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Remnants of a fossil alluvial fan landscape of Miocene age in the Atacama Desert of northern Chile using cosmogenic nuclide exposure age dating

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Abstract

We have used cosmogenic nuclides to estimate limits on the surface exposure durations and erosion rates of alluvial fans and bedrock surfaces in the Atacama Desert in Chile. The oldest landforms we studied are extensive alluvial fans referred to as "Atacama gravels". With the exception of samples collected in Antarctica, the cobbles collected on these alluvial surfaces have the lowest erosion rates of any samples, as determined by cosmogenic nuclides, analyzed to date. The oldest cobble has a model surface exposure age of 9 Myr, based on combined measurements of cosmogenic ^{10}Be, ^{26}Al, and ^{21}Ne concentrations. Cobbles from the alluvial fans are eroding slower than the surrounding steep mountainous bedrock surfaces. Maximum erosion rates for cobbles on alluvial surfaces are uniformly <0.1 m/Myr. The survival of these gravels, specifically, and more generally, the stability of landform features in this geographic area is made possible by the attainment of hyperarid conditions in the Atacama Desert resulting from global climatic cooling about 15 Myr ago combined with the rain shadow effect caused by uplift of the Central Andes. The landform features observed presently in the Atacama Desert are remarkably stable and, despite the inevitable erosion that is detectable using cosmogenic nuclides, undoubtedly bear considerable resemblance to conditions as they existed in the Miocene. Over geologic time, the Atacama landscape is evolving in such a manner as to erode the higher bedrock ridges relative to the more stable, but stratigraphically lower depositional surfaces through which clastic detritus now travels occasionally along the floors of incised drainage systems leaving the older permeable alluvial fan surfaces largely intact as widespread remnants of a Miocene fossil landscape.

Keywords: Atacama Desert; Atacama gravel; complex exposure age; cosmogenic nuclide; erosion rate; surface exposure age

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1. Introduction

The Atacama Desert of northern Chile is one of the most arid regions on Earth; attainment of hyperarid conditions occurred ~13–15 Myr ago, most likely triggered by Miocene global climatic cooling associated with the formation of the Antarctic ice cap and the northern propagation of a cold littoral current along the west coast of South America [1]. It is hypothesized here that the landforms in this region dating to the Miocene the scarcity of rainfall may preclude substantial alteration of landform features by erosion. The hypothesized antiquity of the Atacama landscape, specifically the alluvial surfaces, is based on two lines of evidence. The first is ^{40}Ar–^{39}Ar dating of multiple pyroclastic volcanic tuffs intercalated with aerially-extensive "Atacama" gravels shed from the uplifting Andes [2–4], indicating a Miocene age of deposition of these sediments. Most importantly however, the chronology of landform evolution in the Andes (uplift, erosion, fluvial transport, deposition and in particular, exposure history) is further based on the ages of near surface K-bearing mineral precipitates (alunite, jarosite, and cryptomelane) formed in the oxidized portions of supergene systems related to numerous porphyry copper ore deposits of Chile, Peru, Bolivia, and Argentina (Fig. 1). Fluctuations in ground water levels create hydro-chemical systems in which an unsaturated oxidized zone overlays a saturated reducing zone. As these systems desiccate, the regional ground water table descends causing oxidation and leaching of previously-reduced sulfides, leaving behind dateable mineral assemblages bearing the fossil imprint of the redox conditions prevailing at that time [5,6]. The K-bearing mineral precipitates formed by oxidation of sulfides derived from copper ore deposits are dated using ^{40}Ar–^{39}Ar techniques [1,7–11]. Most ages for these vadose zone mineral assemblages are mid-Miocene, near 11–15 Myr [1,12]. However, age histograms also show cessation of supergene phenomena at about 11 Myr [1,11]. The onset of the hyper-aridity that led to the preservation of this fossil landscape is indicated by the cessation of precipitation of dateable minerals from paleo-ground water at about 9 Myr [1,11]. Long-term aridity and geologic stability produced an environment in which surface features potentially remain intact for many millions of years. To confirm the antiquity of these surfaces based on ^{40}Ar–^{39}Ar dating of supergene minerals with an independent isotopic technique and to quantify the unusually slow long-term erosion rates indicated by the preservation of both the buried volcanic tuffs within the Atacama gravels and the alunite, jarosite and cryptomelane precipitates, cosmogenic nuclides were measured from a suite of sample collected from alluvial fans, stream beds, and bedrock surfaces in the Atacama Desert. Anticipating the antiquity of these surfaces cosmogenic stable noble gas, ^{21}Ne was measured in addition to the ^{10}Be–^{26}Al pair. Although the majority of studies use only one or two cosmogenic nuclides, we demonstrate that the measurement of additional one or more nuclides is essential for establishing whether these samples experienced a relatively simple or a complex exposure history.

