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Snow shielding factors for cosmogenic nuclide dating inferred from Monte Carlo neutron transport simulations

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ABSTRACT

Conventional formulations of changes in cosmogenic nuclide production rates with snow cover are based on a mass-shielding approach, which neglects the role of neutron moderation by hydrogen. This approach can produce erroneous correction factors and add to the uncertainty of the calculated cosmogenic exposure ages. We use a Monte Carlo particle transport model to simulate fluxes of secondary cosmic-ray neutrons near the surface of the Earth and vary surface snow depth to show changes in neutron fluxes above rock or soil surface. To correspond with shielding factors for spallation and low-energy neutron capture, neutron fluxes are partitioned into high-energy, epithermal and thermal components. The results suggest that high-energy neutrons are attenuated by snow cover at a significantly higher rate (shorter attenuation length) than indicated by the commonly-used mass-shielding formulation. As thermal and epithermal neutrons derive from the moderation of high-energy neutrons, the presence of a strong moderator such as hydrogen in snow increases the thermal neutron flux both within the snow layer and above it. This means that low-energy production rates are affected by snow cover in a manner inconsistent with the mass-shielding approach and those formulations cannot be used to compute snow correction factors for nuclides produced by thermal neutrons. Additionally, as above-ground low-energy neutron fluxes vary with snow cover as a result of reduced diffusion from the ground, low-energy neutron fluxes are affected by snow even if the snow is at some distance from the site where measurements are made.

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1. Introduction

For over half a century the relationship between cosmogenic nuclide concentrations and landform ages has been explored (Davis and Schaeffer, 1955), and its application met with considerable success, with several nuclides (^{3}He, ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl) used routinely to date landforms over Earth's surface (Muzikar et al., 2003). Recent efforts, such as the CRONUS project (Phillips, 2012), focus on reducing total methodological uncertainty to permit more precise and accurate assessment of ages and production rates. First- and second-order effects using physically-based parameterizations have been accounted for. These include the effects of erosion and inheritance (Lal, 1991), topographic shielding (Dunne et al., 1999), mass shielding (Cerling and Craig, 1994), spatio-temporal variability in cosmic-ray flux (Dunai, 2001; Desilets and Zreda, 2003; Lifton et al., 2005, 2008) and atmospheric pressure (Staiger et al., 2007). However, despite these successes, other uncertainties remain. One of these uncertainties, the effect of moisture at the land surface on cosmogenic production rates, is addressed here.

We use a Monte Carlo particle transport model to examine how snow affects secondary cosmic-ray neutron intensity near Earth's surface. Models such as these have been used to estimate rates of cosmogenic nuclide production (Masarik and Reedy, 1995) and other effects such as temporal changes in Earth's geomagnetic intensity (Masarik et al., 2001) and boulder size (Masarik and Wieler, 2003). Although snow cover represents only a small (10–15%) effect (Gosse and Phillips, 2001), it is considered necessary when dating boulders within moraine complexes, as the presence of moraines indicates recently glaciated environments. We place particular emphasis on low-energy neutron capture, which is a production pathway for ^{36}Cl. Cosmogenic nuclide techniques give the 'apparent' age of a sample, the age computed under the assumption of continuous exposure at Earth's surface. If the period of exposure was punctuated by times when the sample was shielded, for example by soil, snow, ash or sand (Fig. 1), neutron fluxes and corresponding cosmogenic nuclide production rates near the surface will be affected. As a result, the apparent age will not be the same as the true exposure age, and a shielding correction factor must be computed to convert apparent age to exposure age. Covering materials can have a significant effect on computed exposure ages. For example Schildgen et al. (2005) estimate a spallation

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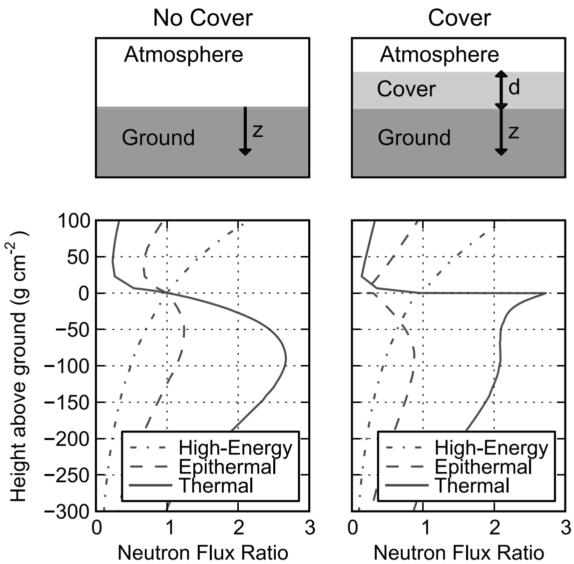

Fig. 1. The effect of ground cover on shielding of cosmic rays. Fluxes are normalized to unshielded surface values. Epithermal and thermal neutron fluxes also change above the snow surface (5 cm snow water equivalent) as a result of reduced net diffusion from the ground, which is not the case for high-energy neutron fluxes.

snow cover correction factor of 14% for a 15.5 ka sample from the Cairngorm Mountains in Scotland. Similarly, Gosse et al. (1995) present snow cover correction factors ranging from 0.6% to 15% for samples from the Wind River Range, Wyoming.

