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On scaling cosmogenic nuclide production rates for altitude and latitude using cosmic-ray measurements

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Abstract

The wide use of cosmogenic nuclides for dating terrestrial landforms has prompted a renewed interest in characterizing the spatial distribution of terrestrial cosmic rays. Cosmic-ray measurements from neutron monitors, nuclear emulsions and cloud chambers have played an important role in developing new models for scaling cosmic-ray neutron intensities and, indirectly, cosmogenic production rates. Unfortunately, current scaling models overlook or misinterpret many of these data. In this paper, we describe factors that must be considered when using neutron measurements to determine scaling formulations for production rates of cosmogenic nuclides. Over the past 50 years, the overwhelming majority of nucleon flux measurements have been taken with neutron monitors. However, in order to use these data for scaling spallation reactions, the following factors must be considered: (1) sensitivity of instruments to muons and to background, (2) instrumental biases in energy sensitivity, (3) solar activity, and (4) the way of ordering cosmic-ray data in the geomagnetic field. Failure to account for these factors can result in discrepancies of as much as 7% in neutron attenuation lengths measured at the same location. This magnitude of deviation can result in an error on the order of 20% in cosmogenic production rates scaled from 4300 m to sea level. The shapes of latitude curves of nucleon flux also depend on these factors to a measurable extent, thereby causing additional uncertainties in cosmogenic production rates. The corrections proposed herein significantly improve our ability to transfer scaling formulations based on neutron measurements to scaling formulations applicable to spallation reactions, and, therefore, constitute an important advance in cosmogenic dating methodology.

Keywords: scale factor; production; rates; cosmogenic elements; neutrons; cosmic rays

1. Introduction

Cosmogenic nuclides produced in situ in terrestrial rocks have been applied to exposure dating since the mid-1980s, but until recently [1], there had been no critical review of the commonly used altitude and latitude scaling of cosmogenic production rates derived by Lal [2] and given in [3,4]. Dunai [1] has proposed a major revision to [2–4] based on data from neutron monitors, nuclear emulsions and cloud chambers. However, as discussed by Desilets et al. [5], Dunai's scaling model has many similar shortcomings to Lal's model. These two models have the following weaknesses: (1) Cosmic-ray data are ordered according to parameters that inadequately describe

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the geomagnetic shielding effect. Latitude survey data are ordered according to geomagnetic inclination [1] and according to geomagnetic latitude [2]. However, the cosmic-ray intensity varies by as much as 15% along both constant geomagnetic latitude and inclination. (2) The effects of solar activity on latitude and altitude survey data are either completely neglected [1] or addressed unclearly [2]. (3) The energy dependence of the nucleon attenuation is either underestimated, because of limited data [2], or ignored [1]. (4) Both models are based on a small selection of cosmic-ray data, confined mostly to the 1950s.

In order for the cosmogenic nuclide dating method to be successfully applied at different locations, the altitude and latitude scaling of nucleon intensity must be accurately constrained. A more refined scaling model can be derived from the numerous latitude and altitude surveys performed since the 1950s; however, these data must be used with caution. The purposes of this paper are to review some of the major cosmic-ray surveys conducted over the past 50 years and to discuss how these data can be used to derive an accurate scaling model. We also review some basic concepts and definitions in cosmic-ray physics in order to build the framework for these discussions.

2. Definitions

Primary cosmic rays are charged particles impinging on Earth with relativistic energies. Cosmic rays arriving from outside the solar system are known as *galactic cosmic rays* (GCRs), whereas those arriving from the sun are known as *solar cosmic rays* (SCRs) [6]. Secular variations in solar activity cause the low-energy ($E < 1$ GeV) GCR flux to vary by as much as an order of magnitude, whereas the high-energy GCR flux ($E > 10$ GeV) is mostly insensitive to solar activity [7].

Secondary cosmic rays are produced through the interaction of primary cosmic rays with atmospheric and terrestrial nuclei. The secondary flux includes strongly interacting particles (e.g. neutrons, protons and pions), weakly interacting particles (e.g. muons), and electromagnetic radiation (e.g. γ and β radiation). Neutrons are responsible for the majority of nuclear transformations near the Earth's surface [4].

Neutrons may be classified by energy according to the types of nuclear reactions in which they are involved. Although there is no standard convention for classifying neutrons, the following definitions are useful [8,9].

High-energy neutrons are produced through direct reactions of primary and secondary cosmic-ray particles with terrestrial nuclei. In a direct reaction, the incident particle interacts separately with a small number of individual nucleons, usually at the surface of the nucleus. A high-energy neutron may in turn liberate additional high-energy particles in a chain reaction process. These reactions may occur within the nucleus (intranuclear cascade) or between nuclei (internuclear cascade). The de Broglie wavelength of a particle is inversely related to particle momentum, and therefore at lower momenta, interactions with the entire nucleus become more probable. The energy of the incident particle is then distributed throughout the entire nucleus in what is known as a compound–nucleus reaction. Spallogenic production of nuclides may occur from both direct- and compound–nucleus reactions. We define high-energy neutrons to be those capable of producing spallation reactions, which corresponds to energies ranging from primary energies down to about 10 MeV.

