash. The surface sample yields an apparent exposure age of only 0.4 Ma. However, measurements of the subsurface nuclide concentrations show that the deposit has not been shielded by ice, and that the age of the ash does not conflict with the apparent exposure age when slow degradation of the deposit (2 m Ma^{-1}) is taken into account. Soil creep, which is a common degradational process in a wide variety of environments, is non-existent at this field site, which likely reflects the persistent lack of bio- and cryoturbation.

Keywords: Degradation; Erosion; Sediment transport; Cosmogenic isotope; Dating; Antarctica; Dry Valleys

Introduction

It is a challenge to unravel the glacial history of Antarctica because almost all (>99%) of the land area is covered by ice. The largest ice free area in Antarctica is the McMurdo Dry Valleys, a valley complex that contains a number of well mapped surficial deposits whose provenance and weathering characteristics suggest a series of glaciations (Nichols, 1966; Calkin, 1971; Brown et al., 1991; Brook et al., 1993, 1995; Hall et al., 1993; Marchant et al., 1993a, 1996; Bockheim, 2002). At present the chronology of surficial deposits in the Dry Valleys is based largely on dated volcanic ashes intercalated with or superposed on glacial deposits. The limiting minimum ages provided by ashes are typically 4–15 Ma (Marchant et al., 1996).

Based on the physical characteristics of the dated, millions of years old ashes that are found at or near soil surface, it is suggested that they were deposited immediately after their eruption and are found today in their primary depositional location (Marchant et al., 1993a,b; Sugden et al., 1995; Marchant et al., 1996). In addition, over 1-Ma-old moraines are found preserved on steep (28°–35°) hillslopes (Brook et al., 1993). The fact that the ancient ashes are still preserved in their original depositional position and that millions of years old moraines have not been eradicated on steep hillslopes has been taken to collectively demonstrate vanishingly small degradation, transport, and deposition of regolith over a million-year time scales. Degradation is here defined as the general lowering of the surface of the land by erosive processes (Rice, 1952). We use the term to describe the mass removal and lowering of both bedrock and regolith surfaces regardless of the geological process responsible.

The suggested extreme preservation of high-altitude (>1000 masl) Dry Valleys sediments (Marchant et al., 1993a,b; Schäfer et al., 1999; Summerfield et al., 1999a,b; Schäfer et al., 2000) challenges our understanding of the landscape degradation rates that generally come from degradation studies of Holocene and ice-age scarps, moraines, and hillslopes in the mid-latitudes (Nash, 1980, 1984; Hanks et al., 1984; Hallet and Putkonen,

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1994; Fernandes and Dietrich, 1997; Heimsath et al., 1997; Hanks, 2000; Schäfer et al., 2000; Roering et al., 2001; Putkonen and Swanson, 2003; Oehm and Hallet, 2005; Putkonen and O'Neal, 2006; Putkonen et al., in press-a). More generally, it challenges our current understanding of the ubiquitous subaerial degradation of regolith on Earth.

It is also interesting that cosmogenic isotope analyses of bedrock surfaces in the same field area (Arena Valley) have revealed assumed steady-state degradation of the bedrock at rates of 0.23–0.6 m Ma^{-1} (Summerfield et al., 1999a). Typically the regolith degradation rate is the same or larger than the bedrock erosion rate in a given location. If the regolith was degrading at this admittedly slow rate it would still alter the landforms over the very long time scale of millions of years.

The advent of cosmogenic isotope dating of mineral material has made it possible to establish exposure ages for rocks and deposits that have resided at or near the soil surface (Lal, 1987, 1991; Nishiizumi et al., 1989, 1993). The well known dependence of cosmogenic isotope production rates as a function of shielding depth allows us to study directly the rate at which the regolith is eroding. Here we attempt to quantify the regolith degradation and resolve the apparent conflict between observations suggesting negligible degradation on a steep slope for many millions of years and our understanding of hillslope processes in arid and polar environments elsewhere (Matsuoka and Moriwaki, 1992; Enzel et al., 1996; Oehm and Hallet, 2005). We do this by directly measuring the soil degradation rate in Arena Valley, at a site where both the geomorphology and the presence of 11.3 Ma old ash suggests negligible degradation of a steep slope since the deposition of the ash.

