MONTE CARLO SIMULATION OF *IN-SITU*-PRODUCED COSMOGENIC NUCLIDES

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Cosmogenic nuclides produced *in situ* in terrestrial surface samples provide an important tool for dating and determining erosional histories of landforms. Reliable interpretation of the measured nuclide contents requires a good understanding of fundamentals of nuclide production mechanisms. We present a pure physical model (Masarik and Reedy 1995) for the simulation of the relevant processes enabling an investigation of nuclide production dependence on depth, composition, atmospheric thickness, and geomagnetic field intensity.

In our simulation model (Masarik and Reedy 1994, 1995), the spectra of particles inducing reactions that produce cosmogenic nuclides are calculated by Monte Carlo numerical simulations using the LAHET Code System (LCS) and the GEANT code. Having calculated neutron fluxes with these codes, the production rates of nuclides are determined by integrating over energy the product of these fluxes with experimental and evaluated cross sections for the reactions producing each nuclide. Technical details of the LCS model and our approach are described in Masarik and Reedy (1995). This approach is similar to that often used and well tested by us for cosmogenic-nuclide production rates in lunar samples and meteorites (*e.g.*, Masarik and Reedy 1994).

We simulated the irradiation of Earth with an isotropic GCR particle flux with an energy distribution corresponding to the GCR primary particle flux averaged over a solar cycle. The Earth was modeled as a sphere with a 6378-km radius and an average crustal elemental composition. The model atmosphere has a 1030-g/cm^2 thickness and its standard composition, density, and temperature profiles (Masarik and Reedy 1995). Running 10^7 primary particles, we obtained surface neutron fluxes with statistical errors of ~8%. Although we calculated muon fluxes, their contribution to the production rate was not considered by us because of the lack of the data needed to convert muon fluxes to production rates.

Except for H and Fe, most changes in the surface composition or the addition of other elements to the assumed composition have very little effect on the calculated fluxes (Masarik and Reedy 1994). Therefore elemental production rates valid for many types of rocks can be obtained from these fluxes. The total production rates (in atoms per gram-element per year) only by neutrons and for high latitudes and sea level are given by

$$P(^{10}Be) = 10.87[O] + 0.52[Mg] + 0.39[Si] + 0.45\,[Al] + 0.16[Fe]$$

$$P(^{14}C) = 31.3[O] + 5.3[Mg] + 4.2[Al] + 4.3[Si] + 1.2[Fe]$$

$$P(^{26}Al) = 225[Al] + 77\,[Si] + 0.15\,[Fe]$$

$$P(^{36}Cl) = 129[K] + 65[Ca] + 16[Ti] + 0.9[Fe]$$

$$P(^{21}Ne) = 98[Na] + 131[Mg] + 65[Al] + 39[Si] + 4[Ca] + 0.20[Fe]$$

$$P(^{3}He) = 135[O] + 116[Mg] + 107[Al] + 111[Si] + 61[Ca] + 40[Fe]$$

in which the target-element concentrations, such as [O], are in weight fractions. The calculated rates for most minor target elements are not well tested and could have considerable uncertainties. Latitude-altitude production rates for all above listed nuclides were also calculated. The results of our model calculations are in good agreement with most recent measurements (Masarik and Reedy 1995).

PRODUCTION RATE OF ^{10}Be AND ^{26}Al ON THE SURFACE OF THE EARTH AND UNDERGROUND

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To apply *in-situ* produced cosmogenic nuclides to the study of Earth surface processes, production rates at the surface of the Earth and the attenuation length of the production underground must be known. I review present understanding of ^{10}Be and ^{26}Al production rates from quartz, based on different methods and covering various time scales. Each method has its merits and limitations that must be understood in order to assess the reliability of the production rates.

A. *Geological Methods*: Geological methods require that the exposure conditions of the samples studied be constant and that they be well known. Production rates are averages over changes of the Earth's magnetic field and of the primary cosmic ray flux.

1. Concentration of ^{10}Be and ^{26}Al in quartz from glacially polished rocks (Nishiizumi *et al.* 1989): Since samples are uneroded, nuclides with various half-lives can be compared in the same sample (Neidermann *et al.* 1994). Uncertainties in the exposure age (glaciation age) and in the geomagnetic latitude correction must be considered.
2. Concentration of ^{10}Be and ^{26}Al in saturated rocks (Nishiizumi *et al.* 1991; Brown *et al.* 1991): The high concentrations of cosmogenic ^{21}Ne (Hudson *et al.* 1991) insure that the activities of ^{10}Be and ^{26}Al in certain Antarctic rocks are saturated (decay rate is the same as the production rate). Effects of changing geomagnetic intensity can be ignored for these high latitude samples. Because of the possible influence of erosion, the production rate estimates are lower limits. In addition, there is an uncertainty arising from uplift of the samples during the million year exposure period.

B. *Theoretical Calculation* (ex. Masarik and Reedy 1995): The accuracy of calculated production rates depends on the model and on knowledge of excitation functions. The increasing availability of laboratory data (Imamura *et al.* 1990; Reedy *et al.* 1994) improves the reliability of the results. The method can be applied to samples of various size and shape.

C. *Direct Measurements of ^{10}Be Production in a Water Target* (Nishiizumi *et al.* 1995): Exposure conditions are unambiguous but the exposure age is very short compared to the geological time scale. There is an uncertainty arising from secular variations of the Earth's magnetic field and of the primary cosmic ray flux.