2. Sampling strategy, experimental procedure, and production rates

We selected 12 samples of quartz-rich surface bedrock and boulders for measurement of in situ produced cosmogenic nuclides. The rocks we sampled typically were about 15 to 20 cm in diameter. Sample locations and descriptions of sample lithologies are indicated in Figs. 1 and 2. Using published geomorphic relative age estimates by Mortimer [3], we chose four geologically distinct landforms representing the latter two stages of landform development described by Mortimer [3]. Mortimer's four surface age interpretations are: (1) the Cumbre Phase 1 Planation Surface which is thought to be the oldest landscape remnant, (2) the Sierra Checo del Cobre Surface of intermediate age, (3) the widespread Atacama pediplain consisting of high alluvial terraces locally incised by the youngest of the surfaces, and (4) the latest drainage incision. The oldest landforms studied here are extensive alluvial fans referred to as "Atacama gravels", which we sampled in two areas: the Damiana alluvial fan area (Samples 23, 24) in the El Salvador Mining District and the Sierra Villanueva Mountains (SVM) (73, 74) about 10 km south of El Salvador where many of the cobbles studied were coated with desert varnish indicating a possible antiquity. The ^{40}Ar–^{39}Ar ages of intercalated rhyolitic ignimbrite ash beds constrain the age of deposition to between 15.3 and 10.5 Myr [2,3]. The second type of