The motivation for this work is twofold: 1) it is counterintuitive and difficult to understand how regolith degradation would be less effective than bedrock degradation, and 2) regolith degradation is ubiquitous on Earth and operates in all environments that have been studied to date. If degradation did not operate or the rate was vanishingly small in the Dry Valleys, it would reveal aspects of the geological processes that have not been observed elsewhere.

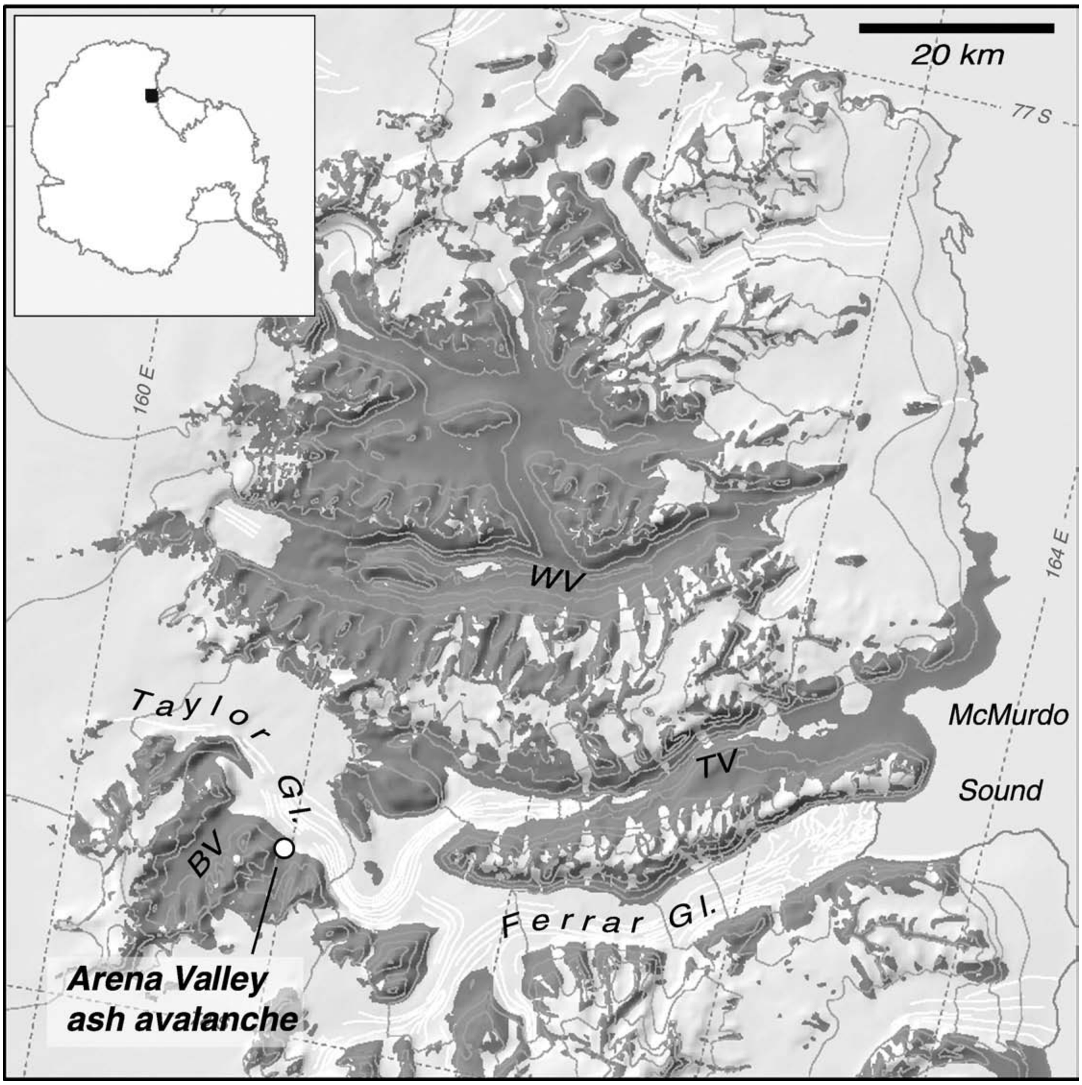

Figure 1. Map of the Antarctica (inset) and the field area in the Arena Valley. BV = Beacon Valley, WV = Wright Valley, and TV = Taylor Valley.

