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# Production rate of cosmogenic $^{21}$Ne in quartz estimated from $^{10}$Be, $^{26}$Al, and $^{21}$Ne concentrations in slowly eroding Antarctic bedrock surfaces

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ABSTRACT

We estimated the production rate of $^{21}$Ne in quartz using a set of samples from slowly eroding sandstone surfaces in the Antarctic Dry Valleys. Geologic evidence as well as cosmogenic $^{10}$Be and $^{26}$Al concentrations indicate that i) these sites have experienced millions of years of surface exposure at low erosion rates, and ii) steady erosion has been sustained long enough that surface $^{10}$Be and $^{26}$Al concentrations have reached equilibrium with the erosion rate. Under these conditions, surface cosmogenic $^{21}$Ne concentrations should be a function only of the erosion rate and the $^{21}$Ne production rate. As the erosion rate can be determined from $^{10}$Be and $^{26}$Al concentrations, this allows an estimate of the $^{21}$Ne production rate. Estimating the reference $^{21}$Ne production rate on this basis, with the assumption that all $^{21}$Ne production is by neutron spallation, yields a poor fit to measured $^{21}$Ne concentrations and a systematic residual that is correlated with the erosion rate of the sample site. The same steady-erosion assumption with a production model that includes production by deeply penetrating muons yields a good fit both to our measurements and to similar, independent, measurements from an Antarctic bedrock core. Both data sets together yield a total reference $^{21}$Ne production rate of $18.3 \pm 0.4$ atoms g$^{-1}$ a$^{-1}$, of which $0.66 \pm 0.10$ atoms g$^{-1}$ a$^{-1}$ is due to muon interactions.

## 1. Introduction

$^{21}$Ne is a rare stable isotope of neon produced in surface rocks by cosmic-ray bombardment. Like a variety of other stable ($^{3}$He) and radioactive ($^{10}$Be, $^{26}$Al, $^{36}$Cl, and $^{14}$C) cosmogenic nuclides, $^{21}$Ne is commonly used to determine surface exposure ages, erosion rates, and rates of sediment production and transport. $^{21}$Ne has important additional applications because, like $^{10}$Be and $^{26}$Al, it is produced in quartz. These nuclides share the same target and production mechanisms, but have different half-lives ($^{21}$Ne is stable; the $^{26}$Al and $^{10}$Be half-lives are 1.36 and 0.7 Ma, respectively). Thus, they can be used to: i) quantify exposure histories that are more complicated than a single period of exposure (Klein et al., 1988; Lal, 1991), and ii) date quartz-bearing sediments by 'burial dating' (Granger, 2006).

All these applications depend on accurate measurements of the absolute surface production rates of these nuclides or their production ratios. The production rates of geologically useful cosmogenic nuclides are only a few to a few hundred atoms g$^{-1}$ a$^{-1}$, so direct measurement of production rates in artificial targets exposed for months or years requires measurement at very low concentrations and is relatively imprecise. Most production rate measurements are geological calibrations, where one infers the production rate from nuclide concentrations in a rock surface whose exposure age is independently known from geologic evidence. Any such site must be old enough to have accumulated measurable nuclide concentrations, but young enough to not have been significantly degraded by weathering and erosion. Currently accepted $^{10}$Be and $^{26}$Al production rates are based on seven such sites (Balco et al., 2008, and references therein). An alternative strategy for short-lived radionuclides is to select sites that have sufficiently low erosion rates and old exposure ages that nuclide concentrations have reached equilibrium between production and decay. In this case, the nuclide concentration $N$ (atoms g$^{-1}$) is related to the production rate $P$ (atoms g$^{-1}$a$^{-1}$) by $N = P/\lambda$, where $\lambda$ is the decay constant (a$^{-1}$) of the nuclide; this approach has been used to measure production rates of cosmogenic $^{14}$C and $^{36}$Cl (Evans et al., 1997; Lifton et al., 2008).

Neither of these approaches is well-suited to measuring the production rate of cosmogenic $^{21}$Ne. $^{21}$Ne is stable, so equilibrium between production and decay does not occur. More importantly, precise measurement of cosmogenic $^{21}$Ne in relatively young surfaces is more difficult than for other commonly measured cosmogenic nuclides. Although measuring the total amount of $^{21}$Ne in a geologic sample is straightforward, this nearly always includes both cosmogenic $^{21}$Ne and trapped or nucleogenic $^{21}$Ne (Niedermann, 2002). Accurately measuring cosmogenic $^{21}$Ne requires measurement of other Ne isotopes and unmixing of multiple Ne components. For the short exposure times characteristic of calibration sites with minimal erosion and precise independent ages, cosmogenic $^{21}$Ne is typically less abundant than $^{21}$Ne from other sources. Resolving these components contributes a large uncertainty to the cosmogenic $^{21}$Ne measurement.