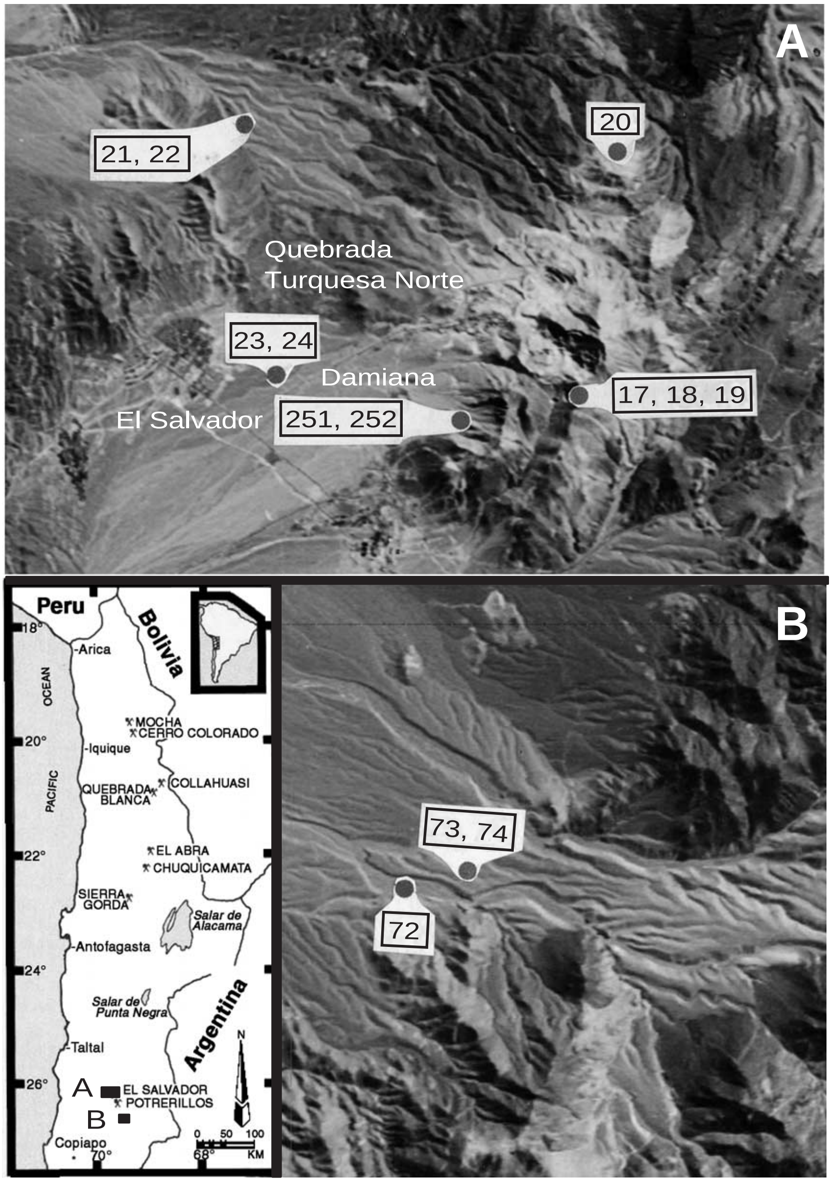

Fig. 1. Location and sample sites plotted on Landsat photo base maps A and B showing the 12 samples studied from the El Salvador Mining District of northern Chile in relation to other porphyry copper deposits. Atacama gravels are light-colored areas labeled “Fan” in A and B.

surface sampled (21, 22) is an alluvial fan in the Quebrada Turquesa Norte area north of El Salvador. Field observations indicate that the upper portions of the fans in Quebrada Turquesa are locally eroded in such a way that their northern proximal faces have been worn down to andesite basement. The third set of samples (72) was collected from incised streambeds in the SVM where rare storm flow is localized. These channels contain cobbles which, according to the relative age assignments of Mortimer [3], should be youngest of all. Finally, bedrock samples (17, 18, 19, 20, 251) from steep slopes in Quebrada Granito were sampled to yield exposure ages of in situ bedrock for comparison with the previous three sample types.

The concentrations of in situ produced cosmogenic ^{10}Be ($t_{1/2}$ = 1.5 Myr) and ^{26}Al (0.705 Myr) were mea-

Fig. 2. Samples 1248-17, 18 (C), and -19 are in-place quartz veins from Quebrada Granito. Sample 1248-20 is a quartz pod from Cerro Pelado. A rock hammer is shown for scale in D, F, and G. Samples 1248-21 and -22 are aplite cobbles from Quebrada Turquesa Norte. Samples 1248-23 and -24 (D) are quartz vein cobbles from the Damiana area. Sample 1248-72 (E) is a cobble within a contemporary intermittent streambed from an incised channel in an Atacama gravel fan in the Sierra Villanueva Mountains (SVM) (B). Samples 1248-73 (F) and -74 (G) are quartz cobbles from the top of the alluvial fan in SVM immediately adjacent to and within 100 meters of sample 1248-72 (E). Sample 1248-251 is a siliceous jarosite cemented ferrocrete in Quebrada Riolita. Sample 1248-252 was not used in this work.

sured for each of the 12 samples. After crushing and grinding the top <2 cm of each sample to an appropriate size, quartz was extracted from these rocks by chemical leaching [13]. After dissolution, Be and Al were separated from each quartz sample and chemically purified [13]. Al concentrations were determined by atomic absorption spectrometry. ^{10}Be and ^{26}Al AMS measurements were carried out at the LLNL AMS facility [14]. Cosmogenic ^{21}Ne in aliquots of quartz from two samples was also measured.

To calculate exposure ages and erosion rates we use the nuclide concentrations from Nishiizumi et al. [15,16] for glacially polished samples from the Sierra Nevada in California. By using the Sierra Nevada site as a calibration site, which has a similar altitude and latitude as the Atacama Desert site, we substantially reduce uncertainties in the production rate due to altitude and latitude scaling. We recalculated the site-specific production rates using a 13,000 deglaciation age [17] and using geographic latitude, i.e. with a local production rate of 52.4 ± 2.5 ^{10}Be atoms/g SiO_2 yr at 685 g/cm^2 and 37°N [15]. We then used the scaling factors of Lal [18] to calculate production rates at the Atacama Desert sites, which differ only slightly in altitude from those of the Sierra Nevada glacially polished calibrated samples and by ~10° in latitude. The original Nishiizumi et al. [15] and Lal [18] papers assumed a 7% muon contribution at this elevation. More recent studies indicate that this value is too high (e.g. [19]); however, the similarity in altitude and latitude between the two sites effectively eliminates this systematic uncertainty. As limiting cases the scaling can first be calculated using the 7% muon contribution as in the original Sierra Nevada work and then assuming no muon contribution at all. For these extreme cases the scaling factors differ by only 2–3%. Likewise, since the calibration site for the ^{21}Ne/^{26}Al production rate ratio is the same Sierra Nevada site [20], uncertainties in the muogenic contribution to ^{21}Ne production are not a factor.