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Field site and data

The McMurdo Dry Valleys of Antarctica have a cold desert climate that receives less than 100 mm water equivalent of solid precipitation in the form of snow per year, as measured at Lake Vanda (Fountain et al., 1999). The mean annual air temperature in the alpine valleys (>1000 masl) is typically around − 24°C (Putkonen et al., 2003) and at lower altitudes − 21°C (Fountain et al., 1999). Running melt water is regularly observed in the lower valleys (~ 200 masl) and we have occasionally witnessed it in the alpine valleys (>1000 masl). The area is free of all higher animal and plant life supporting only lichen, algae, soil microbes, and the sporadic penguin, seal or bird trying to find their way back to McMurdo Sound and open water.

Arena Valley is an alpine valley located in the southwestern Dry Valleys (Fig. 1). The valley mouth is at 1100 m elevation and is blocked by the margin of the Taylor Glacier. A sequence of arcuate moraines extending upward into the valley record past Taylor glacier expansions into the Arena Valley (Brook et al., 1993; Marchant et al., 1993b). These moraines are composed mainly of openwork boulder piles bedded in thin till sheets. Brook et al. (1993) measured the ^{3}He and ^{10}Be exposure ages of large sandstone boulders on these moraines: boulders on the youngest major moraine (Taylor II) have ages near 120 ka. In the older deposits the ^{3}He is assumed to be diffusing out of the rock thus making the boulder ages appear too young (Brook et al., 1993). Therefore, the oldest ^{10}Be age of 1.1 Ma from the Taylor IVa moraine is suggested to approximate the true age of the deposit more reliably than the younger ^{3}He ages. However, it is still likely to be significantly younger than the true age because of boulder surface erosion.

The lower Arena Valley ash avalanche, the focus of this study, was originally described by Marchant et al. (1993b). It is a lobate landslide deposit, 50 m wide and up to 1.5 m thick, that originates in a couloir high on the west valley wall near 1650 m elevation and extends to the valley floor (Fig. 2). The lower part of the landslide is overlain by the Taylor IVa moraine sequence, indicating that the landsliding predates 1.1 Ma. The landslide deposit itself is a diamict composed of approximately equal parts of 11.3 Ma old volcanic ash and colluvial debris (Marchant et al., 1993b). Marchant et al. (1993b) suggest that the landsliding most likely originated by failure of an unstable accumulation of volcanic ash on steep valley walls, and thus must have taken place shortly after deposition of the ash, that is, near 11.3 Ma ago. This scenario, combined with the fact that "the lateral contacts between the avalanche deposit and adjacent colluvium are sharp and are marked by an abrupt change in surface slope" and apparently not modified by degradation or downhill sediment transport, led them to suggest stability or little degradation and downslope sediment transport at this site for 11.3 Ma.

The conclusion of the long-term slope stability, however, rests on the argument that the landslide deposit was in fact emplaced at the time of the ashfall. If the landslide deposit was much younger than the ash itself, its apparently intact preservation would be correspondingly less surprising. Furthermore, the idea that the landslide deposit has not eroded in 11.3 Ma is somewhat in conflict with ^{21}Ne measurements of the erosion rate on adjacent bedrock slopes of 0.23–0.60 m Ma^{-1} (Summerfield et al., 1999b): if the landslide deposit, which is only a few meters thick, was also eroding at this rate, it would have been largely effaced after several Ma. Thus, we attempted to learn about the age of emplacement of the landslide deposit, its surface degradation rate, and whether or not downslope transport of regolith has occurred since initial emplacement, by measuring the cosmic-ray-produced nuclides ^{10}Be and ^{26}Al in a series of surface and subsurface sediment samples from the landslide deposit. The sample site is located at 1290 m altitude (77°50′S, 160°59′E) in the center of the landslide deposit, about 10m above the highest prominent moraine: the Taylor IVa moraine of Marchant et al. (1993b).

