GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 4, PAGES 369-372, FEBRUARY 21, 1992

EFFECTIVE ATTENUATION LENGTHS OF COSMIC RAYS PRODUCING ^{10}Be AND ^{26}Al IN QUARTZ: IMPLICATIONS FOR EXPOSURE AGE DATING

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Abstract. We have measured cosmic ray produced ^{10}Be ($t_{1/2}$ = 1.5 My) and ^{26}Al ($t_{1/2}$ = 0.72 My) as functions of depth in a core of quartz sandstone bedrock collected in South Victoria Land, Antarctica. These data were used to place limits on the exposure age and erosion rate of the exposed surface, and to calculate the effective attenuation lengths of cosmic rays producing these nuclides. These latter results indicate that the production attenuation length for ^{26}Al (156 $^{+13}_{-12}$ g cm^{-2}) is comparable to that for ^{10}Be (145 $^{+8}_{-6}$ g cm^{-2}). This suggests that the production ratio ^{26}Al:^{10}Be does not vary substantially with depth in a rock, and that its value at the surface of exposed rock is not strongly affected by erosional losses, allowing wider use of the ratio in determining exposure ages.

Introduction

Numerous studies have taken advantage of recent advances in analytical techniques to utilize the build-up of cosmogenic nuclides produced *in situ* within mineral lattices for quantification of exposure ages and erosion rates of surficial rocks in glacial deposits, glacially polished surfaces, meteorite craters, and lava flows.

In situ produced nuclides result from a small fraction of the interactions between cosmic rays and terrestrial material, which are dominated by neutron induced spallation reactions in the atmosphere. Because interaction with the atmosphere reduces the cosmic ray flux with a characteristic exponential attenuation length on the order of 160 g cm^{-2} (for altitudes less than 5 km), at the Earth's surface the flux has only a small fraction (~0.1%) of its value at the top of the atmosphere. These secondary cosmic rays (mostly neutrons) continue their interactions, producing cosmogenic nuclides within solid material exposed at the Earth's surface.

Models for quantification of exposure ages from concentrations of cosmogenic nuclides have been reviewed recently [Lal, 1991]. The number of atoms of a cosmogenic nuclide at time t and depth in rock x may be represented as a function of production, radioactive decay, and erosional loss,

$$N(t,x) = \frac{P_0}{(\varepsilon/L + \lambda)}[e^{-x/L}][1-e^{-t(\varepsilon/L+\lambda)}] + N(0,x)e^{-\lambda t},$$

where P_0 is the production rate (at g^{-1} y^{-1}) at the rock's surface, ε is the erosion rate (g cm^{-2} y^{-1}), $N(0,x)$ is the concentration of the nuclide at the beginning of the present exposure episode, and λ is the radioactive decay constant. As is the case in air, the production rate decreases approximately exponentially with the mass of overlying material with a characteristic attenuation length L (g cm^{-2}). The production attenuation length becomes a significant factor in quantifying exposure histories of samples taken at some depth below the rock's surface or in regions where erosion rates are high (ε/L approaches λ for ^{10}Be and ^{26}Al when $\varepsilon \sim 10^{-4}$ g cm^{-2} y^{-1}).

The ratio ^{26}Al:^{10}Be decreases with time of exposure from the production ratio of 6.0 [Nishiizumi et al., 1989] to the steady state ratio (assuming no erosional loss) of 2.8 (Figure 1). Since this ratio has a range of only a factor of 2 its use requires precise measurements. Nevertheless, the use of ratios of nuclides with differing half-lives has significant advantages over the use of a single nuclide in calculating exposure ages. Their use decreases uncertainties due to erosional loss (Figure 2) and exposure geometry, and reduces the dependence on absolute production rates (Figure 3). The latter are subject to variability due to changes in the primary cosmic ray flux, the Earth's geomagnetic field, and solar activity; production ratios are approximately constant and are better constrained. However, to take advantage of the reduction in dependence on erosional loss, knowledge of the ratio's variability with depth in rock is necessary. Should the effective attenuation length differ significantly for production

