AGU Reference Shelf 4

Quaternary Geochronology

Methods and Applications

Jay Stratton Noller
Janet M. Sowers
William R. Lettis
Editors

American Geophysical Union
Washington, DC

Cosmogenic Nuclide Buildup in Surficial Materials

Marek G. Zreda

Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721

Fred M. Phillips

Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM 87801

INTRODUCTION

Cosmogenic nuclide geochronology is a group of isotopic methods of age determination based on accumulation of certain nuclides in materials exposed to cosmic radiation. Because these nuclides are produced only in the top few meters of the crust, they are applicable to studies of landform ages and geomorphic evolution. Tectonic, plutonic and volcanic processes create topographic highs and lows, while weathering and erosion work to counterbalance these orogenic forces. While we understand factors governing these processes, we have long lacked chronologic control to help quantify their rates on geological time scales. For example, fault scarps are the surficial manifestation of active tectonics. Rates of paleoseismic activity can be determined by dating individual surface rupturing events, but conventional dating methods would yield a crystallization or sedimentation age of the offset geological unit. Thus, these methods would fail to produce direct ages of the seismic event. This problem is common for all geomorphic surfaces constructed from existing and redistributed geological material, such as fault-scarp colluvium, moraines, shorelines, fluvial terraces and rims of impact craters. In the past decade, several new geochronologic methods, called surface exposure dating techniques, have been developed. They allow determination of the exposure time of an object at the Earth's surface. Among them are methods based on *in situ* accumulation of cosmogenic nuclides (e.g., Lal, 1987). In this report, we describe cosmogenic nuclide methods and their potential applications to the chronology of Quaternary surfaces.

Cosmogenic nuclides form by interaction of cosmic rays with matter exposed at the Earth's surface. Their accumulation rates are proportional to the cosmic-ray intensity and to the concentrations of target nuclides in the material. The amount of cosmogenic isotopes found in surficial materials can thus be related to the length of time these materials have been exposed to cosmic radiation (Davis and Schaeffer, 1955; Phillips and others, 1986; Kurz, 1986; Nishiizumi and others, 1986). Very low concentrations of several rare radionuclides can now be routinely measured using accelerator mass spectrometry (Elmore and others, 1979; Elmore and Phillips, 1987; Jull and others, 1992; Klein and others, 1982; Middleton and others, 1983) and those of stable nuclides by noble gas mass spectrometry (Kurz and others, 1987; Craig and Poreda, 1986). Half-lives of these cosmogenic nuclides, between 5,730 years and 1.5 millions of years for the radionuclides and infinity for the stable noble gases, make them suitable for dating exposed materials in a range of ages from less than 1,000 years to several millions of years. The choice of nuclides depends on the material dated, its anticipated age and availability of facilities for processing and analysis of samples.

In this review, we discuss the use of cosmogenic nuclides for surface exposure dating. We characterize the spatial distribution of the cosmic ray intensity in the atmosphere and in the top few meters of the crust. Next, we describe mechanisms and production rates of cosmogenic nuclides and formulate equations of their accumulation in rocks exposed at the Earth's surface and in the shallow subsurface. We then review case studies to demonstrate applicability of the methods to dating geomorphic surfaces. Finally, we examine possible effects of postdepositional processes on dating by cosmogenic nuclide buildup and discuss practical aspects of the cosmogenic nuclide accumulation methods. While we discuss all cosmogenic nuclides commonly used for surface exposure dating, we use ^{36}Cl, with which we are most familiar, as an example when discussing specific applications and detailed procedures.

THEORY OF DATING METHOD

The conceptual model of cosmogenic nuclide buildup is

Quaternary Geochronology: Methods and Applications
AGU Reference Shelf 4

straightforward, although many of the underlying physical principles are complex. Rocks buried deeply below the surface are shielded from cosmic radiation and have near zero concentrations of rare, cosmogenic isotopes. Once they are exposed at or near the Earth's surface, they are bombarded by cosmic ray particles, which cause nuclear reactions and formation of new, cosmogenic nuclides. The amount of these new nuclides that accumulate in the surficial material depends on the time this material has been exposed to cosmic radiation. Thus, measured concentrations of these nuclides can be used to determine the exposure time of the surface. In geological applications, however, this scenario is usually unrealistic, for example due to erosion of the surface, and several assumptions are made to calculate surface exposure ages.