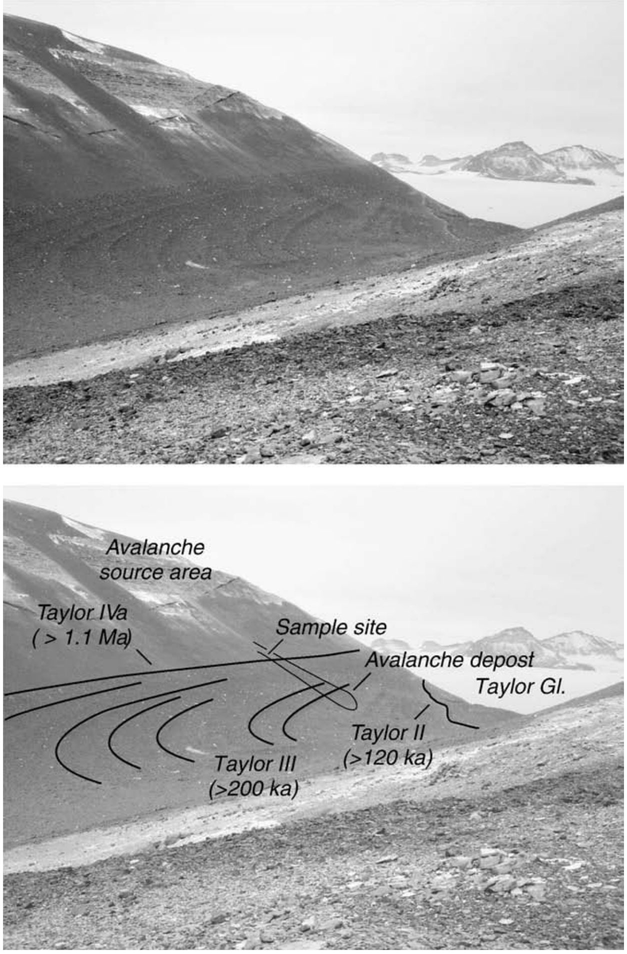

Figure 2. Upper panel shows the field site in the lower Arena Valley, Antarctica showing a view toward North. In the background can be seen Taylor glacier and Asgard Range. Lower panel shows the same view with line drawing highlighting geological features and locations that are discussed in the text. The ages in the lower panel are after Marchant et al. (1993b).

Analyses

We collected a series of four bulk sediment samples from a 1-m-deep hand-dug soil pit. We measured the sediment density, which is required to calculate nuclide production rates at the sample depths, by packing the sediment samples into a container of known volume. We extracted quartz from the samples by dry-

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Table 1
Isotope data that is used in the calculations

Pit 9 lower Arena landslide						
Sample ID	Depth in soil (cm)	Soil density (g cm $^{-3}$)	^{10}Be (atoms g$^{-1}_{\text{quartz}}$)	^{26}Al (atoms g$^{-1}_{\text{quartz}}$)	^{10}Be 1 std uncertainty	^{26}Al 1 std uncertainty
04-AV-Pit 9-1-4	2.5	1.87	7.96E+06	3.82E+07	1.04E+05	1.01E+06
04-AV-Pit 9 32-26	34.0	1.90	6.00E+06	2.56E+07	8.04E+04	6.57E+05
04-AV-Pit 9 60-65	62.5	1.82	4.84E+06	1.88E+07	6.73E+04	5.34E+05
04-AV-Pit 9 84-90	87.0	1.85	3.63E+06	1.37E+07	5.66E+04	4.14E+05
		mean = 1.86 ± 0.1				

sieving to extract the 0.3–0.5 mm size fraction, heavy liquid separation to remove pyroxene grains derived from local dolerite, and repeated etching in 2% HF to purify the quartz. We extracted Be and Al using standard methods (Stone, 2004) and measured Be and Al isotope ratios by accelerator mass spectrometry at Lawrence Livermore National Laboratory in Livermore, California. Combined carrier and process blanks contained $1.85 \times 10^5 \pm 1.6 \times 10^4$ atoms ^{10}Be and $6.3 \times 10^4 \pm 6.5 \times 10^4$ atoms ^{26}Al. Isotope ratios are normalized to the standards KNSTD3110 for Be and KNSTD10650 for Al. Table 1 shows the sample depths, density measurements, and ^{26}Al and ^{10}Be concentrations. We obtained the ^{10}Be and ^{26}Al production rates at our site by using the rates of Stone (2000); these production rates are 20.4 atoms g^{-1} yr^{-1} and 124 atoms g^{-1} yr^{-1} for ^{10}Be and ^{26}Al, respectively. The topographic shielding factor for the field site is 0.97. The results are given in Table 1 and Figure 3.