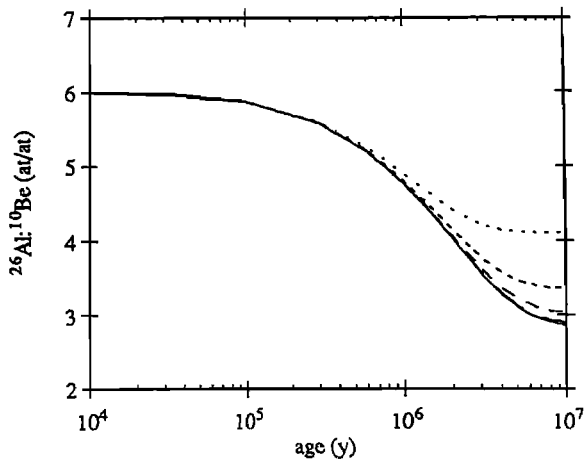

Fig. 1. The evolution of ^{26}Al:^{10}Be with time in a rock at various erosion rates (10^{-4}, 3x10^{-5}, 10^{-5}, 3x10^{-6}, and 0 g cm^{-2}y^{-1} from top to bottom of figure). The ratio is most appropriate for calculating ages in the range of 0.5 to 3 My. Other pairs of cosmogenic radio-nuclides with appropriate differences in half-life may be used similarly for other age ranges.

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Paper number 92GL00266
0094-8534/92/92GL-00266$03.00

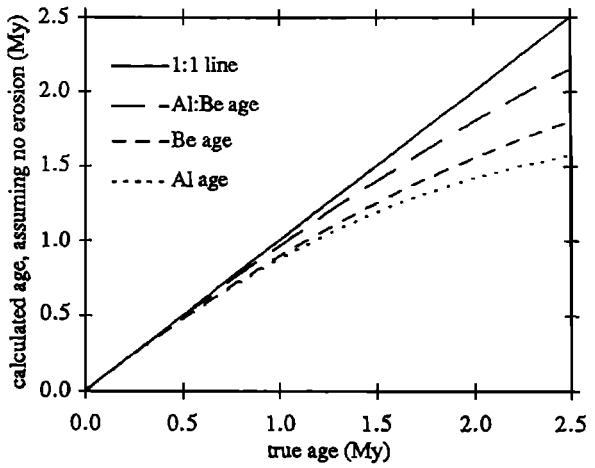

Fig. 2. The effect of the assumption that erosion is insignificant on exposure ages calculated from ^{10}Be, ^{26}Al and ^{26}Al:^{10}Be. The curves are based on a model of cosmogenic nuclide accumulation in a rock surface undergoing erosion at a rate of $3x10^{-5}$ g cm^{-2} y^{-1}. It is evident that the ratio, if determined accurately, is less sensitive to erosional loss than the absolute concentrations of either individual nuclide.

of each nuclide, interpretation of data from a suite of nuclides would become more complex.

It should be noted that the production attenuation length, which is specific for each cosmogenic nuclide, is not formally identical to the absorption attenuation length which characterizes the decrease in cosmic ray flux with depth in air or solids. In addition, because the production excitation function differs for each nuclide, the production rate of each