Cosmic Rays on Earth

There are two sources of primary cosmic rays that reach the Earth's surface: the sun and the galaxy. Solar cosmic rays have typically low energies (on the order of few hundred MeV) while galactic cosmic rays are highly energetic (on the order of MeV to TeV). Near the Earth, cosmic ray particles change their trajectories and energies. Because most of the cosmic ray particles are charged, they are deflected by the Earth's magnetic field. Those particles that reach the Earth collide with matter and lose energy to become secondary cosmic ray particles. The flux of secondary particles near the Earth's surface depends on the geographic latitude and elevation, depth below the surface, and time.

Spatial Distribution

The distribution of cosmic rays on the Earth depends on three spatial coordinates: geomagnetic latitude, elevation above sea level and depth below the surface. The highest low-energy cosmic ray intensity is at high geomagnetic latitudes and at high elevations. Measurements of fluxes of slow (thermal) neutrons at different latitudes and elevations were used by Lal (1991) to formulate a cubic polynomial equation that allows calculation of present-day cosmic-ray intensity at any location relative to any other location (Table 1 and Fig. 1).

Table 1. Scaling Polynomials ($y = a + bx + cx^2 + dx^3$)[e] For Elevation And Geomagnetic Latitude

Geomagnetic latitude	a	b	c	d
0	0.5790	0.4482	0.1723	0.0359
10	0.5917	0.4415	0.1944	0.0363
20	0.6691	0.4764	0.2320	0.0435
30	0.8217	0.6910	0.1712	0.0822
40	0.9204	0.8849	0.2487	0.1031
50	0.9865	1.0298	0.2992	0.1333
60-90	1.0000	1.0889	0.3105	0.1382

[e]x is the elevation above sea level in km and y is the scaling factor (modified after Lal, 1991).

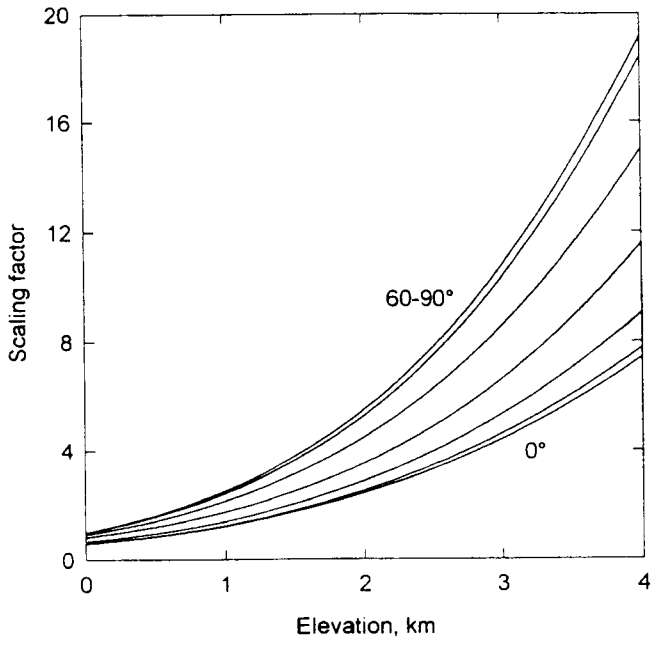

Figure 1. Dependence of cosmogenic nuclide production rates on elevation above sea level and geographic latitude. The curves are plotted using the data in Table 1.

Despite strong atmospheric attenuation, a fraction of the secondary cosmic ray particles reaches the Earth's surface, interacts with matter in the shallow subsurface, and produces cosmogenic nuclides. Three types of particles are most important for production of cosmogenic nuclides: secondary fast neutrons (Yokoyama and others, 1977), thermal neutrons (Davis and Schaeffer, 1955; Fabryka-Martin, 1988; Phillips and others, 1986), and negative slow muons (Kubik and others, 1984; Nishiizumi and others, 1989; Fabryka-Martin, 1988; Zreda and others, 1990, 1991).

Neutrons form the major part of the reactive cosmic-ray flux reaching the Earth. Fast secondary neutrons have high energies (40 to 300 MeV) and are responsible for spallation reactions. They are attenuated in both the atmosphere (Lal, 1987; Zreda and others, 1991) and solid materials (Kurz, 1986; Lal, 1987) according to $\exp(-x/\lambda_n)$ where the attenuation length, λ_n, for the fast component is from 150 to 160 g cm^{-2} (Kurz, 1986; Lal, 1987; Zreda and others, 1991) and x is the atmospheric depth in g cm^{-2}.