Results and discussion

Our approach to interpreting the cosmogenic nuclide measurements is based on the idea that we can use the geologic and geomorphic context of the samples to tell us "what happened", and the cosmogenic-nuclide concentrations to tell us "when" or "how fast". In this case, the important aspects of the geomorphic context, that is, the "what," are as follows. First of all, the quartz sediment in the avalanche deposit was derived from some preexisting colluvium or regolith, higher up on the valley wall that was entrained with the ash at the time the avalanche took place. It was most likely exposed to cosmic rays before it was emplaced, so it must have contained inherited ^{10}Be and ^{26}Al, but we have no information as to what these inherited nuclide concentrations would have been. However, even if we do not know the inherited nuclide concentrations, the fact that the avalanche deposit is unstratified and apparently well-mixed throughout tells us that the inherited nuclide concentrations should be the same at all sample depths.

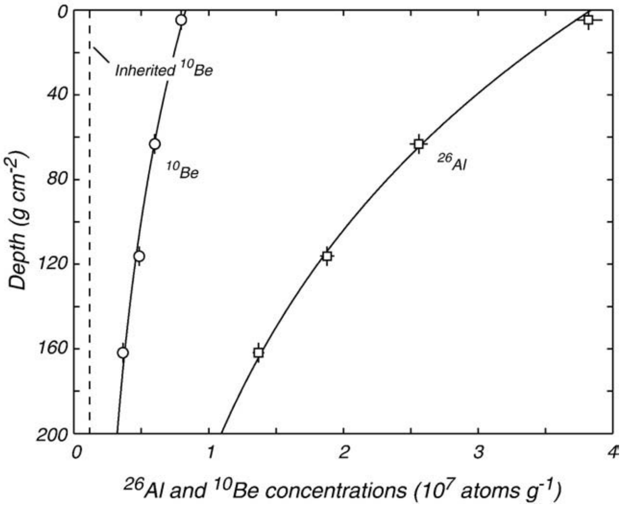

Figure 3. Measured ^{26}Al and ^{10}Be concentrations (atoms g$^{-1}_{\text{quartz}}$) in the soil profile. Circles (^{10}Be) and rectangles (^{26}Al) denote the measurements. The solid thin lines show the best fit model concentrations. The dashed vertical line shows the calculated remaining inheritance of ^{10}Be atoms in the soil. Due to shorter half life no inherited ^{26}Al can be detected in the samples.

Second, after the avalanche deposit was emplaced, it could have simply been exposed until the present time without disturbance, it could have been subject to slow surface degradation without any mixing or transport processes, or it could have experienced a combination of surface degradation and soil mixing during downslope transport by soil creep. Finally, although our site is above the highest prominent moraine in the west side of lower Arena Valley (Taylor IVa of Marchant et al. (1993b)), erratics are found at higher elevations (Marchant et al., 1993b), which is consistent with the mapped position of the Taylor IVb moraine on the east side of the valley at a higher altitude than Taylor IVa. It is also possible that our site was covered by non-eroding ice at some time after the deposition of the Taylor IVa moraine 1.1 Ma ago.

At the altitude of the sample site, and at less than 1 m depth, production of ^{26}Al and ^{10}Be is almost entirely by spallation, which is important because it means that the production rate of nuclide i at depth z is simply described by $P_i(z) = P_i(0)\exp(-z/\Lambda)$, where P_i has units of atoms g^{-1} yr^{-1}, z has units of g cm^{-2} and Λ is generally taken to be 160 g cm^{-2} (see Gosse and Phillips (2001) for a detailed discussion of the value of Λ). Thus, if we leave aside soil mixing for the moment, the processes of steady exposure and steady degradation since avalanche emplacement would result in a nuclide concentration-depth relationship described by:

$$N_i(z) = N_{i,\text{inh}} + N_{i,\text{exp}} e^{-z/\Lambda} \tag{1}$$

where $N_i(z)$ is the concentration of nuclide i (atoms g^{-1}), $N_{i,\text{inh}}$ is the concentration of nuclide i inherited from the time the deposit was emplaced, and $N_{i,\text{exp}}$ is the surface concentration of nuclide i, which depends on the surface degradation rate and the depositional age of the avalanche deposit according to the simple exposure age equation of (Lal, 1991). This argument follows the one in Hancock et al. (1999) and Repka et al. (1997) for fluvial

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terrace sediments and in Balco et al. (2005a,b) for till. The importance of this relationship is that, for each nuclide, the concentration–depth relationship can be described by two unknown parameters, $N_{i,\mathrm{inh}}$ and $N_{i,\mathrm{exp}}$. As we have four measurements of the concentration of each nuclide at different depths, we can uniquely determine both. Thus, the benefit of measuring nuclide concentrations at multiple depths is that we can separate the inherited nuclide concentration from that which developed after the deposit was emplaced by fitting curves of this form to our observations.

