Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 184 (2016) 71–87

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Long term low latitude and high elevation cosmogenic ^{3}He production rate inferred from a 107 ka-old lava flow in northern Chile; 22°S-3400 m a.s.l.

Romain Delunel [a,*], Pierre-Henri Blard [b], Léo C.P. Martin [b], Sébastien Nomade [c], Fritz Schlunegger [a]

[a] Institute of Geological Sciences, University of Bern, Bern, Switzerland
[b] CRPG, UMR 7358, CNRS, Université de Lorraine, Vandoeuvre-lès-Nancy, France
[c] Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA-CNRS-UVSQ et Université Paris-Saclay, Gif-sur-Yvette, France

Received 13 November 2015; accepted in revised form 12 April 2016; available online 19 April 2016

Abstract

Available geological calibration sites used to estimate the rate at which cosmogenic ^{3}He is produced at the Earth's surface are mostly clustered in medium to high latitudes. Moreover, most of them have exposure histories shorter than tens of thousands of years. This lack of sites prevents a qualitative assessment of available production models used to convert cosmogenic ^{3}He concentrations into exposure ages and/or denudation rates. It thus limits our ability to take into account the atmospheric, geomagnetic and solar modulation conditions that might have affected the production of cosmogenic nuclides in the past for longer exposure histories and in low latitude regions. We present the cosmogenic ^{3}He production rate inferred from a new geological calibration site located in northern Chile. Five samples were collected on the surface of the largest and best-preserved lava flow of the San Pedro volcano (21.934°S–68.510°W-3390 m a.s.l.), which displays pristine crease-structure features. ^{40}Ar/^{39}Ar dating yields a reliable plateau age of 107 ± 12 ka for the eruption of this lava flow. Eight pyroxene aliquots separated from the surface samples yield a weighted average cosmogenic ^{3}He concentration of 99.3 ± 1.2 Mat g^{-1} from which a local cosmogenic ^{3}He production rate of 928 ± 101 at g^{-1} yr^{-1} is calculated. The local production rate is then scaled to a sea level high latitude (SLHL) reference position using different combinations of geographic spatialization schemes, atmosphere models and geomagnetic field reconstructions, yielding SLHL production rates between 103 ± 11 and 130 ± 14 at g^{-1} yr^{-1} consistent with the most recent estimates available from the literature. Finally, we use the same scaling frameworks to re-evaluate the mean global-scale cosmogenic ^{3}He production rate in olivine and pyroxene minerals at 120 ± 16 at g^{-1} yr^{-1} from the compilation of previously published calibration datasets.

Keywords: Cosmogenic nuclides; ^{3}He; Production rates; Calibration; Scaling; South America

1. INTRODUCTION

Studies relying on dating landforms and quantifying rates of Earth surface processes have greatly benefitted from the recent development of Terrestrial Cosmogenic Nuclides (TCN; see von Blanckenburg and Willenbring, 2014 and references therein for a review). Since the mid-80s (e.g. Craig and Poreda, 1986; Kurz, 1986), cosmogenic

* Corresponding author. Tel.: +41 316318773.
E-mail addresses: romain.delunel@geo.unibe.ch (R. Delunel), blard@crpg.cnrs-nancy.fr (P.-H. Blard), leom@crpg.cnrs-nancy.fr (L.C.P. Martin), sebastien.nomade@lsce.ipsl.fr (S. Nomade), fritz.schlunegger@geo.unibe.ch (F. Schlunegger).

http://dx.doi.org/10.1016/j.gca.2016.04.023
0016-7037/

helium-3 (^3He) has been successfully used to date geologic features in various environments and over periods of times ranging from hundreds to millions of years (e.g. Kurz et al., 1990; Licciardi et al., 1999; Schäfer et al., 1999; Evenstar et al., 2009). Cosmogenic ^3He combines high production rates (>100 at g^{-1} yr^{-1} at sea level and high latitude) and low analytical detection limits (ca. 10^5 at g^{-1} in most favorable cases) with the absence of radioactive decay (i.e. ^3He is stable). Cosmogenic ^3He also has the advantage to be produced and quantitatively retained over geological timescales in mafic minerals such as olivines and pyroxenes, which offers an interesting alternative for applying surface exposure dating in volcanic terrains where quartz-bearing lithologies might not be available for ^{10}Be and ^{26}Al measurements.