Thermal neutrons (energies from 0.1 to 0.4 eV) are formed from the fast neutrons that collide with atoms in the atmosphere or within a rock mass and lose energy. In contrast to the fast neutron component, the distribution of these neutrons in the subsurface (Fig. 2) cannot be described by a simple exponential term because of the air-ground boundary effect

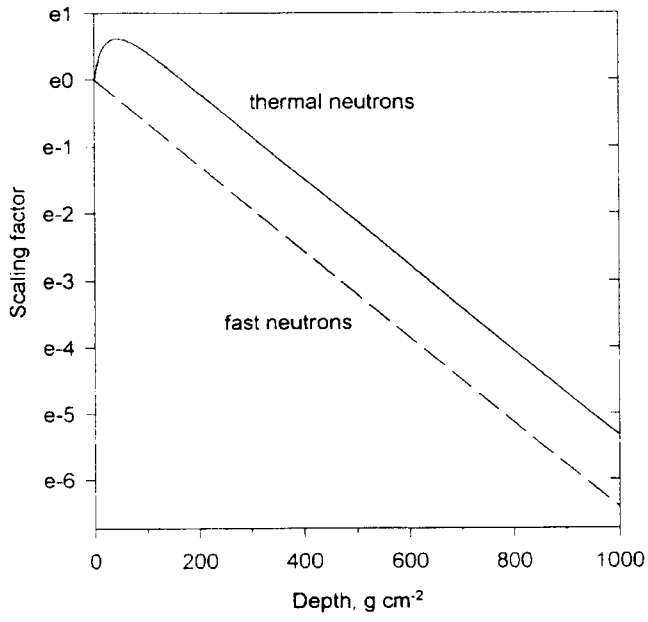

Figure 2. Distribution of thermal and fast neutrons below the surface. The scaling factors for individual components are set arbitrarily to 1 at the surface. Real surface values for fast neutrons and thermal neutrons are different. The intensity of fast neutrons decreases exponentially with depth at a rate determined by the attenuation length (156 g cm^{-2}). The distribution of thermal neutrons may also vary with chemical composition (Dep and others, 1994a).

(O'Brien and others, 1978; Yamashita and others, 1966). The macroscopic thermal neutron absorption cross section of atmospheric gases is much higher than that of common crustal rocks. Therefore, neutrons that are produced in the top several centimeters of the rock mass have a propensity to escape out of the rock and into the air above it, where they are absorbed by nitrogen atoms. This leads to relative depletion of thermal neutrons in the uppermost part of the rock mass. The distribution of thermal neutrons exhibits a maximum at the depth of about 50 g cm^{-2} (Fabryka-Martin and others, 1991; Liu and others, 1994); this dimension is for the product of depth and rock density. The exact position and magnitude of the maximum are functions of the chemical composition of the material (Dep and others, 1994a). Below this depth, the intensity of thermal neutrons decreases exponentially at a rate similar to that for the fast component.

At sea level, the flux of slow negative muons is comparable to that of neutrons and in some materials slow muon capture becomes a significant cosmogenic reaction (Jha and Lal, 1982; Lal and Peters, 1967; Rama and Honda, 1961). Slow negative muons can penetrate deeper due to their lower reactivity (Conversi, 1950; Rossi, 1952), and may dominate cosmogenic production at depths below about three meters (Fabryka-Martin, 1988).

Temporal Distribution

The temporal variability of the incident cosmic ray flux is due to (1) long-term variations in the galactic cosmic ray (GCR) flux, (2) changes of the Earth's magnetic dipole strength, (3) short-term variations in the pole positions and (4) short term variations in solar activity. Long-term variability of the geomagnetic field strength, on the order of 10^3-10^4 years, is the most important factor for cosmogenic nuclide applications. Short-term variations of the pole positions, on the order of 10^2 years, and solar activity (11 years and a few hundred years) are averaged out after about 100 to 1,000 years and become negligible for surface exposure dating. The galactic cosmic ray flux varies within narrow limits (Lal and Peters, 1967) on the time scale of $>10^6$ years; this long-term trend may be neglected in studies of late Quaternary surfaces.