Fast neutrons are produced primarily from the de-excitation of nuclei following compound–nucleus reactions. A common mode of de-excitation is through the emission of neutrons and protons according to a Maxwellian energy spectrum peaked at about 1 MeV [10]. This process is known as nuclear evaporation, by analogy to molecules evaporating from the surface of a heated liquid. Unlike neutrons produced in direct reactions, the energy spectrum and angular distribution of evaporation neutrons does not depend critically on the energy and direction of the initiating particle. In other words, the excited nucleus does not 'remember' these properties of the initiating particle. However, as the energy of the incident nucleon increases, the nucleus is more likely to be excited to a higher 'temperature', and the average number of neutrons evaporated by the nucleus therefore increases. Evaporation reactions may also be induced by particles such as pions, muons and photons. Fast neutrons generally have insufficient energy to produce further evaporation reactions, and therefore do not initiate nuclear spallations. The energy range for fast neutrons is defined here to be approximately from 10 MeV to 100 keV.

Slow neutrons are produced from the slowing down ('moderation') of fast neutrons, through elastic and inelastic collisions with nuclei. We define slow neutrons to be those with energies on the order of 1 keV. Thermal and epithermal neutrons are produced from the slowing down of fast neutrons to energies on the order of the vibrational motion of nearby molecules. An important characteristic of thermal and epithermal neutrons is their relatively high probability of being absorbed by nuclei. Thermal neutrons are defined to be in vibrational equilibrium with the molecules of the surrounding medium, which at a temperature of 293.16 K corresponds to an average energy of 0.025 eV. Epithermal neutrons are defined here as those with energies between 100 eV and the cadmium cutoff energy for transparency to neutrons of 0.5 eV.

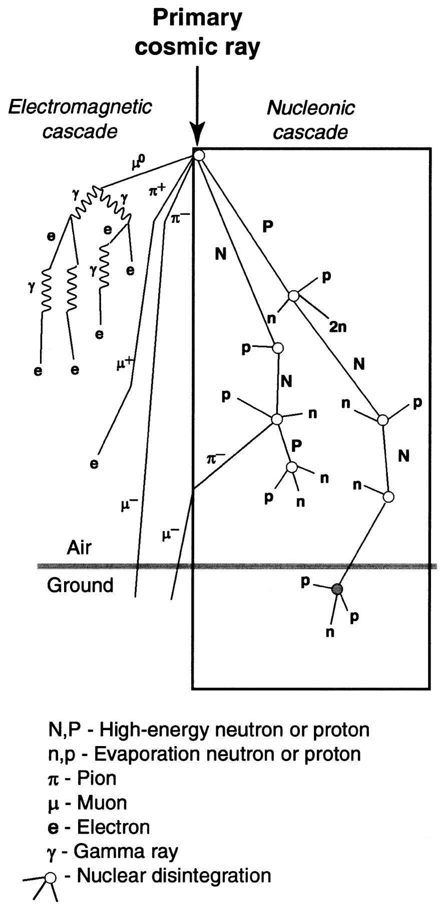

Fig. 1. Propagation of the secondary cascade through the atmosphere (adapted from [11]).

3. The nucleon attenuation length

Primary cosmic rays collide with oxygen and nitrogen nuclei near the top of the atmosphere, initiating cascades of protons, neutrons and other secondary particles (Fig. 1). In the lower atmosphere (>200 g cm^{-2}), the nucleon flux diminishes as a function of mass-shielding depth approximately according to:

$$N_2 = N_1 \exp\left(\frac{Z_1 - Z_2}{\Lambda_N}\right) \quad (1)$$

where N_1 and N_2 are the nucleon fluxes at depths Z_1 and Z_2 (g cm^{-2}), respectively, and Λ_N is the nucleon attenuation length (g cm^{-2}) (also referred to as the absorption mean free path, absorption length [12] or *e*-folding length). A nucleonic cascade loses energy through nuclear collisions and electromagnetic interactions, and this energy loss depends on the total mass of air transited by the cascade. The Earth's atmosphere is approximately 1033 g cm^{-2} thick and has a density that varies with altitude, latitude and time. A hypothetical relationship between mass-shielding depth and altitude corresponding to the year-round, mid-latitude pressure distribution is given by the US standard atmosphere [13] (Fig. 2). Deviations from the US standard atmosphere in areas of statistically high and low pressure, such as the Siberian High and the Aleutian Low, should be taken into account when scaling cosmogenic production rates [14].