Prior research into the role of snow cover in moderating neutron fluxes is sparse, presumably because more rigorous formulations of snow scaling would be hampered by a lack of observational data regarding snow cover over the period of sample exposure. Generally, snow shielding is grouped into the more general category of mass shielding (Cerling and Craig, 1994; Schildgen et al., 2005), where the important characteristic of the shielding material is its 'mass length', reported as density times thickness (g cm^{-2}). For cosmogenic nuclides generated by spallation, it is conventional to invoke a generic mass-shielding approach, in which the high-energy neutron flux beneath covering material ϕ_{cover} is computed from (e.g. Gosse and Phillips, 2001, Eq. 3.75):

$$\frac{\phi_{\text{cover}}}{\phi} = e^{(-Z_{\text{cover}}/\Lambda_f)} \tag{1}$$

where ϕ is the high-energy neutron flux (neutrons cm^{-2} yr^{-1}) in the absence of cover, Z_{cover} the mass length of the material covering the surface (g cm^{-2}), and Λ_f the attenuation length for high-energy neutrons, thought to vary between 140 g cm^{-2} at Earth's poles to 170 g cm^{-2} near the equator (Cerling and Craig, 1994), as Earth's magnetic field blocks fewer low-energy, less penetrating cosmic rays near the poles.

For seasonal cover such as snow, the shielding factor S_{snow} is calculated as the sum of fractional components from a time discretization, such that in each time interval the cover can be assumed to be constant. For example monthly snow cover (e.g. Gosse and Phillips, 2001) is calculated as:

$$S_{snow} = \frac{\phi_{snow}}{\phi} = \frac{1}{12}\sum_{i}^{12} e^{-z_{snow,i}\rho_{snow,i}/\Lambda_f} \tag{2}$$

where $z_{snow,i}$ is the snow thickness during the ith month (cm) and $\rho_{snow,i}$ the density of snow during the ith month (g cm^{-3}). Implicit in Eq. (2) is the notion that if the sample site is above the snowline, such as at the top of a large boulder, the sample can be considered snow free with no correction factor applied.

The above approach is reasonable for spallation because high-energy neutrons responsible for spallation reactions are attenuated by the mass length of materials above a dated surface. However, for low-energy neutrons, which are not only attenuated but also moderated, a different approach to correcting for snow cover is necessary.

2. Numerical simulations

To simulate changes in neutron flux resulting from changes in surface cover we use MCNPX (Monte Carlo N-Particle eXtended; Pelowitz, 2005) Version 2.5.0, a 3-D Monte Carlo particle transport code that can track 34 different particle types and more than 2000 heavy ions at nearly all energies. Interactions between neutrons and earth elements are computed using empirically derived, energy dependent cross sections of scattering and absorption; when these are not available, nuclear models are used.

In the simulations, Earth is approximated as a half space with 32 atmospheric layers and 43 subsurface layers. Atmospheric layers are composed of 22% oxygen and 78% nitrogen, have equal mass lengths of 20 g cm^{-2}, and extend from the surface to a height of 7.6 km. Atmospheric densities are computed from the pressure variation with height according to the International Standard Atmosphere (ISO 2533:1975) approximation.

Snow is represented as a surface layer of pure water with density 1 g cm^{-3}. Initial results with MCNPX showed statistical insignificance to variations in snow density, so we use water as a standard and report all results in terms of mass length (snow water equivalent in this case). Subsurface layers have uniform chemistries and densities, and are modeled as one of three possible types: siliceous dolomite, basalt, or granite (Supplementary Table S1).

In each MCNPX simulation, 10^6 neutrons are injected downwards into the uppermost atmospheric layer as the source function of incoming primary cosmic-ray flux, with an inverse power law energy spectrum (Grimani et al., 2011) over an energy E range between 6 GeV and 100 GeV as the source energy probability distribution. In the absence of a geomagnetic field, this energy spectrum emulates a low-latitude site (Roesler et al., 1998), with simulations using protons as primary cosmic-ray particles showing statistically insignificant differences to those using neutrons.

To reduce Monte Carlo uncertainties, MCNPX expresses neutron fluxes as 'fluences' (neutrons cm^{-2}), defined as time integrated, volume averaged neutron fluxes normalized per unit source particle. Neutron fluences between different model simulations with the same geometry scale with each other in the same way as neutron fluxes. MCNPX partitions fluences into energy dependent bins, so that in any atmospheric or ground layer the neutron fluence within a pre-defined energy range can be estimated. In each layer, neutron fluences are partitioned into high-energy (100 MeV $< E <$ 200 MeV), epithermal (0.5 eV $< E < 10^{-3}$ MeV) and thermal ($E <$ 0.5 eV) components. For a simulation using 10^6 neutrons as cosmic-ray source particles, we find that Monte Carlo uncertainties near the ground are typically smaller than 2%.

3. Results

In the absence of surface ground cover, high-energy neutron fluxes decrease exponentially with depth, whereas thermal and epithermal concentrations increase to reach broad maxima at depths between 50 g cm^{-2} and 100 g cm^{-2} (Liu et al., 1994; Phillips et al., 2001; Fig. 1 LHS). In the absence of any cover, the exponential attenuation with depth for high-energy neutrons is computed here as 156 g cm^{-2}, which for a cutoff rigidity of 6 GV compares reasonably with the 170 g cm^{-2} determined experimentally for ^{3}He in basalt at ca. 13 GV by Kurz (1986). The difference