3. Results and discussion

The concentrations of ^{10}Be, ^{26}Al, and ^{21}Ne (atom/g SiO_2) are shown in Table 1 along with the sample location and the Al concentration in the quartz. The ^{10}Be concentrations and ^{26}Al/^{10}Be ratios are plotted in

Table 1
The concentrations of cosmogenic ^{10}Be, ^{26}Al, and ^{21}Ne in quartz from Atacama Desert samples

ID	Elevation (m)	Latitude (°S)	Longitude (°W)	Al (ppm)	^{10}Be (10^6 atom/g)	^{26}Al (10^6 atom/g)	^{21}Ne (10^6 atom/g)	Minimum ^{10}Be exposure age (Myr)	Maximum erosion rate (m/Myr)
17	3201	26.26	69.56	930	12.34 ± 0.35	61.9 ± 1.5		0.35 ± 0.01	1.68 ± 0.05
18	3201	26.26	69.56	5790	11.61 ± 0.15	59.1 ± 3.6		0.33 ± 0.01	1.80 ± 0.04
19	3212	26.26	69.56	2100	11.16 ± 0.32	55.6 ± 1.6		0.32 ± 0.01	1.93 ± 0.09
20	2701	26.22	69.54	220	2.84 ± 0.08	16.4 ± 0.6		0.10 ± 0.01	6.03 ± 0.15
21	2295	26.20	69.59	4150	30.86 ± 0.38	105.3 ± 3.2	594 ± 30	2.22 ± 0.05	0.17 ± 0.02
22	2295	26.20	69.59	11 300	33.81 ± 0.43	121.0 ± 5.7		2.63 ± 0.06	0.10 ± 0.03
23	2421	26.25	69.58	3590	41.6 ± 1.2	139.2 ± 4.2		3.49 ± 0.24	0.06 ± 0.02
24	2423	26.25	69.58	3050	39.5 ± 1.1	120.2 ± 2.9		3.08 ± 0.19	0.12 ± 0.04
72	1950	26.50	69.74	1320	5.89 ± 0.15	29.7 ± 1.1		0.36 ± 0.01	1.67 ± 0.04
73	1950	26.50	69.74	450	15.94 ± 0.37	74.9 ± 2.6		1.14 ± 0.03	0.36 ± 0.09
74	1950	26.50	69.74	1320	33.79 ± 0.68	106.3 ± 2.5	456 ± 23	4.41 ± 0.29	0.03 ± 0.01
251	2710	26.25	69.57	30 700	8.96 ± 0.15	44.7 ± 9.9		0.34 ± 0.01	1.67 ± 0.04

The observed isotopic ratios were normalized to ICN ^{10}Be ($t_{1/2}=1.5\times10^6$ yr) and NBS ^{26}Al ($t_{1/2}=7.05\times10^5$ yr) standards that were diluted by Nishiizumi. The Ne isotope measurements were performed on a VG 5400 mass spectrometer utilizing ion counting techniques.

Fig. 3. The errors include only uncertainty of AMS measurements (1σ). The ^{10}Be–^{26}Al/^{10}Be diagram (Fig. 3) illustrates the exposure–erosion evolution of both nuclides [18]. Most of the measured data reside on the lower line, consistent with steady-state erosion. The location of a data point on this evolution diagram constrains model exposure ages and erosion rates for a particular sample. Accordingly, Table 1 provides model maximum erosion rates and model minimum exposure ages for each sample. The data form two distinct groups: one group is populated by boulders and cobbles from old fans characterized by exceedingly low erosion rates and long exposures; the other group, consisting of bedrock samples from mountain slopes, is characterized by greater erosion rates and lower minimum exposure ages.

Samples 23, 24, 73, and 74 were taken from the surfaces hypothesized to be the oldest. Three of these four are categorized by long surface exposures and low erosion rates. The cobbles taken from the alluvial fan in the SVM, samples 74 and 73, yield minimum ^{10}Be exposure ages of 4.4 ± 0.3 and 1.14 ± 0.03 Myr, respectively. The cobbles collected from alluvial fans in the Damiana area, samples 23 and 24, had minimum ^{10}Be exposure ages of 3.5 ± 0.2 Myr and 3.1 ± 0.2 Myr. Sample 73 has a slightly higher erosion rate as evidenced by its position on the evolution diagram. The maximum erosion rates for samples 74, 23, and 24 range from 0.03 to 0.12 m/Myr (Table 1).

The second type of surface sampled was the incised streambed in the SVM where occasional storm flow is channeled. The clast collected in the streambed, sample 72, has a maximum erosion rate of 1.7 ± 0.1 m/Myr. Relative to the samples collected from a nearby higher surface (samples 73 and 74), this sample is eroding much faster. Transport of cobbles from the bedrock in mountains upstream is done by direct delivery into the incised streambeds that are adjacent to the Atacama gravel fan surfaces.