Eq. 1 assumes a monodirectional, monoenergetic beam of stable particles that does not initiate

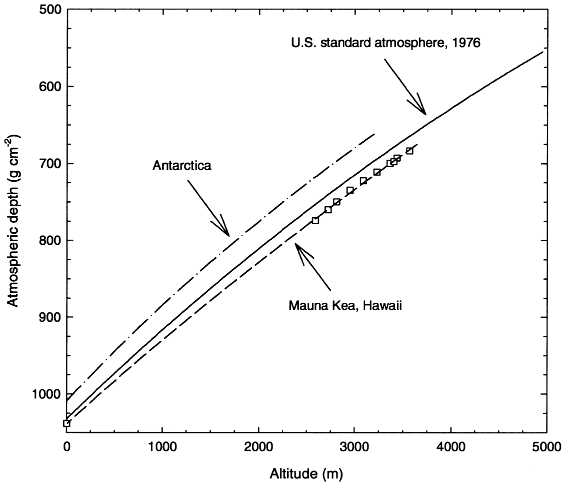

Fig. 2. The relationship between atmospheric depth and altitude in the US standard atmosphere [13]. For comparison, relationships found in Antarctica [14] and in Hawaii (our own data) are shown. The curve for Hawaii is based on global positioning system (GPS) and barometer measurements (given by open squares) taken on 7–12 April 2000. Barometric measurements are 10 min averages and are therefore not necessarily representative of long-term or even recent pressure conditions on Hawaii.

chain reactions. The terrestrial cosmic-ray flux, however, follows an approximately power-law energy spectrum, propagates as a cascade, includes short-lived particles (e.g. pions and muons), and is distributed about the zenith roughly according to a cosine function [15]. Nonetheless, Eq. 1 provides a satisfactory description of cosmic-ray nucleon absorption over small atmospheric depths ($\sim$100 g cm^{-2}).

Previous workers [1,4] used atmospheric measurements of nucleon intensity to derive the altitude dependence of spallation reactions. According to Dunai [1], Lal's [4] scaling model overestimates the value of the atmospheric attenuation length for cosmogenic nuclide production by nucleons (here termed $\Lambda_{\mathrm{prod},N}$) at both high and low latitudes. This claim is based on measurements from cloud chambers, nuclear emulsions and neutron monitors [1] that seem to indicate low-altitude attenuation lengths of 130 g cm^{-2} at high latitudes and 149 g cm^{-2} at low latitudes. Lal's scaling formula gives values of 135 g cm^{-2} and 157 g cm^{-2}, respectively, for these locations. Here, we discuss how instrumental biases affect measurements of the nucleon attenuation length and how these biases can at least partially reconcile discrepancies between measured attenuation lengths. We also introduce neutron monitor data from extensive altitude and latitude surveys of nucleon intensity.

3.1. Neutron monitor data

The most comprehensive and well-reported investigation of the global distribution of nucleon intensity is probably the neutron monitor survey conducted by Carmichael et al. [16–18] during the International Quiet Sun Year (1965–1966). These measurements are ideally suited for scaling neutron monitor counting rates because: (1) they cover a wide range of geomagnetic cutoffs (0.5–13.3 GV) and atmospheric depths (200–1033 g cm^{-2}); (2) they have been corrected for secular variations in the primary cosmic-ray intensity and temperature effects; and (3) they were taken with a land-based neutron monitor and an airborne monitor that had been cross-calibrated.

Several other surveys of neutron monitor attenuation lengths have also been published, but unfortunately the experimental procedures, corrections and raw data have not always been reported in adequate detail. The only survey of comparable scope to [16–18] covered a similar range of cutoffs, but was mostly limited to depths greater than 880 g cm^{-2} [19]. An earlier survey by Bachelet et al. [20] defined the general characteristics of the neutron monitor attenuation length (Λ_{NM}) as a function of atmospheric depth and cutoff rigidity, but was more limited in scope. Neutron monitor attenuation lengths have also been evaluated using data from the world-wide network of fixed neutron monitors [21]. Other surveys generally give relationships consistent with that found by [16–18].

The primary goal of [16–20,22] was to determine the altitude and latitude dependence of Λ_{NM} so that counting rates of neutron monitors could be corrected for small temporal variations in barometric pressure. The survey by [16–18] shows that Λ_{NM} reaches a minimum near 850 g cm^{-2} (Fig. 3), in agreement with [19] and [20].

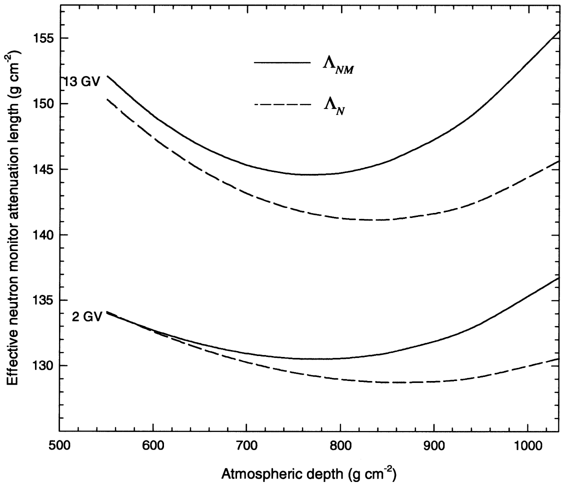

Fig. 3. Effective attenuation lengths for an NM-64 neutron monitor based on measurements taken in April–June, 1965 [18]. The effective nucleon attenuation length was calculated by removing the contribution of muons and background to Λ_{NM} using Table 1 and Eq. 2. The effective attenuation length reduces the neutron monitor counting rate at some depth to the sea level counting rate.