Following this reasoning, we fit Eq. (1) to our measurements. We carried out the fitting procedure by an error-weighted least-squares method, and derived the uncertainties in the fitted parameters by a Monte Carlo simulation that took uncertainties in measured nuclide concentrations and sediment density into account. The results are as follows: the surface nuclide concentrations attributable to postdepositional exposure of the avalanche deposit are $7.08 \pm 0.18 \times 10^6$ atoms g^{-1} ^{10}Be and $37.4 \pm 0.59 \times 10^6$ atoms g^{-1} ^{26}Al, and the inherited nuclide concentrations are $1.10 \pm 0.09 \times 10^6$ atoms g^{-1} ^{10}Be and $0.03 \pm 0.15 \times 10^6$ atoms g^{-1} ^{26}Al. These values fit the data with reduced χ^2 statistics of 2.4 and 1.1 for ^{10}Be and ^{26}Al respectively. Figures 3 and 4 show these results.

This exercise leads to our first important observation, which is that both ^{26}Al and ^{10}Be measurements do in fact fit Eq. (1) above. This means that vertical mixing of soil has apparently not occurred during the period of exposure recorded by our measurements. This, in turn, strongly suggests that if the regolith has degraded and been transported downhill it must have been limited to the immediate surface of the deposit (less than a few centimeters depth). Given that the avalanche deposit is a rocky diamict, it is difficult to visualize a means by which significant soil creep could occur in an entirely laminar or bulk fashion.

Having separated the inherited nuclide concentration from that developed after the avalanche was emplaced, we can discuss what we learn from these two quantities separately. The postdepositional nuclide concentrations reflect the exposure age and degradation rate of the avalanche deposit according to the simple exposure equation of Lal (1991). First, the postdepositional ^{26}Al and ^{10}Be concentrations lie near the steady-state erosion line of Lal (1991) (Fig. 4). This means that there is no evidence that our site was ever covered by ice in the time period during which the present nuclide concentrations accumulated. This observation highlights the importance of accounting for the inherited nuclide concentration in sedimentary deposits: the raw nuclide concentrations in all of our samples fall below the steady erosion line and, if inheritance were not taken into account, might be wrongly interpreted as evidence for ice cover of the site.

Second, if the postdepositional nuclide concentrations were interpreted as exposure ages without taking account of degradation, they would suggest that the avalanche deposit was deposited 0.4 Ma. This cannot be true, as they are overlain by a moraine whose exposure age is 1.1 Ma. This, taken with the observation that the postdepositional nuclide concentrations lie on the steady erosion line, indicates that they reflect the surface degradation rate of the avalanche deposit, not its exposure age. Following this reasoning, we find that the surface degradation rate at the site is 2.1 m Ma^{-1}. Besides telling us the degradation rate of the deposit, this observation is important because it tells us over what period of time the conclusions that we draw from the postdepositional nuclide concentrations apply. This period is essentially the time required to remove material equivalent to several attenuation lengths, in this case not more than 2 Ma.