The rate at which cosmogenic ^3He is produced at the Earth's surface has been estimated between 100 and 140 at g^{-1} yr^{-1} (see Dunai, 2010 and reference therein) from several geological calibration datasets with independent age assignments (e.g. Cerling and Craig, 1994; Licciardi et al., 1999, 2006; Dunai and Wijbrans, 2000; Ackert et al., 2003; Blard et al., 2006; Goehring et al., 2010; Amidon and Farley, 2011; Foeken et al., 2012; Fenton et al., 2013; Blard et al., 2013a; Fenton and Niedermann, 2014). At a global scale, cosmogenic ^3He production rates at sea level and high latitude (SLHL) were estimated using the time-dependent adaptation of the Lal (1991)/Stone (2000) scaling scheme ("Lm"; Balco et al., 2008). The available calibration datasets yielded values of 119 ± 10 at g^{-1} yr^{-1} for pyroxene (Goehring et al., 2010) and 116 ± 13 (Goehring et al., 2010), 122 ± 15 (Blard et al., 2013a) and ca. 117 at g^{-1} yr^{-1} (Borchers et al., 2016) when ^3He concentrations of both pyroxene and olivine minerals are considered. Although the global-scale SLHL cosmogenic ^3He production rates are consistent within associated uncertainties, Phillips et al. (2016) recently emphasized that the initial datasets used in these compilations are clustered both in space (medium to high latitudes) and time (ca. 5–20 ka). According to these authors, this circumstance prevents reliable integrations of past atmospheric, geomagnetic and solar modulation conditions that might have affected the production of cosmogenic nuclides at the Earth's surface. In particular, cosmogenic ^3He calibration data are lacking at latitudes <25° (Blard et al., 2013a), where large temporal variations in the paleo magnetic-field intensity might have significantly affected the production of cosmogenic nuclides (e.g. Dunai and Lifton, 2014). Accordingly, improving the accuracy of time dependent corrections requires more low latitude calibration sites with exposure durations significantly longer than 20 ka.

This article presents a new calibration of the cosmogenic ^3He production rate from a site located in the hyperarid region of northern Chile (3400 m a.s.l., ca. 22°S), over a long exposure time (ca. 107 ka). The aim is to reduce the lack of long exposure calibration sites located at high elevation/low latitude. Five samples were collected for helium analyses on top of an andesitic lava flow. This surface is characterized by pristine crease-structure features, which are common on silicic volcanic flows and previously identified as reliable targets for surface exposure dating (Anderson et al., 1994). First we document the age of a lava flow of the San Pedro volcano using $^{40}Ar/^{39}Ar$ dating techniques. We then report the results of the cosmogenic ^3He measurements from five samples (8 aliquots) from which we infer the local production rate of cosmogenic ^3He, as well as the production normalized to sea level and high latitude (SLHL), both integrated over the age of the lava flow. Finally, we combine our results with previously reported cosmogenic ^3He calibration datasets, to re-evaluate the global ^3He production rate at SLHL.

2. GEOLOGICAL SETTING AND SAMPLING

2.1. Volcanic architecture

The San Pedro volcano (6159 m a.s.l., Fig. 1) is situated in the El Loa province of northern Chile ca. 80 km north east of Calama and 100 km north of San Pedro de Atacama. While the San Pedro volcano is located on the western slope of the High Andean Cordillera and therefore does not belong to the Atacama Desert *stricto sensu*, it is characterized by a hyperarid climate, with annual precipitation <100 mm/y (Houston and Hartley, 2003). The San Pedro volcano is paired with the San Pablo volcano (6118 m a.s.l.) located 5 km further to the east. It represents one of the highest and best-preserved volcanic edifices of the Central Volcanic Zone (de Silva, 1989), one of the four active volcanic zones in the Andes (see Hora et al., 2007 and reference therein). Only few studies (Francis et al., 1974; Thorpe et al., 1976; O'Callaghan and Francis, 1986) described and identified the nature and composition of erupted materials and the history of eruption of these volcanoes. The San Pedro volcano represents a composite andesitic stratovolcano (Fig. 2) made of two east–west oriented coalescent cones that have been successively built as the volcanic belt shifted westward (O'Callaghan and Francis, 1986). The cones stand >2 km above an extensive ignimbrite plateau (Fig. 1) that has formed since the Late Miocene at ca. 10.4 Ma during the development of the Altiplano-Puna volcanic complex (de Silva, 1989). The San Pedro cones have been built due to the eruption of silicic materials ranging from basaltic andesite to potassium-rich dacite (O'Callaghan and Francis, 1986). Structural mapping and petrologic investigations (Francis et al., 1974; O'Callaghan and Francis, 1986) revealed that the San Pedro Volcano records three evolutionary steps, comprising (i) the edification and subsequent collapse of an "old cone", whose summit marks the highest peak of the volcano, (ii) the construction, c.a. 5 km to the west, of the "young cone" that has produced several large lava flows and is still marked by fumarolic activity and (iii) the formation of the South West Dome and La Poruña scoria cone, representing the last eruptive episode and associated with the emission of two large and well preserved lava flows (Fig. 1). Above 4500 m a.s.l., Francis et al. (1974) reported the presence of glacial moraines and cirques on the southern flanks of both the San Pablo and San Pedro volcanoes. Thus, the last eruptions are probably older than the last large glacial advances in the region (i.e. ca. >15 ka; Blard