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An improved experimental determination of cosmogenic $^{10}Be/^{21}Ne$ and $^{26}Al/^{21}Ne$ production ratios in quartz

M.M. Goethals [a,b], R. Hetzel [a,*], S. Niedermann [b], H. Wittmann [c,1], C.R. Fenton [b,2], P.W. Kubik [d], M. Christl [d], F. von Blanckenburg [c,1]

[a] Geologisch-Paläontologisches Institut, Westfälische Wilhelms-Universität Münster, Corrensstr. 24, D-48149 Münster, Germany
[b] Helmholtz-Zentrum Potsdam - Deutsches GeoForschungsZentrum, Telegrafenberg, D-14473 Potsdam, Germany
[c] Institut für Mineralogie, Universität Hannover, Callinstrasse 3, D-30167 Hannover, Germany
[d] Laboratory of Ion Beam Physics ETH Zurich, CH-8093 Zurich, Switzerland

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ABSTRACT

The confidence in surface exposure dating and related research, such as erosion rate studies or burial dating, strongly depends on the accuracy and precision of the currently used production rates of in situ-produced cosmogenic nuclides. Reducing the uncertainties of nuclide production rates by more accurate calibrations with independently dated natural rock surfaces is crucial for further improving the quantification of earth surface processes. Here we use surface samples from the 760 ± 2 ka old Bishop Tuff in eastern California to quantify the $^{10}Be/^{21}Ne$ and $^{26}Al/^{21}Ne$ production rate ratios in quartz. Our determination is based on (1) measured nuclide concentrations of cosmogenic ^{10}Be, ^{21}Ne, and ^{26}Al, (2) a conservative estimate for the erosion of the tuff in the Volcanic Tableland area, which we base on our previously published ^{21}Ne concentrations [Goethals, M.M., Niedermann, S., Hetzel, R., Fenton, C.R., 2009. Determining the impact of faulting on the rate of erosion in a low-relief landscape: A case study using *in situ* produced ^{21}Ne on active normal faults in the Bishop Tuff, California. Geomorphology 103, 401–413] and a conservative estimate for the uncertainty of the ^{21}Ne production rate, and (3) the assumption of steady-state erosion. Other assumptions, such as the applied scaling procedure, the muon contribution to nuclide production, or the attenuation lengths of neutrons and muons in rock, do not substantially affect the results. Based on 13 samples, the following average production rate ratios and conservative uncertainty estimates are obtained for sea level, high latitude, open sky, and rock surface: 0.249 ± 0.009 or 0.232 ± 0.009 for $^{10}Be/^{21}Ne$ using ^{10}Be half-lives of 1.51 and 1.39 Ma, respectively, and 1.80 ± 0.09 for $^{26}Al/^{21}Ne$ (for an ^{26}Al half-life of 0.72 Ma). The $^{10}Be/^{21}Ne$ and the $^{26}Al/^{21}Ne$ production ratios are consistent with currently used production rates but the ratios are much more precise than previous determinations. The resulting $^{26}Al/^{10}Be$ production ratio of 7.23 ± 0.45 (for a ^{10}Be half-life of 1.51 Ma) or 7.76 ± 0.49 (for a ^{10}Be half-life of 1.39 Ma) is high when compared to previously published values. We discuss reasons for this difference, amongst them the possibility that ^{26}Al analyses in general might be compromised by artefacts affecting the stable Al concentration measurements. When combined with a ^{10}Be production rate of 5.01 at g^{-1} a^{-1} for the 1.51 Ma half-life (or 4.61 at g^{-1} a^{-1} for the 1.39 Ma half-life), our production ratios convert to ^{21}Ne and ^{26}Al production rates of 20.1 and 36.2 at g^{-1} a^{-1} (or 19.9 and 35.7 at g^{-1} a^{-1}), respectively.

1. Introduction

Exposure ages and erosion rates derived from cosmogenic nuclides are, in the best case, as accurate as the production rates they rely on. Although both experimental determinations and model calculations are available for the production rates of commonly used cosmogenic nuclides, their accuracy is limited by, e.g., the difficulty of obtaining suitable independently dated material, the intricacies involved in scaling from one location on the earth's surface to another one, or the limited knowledge on nuclear excitation functions for neutron-induced spallation reactions, and is usually estimated at ~10–20%.