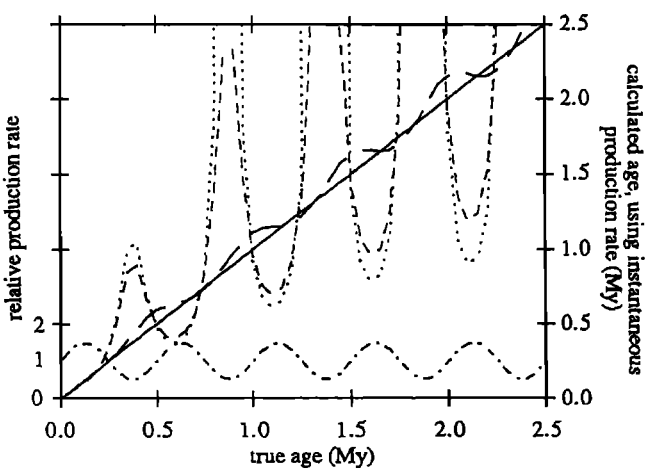

Fig. 3. An example of the effect of variable production rates on exposure ages calculated from ^{10}Be, ^{26}Al and ^{26}Al:^{10}Be (see Figure 2 for legend). The production rate was arbitrarily assumed to vary sinusoidally about a value of $1 \pm 50\%$ with a period of $5x10^5$ years; it is illustrated at the bottom of the figure. The calculated exposure ages are based on present day production rates (the instantaneous values along the production rate curve). Use of the ratio greatly reduces the dependence of calculated exposure ages upon absolute production rates. This is particularly significant because measured production rates (e.g. Nishiizumi et al. [1989]) are based on relatively short exposure periods (~10^4 y) which may not be representative of the long-term (~10^6 y) average.

nuclide has an energy-dependent relationship with the total number of reactions ("stars") between cosmic ray particles and terrestrial material. However, because the energy spectrum of cosmic rays is relatively invariant at atmospheric depths > 200 g cm^{-2} (altitudes < 12 km), production attenuation lengths in air have been estimated [Lal, 1991; Lal and Peters, 1967] using the relationships among slow neutron fluxes (which have been extensively studied by Lingenfelter [1963] and Soberman [1956] among others), star production, and cosmogenic nuclide production. The resulting estimates of production attenuation lengths, for altitudes less than 5 km, decrease from 160 g cm^{-2} at the equator to 140 g cm^{-2} at latitude greater than 60°. The production attenuation length in the atmosphere has also been directly constrained by measurements of cosmogenic nuclide production as a function of altitude at geomagnetic latitudes of 20° [Zreda et al., 1991] and 25° [Mabuchi et al., 1971]; these yield values of ~152 and 160±5 g cm^{-2}, respectively.

Early work on interaction of cosmic rays with other materials showed (in spite of substantial experimental uncertainties) that attenuation lengths increase with increasing atomic weight (reviewed in Schopper et al., 1967). In addition it has been proposed that greater attenuation lengths may be observed in solids relative to gases because of the interaction of charged pions (which decay rapidly in the atmosphere) with condensed materials [Lal, 1991], and the greater attenuation length of muons in solids relative to the atmosphere [Lal, 1987]. Measurement of cosmogenic ^3He as a function of depth in Hawaiian volcanic rocks (20° geomagnetic latitude) yielded an effective attenuation length of ~170 g cm^{-2} [Kurz, 1986], consistent with these general observations. The present study examines the variability of *in situ* produced ^{10}Be and ^{26}Al with depth in quartz to establish values for the production attenuation lengths for these nuclides in geological materials, and to compare those values with the existing ^3He results [Kurz, 1986].

Sample Collection and Analysis

A 1.1 m vertical drill core (sample ID KBA89-77) was collected during austral summer 1989-90 from a quartz sandstone bedrock surface in the Quartermain Mountains, Southern Victoria Land, Antarctica (77°50'S, 161°E) at an altitude of 1700 m. Quartz is a particularly appropriate mineral for *in situ* dating studies using ^{10}Be and ^{26}Al. It is an abundant and compositionally simple mineral with a minimal number of targets for spallation reactions, and it has low levels of ^{27}Al [Lal and Arnold, 1985; Yiou et al., 1984]. The latter attribute is a requirement for the determination of cosmogenic ^{26}Al; at ^{27}Al concentrations exceeding ~1000 ppm ^{26}Al:^{27}Al becomes difficult to measure. Subsamples of 3 to 5 cm sections of the core were prepared for analysis of cosmogenic nuclides by crushing into individual grains. Between 3 and 7 g of a sieved 0.5 to 1.0 mm size fraction were used for ^{10}Be and ^{26}Al analyses when sufficient material was present, although in some samples a 0.25 to 1.0 mm fraction was used. No systematic difference in ^{10}Be or ^{26}Al was observed between the two size factions. Analyses of ^3He in these samples will be presented elsewhere [Brook et al., 1991].