The evidence of the long-term variability of the cosmic ray

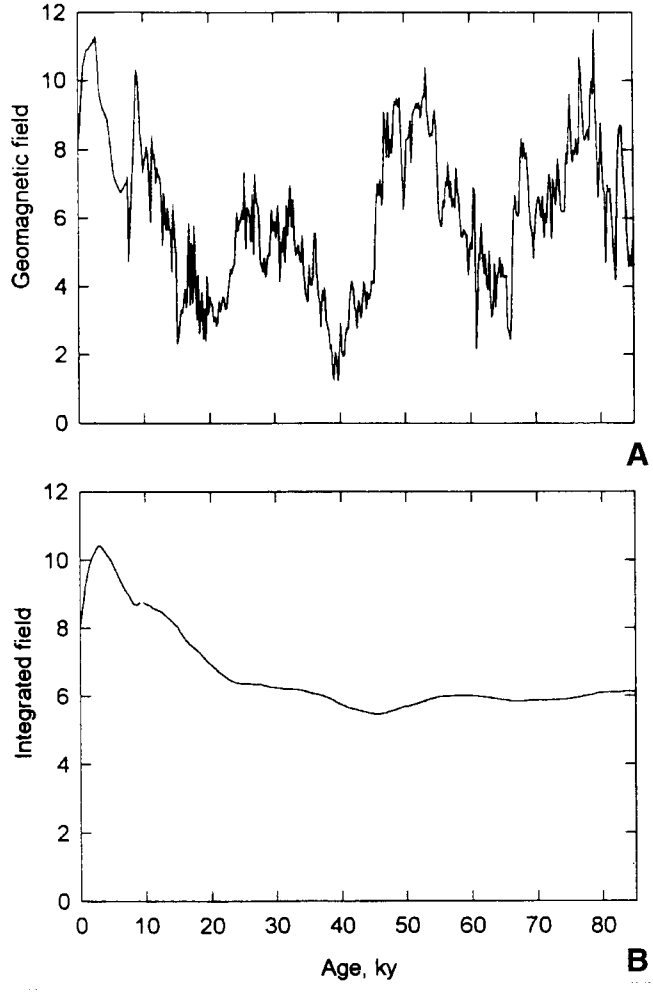

Figure 3. (A) Reconstructed geomagnetic field intensity in the last 85 ky (from Mazaud and others, 1991). (B) Integrated geomagnetic field intensity for the same time interval. The graph shows the value of average intensity between a given point in time and the present.

Table 2. Relative Contribution Of Major Cosmogenic Reactions Leading To Production of ^{36}Cl, ^{10}Be, ^{26}Al, and ^{3}He[a]

N[b]	Reaction Type	Notation	Percent of Total
^{36}Cl	Spallation of ^{39}K and ^{40}Ca	$^{39}K(n,2n2p)^{36}Cl$ $^{40}Ca(n,2n3p)^{36}Cl$	16-80
	^{35}Cl thermal neutron activation	$^{35}Cl(n,\gamma)^{36}Cl$	11-80
	Negative muon capture by ^{40}Ca	$^{40}Ca(\mu^-,\alpha)^{36}Cl$	0-10
^{10}Be	Spallation of ^{16}O	$^{16}O(n,4p3n)^{10}Be$	84
	Negative muon capture by ^{16}O	$^{16}O(\mu^-,3p3n)^{10}Be$	16
^{26}Al	Spallation of ^{28}Si	$^{28}Si(n,p2n)^{26}Al$	83
	Negative muon capture by ^{28}Si	$^{28}Si(\mu^-,2n)^{26}Al$	17
^{3}He	Spallation of ^{40}Ca, ^{7}Li, ^{58}Ni, ^{64}Zn, ^{40}K	various	>90
	n-α reaction	$^{6}Li(n,\alpha)^{3}H \rightarrow ^{3}He$	<10

[a]For production of ^{36}Cl (Zreda and others, 1991, modified after Fabryka-Martin, 1988), ^{10}Be and ^{26}Al (after Nishiizumi and others, 1989) and ^{3}He (Kurz and others, 1986; Lal, 1987; Trull and others, 1991) at the earth's surface, sea level and high geomagnetic latitudes.
[b]Nuclide.

intensity comes from studies of ^{14}C in tree rings (Stuiver and others, 1986), ^{10}Be in ice cores (Yiou and others, 1985) and deep-sea sediments (Raisbeck and Yiou, 1984), ^{3}He in lava flows (Kurz and others, 1990; Cerling and Craig, 1994) and from paleomagnetic studies in volcanic rocks (Mazaud and others, 1991). This variability is quasi cyclic around a mean value slightly lower than the modern intensity (Fig. 3a). Because of cyclicity, the long-term variations of the geomagnetic field strength are also averaged out over time (Fig. 3b), but the time necessary for this integration is long, on the order of 10^4 years. This integration can be expressed as

$$G(t) = \frac{\int_0^t g(t)dt}{\int_0^t dt}, \qquad (1)$$

where t is the time, $g(t)$ is the geomagnetic field strength, a function of time, and $G(t)$ is the average intensity over the last t years.