The third type of surface sample is an erosional remnant of a once more extensive alluvial fan north of Damiana in the Quebrada Turquesa area. These aplite cobbles, samples 22 and 21, have minimum ^{10}Be exposure ages of 2.6 ± 0.1 and 2.2 ± 0.1 Myr, respectively, and maximum erosion rates of 0.10 and 0.17 m/Myr, respectively. The erosion rates from these samples are somewhat greater than the cobbles taken from the older surfaces at Damiana area. These results are consistent with previous work by Mote et al. [6] showing that the upper parts of the Quebrada Turquesa fans are eroding and exposing andesitic basement in an erosional window beneath the paleo-channel.

In contrast, all bedrock samples from the steep slopes in Quebrada Granito, samples 17, 18, 19, and 251 have higher erosion rates, ranging from 1.7 to 1.9 m/Myr. The data from the bedrock samples are most consistent with the steady state erosion line in Fig. 3; we also interpret these ^{10}Be and ^{26}Al data as indicating that the bedrock is in erosional steady state. The sur-

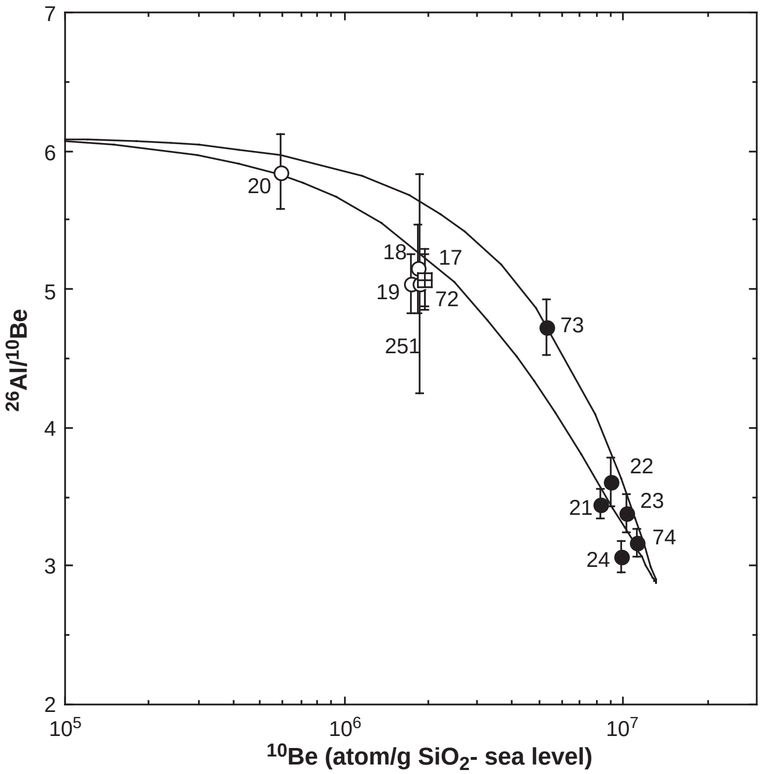

Fig. 3. ^{10}Be concentrations (normalized for atom/g SiO_2 at sea level) plotted against ^{26}Al/^{10}Be ratios for Atacama Desert samples. The open circles indicate bedrock exposed on mountain slopes. The open square indicates a small boulder lying in a stream recently incised in an older alluvial fan. The filled circles indicate cobbles and boulders on alluvial fans. The numbers indicate sample ID.

faces of the steep bedrock slopes have eroded at average rates of 1.7–1.9 m/Myr, rates that are an order of magnitude higher than those of the older alluvial fan surfaces.