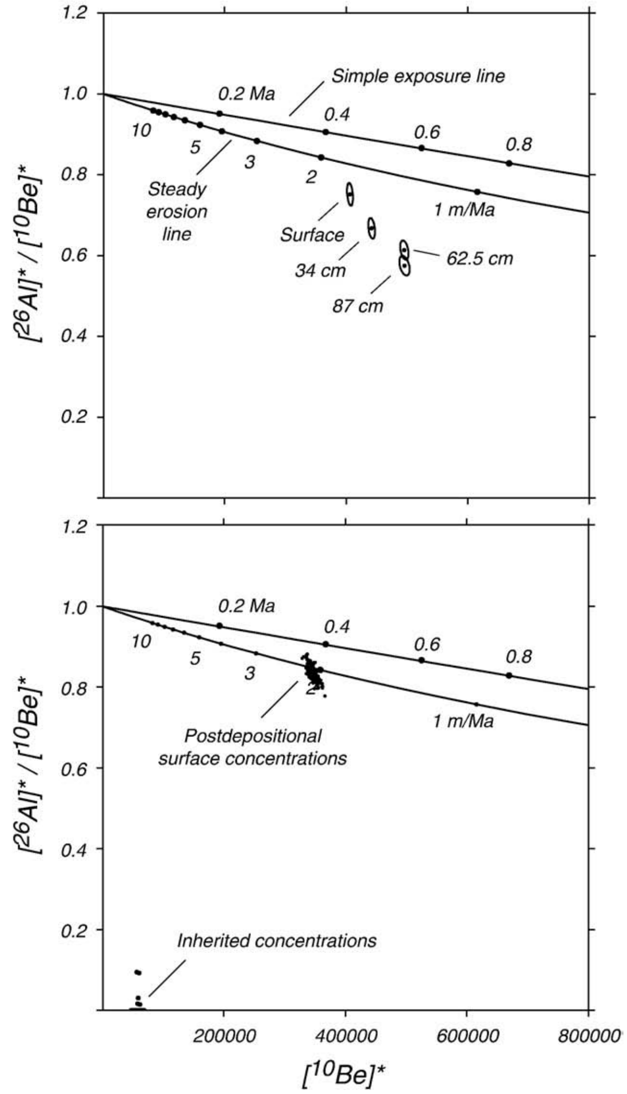

Figure 4. Upper panel: measured ^{10}Be and ^{26}Al concentrations in surface and subsurface samples. Nuclide concentrations in all samples have been normalized to the production rate at the corresponding depths in the soil. This allows all the data to be represented on the same diagram. The ellipses show 68% confidence regions. Nuclide concentrations in surfaces that have experienced only a single period of steady exposure without erosion plot on the simple exposure line; those who have experienced simple exposure with steady erosion plot on the steady erosion line. A fuller explanation of this diagram is given by Bierman et al. (1998), Lal (1991) and Balco et al. (2005b). Lower panel: results of separating the inherited and postdepositional nuclide concentrations as described in the text, again normalized to the production rate at the corresponding depths in the soil. Each point represents a single realization of a 200-point Monte Carlo error analysis. The resulting postdepositional concentrations plot directly on the steady erosion line. The inherited ^{26}Al concentration is indistinguishable from zero, suggesting that the deposit is older than several half-lives of ^{26}Al.

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Thus, our conclusions that there was no soil mixing, that the surface degradation rate was 2.1 m Ma^{-1}, and that there is no evidence for ice cover of the site, only apply to the last 2 Ma.

We now consider the inherited nuclide concentrations. The inherited nuclide concentrations that we observe at present are the result of radioactive decay of the original nuclide concentrations present at the time of emplacement. If we can put some limits on the possible nuclide concentrations at the time of emplacement, we can limit the age of the avalanche deposit. In order to do this, we must assume that the sediment in the ash avalanche originated from erosion of sandstone bedrock on the upper valley wall above the ash avalanche and that, when they were transported by avalanching, they had ^{26}Al and ^{10}Be concentrations in equilibrium with steady erosion at that site. These assumptions would in principle allow us to determine the erosion rate on the upper valley wall and the depositional age of the avalanche by following the procedure for burial dating of river terraces described by Granger et al. (1997, 2001). These assumptions are plausible, but unlike those that we made in constructing Eq. (1) they are not clearly supported by stratigraphic evidence. Thus, the conclusions we draw from this exercise are more speculative. We are also hampered in applying the burial-dating method by the fact that the ^{26}Al concentration is indistinguishable from zero. This prevents us from obtaining a unique burial age, but it tells us that the avalanche deposit must be older than several half-lives of ^{26}Al. As the half-life in question is 0.705 Ma, this suggests that the avalanche is older than approximately 3–4 Ma. We can also limit the maximum age of the avalanche by observing that, at the time of avalanche emplacement, its ^{10}Be concentration can have been no higher than the saturation concentration, at zero erosion, at the source area. The time required for this to decay to the observed ^{10}Be concentration gives a maximum age for the deposit. This value is $N_{10,\mathrm{sat}} = P_{10,\mathrm{source}}/\lambda$ where $P_{10,\mathrm{source}}$ is the ^{10}Be production rate at the source area, and λ is the decay constant. If the source was near 1800m (the elevation of the ridge crest at that site), the saturated ^{10}Be concentration would be near 6.5×10^7 atoms g^{-1}, and the age of the deposit could be no older than 9 Ma. Although this is younger than the radiometric age of the ash in the avalanche deposit, the fact that the assumptions used to obtain it are not clearly grounded in stratigraphic evidence prevents us from interpreting it as strong evidence that the deposition of the ash significantly postdated the age of the eruption.