The variability of the integrated geomagnetic field intensity is most notable in the last 20 ky, when the average intensity changes from ~6 at 20 ka to ~8 now (Fig. 3b). Beyond 20 ka, the average intensity is approximately constant with time around a mean value of ~6. Cosmogenic nuclide production rates are inversely correlated with the geomagnetic field changes, i.e., stronger field leads to lower production rates and vice versa. The result from Figure 3b means that only young surfaces may potentially be affected by these changes in the magnetic field, provided that production rates are interpreted over long (>20 ky) time interval. The magnitude of the associated production rate changes is smaller than that of the mag-netic field changes and is also non-uniformly distributed in space. The largest temporal variability is expected at low latitudes, whereas at polar latitudes, the production rates are constant with time (Lal, 1991).

Cosmogenic Nuclides on Earth

Production of cosmogenic nuclides depends on the intensity of incident cosmic rays, availability of target nuclei in the exposed material, and probability with which a nuclear reaction produces the nuclide of interest (also termed the reaction cross section). Each nuclide is produced by a different set of nuclear reactions and the relative production of each nuclide depends on the elemental composition of the target material (Table 2). Figure 4 shows schematically the main cosmogenic reactions leading to the formation of ^{36}Cl.

The accumulation rates of cosmogenic nuclides in terrestrial materials depend on the rate of *in situ* production and, in the case of radioactive nuclides, the removal rate due to radioactive decay. With the production rate P (atoms kg^{-1} y^{-1}), the number of atoms N increases by $dN=Pdt$ in the time interval dt. The number of atoms of radioactive isotopes decreases in proportion to its abundance and the decay constant λ (y^{-1}) as $dN=-\lambda Ndt$. Because the cosmic ray intensity varies with time and depth, the production rate is a function of these two variables, i.e., $P=P(t)D(x)$, where $D(x)$ is a function describing the distribution of production rates below the surface (Fig. 2). All these processes occur simultaneously, and their combined effect is described by

$$\frac{dN}{dt} = P(t)D(x) - \lambda N \qquad (2)$$

which simplifies to

$$\frac{dN}{dt} = P - \lambda N \qquad (2a)$$

if the production rate is constant in time.

The lack of independent variables in the production term P of Equation 2a emphasizes important assumptions underlying its applications to geological problems. Our major assumption is that the production rates are constant with time. We know, from the discussion above, that due to the temporal variability of the Earth's magnetic field, the cosmic ray intensity is variable and thus the production rates of cosmogenic nuclides also vary in time. However, this variability is progressively less important at longer time scales because of averaging properties of continuous cosmic irradiation (Fig. 3b). While the largest temporal effects are expected for young, latest Pleistocene and Holocene surfaces (e.g., Kurz and others, 1990), these effects should become less dramatic for surfaces older than ~20 ka (Cerling and Craig, 1994; Zreda, 1994).