Between the top of the atmosphere and 850 g cm^{-2}, Λ_{NM} decreases with increasing depth as the overall energy of the cascade dissipates [23]. However, beyond this depth Λ_{NM} increases with increasing depth, which is attributable to the combined effects of three phenomena [18]: (1) Muons interact with the lead portion of a neutron monitor to produce neutrons that contribute to the total counting rate. Because the muon flux is more highly penetrating than the nucleon flux, Λ_{NM} at greater atmospheric depths reflects the increased proportion of muons contributing to the counting rate. Muon sensitivity near sea level appears to be a feature of all neutron monitors based on the IGY/NM-64 design [24]. (2) α-Contamination of the counter tubes produces a constant background amounting to about 1% of the high-latitude sea level counting rate. (3) Cosmic-ray nucleons incident from oblique angles are selectively filtered with depth in the atmosphere. The omnidirectional nucleon flux therefore attenuates more rapidly with increasing atmospheric depth than does the vertical nucleon flux.

For neutron monitor counting rates to be used for scaling production rates, muon and background contributions must be removed. Fortunately, the relative contributions of muons and neutrons to the neutron monitor counting rate are fairly well known (Table 1). Attenuation lengths for fast muons and slow negative muons as a function of P_C are also fairly well known [15]. Assuming, after [18,19] and based on [25], that slow and fast muon fluxes have similar latitude distributions, we calculated Λ_N from the neutron monitor data of [16,17] and the values in Table 1 using the relationship:

$$\frac{1}{\Lambda_{\mathrm{NM}}} = \frac{\sum_{i=1}^{n} \frac{\Lambda_i}{N_i}}{\sum_{i=1}^{n} N_i} = \frac{\frac{\Lambda_N}{N_N} + \frac{\Lambda_{\mu^-(\mathrm{s})}}{N_{\mu^-(\mathrm{s})}} + \frac{\Lambda_{\mu(\mathrm{f})}}{N_{\mu(\mathrm{f})}} + \frac{\Lambda_B}{N_B}}{N_N + N_{\mu^-(\mathrm{s})} + N_{\mu(\mathrm{f})} + N_B} \quad (2)$$

where N_i and Λ_i are the counting rate and attenuation length, respectively, for the i^{th} component. At sea level and high latitude, contributions from nucleons, slow negative muons, fast muons and constant background (N_N, $N_{\mu^-(\mathrm{s})}$, $N_{\mu(\mathrm{f})}$, and N_B, respectively) account for more than 98% of the neutron monitor counting rate.

Attenuation lengths given by Dunai [1] (~130 g cm^{-2} at 2 GV) appear to agree reasonably well with Λ_N measured with a neutron monitor (Fig. 3). However, Λ_N is equivalent to $\Lambda_{\mathrm{prod},N}$ only if either the nucleon attenuation length is indepen-

Table 1
Contributions to the NM-64 neutron monitor counting rate [24] and attenuation lengths for fast and slow muons [15]

	2 GV		13 GV	
	Contribution (%)	Λ (g cm^{-2})	Contribution (%)	Λ (g cm^{-2})
Slow muons	3.6 ± 0.7	240	6.0	281
Fast muons	2.0 ± 0.4	560	3.3	640
Background	1.0	∞	1.8	∞

dent of energy (the shape of the nucleon energy spectrum is invariant with depth) or the energy sensitivity of the measuring apparatus is identical in form to the energy dependence of nuclide production. In Sections 3.2–3.4 we show that, strictly speaking, neither assumption is valid.

3.2. Energy dependence of the nucleon attenuation length

Data from neutron multiplicity counters [26–28] demonstrate that Λ_N decreases with median nucleon energy. A multiplicity counter is a neutron monitor that records the number of counting events occurring within a gating time of about 700–1000 ms [27,29]. Each high-energy nucleon interacting with the monitor produces about 1.44 counts, on average, at high latitude and sea level [29]. However, the number of counts resulting from each interaction depends on the energy of the incoming nucleon. This is because a neutron monitor records evaporation neutrons, and the average number of evaporation neutrons produced in a reaction increases with the increasing energy of the interacting nucleons. A neutron multiplicity counter, therefore, provides information on the energy spectrum of secondary cosmic-ray nucleons [29]. Fig. 4 demonstrates that the attenuation length decreases with increasing median nucleon energy, at least in the range 120–700 MeV. This behavior is a consequence of the fact that the lower energy nucleons in a particle cascade are produced (both directly and indirectly) from nucleons of higher energy, and since no cosmic-ray effect can decrease with increasing depth any faster than the primary radiation from which it originates [30] the attenuation length must decrease or remain constant with increasing nucleon energy.

