Quaternary Geochronology 22 (2014) 175–182

Contents lists available at ScienceDirect

Quaternary Geochronology

journal homepage: www.elsevier.com/locate/quageo

Research paper

Simple computer code for estimating cosmic-ray shielding by oddly shaped objects

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A R T I C L E I N F O

Article history:
Received 5 October 2013
Received in revised form
18 December 2013
Accepted 20 December 2013
Available online 1 January 2014

Keywords:
Cosmogenic nuclide geochemistry
Exposure-age dating
Monte Carlo integration
Precariously balanced rocks

A B S T R A C T

This paper describes computer code for estimating the effect on cosmogenic-nuclide production rates of arbitrarily shaped obstructions that partially or completely attenuate the cosmic ray flux incident on a sample site. This is potentially useful for cosmogenic-nuclide exposure dating of geometrically complex landforms. The code has been validated against analytical formulae applicable to objects with regular geometries. It has not yet been validated against empirical measurements of cosmogenic-nuclide concentrations in samples with the same exposure history but different shielding geometries.

1. Importance of geometric shielding of the cosmic-ray flux to exposure dating

Cosmogenic-nuclide exposure dating is a geochemical method used to determine the age of geological events that modify the Earth's surface, such as glacier advances and retreats, landslides, earthquake surface ruptures, or instances of erosion or sediment deposition. To determine the exposure age of a rock surface, one must i) measure the concentration of a trace cosmic-ray-produced nuclide (e.g., ^{10}Be, ^{26}Al, ^{3}He, etc.); and ii) use an independently calibrated nuclide production rate to interpret the concentration as an exposure age (see review in Dunai, 2010).

Typically (Dunai, 2010), estimating the production rate at a sample site employs simplifying assumptions that i) the sample is located on an infinite flat surface; ii) all cosmic rays responsible for nuclide production originate from the upper hemisphere; and iii) any topographic obstructions to the cosmic-ray flux can be represented as an apparent horizon below which cosmic rays are fully obstructed, and above which they are fully admitted (the 'opaque-horizon' assumption). These assumptions are adequate for a wide range of useful exposure-dating applications, but they fail for sample sites located on irregular surfaces with a roughness scale similar to the characteristic cosmic ray attenuation length in rock (order 1 m), or likewise for sample sites located on or near meter-scale boulders or other objects.

The opaque-horizon assumption fails in these situations for two reasons. First, rock is denser than air. Attenuation of cosmic rays is proportional to the amount of mass they travel through. Thus, if cosmic rays must penetrate both the overlying atmosphere and also some additional thickness of rock (or any massive material, e.g., soil, sediment, water, etc.) to reach a sample site, then the production rate at that site will be less than it would be in the reference case of an infinite flat surface (where cosmic rays only travel through air to reach the sample site). If the thickness of rock traversed is much longer than the cosmic-ray attenuation length (e.g., tens of meters or more), then the cosmic-ray flux from that direction is completely attenuated and the opaque-horizon assumption is adequate. However, if it is relatively short (order 1 m) then the cosmic-ray flux is only partially attenuated and this assumption fails. This effect is referred to in this paper as 'geometric shielding.' The term 'self-shielding' is sometimes used to describe this effect, although that term is somewhat misleading because both the rock that is being sampled ('self') and other nearby objects could shield the sample site.

Second, a fraction of cosmogenic-nuclide production at a sample site near the Earth's surface is due to secondary particles that originate in nuclear reactions relatively close to the sample site. Because the mean atomic weight of rock is greater than that of air, and also because air is less dense than rock so it is more likely that some particles will decay before interacting, the yield of these secondary particles is greater from rock that from air. Thus, when a

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http://dx.doi.org/10.1016/j.quageo.2013.12.002

sample is surrounded by more air, and less rock, than it would be if it was embedded in the reference infinite flat surface – for example if it lies on a steeply dipping surface, or within a relatively small boulder – then the flux of these secondary particles, and therefore the production rate, is correspondingly less. This effect is referred to here as the 'missing mass effect;' Masarik and Wieler (2003) also called it the 'shape effect.'

The magnitude of the geometric shielding effect can vary from negligible to complete attenuation depending on the arrangement and size of obstructions. The magnitude of the missing mass effect is expected to be at most ~10% of the production rate (i.e., for the extreme case in which a sample lies at the top of a tall, thin pillar; Masarik and Wieler, 2003). Thus, in many common geomorphic situations, geometric shielding is expected to be significantly more important (a tens-of-percent-level effect on the production rate) than the missing mass effect (a percent-level effect). Geometric shielding is also easier to calculate. The remainder of this paper describes computer code that computes geometric shielding for arbitrary geometry of samples and obstructions; this calculation only requires determining the lengths of ray paths that pass through objects and applying an exponential attenuation factor to each ray path. Computer code to implement this is simple and fast enough to permit, for example, dynamic calculation of shielding factors in a model where the shielding geometry evolves during the exposure history of a sample. Previous attempts to quantify the missing mass effect, on the other hand, have employed a complete simulation of the cascade of nuclear reactions in the atmosphere and rock that give rise to the particle flux at the sample site, using first-principles particle interaction codes such as MCNP or GEANT (Masarik and Beer, 1999, and references therein). These codes are slow, complex, and require extensive computational resources. To summarize, because of the difference in the potential magnitude of these two effects, there are likely to be many geomorphically relevant situations involving samples with complicated shielding geometry in which one can estimate production rates at useful (i.e., percent-level) accuracy using only the relatively simple geometric shielding calculation. The calculations in this paper consider only the geometric shielding effect and do not consider the missing mass effect. A valuable future contribution would be to develop a simplified method of approximating the missing mass effect using only geometric considerations that would not require complex particle physics simulation code.

