Cosmogenic ³He and ²¹Ne production rates calibrated against ¹⁰Be in minerals from the Coso volcanic field

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ARTICLE INFO

ABSTRACT

This study calibrates the production rate of cosmogenic ³He in pyroxene, olivine, garnet, zircon and apatite as well as ²¹Ne in quartz and pyroxene against the known production rate of ¹⁰Be in quartz. The Devil's Kitchen rhyolite from the Coso volcanic field in southeastern California (elev. ~1300 m) was chosen for this study due to its young age (~610 ka) and diverse mineral assemblage. Based on ¹⁰Be, our two rhyolite samples have apparent exposure ages of ~49 and 93 ka, indicating substantial erosion after eruption. Combining data from the two samples, we estimate sea level high latitude ³He spallation production rates of 145 ± 11, 141 ± 16, and 144 ± 30 at $g^{-1} a^{-1}$ (2σ) for pyroxene, olivine and spessartine garnet respectively. For zircon and apatite, we estimate apparent ³He spallation production rates of 114 ± 8 and 149 ± 28 at $g^{-1} a^{-1}$ (2σ) respectively. The rates for zircon and apatite are reported as apparent production rates because we do not explicitly address the redistribution of spallation produced ³He from adjacent minerals. These estimates quantitatively account for production of ³He from both cosmogenic and radiogenic neutron reactions on ⁶Li within the analyzed phases and also implanted from nuclear reactions in neighboring minerals; the high U, Th and Li content of this rhyolite provides a particularly rigorous test of this correction. We estimate ²¹Ne production rates of 17.7 ± 1.6 and 34.1 ± 3.2 at $g^{-1} a^{-1}$ (2σ) in quartz and pyroxene (Fe/Mg = 0.7 by mass) respectively. Although high U and Th contents create the potential for significant production of nucleogenic ²¹Ne, this component is small due to the young eruption age of the rhyolite.

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1. Introduction

Dating of geologic surfaces using cosmogenic ³He or ²¹Ne offers a fast and relatively simple alternative to cosmogenic dating using radioisotopes such as ¹⁰Be and ²⁶Al (Gosse and Phillips, 2001). Although cosmogenic dating using ³He has most often been performed on olivine and pyroxene, all major elements produce spallogenic ³He as well as ³H, which quickly decays to ³He ($t_{1/2} = 12.5$ a). Therefore, cosmogenic ³He dating can be applied to any mineral phase that is retentive to helium and for which the production rate of cosmogenic ³He is known. The He retentivity of many mineral phases is well established (Dunai and Roselieb, 1996; Farley, 2002; Shuster and Farley, 2005; Copeland et al., 2007), but ³He production rates remain uncertain.

Previous studies provide several ³He production rate estimates for olivine and pyroxene (Kurz et al., 1990; Cerling and Craig, 1994; Licciardi et al., 1999; Dunai and Wijbrans, 2000; Ackert et al., 2003; Blard et al., 2006; Licciardi et al., 2006), a few estimates in garnet, zircon, apatite, titanite and kyanite (Gayer et al., 2004; Farley et al., 2006; Gayer et al., 2006; Amidon et al., 2008a), and some results on Fe–

Ti oxides and calcite (Bryce and Farley, 2002; Kober et al., 2005; Amidon et al., 2008b). ³He production rates in pyroxene and olivine range from ~100 to ~150 at $g^{-1} a^{-1}$ at sea level and high latitude (SLHL), a wider range than for comparable calibration studies of ¹⁰Be or ²⁶Al and outside of the stated analytical uncertainties. This large scatter may arise from incomplete or inaccurate consideration of one or more of the following factors: 1) significant amounts of ³He can be produced by capture of radiogenic or cosmogenic slow neutrons by ⁶Li (Andrews and Kay, 1982; Dunai et al., 2007), 2) newly created ³He (and ³H) nuclei experience redistribution into adjacent mineral phases due to their small size and high energy (Farley et al., 2006); 3) cosmogenic ³He must be deconvolved from mantle-derived ³He in common mafic phases (Kurz, 1986; Blard and Pik, 2008); 4) ³He spallation production rates may not follow accepted elevation scaling laws (Gayer et al., 2004; Farley et al., 2006; Gayer et al., 2006; Amidon et al., 2008a).