In contrast to Dunai [1], Lal [2] explicitly recognized the energy dependence of Λ_N in deriving his scaling model. However, prior to [27], Λ_N was commonly assumed to be constant with energy up to about 400 MeV. This assumption was based on early experiments and simplified cascade models [2,10,12,27], despite other experimental evidence to the contrary [30–32]. Under the assumption that the slow neutron flux is proportional to the high-energy nucleon flux for energies below 400 MeV, Lal [2] based a major portion of his scaling on airborne measurements of slow neutron fluxes [33]. Recognizing that for some reactions a significant portion of cosmogenic nuclide production occurs at energies above 400 MeV, and that at these higher energies the nucleon attenuation length decreases with energy, Lal [2] applied corrections that tended to decrease attenuation lengths derived from slow neutron measurements. Hence, Lal [2–4] gives scaling factors for both slow neutron fluxes and for the total nuclear disintegration rate in the atmosphere. Although the correction applied by Lal [2] is approximate and fails to account for the energy dependence of Λ_N below 400 MeV, Lal considered that the altitude dependence of a particular reaction may depend on the energy at which that reaction occurs. Future work should also consider this energy dependence.

3.3. Energy sensitivity of neutron monitors

Because high-energy nucleons produce more neutron monitor counts per interaction than

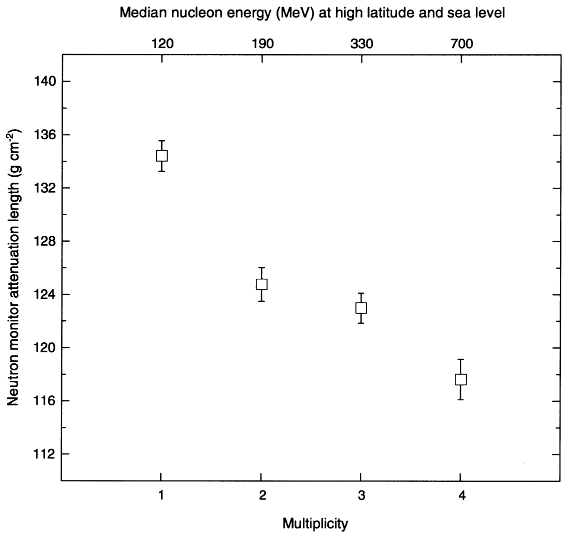

Fig. 4. Neutron monitor attenuation length (corrected for muon and background contributions) as a function of neutron multiplicity. Measurements taken between 952 and 544 g cm^{-2} at 2 GV with an IGY type monitor [28]. Median nucleon energies are based on calculations for a high-latitude sea level IGY neutron monitor [24].

low-energy nucleons, the neutron monitor response is biased towards the higher end of the nucleon energy spectrum. An additional effect is produced by 7.5 to 28 cm of paraffin or polyethylene (known as the 'reflector') on the outside of the monitor which substantially modulates the flux of nucleons with $E < 50$ MeV. Hughes and Marsden [29], for example, showed that an IGY neutron monitor records a negligible number of counts from nucleons with $E < 50$ MeV. These considerations imply that for nuclide production at low thresholds ($\sim$20 MeV), such as $K(n,x)^{36}Cl$ and $Ca(n,x)^{36}Cl$ reactions [15], Λ_N measured from a neutron monitor may underestimate $\Lambda_{prod,N}$, and, therefore, a correction may be needed in the direction opposite to that applied by [2] to slow neutron data. This correction should be most important for neutron monitors with thick reflectors, such as the IGY type, and less important for those with thin reflectors, such as the NM-64 type. On the other hand, for the reaction $O(n,x)^{10}Be$ produced by neutrons having a median energy (E_{med}) of $\sim$140 MeV at high latitude and sea level, the neutron monitor response (E_{med} = 130–160 MeV) may accurately describe the altitude dependence of cosmogenic nuclide production [15].

3.4. *Energy sensitivity of cloud chambers and emulsions*

Cloud chambers and nuclear emulsions record the tracks of ionizing particles produced in nuclear disintegrations (or 'stars') initiated by cosmic rays. Each track is known as a prong, and the number of prongs (or 'star size') produced in a disintegration is proportional to the kinetic energy of the disintegration-producing particle. Although the precise relationship between incident nucleon energy and prong number is somewhat ambiguous, it is clear from theoretical considerations [34] that mean star size increases monotonically with increasing nucleon energy. Above sea level, most stars recorded in emulsions are initiated by protons and neutrons, while the contribution from slow muons is negligible [35].

Due to the undercounting of one- and two-prong stars, nucleon attenuation lengths measured with cloud chambers and nuclear emulsions are typically biased towards high energies. Undercounting occurs because tracks left by one- and two-prong stars are difficult to distinguish from tracks left by proton recoils and scattering events. Also, there is generally a low scanning efficiency for one- and two-prong stars [2]. For example, Brown [32] undercounted one- and two-prong stars occurring in a cloud chamber, while Dixit [36] and Roederer [31] neglected these altogether. In the silver bromide emulsions used by [36] and [31], one- and two-prong stars correspond to energies of about 41 MeV and 90 MeV, respectively [34]. As with neutron monitors, the effect of energy bias is to underestimate the total nucleon attenuation length. Correcting the data of [32] for this effect using the procedure outlined by Lal [2] yields a value of 137 ± 5 g cm^{-2} for the flux-weighted attenuation length of nucleons with $E > 40$ MeV between 700 and 1032 g cm^{-2}. This compares to the value of 132 ± 4 g cm^{-2} originally given by [32] for the uncorrected nucleon attenuation length between these depths. Failure to make corrections such as this can account for apparent discrepancies between attenuation lengths.