Concordance of ^{10}Be and ^{26}Al is usually taken as evidence of a single-stage exposure geometry. Many geologic processes may however occur on time-scales that are not accessible by ^{26}Al or ^{10}Be. Accordingly, to unequivocally demonstrate radionuclide saturation and to assess the possibility of complex exposure scenarios we have measured a third cosmogenic nuclide, ^{21}Ne from two samples. Fig. 4 shows the ^{26}Al–^{21}Ne evolution diagram for samples 21 and 74. The ^{21}Ne exposure age of sample 74 is 8.2–9.0 Myr, based on a 0.03–0.05 m/Myr erosion rate and a ^{21}Ne/^{26}Al production rate ratio of 0.65 [20]. Based on its position in the ^{21}Ne–^{26}Al evolution diagram, sample 74 was exposed to cosmic rays in the same geometry for nearly 9 Myr; the ^{10}Be concentration of this sample is unequivocally in equilibrium. However, for sample 21, although the ^{10}Be–^{26}Al/^{10}Be diagram indicates a simple steady state exposure the ^{26}Al–^{21}Ne diagram clearly indicates that this sample does not have a simple exposure history. There are several geologically possible models. This boulder could have been exposed in two stages. The first stage lasted for 10 Myr, with an erosion rate of 0.05–0.1 m/Myr, similar to sample 23 or 74. The second stage commenced relatively recently with 10–15 cm of material spalling off the surface. Other models are possible but even with three nuclides it is impossible to define the exposure conditions unequivocally.

It is worth re-emphasizing that from the ^{10}Be and ^{26}Al measurements alone a simple single-stage irradiation history would be a reasonable deduction, however the ^{21}Ne measurements clearly indicate a complex exposure. The determination of complex exposure histories using more than two nuclides, encompassing both radionuclides and stable nuclides, is routinely

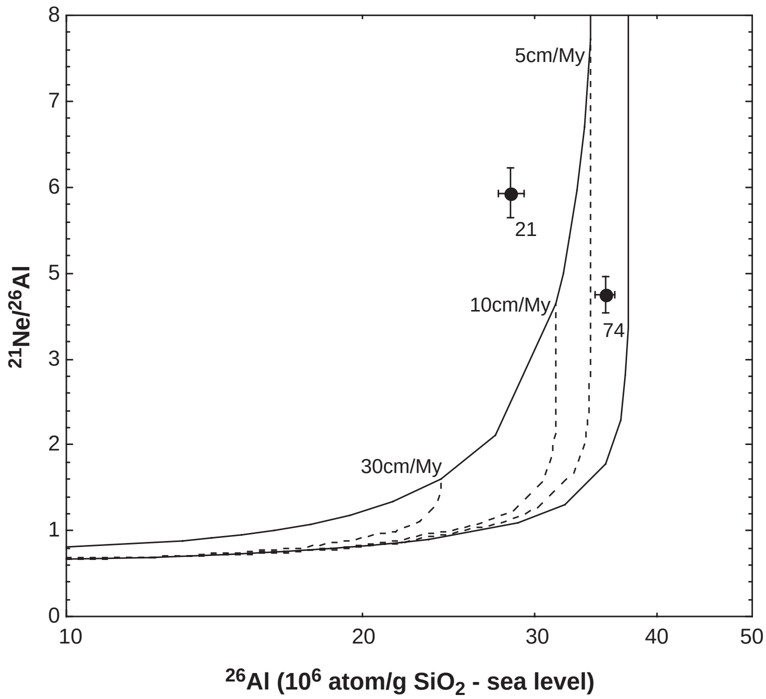

Fig. 4. ^{26}Al concentrations (10^6 atom/g SiO_2 at sea level) vs. ^{21}Ne/^{26}Al ratios. Calculated ^{21}Ne/^{26}Al evolution lines are shown. The top solid line indicates steady state erosion and the bottom of solid line indicates exposure without erosion. The dashed lines indicate various erosion rates (cm/Myr).

employed for extraterrestrial materials (e.g. [21]); this is the first application of this approach to terrestrial samples.

Based on the ^{10}Be and ^{26}Al data alone, we could conclude that there are two distinct erosional regimes in the Atacama Desert: the alluvial fans have extremely low erosion rates and represent the oldest features in this area; the bedrock and stream beds are characterized by higher erosion rates relative to the alluvial fans. The maximum erosion rates at some of these sites, less than 0.2 m/Myr, are nevertheless extremely low in comparison to most environments. With the notable exception of exposed surfaces in Antarctica (e.g. [22]), which have extremely low erosion rates, <0.1 m/Myr, the alluvial fans from which these samples were gathered may be the oldest stable surfaces, possessing the slowest erosion rates, on Earth's surface. Other landforms have been extensively characterized using cosmogenic nuclides: cobbles and bedrock from the Namib Desert (e.g. [23,24]); and bedrock landforms from Australia (e.g. [25]). Bierman and Caffee [23] observed exposure ages range from 0.3 to 2.4 Myr and erosion rates are as low as 0.22 m/Myr in the Namib Desert. Erosion rates from the Atacama Desert fans range from 0.03 to 0.17 m/Myr. A common feature of all these areas is hyperaridity: the average precipitation in the Atacama Desert is <20 mm/yr; and in the coastal regions of Namibia, where the lower erosion rates were observed, annual precipitation is <50 mm/yr. Although the snow precipitation rate (water equivalent) in Antarctica is higher than many dry areas outside of Antarctica, continuous low temperatures in Antarctica preclude the interaction of liquid water with exposed rock.