* Corresponding author. Tel.: +49 251 8333908; fax: +49 251 8333968.
E-mail addresses: mirjamgoethals@yahoo.com (M.M. Goethals), rahetzel@uni-muenster.de (R. Hetzel), nied@gfz-potsdam.de (S. Niedermann), wittmann@gfz-potsdam.de (H. Wittmann), c.fenton@suerc.gla.ac.uk (C.R. Fenton), kubik@phys.ethz.ch (P.W. Kubik), christl@phys.ethz.ch (M. Christl), fvb@gfz-potsdam.de (F. von Blanckenburg).
[1] Present address: Helmholtz-Zentrum Potsdam — Deutsches GeoForschungsZentrum, Telegrafenberg, D-14473 Potsdam, Germany.
[2] Present address: Scottish Universities Environmental Research Centre (SUERC), Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride G75 0QF, United Kingdom.

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While the number of different experimental production rate determinations is rather large for ^{3}He in olivine and ^{10}Be in quartz (e.g. Gosse and Phillips, 2001; Licciardi et al., 2006; Balco et al., 2008), the database for ^{26}Al and ^{36}Cl is considerably smaller, and there has only been one single value for ^{21}Ne in quartz until very recently (Niedermann et al., 1994; revised by Niedermann, 2000); an additional study reporting an independently determined ^{21}Ne production rate (Balco and Shuster, 2009) has just appeared. As the accuracy of a production rate is expected to increase with the number of independent determinations (under the assumption that deviations are mainly of statistical nature), it could be favourable to link poorly known production rates to those with better confidence, e.g. those of ^{21}Ne and ^{26}Al in quartz to that of ^{10}Be in the same mineral. In other words, instead of determining all production rates individually, it would suffice to know a single one of them absolutely, while only accurate production rate *ratios* would be needed for the other ones.

Indeed, production rate ratios have already been reported in the earliest studies dealing with production rate determinations in quartz: Nishiizumi et al. (1989) obtained a mean ^{26}Al/^{10}Be production ratio of 6.02 ± 0.44 (1σ) from ten glacially polished granite surfaces sampled in the Sierra Nevada, California. Later Niedermann et al. (1994) measured ^{21}Ne in two of the same samples, yielding a ^{21}Ne/^{26}Al production ratio of 0.65 ± 0.11. However, since these ratios were determined in rather young (~13 ka) samples, their precision is limited due to low cosmogenic nuclide concentrations, and the same holds for subsequent studies of this kind (e.g. Kubik et al., 1998). In principle, production rate ratios can be determined in any sample in which more than one cosmogenic nuclide is measured, provided that a single-stage exposure history with no erosion is ensured. Whenever erosion or any other change in exposure conditions is involved, the production ratio of two cosmogenic nuclides can no longer easily be calculated from their concentration ratio and their half-lives (unless both nuclides are stable). In practice, this has been a serious obstacle to accurate determinations of ^{10}Be–^{21}Ne–^{26}Al production ratios, because it is rarely possible to exclude changing irradiation conditions for old samples, whereas for younger samples the precision of nuclide concentration measurements is often not sufficient, especially for ^{21}Ne.

Here we show that erosion does not necessarily preclude a determination of the ^{10}Be–^{21}Ne–^{26}Al production ratios, provided that some constraint on the erosion rate is available. Our samples originate from the Volcanic Tableland in the southeastern part of the Bishop Tuff, an ignimbrite erupted from Long Valley Caldera (California) 760 ± 2 ka ago as established by ^{40}Ar/^{39}Ar dating (van den Bogaard and Schirnick, 1995), where we carried out an erosion study based on cosmogenic ^{21}Ne in quartz (Goethals et al., 2009). The precise age of the tuff, which was confirmed by Sarna-Wojcicki et al. (2000), along with high cosmogenic nuclide concentrations in the quartz allow us to use the same samples to determine precise production ratios of ^{10}Be/^{21}Ne and ^{26}Al/^{21}Ne. To do so, we only need to make a conservative assumption for the absolute ^{21}Ne production rate in order to set limits on the erosion of the studied surfaces.