4. The geomagnetic effect and cutoff rigidity

The geomagnetic field imposes a rigidity (momentum-to-charge ratio) cutoff on primary cosmic-rays. The value of this cutoff tends to increase with decreasing latitude, resulting in lower cosmic-ray intensity towards the equator. However, only in a centered dipole field is the cosmic-ray intensity a unique function of geomagnetic latitude. In a magnetic field with substantial non-dipole components, such as the present geomagnetic field, there is also a 'longitude effect' in cosmic-ray intensity. Data from so-called 'latitude surveys' must therefore be ordered in terms of a parameter that accounts for both latitude and longitude effects.

Prior to the mid-1950s most cosmic-ray measurements were ordered according to geomagnetic latitude (λ_m) calculated from a centered dipole representation of the geomagnetic field [8]. However, the first latitude surveys [8,23] proved that non-dipole components have a substantial effect on the cosmic-ray intensity. Early investigators also attempted to characterize primary cosmic-ray access by using the lower vertical cutoff rigidity (P_L) based on a dipole representation of the geomagnetic field [37]:

$$P_L(\lambda_m) = \frac{30\ M_0}{4\ r^2}\cos^4 \lambda_m = 14.9\ GV \left(\frac{M}{M_0}\right) \cos^4 \lambda_m \quad (3)$$

where M_0 is a reference dipole moment (7.90622×10^{22} A m^2 for Epoch 1980.0 [37]), M is the dipole moment at some other time and r is the average radius of the Earth (6.371×10^6 m [37]). A coefficient of 14.9 GV, based on the magnetic survey of 1944 [7], is often given in Eq. 3.

Eq. 3 gives the minimum momentum-to-charge ratio that a vertically incident primary cosmic-ray particle must possess in order to gain access to a certain geomagnetic latitude (λ_m) in a centered dipole field. Besides the limitation that Eq. 3 only applies to a centered dipole field, there is the additional shortcoming that it implicitly ignores the presence of the solid Earth. Consequently, particles with rigidities above the lower cutoff may still fail to reach latitudes permitted by Eq. 3, since these particles may travel along complex trajectories which intersect the Earth elsewhere [39]. Hence, there also exists an upper cutoff rigidity, P_U, above which all primary particles are accepted. The region between the lower and upper cutoff is termed the penumbra, and here acceptance or rejection of primary cosmic-rays depends on individual particle trajectories. In the 1950s and early 1960s, several investigators [40–42] derived analytical and semi-empirical equations for cutoff rigidity in attempt to at least partially account for non-dipole and penumbral effects. Although these efforts led to successive improvements in ordering cosmic-ray data from latitude surveys, satisfactory cutoffs did not arise until computer-intensive calculations first became practical in the middle 1960s [43].

Since the late 1960s, most neutron monitor measurements have been ordered in terms of effective vertical cutoff rigidity (P_C) (Fig. 5) calculated by integrating cosmic-ray trajectories through a high-order mathematical model of the geomagnetic field [44–47]. This method involves tracing the paths of negatively charged particles as they are leaving specific locations above the Earth in the vertical direction. Anti-protons that escape the geomagnetic field to infinity follow paths identical to those of cosmic-ray protons incident on the same location from infinity. In order to locate the lower, upper and effective cutoffs, a large number of trajectories corresponding to a range of particle energies must be numerically traced.

The primary flux is nearly omnidirectional and therefore a complete description of primary cosmic-ray access to the Earth requires calculation of cutoff rigidities for all angles of incidence [48].

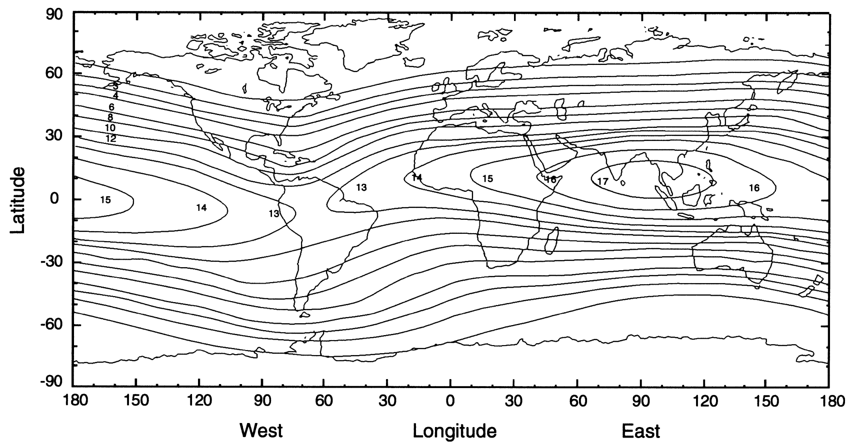

Fig. 5. The world-wide distribution of P_C (GV) for Epoch 1955.0 [44].