Our other assumption, one inherent in Equation 2a, is that

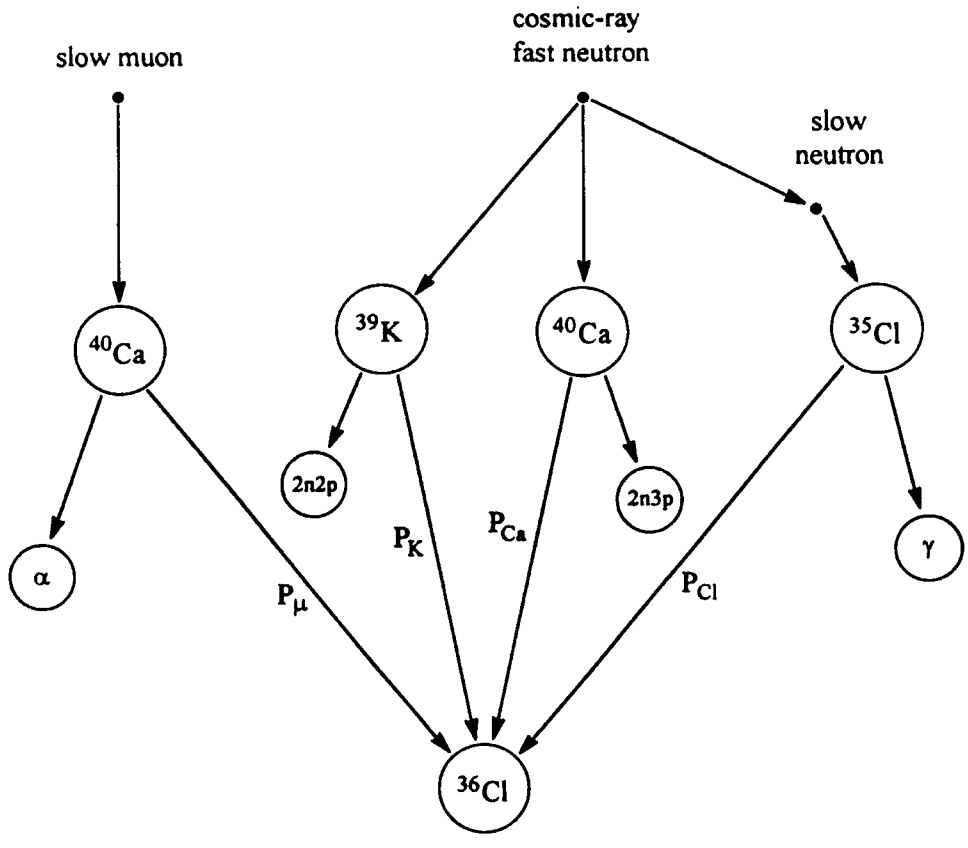

Figure 4. Cosmogenic reactions for ^{36}Cl. Fast and thermal neutrons and slow muons interact with three main target elements, ^{35}Cl, ^{39}K and ^{40}Ca, to produce ^{36}Cl with probabilities P. Formation of ^{36}Cl is accompanied by the emission of various elementary particles.

the surface has been in its original position since first exposure to cosmic radiation. This includes assumptions of negligible erosion, absence of cover of any kind, no chemical weathering and no precipitation of secondary minerals. We can quantify effects of these processes with considerable effort, for example by using multiple isotopes (Lal, 1991) or multiple samples from the same surface (Zreda and others, 1994). However, ultimately the most cost-effective strategy is to minimize these effects through careful sampling.

Equation 2 is solved for N to yield accumulation of cosmogenic nuclides with time (Zreda and others, 1994).

$$N = e^{-\int \lambda dt} \int [P(t)D(x)] e^{\int \lambda dt} dt + Ce^{-\int \lambda dt} \quad (3)$$

Assuming constant production rate P and initial condition $N(t = 0) = 0$, Equation 3 simplifies to

$$N = \frac{P}{\lambda}\left(1 - e^{-\lambda t}\right) \quad (4)$$

For stable nuclides, such as ^{3}He, λ is equal to 0 and by taking the limit with λ approaching 0, we obtain a simple relationship

$$N = \lim_{\lambda \to 0} \frac{P}{\lambda}\left(1 - e^{-\lambda t}\right) = Pt \quad (4a)$$

Accumulation of radioactive and stable cosmogenic nuclides on geomorphically stable surfaces is shown in Figure 5. Stable nuclides accumulate indefinitely with time. Their buildup function is a straight line, whose slope is equal to the production rate P (cf. Equ. 4a).

progressively more important. This change is reflected in the shape of the accumulation function, which becomes flatter and ultimately reaches secular equilibrium equal to P/λ. In equilibrium, the production and decay rates are equal and the concentration of the nuclide remains constant with time.

Surface Exposure Dating

Surfaces can be dated using the above equations if the production rates are known and concentrations of cosmogenic

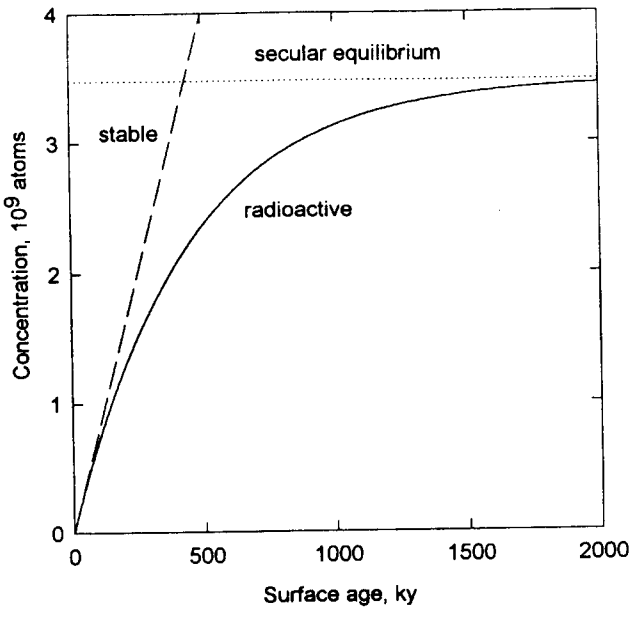

Figure 5. Accumulation of radioactive and stable cosmogenic nuclides in rocks exposed continuously at the surface. Radioactive nuclides reach a limit determined by the production and decay rates. The production rates are assumed constant with time.