Samples were cleaned and dissolved using previously reported methods [Brown et al., 1991]. Addition of carrier, separation of Be from Al, and preparation of targets for ^{10}Be

analyses were performed following procedures described elsewhere [Bourlès, 1988; Brown, 1990]. An enhanced purification of aqueous Al was accomplished by extraction of 2-methyl 8-quinolinol derivatives of other elements into chloroform (this ligand does not interact strongly with Al). Targets were prepared from this purified Al according to previously described methods [Bourlès, 1988; Brown, 1990]. All ^{10}Be and ^{26}Al measurements were performed by accelerator mass spectrometry at the Tandetron AMS Facility, Gif-sur-Yvette, France [Raisbeck et al., 1987].

Results and Discussion

Both ^{10}Be and ^{26}Al show the expected exponential decrease with overlying mass, scattering about the best fit lines in a manner consistent with their analytical uncertainties (Figure 4). These uncertainties (1σ) are based on counting statistics and upper limits for variability in machine response; the latter are <5% for ^{10}Be and <10% for ^{26}Al. Blank corrections were insignificant (<0.5%) for all samples. For the purposes of calculations, each sample's depth range was normalized to yield the average overlying mass. Samples taken over the adjacent depth intervals 86-95 cm and 104-111 g cm^{-2} were inadvertently combined; the reported overlying mass for this combined sample is the weighted average for the two intervals. The decrease in concentration with depth was modeled using the relationship

$$N(x) = N(0)e^{-x/L},$$

an approximation which ignores the zenith angle dependence of cosmic rays, but is valid for the shallow depths below a flat surface discussed here. Weighted least squares best fit lines [York, 1966] yield apparent attenuation lengths of 145 ($^{+8}_{-6}$) g cm^{-2} and 156 ($^{+13}_{-12}$) g cm^{-2} for ^{10}Be and ^{26}Al, respectively. Surface concentrations yielded by the intercepts of these best fit lines are 21.8 (±1.0) x 10^6 and 103 (±6.5) x 10^6 at g^{-1} for ^{10}Be and ^{26}Al, and ^{26}Al:^{10}Be is thus 4.72 (±0.37). The individual values of the ratio scatter about a constant value, but also have a general tendency to increase with depth (as manifested by the slight difference between the attenuation lengths).

Attenuation Lengths

The attenuation lengths calculated from production of ^{26}Al (156 $^{+13}_{-12}$ g cm^{-2}) and ^{10}Be (145 $^{+8}_{-6}$ g cm^{-2}) in quartz are comparable to, but slightly greater than, the value of 140 g cm^{-2} calculated for air at high latitude, consistent with the prediction that the production attenuation length in solids would be at most 10% greater than in the atmosphere [Lal, 1991]. Attenuation lengths of ~175 g cm^{-2} were found for

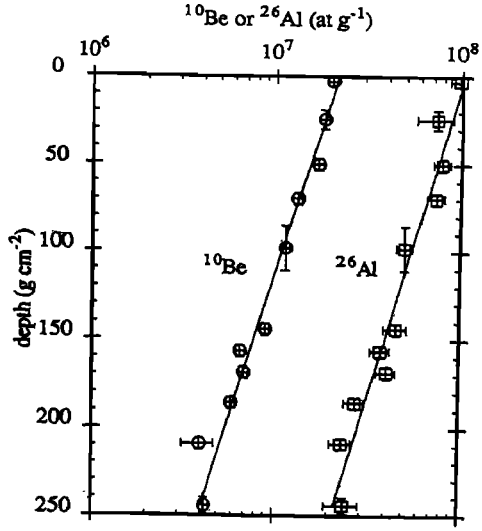

Fig. 4. ^{10}Be and ^{26}Al as functions of depth in rock. Vertical error bars represent sampling intervals which were normalized to represent the weighted mean depth. See text for details of analytical uncertainties and curve fitting.

production of ^{10}Be and ^{26}Al by neutrons (over the depth range 150 to 400 g cm^{-2}) in a lunar soil profile [Nishiizumi et al., 1984a, b]. The lunar values are greater than those reported here, consistent with the greater hardness of the energy spectrum of incident neutrons below the lunar surface.