However, because vertically incident primaries produce most of the sea level nucleon flux, it has proved adequate in practice to order cosmic-ray data according to cutoffs calculated only for the vertical direction. The reliability of P_C has been confirmed by numerous sea level latitude surveys which show a smooth and consistent relationship between cutoff rigidity and nucleon intensity [45–47]. Failure to account for obliquely incident primary particles appears to have only a minor effect on ordering cosmic-ray data [47,48].

The adoption of P_C for cosmic-ray surveys was a major advance in experimental cosmic-ray physics. However, the currently available scaling models order cosmic-ray data according to geomagnetic inclination [1] and geomagnetic latitude [2–4], both of which are ineffective at describing shielding effects of the prevailing geomagnetic field [5,49]. Most importantly, the geomagnetic field contains a substantial quadrupole component, which makes the present-day geomagnetic field approximately equivalent to a dipole field shifted about 392 km from the center of the Earth towards Southeast Asia [38]. This effect causes sea level nucleon intensity along the cosmic-ray equator (the line of minimum cosmic-ray intensity around the Earth) to decrease by about 15% from South America to Southeast Asia. Geomagnetic inclination and geomagnetic latitude cannot possibly account for this effect.

Direct measurements of the cosmic-ray intensity are collected in the present-day geomagnetic field and therefore should be ordered according to P_C. Unfortunately, P_C cannot be accurately calculated for the past 200–10 000 years because the geomagnetic field parameters are not known. However, if the long-term ($>$10,000–20,000 years) behavior of the Earth's magnetic field can be approximated by an axial dipole field, as is often assumed [1,50] then geomagnetic latitude (λ_m) is equivalent to geographic latitude (λ) over the long term. P_L can then be calculated from Eq. 3, and P_C can be estimated from Fig. 6. It should be noted that, strictly speaking, Fig. 6 represents the penumbral correction corresponding only to a centered dipole model of the recent (past $\sim$50 years) geomagnetic field. Deviations caused by

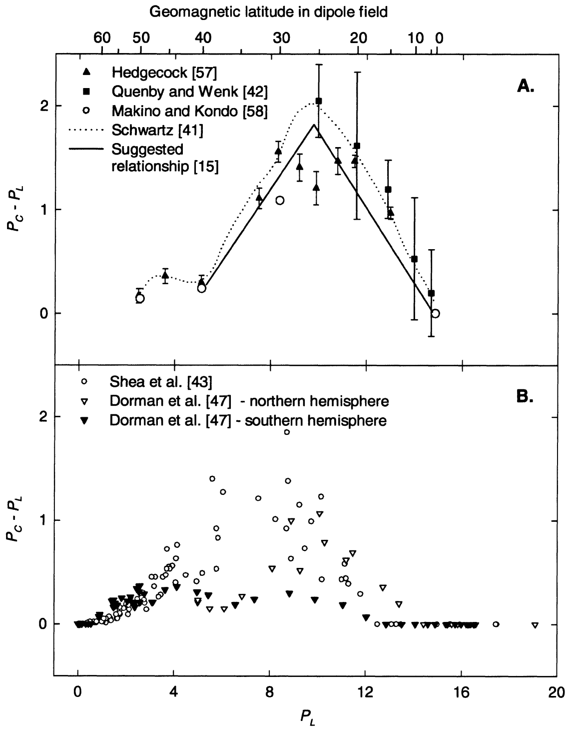

Fig. 6. The penumbral correction in (A) a centered dipole field [15,41,42,57,58] and (B) a high-order model of the real geomagnetic field [43,47].

non-dipole characteristics of the geomagnetic field (Fig. 5) and variations in dipole intensity are not accounted for.

5. Solar activity

Solar activity substantially reduces the flux of GCR particles at high latitudes, but has only a small effect on the flux at low latitudes. During periods of high solar activity, the sun emits a substantial flux of low-energy SCR protons, enhancing the overall flux of low-energy primary particles traveling through the interplanetary medium. However, associated with these low-energy SCR particles are traveling magnetic fields which screen the Earth from low-energy GCR particles [7]. The net effect is a decrease in the cosmic-ray intensity reaching the Earth while the sun is active.

Solar modulations cause the GCR flux reaching the Earth to vary in time according to an 11-year cycle. Because low-energy primaries are always rejected by the geomagnetic field at low latitude (high P_C), the effects of solar modulation are significant only at high latitude (low P_C). Also, because secondary cascades initiated by low-energy GCRs tend to be weakly penetrating, variations in secondary intensity due to solar effects become more subdued towards sea level.