nuclides are measured. To use cosmogenic dating techniques efficiently, we assume that prior to exposure at the surface rocks have low background concentrations of nuclides of interest. Once rocks are exposed to cosmic radiation, for example due to excavation and redeposition, their nuclei interact with cosmic ray particles and undergo nuclear transformations. These nuclear reactions lead to formation of new nuclides and each such reaction has certain probability of occurring. The reaction probabilities are assessed theoretically, using principles of nuclear physics (e.g., Lal and Peters, 1967), or empirically, using measured concentrations of cosmogenic nuclides in rocks of known ages. The latter approach has been used to determine average production rates of several nuclides (Table 3).

Surface exposure ages are calculated using the accumulation Equation 2. Because the exact functional form of $P(t)$ is unknown, Equation 2 must be solved numerically. The simplified Equation 2a has the analytical solution for the time t

$$t = \frac{-1}{\lambda} \ln\left(1 - \frac{N\lambda}{P}\right). \tag{5}$$

By taking the limit with λ approaching 0, the following simple solution for stable nuclides is obtained

Table 3. Experimental Production Rates Of Cosmogenic Nuclides In Terrestrial Environments

	Production			
Nuclide	Mechanism	Rate	Averaging time	References
^{21}Ne	Spallation	45 atoms (g olivine)$^{-1}$ y^{-1}	17,800 calendar yr	Poreda and Cerling, 1992
^{3}He	Spallation	115 atoms (g olivine)$^{-1}$ y^{-1}	2,200-14,500 ^{14}C yr	Cerling & Craig, 1994
^{10}Be	Spallation Muon capture	5 atoms (g SiO_2)$^{-1}$ y^{-1} 1 atom (g SiO_2)$^{-1}$ y^{-1}	ca. 11,000 calendar yr (estimated)	Nishiizumi and others, 1989
^{14}C	Spallation	20 atoms (g basalt)$^{-1}$ y^{-1}	17,800 calendar yr	Jull and others, 1994
^{26}Al	Spallation Muon capture	30 atoms (g SiO_2)$^{-1}$ y^{-1} 6 atoms (g SiO_2)$^{-1}$ y^{-1}	ca. 11,000 calendar yr (estimated)	Nishiizumi and others, 1989
^{36}Cl	Spallation of ^{39}K Spallation of ^{40}Ca Activation of ^{35}Cl	7,520 atoms (mol K)$^{-1}$ y^{-1} 2,900 atoms (mol Ca)$^{-1}$ y^{-1} 313,500 n (kg rock)$^{-1}$ y^{-1}	2,200-55,000 calendar yr	Phillips and others, 1993; Zreda, 1994

[a]At sea level and high (>50°) latitudes, integrated over long, geological time scales, and calculated using Lal's (1991) formulation for elevation and latitude. [b]The values reported herein are based on the newest and/or most comprehensive studies. We think that they are the best estimates obtained to date. Other empirical production rates have been reported for ^{36}Cl (Swanson and others, 1993; Phillips and others, 1996), ^{3}He (Brook and Kurz, 1993) and ^{21}Ne (Staudacher and Allègre, 1993).

$$t = \lim_{\lambda \to 0}\left[\frac{-1}{\lambda}\ln\left(1-\frac{N\lambda}{P}\right)\right] = \frac{N}{P}. \quad (5a)$$

Example

We end this section by giving a hypothetical example of surface exposure age calculation using the ^{10}Be method. A quartzite boulder from the Fresh moraine in the Exposed Mountains was sampled. The geographic latitude of the sampling site is 40°N and elevation is 3.2 km above sea level. Our AMS laboratory reported a blank-corrected ratio ^{10}Be/^{9}Be, which corresponds to (8.1 ± 0.61) x 10^5 atoms of ^{10}Be per gram of SiO_2.

