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Earth and Planetary Science Letters 247 (2006) 222–234
EPSL
www.elsevier.com/locate/epsl

Cosmogenic ^{3}He production rates revisited from evidences of grain size dependent release of matrix-sited helium

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Received 3 January 2006; received in revised form 4 May 2006; accepted 5 May 2006
Available online 21 June 2006
Editor: R.W. Carlson

Abstract

Measurements of the cosmogenic ^{3}He ($^{3}He_c$) content of various size aliquots of exposed olivines show that the fine fraction (<140 μm) has $^{3}He_c$ concentrations between 14 and 100% lower than that of the coarse fractions (0.14–1 mm). Such differences attest to a grain size dependent partial release of $^{3}He_c$ from the phenocrysts matrix during the preliminary in vacuo crushing. This result might have important implications since most $^{3}He_c$ measurements have used for ~20 yr a standard routine based on the fusion of bulk *powdered* phenocrysts, whatever their grain size. A suite of new data obtained from coarse olivine grains yielded a mean Sea Level High Latitude $^{3}He_c$ production rate (SLHL P_3) of 128±5 and 136±6 at. g^{-1} yr^{-1}, depending on the scaling factors used. This new value, which is ~15% higher than previously published rates, is obtained from 5 ropy flow surfaces of Mt Etna (38°N) and Hawaiian (19°N) volcanoes, at elevations between sea level and 870 m and ranging in age from 1.47±0.05 to 149±23 ka according to independent ^{14}C or K/Ar dating. ^{3}He loss during the crushing step might account for the discrepancy between the standard reference value of 110–115 at. g^{-1} yr^{-1} and the higher SLHL P_3 proposed here. More generally, removal of the powdered fraction before fusion is an important point to consider in further studies in order to avoid any $^{3}He_c$ systematic underestimates.

An altitudinal section has also been sampled on the ropy surface of a ~1500 yr single flow of Mauna Loa (19°N) which allowed a new empirical atmospheric attenuation length of 149±22 g cm^{-2} to be documented for $^{3}He_c$ in olivines between 2400 and 4000 m elevations.

Keywords: cosmogenic; ^{3}He; production rates; calibration; basalt; flows; ^{14}C; K–Ar; dating; Hawaii; Mauna Loa; Mauna Kea; Etna

1. Introduction

The impact of studies based on terrestrial cosmogenic nuclides (TCN) is becoming more and more important in surface Earth sciences. TCN have indeed

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doi:10.1016/j.epsl.2006.05.012

wide applications in surface dating, burial age estimation, and erosion rates assessment (see review in [1]). However, extending the limits of the TCN applications requires improving the knowledge of cosmogenic nuclides production systematics. One of the main sources of uncertainty affecting any TCN-derived age is linked to the knowledge of production rates [1]. Production rate uncertainties are not lower than 10–15%, while the analytical uncertainty may be better than 5% for several TCN (e.g. ^{3}He, ^{10}Be). Improving the knowledge of (i) the reference Sea Level High Latitudes (SLHL) production rates and (ii) the spatial and temporal variations of these rates (e.g. [2–4]) is thus a major issue to extend the frontiers of TCN applications. The estimation of references SLHL production rates is based either on (i) calibrations using independently dated natural surfaces (e.g. [5,6]), or on (ii) physical modelling of the cosmogenic particles interactions with target nuclei (e.g. [7]).

The SLHL production rate of cosmogenic ^{3}He (^{3}He$_c$) in olivines (Fo$_{75–85}$) and clinopyroxenes is the best constrained of all TCN, presenting an apparent agreement between calibrated data (from 110 to 115 at. g^{-1} yr^{-1}, see review in [1]) and simulated values ~110 at. g^{-1} yr^{-1} [7]). Moreover, the use of ^{3}He$_c$ theoretically allows deciphering very young (<1 kyr) exposure ages with accuracy and precision (<15%) since this TCN has the lowest detection limit (from 5.10^{4} to 10^{5} at. g^{-1} in quaternary basaltic lavas).

The measurement of ^{3}He$_c$ in mafic phenocrysts (olivines and clinopyroxenes) has been based on a two-step routine for ~20 yr (e.g. [8]). The first step is designed to selectively release the magmatic helium component (from fluid and melt inclusions) through in vacuo crushing. Up to now, negligible ^{3}He$_c$ release was assumed during this step. The second step extracts all the remaining helium components, including the cosmogenic ^{3}He, by fusion of the powder obtained from the first step. However, a recent study by [9] showed evidence of significant cosmogenic helium release (up to 25%) during prolonged crushing. The major implication of this ^{3}He$_c$ loss by crushing is a possible systematic underestimate of the measured ^{3}He$_c$ when the subsequent melting is performed on the bulk powder resulting from crushing the phenocrysts.

In order to test the implications of this ^{3}He$_c$ loss, a specific protocol has been adopted here, separating the fine grained powders from the coarse uncrushed phenocrysts. Then, using this refined analytical procedure, revised SLHL ^{3}He$_c$ production rates (SLHL P$_3$) are proposed from independently dated ropy flow surfaces.

2. Material and methods

2.1. Samples

Calibration of TCN production rates requires analysis of natural surfaces which (i) can be independently dated with precision, (ii) have suffered negligible erosion, and (iii) have not been buried in anyway since the start of their exposure. Basaltic flows may be considered as ideal objects for such calibrations as their ropy flow surfaces can be used as a qualitative check of the “negligible erosion” condition, and also because

Table 1
Samples description

Site	Sample	Altitude (m)	Lat. (N)	Long. (E)	Depth (cm) top–bottom	Description	Petrology	Flow age[a] (kyr±1σ)
Etna, Sicily								
Simeto	SI47	190	37°36′.35	14°49′.88	0–10	Pahoehoe cords	Trachybasalt	41±3
Nave	SI41	820	37°50′.91	14°50′.10	0–15	Top of a tumulus	Trachybasalt	33±2
Mauna Loa, Hawaii								
Kaunamano	ML1A	80	19°03′.66	155°33′.31	0–5	Pahoehoe cords	Picrite	*8.23±0.08*
Kaunamano	ML1B	40	19°03′.24	155°33′.25	0–5	Pahoehoe cords	Picrite	*8.23±0.08*
Kaunamano	ML1C	60	19°03′.63	155°33′.29	0–5	Pahoehoe cords	Picrite	*8.23±0.08*
Kapapala	ML5A	870	19°20′.44	155°23′.86	0–5	Pahoehoe cords	Basalt	*1.47±0.05*
Ainapo	ML10	3950	19°26′.12	155°34′.70	0–5	Pahoehoe cords	Basalt	*~1.5*
Ainapo	ML12A	3440	19°25′.02	155°33′.35	0–8	Pahoehoe cords	Basalt	*~1.5*
Ainapo	ML12B	3440	19°25′.07	155°33′.29	0–5	Pahoehoe cords	Basalt	*~1.5*
Ainapo	ML13	3000	19°24′.07	155°32′.40	0–8	Pahoehoe cords	Basalt	*~1.5*
Ainapo	ML14A	2440	19°22′.98	155°30′.95	0–5	Pahoehoe cords	Basalt	*~1.5*
Ainapo	ML14B	2450	19°23′.00	155°30′.93	0–5	Hummocky feature	Basalt	*~1.5*
Mauna Kea, Hawaii								
Waimea airport	MK4	840	19°59′.32	155°40′.00	0–20	Pahoehoe cords	Trachybasalt	149±23

[a] ^{14}C ages *(in italic)* were corrected using the Reimer et al. [14] calibration curve. Other ages are from K–Ar dating [11].