Several experiments demonstrate that even at depths ranging from 680 to 1033 g cm^{-2} the shape of the neutron flux latitude curve depends considerably on solar activity (Fig. 7) [20,50–53]. From solar minimum to solar maximum, the high-latitude sea level nucleon flux decreases by about 8%, whereas at 680 g cm^{-2} the flux decreases by about 21%. At low latitudes ($\sim$14 GV), solar modulations have a negligible effect on sea level neutron intensity [50], while at 680 g cm^{-2} the neutron flux varies by only about 5% [28].

The nucleon attenuation length also varies with solar activity (Fig. 8). This effect is related to changes in the primary energy spectrum caused by solar modulations. Periods of high solar activity are associated with a lower primary flux but a harder primary energy spectrum. Cascades initiated by more energetic primaries tend to have correspondingly longer attenuation lengths. During low solar activity, the overall nucleon attenuation length reflects the increased contribution of low-energy cascades which attenuate rapidly in the atmosphere.

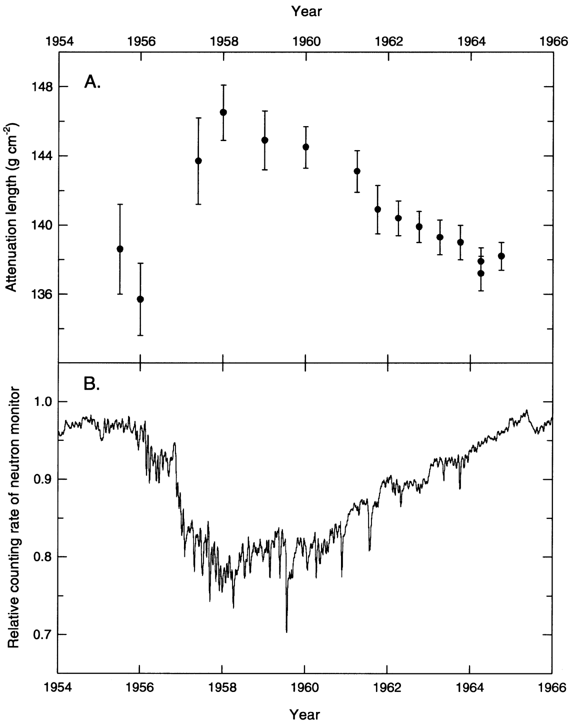

Fig. 8. (A) Attenuation lengths measured from an IGY monitor at 2 GV and sea level [60] over one solar cycle. (B) A 10-day moving average of the relative counting rate of the Climax IGY neutron monitor over the same period (http://ulysses.uchicago.edu/NeutronMonitor/).

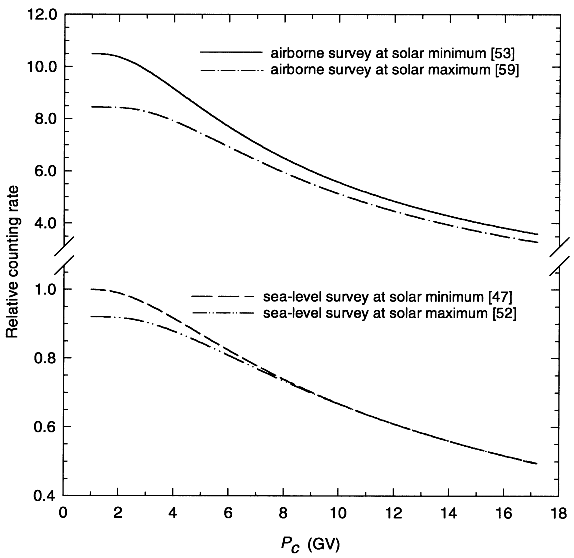

Fig. 7. Latitude surveys of nucleon intensity conducted at solar maximum and solar minimum, normalized at 14 GV. Airborne and sea level curves correspond to atmospheric depths of 680 g cm^{-2} and 1033 g cm^{-2}, respectively [47,52,53,59].

6. Conclusions

The development of an accurate model for scaling production rates is an essential step towards refining the cosmogenic nuclide dating method. Improvements to existing scaling models [1,4] could be made by: (1) considering all cosmic-ray data accumulated since the 1950s; (2) using improved corrections for instrumental biases (3) ordering cosmic-ray latitude survey data according to P_C; and (4) using more realistic relationships between atmospheric mass-shielding depth and altitude.

There appears to be general agreement that more work is needed to constrain the altitude and latitude dependence of $\Lambda_{prod,N}$ [1,5,54–56]. We are currently working on this issue. By far the largest body of data on nucleon intensity is from neutron monitors, which require corrections. However, without more accurate knowledge of nucleon excitation functions and of the energy dependence of the nucleon attenuation length, any correction to Λ_{NM} could potentially carry a large uncertainty. On the other hand, the direct measurement of $\Lambda_{prod,N}$ in geological samples, such as lava flows that extend from high altitudes to sea level, requires exceptional field conditions (easily distinguishable flows, evidence of minimal erosion and minimal ash cover) if long-lived nuclides are to be applied. It also seems unlikely that a sufficient number of sites can be found to give adequate latitude and altitude coverage for developing an accurate scaling model based entirely on geological samples. Work being done with artificial targets [55,56] should therefore play an important role in validating scaling models.

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