Conclusions

The apparent excellent preservation of soil surfaces on relatively steep slopes (28°–35°) over millions of years in the Dry Valleys of Antarctica is intriguing in the light of generally ubiquitous degradation of all soil-mantled hillslopes on Earth. Currently no quantitative estimates of the regolith degradation in cold deserts exist, which hinders numerical modeling of landscape evolution and general analyses of regolith mobility.

The analyses of the measured cosmogenic ^{10}Be and ^{26}Al isotope concentrations in the shallow (0.9 m) soil profile in a landslide deposit in the lower Arena Valley leads to four conclusions: 1) based on the superposition of >1 Ma old moraine and the cosmogenic isotope accumulation in the regolith, the young (~0.4 Ma) apparent surface age of the deposit is the result of slow degradation of the surface at a rate of 2.1 m Ma^{-1} over a minimum of the past 2 Ma, 2) based on the undisturbed cosmogenic isotope concentration profiles, no soil creep or mixing has occurred in the interior (0.02–0.87 m depth) of the regolith deposit, 3) the field site has not been shielded by cold based non-eroding ice within the past 2 Ma, and 4) based on the decay of the inherited cosmogenic isotopes in the regolith, a weak argument can be made for the age of the landslide deposit being 4–9 Ma old.

Our conclusions have the following implications. The findings show that in cold desert of Arena Valley, Antarctica, the regolith degrades continuously at a slow rate (2.1 m Ma^{-1}). As many of the surfaces in the field area have been exposed for millions of years since last ice cover (Marchant et al., 1993b) it can be expected that the total regolith degradation over time amounts to meters to tens of meters on similar slopes. Such a substantial degradation alters the current perception of stability of regolith surfaces in Antarctica and has to be accounted for in any research that relies on long-term immobility of the substrate.

Soil creep, which is a common degradational process in a wide variety of environments (Oehm and Hallet, 2005), is nonexistent at this field site, which certainly reflects the persistent lack of plant and animal life and consequently the lack of bioturbation, and the lack of water and related cryoturbation in the regolith. Therefore, the regolith transport that is implied by the slow degradation must be confined to the soil surface, which agrees with the findings by Putkonen et al. (in press-b).

Based on the cosmogenic isotope measurements within the regolith we found no evidence that the field site that is about 10 m above the Taylor IVa moraine (dated at >1.1 Ma) has been shielded by non-eroding ice within the past about 2 Ma; this suggests that the Taylor glacier has not advanced beyond the Taylor IVa moraine at this site since it receded prior to 1.1 Ma ago.

If our weak argument that the landslide deposit is 4–9 Ma old is correct it implies that the landsliding event may have postdated the primary ash fall by several Ma, which raises the possibility that the ash deposits in general may be remobilized well after their initial deposition, which is recorded by their respective eruption age.

We speculate that since there is no creep within the regolith that could explain the degradation and the regolith is at least today free of soil ice and visible moisture, the only plausible mechanism to transport the regolith at the surface is wind that can only affect a thin surface layer. We suspect that as the regolith weathers the resulting finer fractions are mobilized by wind that due to longer downhill trajectories predominantly moves the particles down hill or in case of the finest fractions may become suspended and be completely evacuated from the area. The commonly seen ventifacts, sand dunes, and direct measurements attest of the eolian activity and availability of mobile sediments (Nichols, 1966; Malin, 1985, 1991; Lancaster, 2002).

We conclude that the cosmogenic-nuclide concentrations amend the previously published research in one important aspect: the regolith degradation at the field site is measurable

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and amounts to 2 m Ma^{-1} or a total of at least 4 m over the past 2 Ma. In the global scale this regolith degradation rate is small. It is over an order of magnitude smaller than measured bedrock degradation in actively denuding areas such as Himalaya (Burbank et al., 2003). However, even a low rate of degradation sustained over a period of millions of years is capable of transforming a landscape by exhuming elevated areas and burying original surfaces in local lows.

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