Although a lack of precipitation alone could be invoked as an explanation for the low erosion rates in Atacama this does not account for the dichotomy in erosion rates seen in Atacama between bedrock and alluvial surfaces. A possible explanation for this somewhat surprising circumstance may be related to the lithologies of the cobbles themselves. The cobbles sampled for this work are vein-quartz and aplite, minerals that are derived from nearby bedrock and are also highly resistant to chemical weathering: surviving pre- and post-depositional and hydrothermal alteration processes. Their deposition creates a stable landform that is highly resistant, more so than the bedrock to alteration processes. The ^{21}Ne results further attest to the antiquity of these landforms. The ^{21}Ne data from sample 74 is most easily explained by a single stage exposure of ~9 Myr. While the second cobble, sample 21, shows clear evidence of a complex exposure, its first exposure geometry was probably 10 Myr in duration, and only recently was it exposed in a new geometry. The cosmogenic nuclides measured in this work clearly demonstrate the preservation and antiquity of these surfaces. Desertification subsequent to deposition preserved this middle Miocene fossil landscape that we observe today.

The existence of two erosion regimes in the Atacama region attests to an extreme disequilibrium in landform evolution. The alluvial surfaces, consisting of quartz and aplite are eroding almost imperceptibly. The bedrock erosion rates are substantially higher and are in fact essentially the same as bedrock erosion rates measured by cosmogenic nuclides in desert regions of Australia and Namibia. Although the bedrock surfaces in the Atacama are higher than the alluvial surfaces, erosion is inexorably wearing them down and will eventually leave the depositional surfaces as the oldest and highest landforms.

4. Summary

Cosmogenic nuclides have been measured in samples collected on alluvial and bedrock surfaces in the Atacama Desert. Measurements of ^{10}Be, ^{26}Al, and ^{21}Ne indicate a single-stage 9 Myr exposure for a cobble taken from an alluvial fan. Other cobbles yield exposure ages nearly as old verifying the Miocene age of these alluvial features. Measurements of three cosmogenic nuclides also identified a case of complex exposure history. The erosion rates of these cobbles are the lowest measured quantified using cosmogenic nuclides on Earth's surface outside of Antarctica. Erosion rates from adjacent steep bedrock surfaces yield an order of magnitude higher than those of cobbles at the alluvial fans. Over geologic time, the Atacama landscape is evolving in such a manner as to erode the higher bedrock ridges relative to the more stable, but stratigraphically lower depositional surfaces through which clastic detritus now travels occasionally along the floors of incised drainage systems leaving the older alluvial fan surfaces largely intact as widespread remnants of a Miocene fossil landscape.

Acknowledgments

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References

[1] C.N. Alpers, G.H. Brimhall, Middle Miocene climatic change in the Atacama Desert, northern Chile: evidence from supergene mineralization at La Escondida, Geol. Soc. Amer. Bull. 100 (1988) 1640–1656.

[2] A.H. Clarke, R.U. Cooke, C. Mortimer, R. Sillitoe, Relationships between supergene mineral alteration and geomorphology, southern Atacama Desert, Chile—An interim report, Trans. Inst. Min. Metall., B 76 (1967) 89–96.

[3] C. Mortimer, The Cenozoic history of the southern Atacama Desert, Chile, J. Geol. Soc. (Lond.) 129 (1973) 505–526.

[4] R. Sillitoe, C. Mortimer, A.H. Clark, A chronology of landform evolution and supergene mineral alteration, southern Atacama Desert, Chile, Trans. Inst. Min. Metall., B 77 (1968) 166–169.

[5] G.H. Brimhall, C.N. Alpers, A.B. Cunnigham, Analysis of supergene ore-forming processes and ground water solute transport using mass balance principles, Econ. Geol. 80 (1985) 1227–1256.

[6] T.I. Mote, G.H. Brimhall, E. Tidy-Finch, G. Muller, P. Carrasco, Application of mass-balance modeling of sources, pathways, and sinks of supergene enrichment to exploration and discovery of the Quebrada Turquesa exotic copper orebody, El Salvador District, Chile, Econ. Geol. 96 (2001) 367–386.

