Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Earth and Planetary Science Letters 237 (2005) 499–507
EPSL
www.elsevier.com/locate/epsl

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

K. Nishiizumi [a,*], M.W. Caffee [b,1], R.C. Finkel [b], G. Brimhall [c], T. Mote [c,2]

[a]Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, United States
[b]Geosciences and Environmental Technology Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, United states
[c]Department of Earth and Planetary Sciences, University of California, Berkeley, CA 94720-4767, United States

Received 24 May 2005; received in revised form 24 May 2005; accepted 30 May 2005
Available online 8 August 2005
Editor: S. King

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

* Corresponding author.
E-mail address: kuni@ssl.berkely.edu (K. Nishiizumi).
[1] Present address: Department of Physics, Purdue University, West Lafayette, IN 47906-1396, United States.
[2] Present address: Geomatrix Consultants, 2101 Webster St. 12th, San Francisco, CA 94612, United States.

0012-821X/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2005.05.032

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