Here we attempt to eliminate some of these sources of uncertainty and expand the utility of cosmogenic ³He dating by cross-calibrating its production rate in pyroxene, olivine, garnet, zircon, and apatite against the known production rate of ¹⁰Be in co-existing quartz. The rhyolite domes of the Coso volcanic field were chosen for this study because they are well studied petrographically and geochemically, and the Devil's Kitchen dome contains abundant coarse-grained crystals of all of the above mineral phases in a single rock (Manley and Bacon,

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2000). In addition, the high U, Th and Li of this rock presents an opportunity to develop and validate an approach to quantifying Li-produced ^{3}He in these phases.

2. Geologic overview

The Coso volcanic field is located in the southern Owens Valley, east of the Sierra Nevada Mountains. The focus of this study, the Devil's Kitchen rhyolite dome, has an ^{40}Ar/^{39}Ar isochron age of 0.613 ± 0.003 Ma (Simon et al., 2008). It contains an unusual assemblage of 0.1–1 mm sized phenocrysts including quartz, sanidine, plagioclase, magnetite, ilmenite, pyroxene, hornblende, biotite, olivine, and trace amounts of zircon and apatite (Bacon et al., 1981; Manley and Bacon, 2000). The rock typically exhibits a fine-grained (<10 μm) quartz–feldspar matrix. Of particular importance to this study is that the rhyolite is unusually rich in U, Th and Li, with concentrations of 14, 42, and 156 ppm respectively (Bacon et al., 1981). Zircons contain up to 2.5 wt.% of U, and up to 1.5 wt.% of Th (Miller and Wooden, 2004). The Devil's Kitchen rhyolite also contains dm-sized inclusions of a porphyritic andesite (Bacon and Metz, 1984). The andesitic inclusions contain 0.5 to 4 mm phenocrysts of plagioclase, as well as smaller (<few mm) phenocrysts of quartz, clinopyroxene, olivine, and Fe–Ti oxides. In addition to andesitic inclusions, one of our rhyolite samples (co-5) also contains small plagioclase-garnet xenoliths.

3. Methods

3.1. Sampling

Two closely-spaced localities were sampled on a low ridge on dome 28, at ~1333 m elevation (Bacon et al., 1980). Locality co-5 (N 36.03014, W 117.79654) was a flat bedrock surface about 40 cm above the alluvial surface of the ridge. A sample of the rhyolite (denoted co-5) was collected from the surface, along with an andesitic inclusion (sample co-5x). The inclusion measured approximately $10 \times 8 \times 5$ cm and was sampled from an average depth of 8 cm directly below co-5. Locality co-6 (N 36.0299, W 117.79658), about 25 m away from co-5, was a bedrock knob rising about 80 cm above the surface of the ridge on the west side and about 2 m above the steeply sloping edge of the ridge on the east side. Again a rhyolite sample (co-6) was collected from the surface and an andesitic inclusion (sample co-6x, from an average depth of 5 cm) directly below this surface. The inclusion measured approximately $12 \times 7 \times 7$ cm in dimension.

We thus have four rock samples for analysis: one rhyolite and one andesitic inclusion from each of two localities. The two lithologies from each location will have the same cosmic ray exposure history after correction for the sub-surface depth at which the inclusion was located. Similarly, we assume that the chemical composition of each lithology is the same at the two localities (see Appendix A). As we show below, the two localities have very different exposure histories, providing us the opportunity to see how ^{3}He concentrations vary with the total cosmic ray exposure derived from ^{10}Be.

No topographic shielding corrections are necessary at either locality, nor do we attempt to correct for shielding by snow or ice. Ignoring these corrections is further justified by the fact that we are comparing ^{3}He and ^{21}Ne directly to ^{10}Be, so shielding effects should cancel when production rates are calculated.

Mineral separations were done following standard heavy liquid procedures followed by HF leaching of quartz for ^{10}Be and ^{21}Ne analysis. All samples were handpicked of contaminant phases prior to analysis.

