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Physics-based modeling of cosmogenic nuclides part II – Key aspects of *in-situ* cosmogenic nuclide production

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ABSTRACT

Characteristics of the spallogenic component of nuclide production are investigated through the use of a physics-based model. Calculated production rates for commonly used nuclides indicate differences in scaling up to 15% at very high altitude. Angular distribution of nuclide forming particles suggests the current method of shielding correction, which is neither altitude nor latitude dependent, can be improved on. Subsurface production profiles suggest that erosion corrections should be performed with non-constant attenuation lengths. Results are parameterized for easy application.

1. Introduction

1.1. Overview

Cosmogenic nuclide methods have opened the door to quantification of numerous aspects of geomorphology and holds promise for even more. As geomorphic and climatic studies continue to require increasing accuracy, our understanding of the physics and characteristics of nuclide production must also grow. We have developed a model of cosmogenic nuclide production which includes a definition of the primary cosmic-ray protons and alpha particles, Monte Carlo style radiation transport of the radiation through the atmosphere into various surface materials such as sea water or rock, and folding the particle spectra with cross sections to generate production rates of cosmogenic nuclides. This model allows us to investigate the characteristics of both the cosmic-ray radiation field and the resulting production rate potential of that field (we define the production rate potential as the result of folding particle flux with cross sections, giving a nuclide production rate in a specific target material). Argento et al. (2015) describes our physics-based system in detail. The results presented are strictly spallogenic; production by muons will be investigated in future work. It is also important to note that these results were not adjusted to achieve agreement with benchmarks or observed empirical values. Here we present (1) parameterized production rate results as functions of altitude and latitude, (2) angular distributions of nuclide forming particles that are also a function of altitude and latitude, and (3) parameterized subsurface production rates in quartz, granite, and basalt.

Many independently dated calibration sites have been sampled by the Cosmic Ray prOduction of NUclides on Earth (CRONUS) collaboration and others. The calibration sites were meant to be used both as local calibrations as well as benchmarks for assessing the ability of scaling schemes to predict sample concentrations at sites differing widely in altitude, latitude and exposure age. Surprisingly, models that account for changes in the geomagnetic field over time (Desilets and Zreda, 2003; Dunai, 2001; Lifton et al., 2008) do not predict the calibration data any better than the original time-invariant model of Lal (1991) (Borchers et al., 2015; Phillips et al., 2015). This indicates a problem with scaling schemes or the calibration sites, or both (Blard et al., 2013b; Lifton et al., 2014; Schimmelpfennig et al., 2012). Here we examine the possibility of errors in other systematic correction factors that may contribute to the discrepancies.

The approach described here provides another way to estimate parameters and check correction procedures (e.g. for sample

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thickness, exposure geometry, etc) that are used in exposure dating but often incompletely verified. For example, the corrections for horizon geometry have never been checked with measurements on natural samples; because such measurements integrate over zenith angle, such an experiment has been elusive. In contrast, radiation transport modeling allows us to separate contributions to nuclide production by particle type and energy as well as zenith angle, and therefore provides a great deal of insight into production mechanisms and how exposure ages should be corrected for horizon geometry (cf Dunne et al., 1999).

Systematic errors due to nuclide specific scaling with altitude and latitude (Lifton et al., 2008), non-exponential subsurface attenuation (Masarik and Reedy, 1995), and oversimplified shielding corrections (Dunai, 2010; Gosse and Phillips, 2001) may be significant. As shown here, (1) neglecting nuclide specific scaling can potentially incur up to 15% error at very high altitudes; (2) low angle shielding corrections should be more substantial than currently estimated (Gosse and Phillips, 2001); and (3) subsurface production rates are not adequately described by simple exponentials. Our physics-based model allows us to investigate these subtle yet important phenomena.

1.2. Evolving energy spectra

As shown in Argento et al. (2013, 2015), presented here and previously discussed by Desilets and Zreda (2001) and Lal (1958), the energy spectra of both neutrons and protons changes throughout the atmosphere. Fig. 1, first published in Argento et al. (2015) shows high-latitude neutron and proton energy spectra sampled at atmospheric-depth intervals of 100 g/cm^2 and normalized to the spectra at 500 g/cm^2. For both the high and low latitudes, the neutron and proton spectra at 1000 g/cm^2 (low altitude) have the greatest relative enhancement of lower energies ("softest" spectra), while the 400 g/cm^2 (~7250 m) spectra have the greatest relative enhancement in the higher energies ("hardest" spectra). This demonstrates how the neutron and proton energy distributions shift towards lower energies with atmospheric depth. Each cosmogenic nuclide has its own set of target elements and unique set of cross sections (Reedy, 2013). Taken together, this suggests that we should expect each nuclide production rate to scale uniquely.