Although the value for the attenuation length for ^{26}Al production is somewhat larger than that for the production of ^{10}Be, the difference is not statistically significant. Enhanced production of ^{26}Al relative to ^{10}Be at depth could be associated with muon-induced reactions or changes in the energy spectrum of neutrons as cosmic rays begin to interact with solid materials [Brown et al., 1991]. However, experimental results have indicated that muons produce ^{26}Al and ^{10}Be at a ratio comparable to that yielded by neutron induced spallation [Reedy, 1990]. The present data confirm the minor effects of such mechanisms on the production ratio at relatively shallow rock depths; the similarity of the production attenuation lengths of the two nuclides allows wider use of their ratio in calculating exposure ages.

Exposure Ages and Erosion Rates

The concentrations of ^{10}Be and ^{26}Al extrapolated to the surface have lower uncertainties than do the individual analyses and were used in defining the history of the exposed surface. Assuming that there has been no erosional loss (and using present day production rates of 24.7 and 149 at g^{-1} y^{-1}

TABLE 1. Dependence of calculated ages on assumed erosion rates

erosion rate (g cm^{-2}y^{-1})	^{10}Be age (My)	lower limit	upper limit	^{26}Al age (My)	lower limit	upper limit	^{26}Al:^{10}Be age (My)	lower limit	upper limit
0.0	1.14	1.07	1.21	1.18	1.05	1.33	1.05	0.69	1.49
10^{-6}	1.15	1.08	1.22	1.19	1.05	1.34	1.06	0.69	1.50
$3x10^{-6}$	1.16	1.09	1.23	1.20	1.06	1.36	1.06	0.69	1.50
10^{-5}	1.20	1.12	1.27	1.26	1.11	1.44	1.06	0.70	1.53
$3x10^{-5}$	1.33	1.24	1.44	1.48	1.26	1.78	1.10	0.71	1.62
$5x10^{-5}$	1.53	1.40	1.68	1.92	1.50	2.92	1.15	0.73	1.72

based on the empirical calculations of Lal [1991] for high latitude and 1700 m) minimum exposure ages of 1.14 (±0.07) and 1.18 ($^{+16}_{-13}$) My may be calculated from ^{10}Be and ^{26}Al (Table 1). Conversely, the assumption that the surface is at steady state with respect to erosional loss and radiodecay, allows calculation of upper limits on erosion rates of 9.4 (±0.7) x 10^{-5} and 7.5 (±1.4) x 10^{-5} g cm^{-2} y^{-1} for ^{10}Be and ^{26}Al respectively. However, this steady state assumption is probably not valid for these samples; the maximum erosion rates are nearly an order of magnitude higher than those calculated for similar exposed surfaces at the nearby Taylor IVb Moraine and Quatermain Drift [Brown et al., 1991], and in other regions of Antarctica [Nishiizumi et al., 1991].

Uncertainties in ages associated with the assumptions of minimal erosional loss and constant production rate can be reduced through the use of ^{10}Be:^{26}Al (Table 1; Figures 2, 3), but such ages are sensitive to analytical uncertainties. In addition, the ratio is most useful only in the range of 0.5 to 3 My. Nevertheless, as analytical capabilities improve, the benefits of measuring ratios of cosmogenic nuclides can be extended to other timescales using ratios of cosmogenic radionuclides with a range of half-lives (^{14}C:^{10}Be, ^{36}Cl:^{10}Be, ^{10}Be:^{21}Ne, ^{10}Be:^{3}He etc.).

Acknowledgements. We thank J. Lestringuez and D. Deboffle for their continuing expertise in AMS measurements, R. Ackert for his considerable assistance in sampling, and the helicopter crews of VXE-6 and D. Kammer for their assistance in logistical aspects of this endeavor. This work was supported by the NSF through grant DPP-8817406 (MDK) and through an NSF-NATO Postdoctoral Fellowship and grant INT-9008641 (ETB). Tandetron operation is supported by the CNRS, CEA and IN_2P_3.

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(Received December 9, 1991;
accepted January 6, 1992.)