3.2. ^{10}Be analyses and ^{10}Be production rate

Analysis of ^{10}Be concentrations in quartz was performed at Lawrence Livermore National Laboratory (LLNL). Quartz samples were purified by HF leaching following Kohl and Nishiizumi (1992), and Be was extracted and analyzed following standard LLNL procedures. Measured ^{10}Be/^{9}Be ratios are normalized to the 07KNSTD3110 with a ^{10}Be/^{9}Be ratio of 2.85×10^{-12}, based on a ^{10}Be half life of 1.36 million years (Niishizumi et al., 2007). To calculate ^{3}He and ^{21}Ne production rates we adopt a SLHL ^{10}Be production rate of 4.87 at g^{-1} a^{-1}. This is based on the average production rate published in Balco et al. (2008) scaled following Lifton et al. (2005), and reduced by a factor of 0.904 to reflect the newly adopted ^{10}Be half life mentioned above. This ignores muogenic production of ^{10}Be, which should be ~2–3% of spallogenic production (Heisinger et al., 2002a,b).

3.3. Helium analyses

Samples were analyzed for ^{3}He either directly as obtained from mineral separation or after crushing, either in vacuum or in air. Crushing is required in some mineral phases to release and/or measure magmatic helium contained in inclusions. Samples crushed under vacuum were crushed for 3 min in a steel tube following published procedures (Patterson et al., 1997). After crushing either on-line or in air sample material was wet-sieved through a 24 μm sieve and recrushed as necessary until all material was smaller than 24 μm. Three samples were re-crushed for a second 3 minute cycle and analyzed to verify that all ^{3}He is removed during the initial crushing phase. None of the zircon or apatite samples were crushed prior to analysis, under the assumption that the magmatic ^{3}He component is negligible in these very fine grained phases.

Only grains from the >150 μm size fraction were used during analysis of pyroxene, olivine and garnet, making the effect of implanted ^{3}He from adjacent mineral phases negligible. To document the effect of implanted ^{3}He on fine-grained phases, zircons were sieved into grain size fractions if enough sample material was available. The average dimensions of mineral grains are expressed in terms of the equivalent radius of a sphere with the same surface area to volume ratio (Farley et al., 1996).

Extraction of matrix-sited ^{3}He was performed by diffusing helium gas out of the sample either by heating to ~1300 °C in a double-walled resistance furnace, or to similar temperatures by heating with a Nd-YAG laser in a Pt capsule. Complete helium extraction from each sample was verified by re-extracts under identical heating conditions. In both cases, helium was purified by exposure to hot and cold SAES getters, and was cryogenically focused on charcoal at 12 K before release of He at 32 K into a MAP 215-50 mass spectrometer. Sensitivity of the mass spectrometer was determined by analysis of gas standards at similar helium pressures and ^{3}He/^{4}He ratios to the samples being analyzed. The precision of our measurements can be estimated from five replicate analyses of sample co-5x (pyroxene), which gave a 1σ standard deviation of ~5.5% for ^{3}He counting rates of 5–10 cps. Zircon and apatite were typically measured at lower counting rates of 1–3 cps, a range in which replicate standards yield a 1σ standard deviation of ~8% on ^{3}He.

3.4. ^{21}Ne analyses

Uncrushed quartz samples were either heated in a single step to 1300 °C or step-heated at 250, 800, and 1300 °C to preferentially release matrix-sited neon from adsorbed or inclusion-held neon (Niedermann, 2002). None of the 250 or 1300 °C steps contained excess ^{21}Ne, although the 1300° step contained large air components. Pyroxene was either heated in a single temperature step at ~1500 °C, or fused by rastering a Nd-YAG laser over bare grains. Neon was purified over hot and cold SAES getters and then cryogenically focused at 32 K on charcoal before release at 75 K into a GV Helix-SFT split tube mass spectrometer operating in peak-jumping mode on the electron multiplier spur. Because the ^{40}Ar^{++} peak is resolved from the ^{20}Ne$^+$ peak, no correction for the ^{40}Ar isobar was applied. Corrections for the ^{44}CO$_2$ isobar were <2% and were made by determining a ^{44}CO$_2^{++}$/^{44}CO$_2^+$