2. Geological, geomorphological and climatic setting of the Bishop Tuff area

The Bishop Tuff (Fig. 1) is an ignimbrite that erupted during the formation of the Long Valley Caldera in eastern California (e.g. Wilson and Hildreth, 2003). The tuff lies in the rainshadow of the Sierra Nevada, the mountain range west of the tuff, and it is situated in the northern part of Owens Valley just north of the town of Bishop. In the east, the Bishop Tuff is bordered by the White Mountains, the easternmost range of the Basin and Range Province.

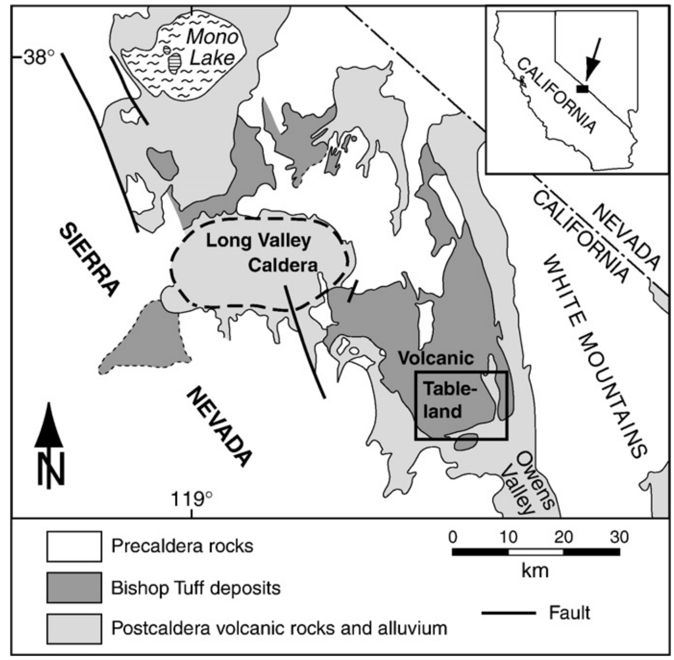

Fig. 1. Map showing the location of the Bishop Tuff in eastern California (modified from Sarna-Wojcicki et al., 2000). The black rectangle indicates the Volcanic Tableland where samples for this study were taken. For more detailed maps refer to Goethals et al. (2009).

The Bishop Tuff area has a desert climate and a vegetation of scattered small bushes and scrubs. In the south-eastern part of the Bishop Tuff, known as the Volcanic Tableland, the uppermost part of the tuff consists of a 40 to 80-m-thick ignimbrite unit referred to as Ig2Eb by Wilson and Hildreth (1997). The rocks contain abundant pumice and rhyolite lithics with ortho- and clinopyroxene phenocrysts, sanidine, magnetite (Wilson and Hildreth, 1997), and quartz phenocrysts up to 3 mm in size, with a mean diameter of 1–2 mm. The ignimbrite unit is increasingly welded towards the top and has a remarkably flat, low relief surface at around 1400 m elevation. Erosion of the Bishop Tuff surface in the sampled area of the Volcanic Tableland has been assessed based on ^{21}Ne concentrations in quartz samples, showing that (under the assumption of steady state erosion) 85–320 cm of the surface have been removed from the sample sites since the eruption 760 ka ago (Goethals et al., 2009).

3. Experimental procedures

3.1. Sampling and quartz separation

Ignimbrite samples were taken from both bedrock and desert pavement on the erosion-resistant surface of the Ig2Eb unit of the Volcanic Tableland (Goethals et al., 2009). For this study, only a subset of the bedrock samples was used (Table 1); desert pavement samples were discarded because they represent mixtures of clasts, each of which may have experienced a different irradiation history. Images of the sample sites are shown in Fig. S1 in the electronic supplement and in Goethals et al. (2009). Most of the investigated samples were taken from the subhorizontal part of the footwalls of normal faults, several metres away from the steep fault scarps, or in areas not affected by faulting. The relatively high sampling sites in the uplifted footwall blocks were least likely covered by local alluvium, and were presumably blown free of snow first in colder periods. Two samples (05BT16 and −17) were taken from bedrock exposures in ephemeral streams to assess the maximum amount of erosion in this part of the