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Thus, the sites that are best suited for production rate calibration are by nature those where precise cosmogenic $^{21}$Ne measurements are most difficult.

There exists only one published geological calibration of the $^{21}$Ne production rate in quartz (Niedermann et al., 1994; Niedermann, 2000), based on two samples from a site in the California Sierra Nevada exposed by deglaciation 13 ka. This study was a striking analytical accomplishment in that the authors made relatively precise measurements at low cosmogenic $^{21}$Ne concentrations in the presence of multiple interfering Ne components. They determined the $^{21}$Ne/$^{26}$Al production ratio to be $0.65 \pm 0.11$. Given the $^{26}$Al production rate (30.3 atoms $g^{-1}$ $a^{-1}$) inferred from the commonly used production rate scaling scheme of Stone (2000) (as implemented in Balco et al. (2008)) and the $^{10}$Be–$^{26}$Al production rate calibration data set in Balco et al. (2008), this implies a reference $^{21}$Ne production rate of $19.6 \pm 3.3$ atoms $g^{-1}$ $a^{-1}$ (following common practice, by 'reference production rate' we mean the production rate at 1013.25 mbar and high latitude). This value is consistent with model calculations (18.4 and 21.3 atoms $g^{-1}$ $a^{-1}$ from Masarik and Reedy (1996) and Schäfer et al. (1999) respectively), and $^{21}$Ne exposure ages calculated using this value generally agree with $^{10}$Be and $^{26}$Al exposure ages on the same surfaces (Hetzel et al., 2002; Schäfer et al., 2008; Kober et al., 2008). However, this production rate estimate is less precise than those for other commonly used cosmogenic nuclides. In addition, the lack of estimates from multiple sites makes it impossible to evaluate scaling relationships between $^{21}$Ne and other cosmogenic nuclides that might yield insight into production mechanisms.

Here we suggest a new strategy for determining the production rate of cosmogenic $^{21}$Ne in quartz that does not rely on sites with short exposure times. Instead we select sites where the surface $^{21}$Ne concentration has reached steady state such that $^{21}$Ne production is balanced not by radioactive decay, but by loss of quartz at the surface and advection of lower-$^{21}$Ne quartz from below due to steady erosion. If erosion at an approximately constant rate is sustained for long enough that a thickness of rock equal to several attenuation lengths for subsurface production is removed, surface concentrations of $^{26}$Al, $^{10}$Be, and $^{21}$Ne will reach production-erosion equilibrium. As $^{10}$Be and $^{26}$Al production rates are independently known, this should permit determination of the erosion rate from the $^{10}$Be and $^{26}$Al concentrations, and in turn determination of the $^{21}$Ne production rate from this erosion rate and the $^{21}$Ne concentration.

This approach has the advantage that sites with low erosion rates have high cosmogenic $^{21}$Ne concentrations. This limits the importance of interfering Ne components and improves measurement precision. We chose a set of sandstone bedrock sites in the Antarctic Dry Valleys where: i) geomorphic and stratigraphic evidence indicates that surfaces have remained continuously exposed for ~14 Ma; ii) geomorphic evidence as well as cosmogenic $^{10}$Be and $^{26}$Al concentrations indicate that erosion rates are extremely slow (<2 m/Ma); and iii) paired $^{10}$Be and $^{26}$Al measurements indicate that erosion rates have been steady for a long enough time that $^{10}$Be and $^{26}$Al concentrations have reached steady state. Surface $^{21}$Ne concentrations at these sites are orders of magnitude higher than at the Sierra Nevada sites of Niedermann et al. (1994).

## 2. Methods

### 2.1. $^{10}$Be and $^{26}$Al measurements

We carried out quartz separation and Be and Al extraction at the University of Washington Cosmogenic Nuclide Laboratory. We purified quartz by crushing and sieving at 0.25–0.5 mm and repeated etching in dilute HF, then extracted Be and Al by HF dissolution and column chromatography (Stone, 2004). Our Be carrier was a commercially available ICP standard solution. We determined total Al concentrations by subsampling the dissolved quartz–HF solution, evaporating HF in the presence of $H_2SO_4$ to expel fluoride, and redissolving in dilute $HNO_3$ for Al measurement by ICP-OES. Al concentrations in quartz were 80–120 ppm with uncertainties of 0.5–2%. We measured Be and Al isotope ratios at PRIME Lab, Purdue University. Combined process and carrier blanks were $2.8 \pm 0.8 \times 10^5$ atoms $^{10}$Be and $2.3 \pm 0.9 \times 10^5$ atoms $^{26}$Al, always <0.2% of the total number of $^{10}$Be atoms and <0.05% of the total number of $^{26}$Al atoms in any sample.