1.3. Nuclide specific scaling

Nuclide production rates will vary differently from each other with altitude and latitude because each nuclide has distinct energy dependent cross sections for production (Caffee et al., 2013; Reedy, 2013). Scaling differences between nuclides are close to the limits of what can be resolved in measurements on natural samples, but have been suggested by a number of studies may become more evident in the future (Amidon et al., 2008; Blard et al., 2013a; Gayer et al., 2004; Masarik and Reedy, 1995; Schimmelpfennig et al., 2011; Vermeesch et al., 2009). Because scaling schemes have been evaluated primarily based on ^{10}Be, it is likely that studies employing other nuclides (^{3}He, ^{21}Ne, ^{26}Al, ^{36}Cl, etc.) contain systematic errors in scaling between sea level high latitude (SLHL) and other sites. For example, it is not evident that the scaling scheme which best fits ^{10}Be calibration data (Borchers et al., 2015; Lifton et al., 2014), will also best account for ^{3}He data (Goehring et al., 2010). In Argento et al. (2013, 2015), it is shown that a single exponential function with a single attenuation length cannot adequately describe the variation of nuclide production rates as functions of atmospheric depth and cutoff rigidity. Instead, each nuclide's production rate is described by a unique function, and nuclide production ratios vary with both altitude and geomagnetic cut-off rigidity. We use

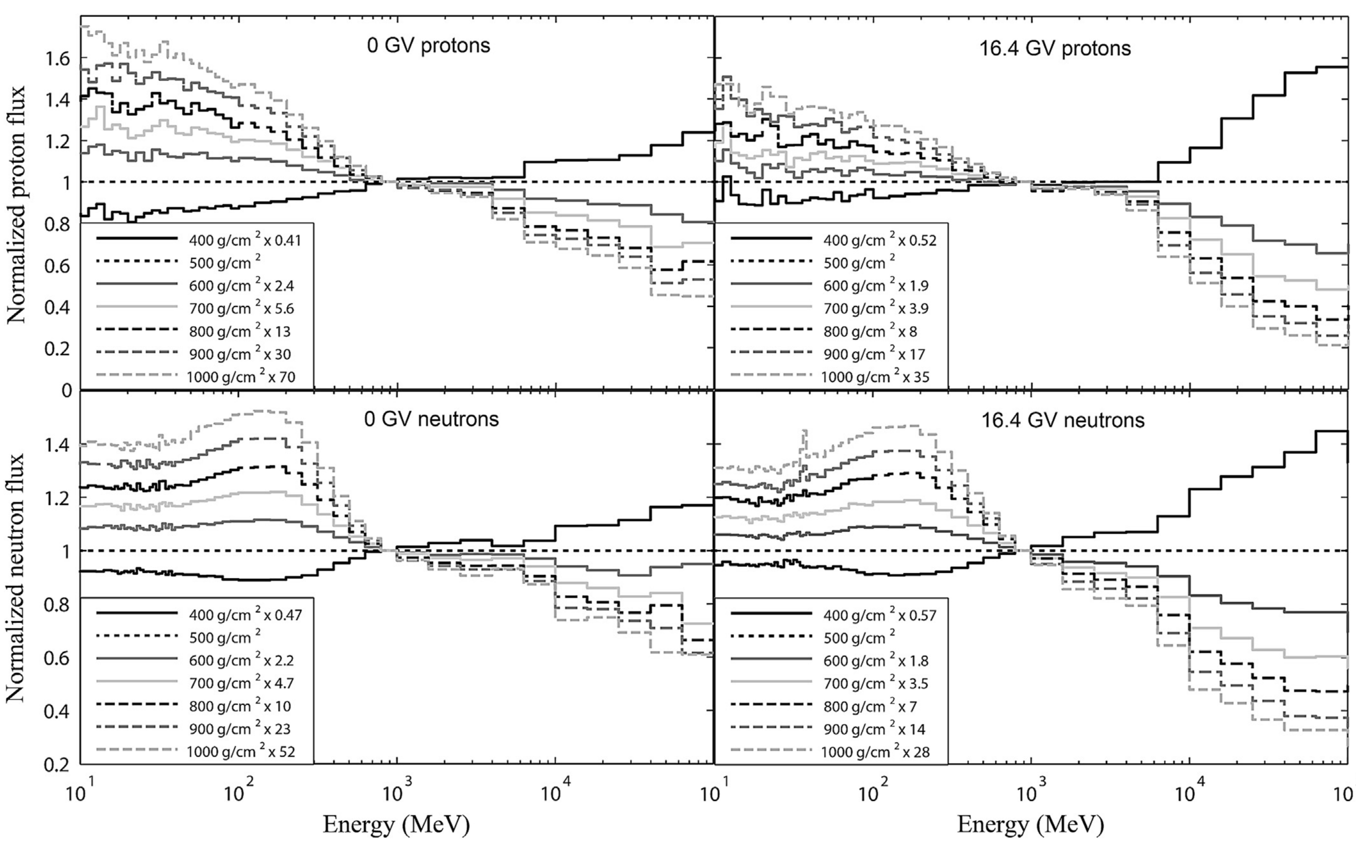

Fig. 1. Neutron and proton energy distributions normalized and compared to the energy distribution at 500 g/cm^2 (~5700 m asl) for high (0 GV) and low (16.4 GV) latitude. With increasing atmospheric depth (decreasing altitude), the energy distribution for both neutrons and protons "softens" or shifts towards the lower energies.