Although both the geometric shielding effect and the missing mass effect follow from well-established physical principles, there has been very little attempt to verify calculations of these effects by measuring cosmogenic-nuclide concentrations in natural situations where they are expected to be important. For example, simulations of the missing mass effect predict a relationship between boulder size, sample location on a boulder, and cosmogenic-nuclide concentration. Although some researchers have argued that this relationship is or is not present in certain exposure-age data sets (Masarik and Wieler, 2003; Balco and Schaefer, 2006), the scatter in the data sets is similar in magnitude to expected effects, so these results were ambiguous. Kubik and Reuther (2007) attempted to conduct a better constrained experiment by matching cosmogenic ^{10}Be concentrations measured on and beneath a cliff surface, where both geometric shielding and missing mass effects would be expected to be important, with model estimates of these effects. However, they were not able to reconcile observations with predictions at high confidence. One purpose of this paper is to facilitate future attempts to validate geometric shielding factor estimates by simplifying the calculation of shielding factor estimates for irregular shapes characteristic of natural outcrops or boulders.

The computer code described in this paper was originally developed for exposure-dating of precariously balanced rocks used in seismic hazard estimation. These rocks are 1–2 m in size and irregular in shape (e.g., Fig. 1), so most sample locations are partially shielded by the rocks themselves. To quantify these effects, in Balco et al. (2011) we developed computer code to calculate geometric shielding factors for arbitrarily shaped objects. However, that paper did not include the code or describe it in detail. The present paper provides a complete description and includes the code as supplementary information. In addition, the code and accompanying documentation are available online at http://hess.ess.washington.edu/shielding.

2. Definition of geometric shielding; previous work

The treatment of geometric shielding in this paper follows that of Lal (1991), which was also adopted by Dunne et al. (1999), Lal and Chen (2005), and Mackey and Lamb (2013). Dunne et al. (1999) provide a complete and clear derivation of the following equations. Cosmic ray intensity as a function of direction $I(\theta,\phi)$, where θ is the zenith angle measured down from the vertical and ϕ is the azimuthal angle, is assumed to be constant in azimuth but vary with zenith angle, such that:

$$I(\theta,\phi) = I_0 \cos^m(\theta) \tag{1}$$

I_0 is the maximum intensity (in the vertical direction) and the value of m has been estimated from cosmic-ray observations and is generally taken to be 2.3 (see Gosse and Phillips, 2001, for additional discussion). The total flux F_{ref} that an object receives in the reference case of full exposure to the entire upper hemisphere, that is, when a sample site is located on an infinite, unshielded, flat surface, is:

$$F_{\mathrm{ref}} = I_0 \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \cos^m(\theta)\sin(\theta)\mathrm{d}\theta\, \mathrm{d}\phi \tag{2}$$

This can be evaluated analytically with the result that:

$$F_{\mathrm{ref}} = I_0 \frac{2\pi}{m+1} \tag{3}$$

Intensity I would typically have units of particles cm^{-2} sr^{-1} s^{-1}. However, the purpose of this work is to calculate a dimensionless shielding factor that is the ratio of the production rate at a shielded site to that at an identically located unshielded site, so neither the units nor the absolute value of I or F_{ref} are relevant.

Geometric shielding is here defined to be the integrated shielding effect of any objects more dense than air that cosmic rays must traverse to reach a sample site. This depends on the size and location of nearby objects relative to the sample. Geometric shielding of the cosmic-ray flux from a particular direction, incident on a particular sample location, can be represented as the mass thickness traversed by cosmic rays from that direction before they reach the sample. This mass thickness is $\rho r(x,y,z,\theta,\phi)$ and has units of g cm^{-2}. ρ is the mean density of the material traversed by the cosmic rays (g cm^{-3}). $r(x,y,z,\theta,\phi)$ is the linear thickness (cm) of this material that a cosmic ray arriving from zenith angle θ and azimuth ϕ must traverse to reach a sample site whose location is defined by Cartesian coordinates x, y, and z. Attenuation of cosmic rays traveling in a particular direction is then defined to be exponential in mass thickness with a constant attenuation length Λ_p, such that if the intensity of the incoming cosmic-ray flux in that direction is I and the intensity of the cosmic ray flux in that direction at the sample site is I_s, then $I_s/I = \exp(-\rho r/\Lambda_p)$. Note that Λ_p, which represents an attenuation length along a single incidence direction for