Be isotope ratios were referenced at the time of measurement to the isotope ratio standards described in Nishiizumi (2002). Recently, Nishiizumi et al. (2007) revised the nominal isotope ratios of those standards. We renormalized our measurements to reflect this revision, and adopt the associated $^{10}$Be decay constant ($5.10 \pm 0.26 \times 10^{-7}$ $a^{-1}$). $^{26}$Al measurements are referenced to the isotope ratio standards of Nishiizumi (2004), and we use the corresponding $^{26}$Al decay constant ($9.83 \pm 0.25 \times 10^{-7}$ $a^{-1}$). Table 1 shows $^{26}$Al and $^{10}$Be concentrations.

### 2.2. $^{21}$Ne measurements

We measured cosmogenic $^{21}$Ne in aliquots of the same quartz separates that were used for $^{26}$Al and $^{10}$Be measurements. We analyzed at least two aliquots of each sample (Table 1, Table S1). These samples were heated at 70 °C for several days during quartz purification; measured diffusion kinetics for $^{21}$Ne in quartz (Shuster and Farley, 2005) indicate that this should not cause detectable Ne loss.

**Table 1**

Site and sample information and cosmogenic-nuclide concentrations.

| Sample name[a] | Latitude (DD) | E Longitude (DD) | Elevation[b] (m) | Sample thickness (cm) | Topographic shielding | $[^{10}Be]$[c] ($10^6$ atoms $g^{-1}$) | $[^{26}Al]$[d] ($10^6$ atoms $g^{-1}$) | $[^{21}Ne]$[e] ($10^6$ atoms $g^{-1}$) | No. of $^{21}$Ne measurements | $(\chi^2/\nu)$[f] |
|---|---|---|---|---|---|---|---|---|---|---|
| 05-EG-118-BR | −77.6419 | 160.9399 | 1721 | 7 | 0.9823 | $20.56 \pm 0.20$ | $101.7 \pm 3.3$ | $133.8 \pm 3.2$ | 2 | 0.3 |
| 05-EG-119-BR | −77.6442 | 160.9446 | 1671 | 7 | 0.9978 | $12.69 \pm 0.20$ | $66.4 \pm 1.8$ | $78.3 \pm 2.4$ | 3 | 1.4 |
| 04-AV-001-BR | −77.8569 | 160.9303 | 1289 | 1.5 | 0.9856 | $5.75 \pm 0.21$ | $34.4 \pm 1.3$ | $38.1 \pm 1.9$ | 3 | 0.9 |
| 04-AV-005-BR | −77.8806 | 160.8222 | 1455 | 5 | 0.9861 | $20.75 \pm 0.57$ | $95.2 \pm 2.4$ | $176.1 \pm 3.5$ | 4 | 0.6 |
| 04-AV-006-BR | −77.8866 | 160.7736 | 1681 | 3 | 0.9828 | $16.21 \pm 0.34$ | $80.5 \pm 2.1$ | $93.6 \pm 6.3$ | 3 | 2.2[g] |
| 04-AV-010-BR | −77.8882 | 160.8060 | 1628 | 2.5 | 0.9971 | $15.4 \pm 0.61$ | $82.3 \pm 2.2$ | $95.0 \pm 1.7$ | 4 | 0.8 |
| 04-AV-018-BR | −77.8791 | 160.9183 | 1690 | 4 | 0.9987 | $25.04 \pm 0.40$ | $118.1 \pm 3.6$ | $168.4 \pm 2.8$ | 3 | 0.6 |
| 05-WO-137-BR | −77.5055 | 161.0031 | 1463 | 1 | 0.9983 | $29.51 \pm 0.86$ | $123.7 \pm 4.0$ | $364 \pm 18$ | 3 | 3.0[g] |
| 05-WO-140-BR | −77.5055 | 161.0031 | 1463 | 1.5 | 0.9983 | $28.00 \pm 0.69$ | $123.3 \pm 4.5$ | $299.2 \pm 4.9$ | 3 | 0.9 |

Complete results of the step-degassing Ne analyses appear in Table S1.

[a] First two letters of sample names reflect field areas: EG, East Groin (western Asgard Range); AV, Arena Valley; WO, western Olympus Range.

[b] Measured by barometric traverse from benchmarks surveyed with high-precision GPS. Uncertainty in elevation is ± 3 m.

[c] Normalized to the isotope ratio standards of Nishiizumi et al. (2007).

[d] Normalized to the isotope ratio standards of Nishiizumi (2004).

[e] Error-weighted mean of multiple measurements on distinct quartz aliquots (see Table S1).

[f] Reduced $\chi^2$ of multiple measurements with respect to the error-weighted mean.

[g] The stated uncertainty in $^{21}$Ne concentrations in these samples is the standard deviation of the measurements rather than the error of the weighted mean.