[7] G.H. Brimhall, The genesis of ores, Sci. Am. 264 (1991) 84–91.
[8] P.M. Vasconcelos, T.A. Becker, P.R. Renne, G.H. Brimhall, Age and duration of weathering by ^{40}K–^{40}Ar and $^{40}Ar/^{39}Ar$ analysis of potassium–manganese oxides, Science 258 (1992) 451–455.
[9] P.M. Vasconcelos, G.H. Brimhall, T.A. Becker, P.R. Renne, $^{40}Ar/^{39}Ar$ Analysis of supergene jarosite and alunite: implications to the weathering history of Western U.S. and West Africa, Geochim. Cosmochim. Acta 58 (1994) 401–420.
[10] P.M. Vasconcelos, P.R. Renne, G.H. Brimhall, T.A. Becker, Direct dating of weathering phenomena by $^{40}Ar/^{39}Ar$ and K–Ar analysis of supergene K–Mn oxides, Geochim. Cosmochim. Acta 58 (1994) 1635–1665.
[11] T.I. Mote, T.A. Becker, P. Renne, G.H. Brimhall, Chronology of exotic mineralization at El Salvador, Chile, by $^{40}Ar/^{39}Ar$ dating of copper wad and supergene alunite, Econ. Geol. 96 (2001) 351–366.
[12] R. Sillitoe, E. McKee, Age of supergene oxidation and enrichment in the Chilean porphyry copper deposit province, Econ. Geol. 91 (1996) 164–179.
[13] C.P. Kohl, K. Nishiizumi, Chemical isolation of quartz for measurement of in-situ-produced cosmogenic nuclides, Geochim. Cosmochim. Acta 56 (1992) 3583–3587.
[14] J.C. Davis, I.D. Proctor, J.R. Southon, M.W. Caffee, D.W. Heikkinen, M.L. Roberts, T.L. Moore, K.W. Turteltaub, D.E. Nelson, D.H. Loyd, J.S. Vogel, LLNL/UC AMS facility and research program, Nucl. Instrum. Methods, B 52 (1990) 269–272.
[15] K. Nishiizumi, E.L. Winterer, C.P. Kohl, D. Lal, J.R. Arnold, J. Klein, R. Middleton, Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks, J. Geophys. Res. 94 (1989) 17907–17915.
[16] K. Nishiizumi, R.C. Finkel, J. Klein, C.P. Kohl, Cosmogenic production of ^{7}Be and ^{10}Be in water targets, J. Geophys. Res. 101 (1996) 22225–222232.
[17] D.H. Clark, P.R. Bierman, P. Larsen, Improving in situ cosmogenic chronometers, Quat. Res. 44 (1995) 367–377.
[18] D. Lal, Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models, Earth Planet. Sci. Lett. 104 (1991) 421–439.
[19] E.T. Brown, D.L. Bourles, F. Colin, G.M. Raisbeck, F. Yiou, S. Desgarcesux, Evidence for muon-induced production of ^{10}Be in near surface rock from the Congo, Geophys. Res. Lett. 22 (1995) 703–706.
[20] S. Niedermann, T. Graf, J.S. Kim, C.P. Kohl, K. Marti, K. Nishiizumi, Cosmic-ray-produced ^{21}Ne in terrestrial quartz: the neon inventory of Sierra Nevada quartz separates, Earth Planet. Sci. Lett. 125 (1994) 341–355.
[21] G.F. Herzog, S. Vogt, A. Albrecht, S. Xue, D. Fink, J. Klein, R. Middleton, H.W. Weber, L. Schultz, Complex exposure histories for meteorites with "short" exposure ages, Meteorit. Planet. Sci. 32 (1997) 413–422.
[22] K. Nishiizumi, C.P. Kohl, J.R. Arnold, J. Klein, D. Fink, R. Middleton, Cosmic ray produced ^{10}Be and ^{26}Al in Antarctic rocks: exposure and erosion history, Earth Planet. Sci. Lett. 104 (1991) 440–454.
[23] P.R. Bierman, M. Caffee, Slow rates of rock surface erosion and sediment production across the Namib desert and escarpment, southern Africa, Am. J. Sci. 301 (2001) 326–358.
[24] F.M.V.D. Wateren, T.J. Dunai, Late Neogene passive margin denudation history—cosmogenic isotope measurements from the central Namib desert, Glob. Planet. Change 30 (2001) 271–307.
[25] P.R. Bierman, M. Caffee, Cosmogenic exposure and erosion history of Australian bedrock landforms, Geol. Soc. Amer. Bull. 114 (2002) 787–803.