From Table 3, the production rate at sea level and polar latitudes is six atoms of ^{10}Be per one gram of SiO_2 per year. The scaling factor, calculated using the polynomial formulation of Lal (1991) with coefficients from Table 1, is 9.68. This means that the production rate at the sampling site is 9.68 x 6 = 58 atoms per gram of SiO_2 per year. Using Equation 5 and the decay constant for ^{10}Be of 4.62 x 10^{-7} y^{-1}, we calculate the exposure time t:

$$t = \frac{-1}{4.62\times10^{-7}} \bullet \ln\left[1-\frac{8.1\times10^{5}\bullet 4.62\times10^{-7}}{58}\right] \quad (5b)$$

$$t = 14.0 \pm 1.1 \text{ ky}$$

The error represents only the analytical uncertainty of the ^{10}Be measurement.

Factors Affecting Surface Exposure Ages

In a physically and chemically stable environment, accumulation of cosmogenic nuclides is a function of time alone and by measuring their concentration one can directly obtain the surface exposure age from Equations 5 or 5a. An implicit assumption in the above simple model is that the production rate (P) is constant. However, postdepositional modifications of landforms and other environmental changes may invalidate this assumption and corrections to the above model may be necessary. In this section, we explore the issue of environmental factors that may influence the buildup of cosmogenic nuclides in surficial materials, examine their possible impact on exposure dating, and discuss ways of accounting for their effects.

Temporal Variability Of Geomagnetic Field Strength

Geomagnetic field strength changes are quasi-cyclic and result in changes in the cosmic-ray flux (see *Theory of Dating Method* above) and thus the cosmogenic nuclide production rates. The two are inversely correlated, i.e., higher magnetic field strength leads to lower production rates and vice versa. These changes may have significant effects on young surfaces. However, for older landforms the variability is integrated over time and the production rates converge to the average value. The effects of variable geomagnetic field strength can be assessed using the function of magnetic strength versus time (Mazaud and others, 1991), and corrections for any desired time interval can then be calculated.

Erosion

Erosion is an important process that affects cosmogenic surface exposure ages. The production rates of cosmogenic nuclides vary with depth below the surface. Consequently, on eroding landforms, they also vary in time. As a result, the calculated cosmogenic ages differ from the true landform age. Erosional processes important for surface exposure dating include soil erosion, stream dissection, erosion of rock surface and spalling.

Soil erosion and gradual exposure of surfaces are common postdepositional processes that affect cosmogenic ages. Erosion of soft moraine matrix and gradual exposure of morainal boulders at the surface is an example of this process. As a result, apparent cosmogenic ages of boulders are usually younger than the true landform age. One can account for these effects in the following ways: (1) collecting multiple samples from each landform and determining the variance of apparent ages (Zreda and others, 1994); (2) sampling from horizontal surfaces that are less likely to have been modified by erosion; (3) using geological characteristics, such as glacial polish or slickensides, to assess landform stability.

Stream dissection is similar in its nature to the above, but varies in the extent of the modification. The calculated exposure ages are for the erosion episode rather than the landform construction and can be useful in studies of regional geomorphic evolution. Analysis of landform morphology and its position with respect to the streams should help one sample appropriately for cosmogenic nuclide dating.

Erosion of a rock surface has an effect similar to that of erosion of soil, but the rate is much slower because solid rocks are much more resistant to erosion than are soils. The effects of erosion of a rock surface can be minimized by selecting surfaces that show indications of minimal erosion (e.g., glacial polish or heavy varnish development) or on which erosion can be quantified (e.g., differential erosion of rocks with variable lithology). They can also be accounted for by using two radionuclides with different decay constants (e.g., Lal, 1991) and by using depth profiles of ^{36}Cl (Dep and others, 1994b).

Spalling of rock surfaces, for example due to fire (Bierman

and Gillespie, 1991) is similar to erosion of rock surfaces, but it occurs at an episodic rate. Spalled surfaces should be avoided, if possible. Where potentially spalled surfaces cannot be avoided, e.g., boulders in a forest, multiple samples are necessary to obtain a good estimate of the minimum surface exposure age.

Shielding

Shielding reduces the intensity of cosmic radiation reaching the surface and thus results in apparent ages that are different from the true surface age. Important shielding materials include snow, volcanic ash, dust, sand, and vegetation.

Snow cover will temporarily reduce the cosmic-ray flux reaching the surface and usually results in an underestimation of the true age. This factor is especially important in polar and mountain areas where snow cover is thick and persists for a long time. Sampling from topographic highs from which snow is quickly removed by wind should minimize the effect of snow cover on accumulation of cosmogenic nuclides.

Volcanic ash, dust, or sand cover temporarily reduces the cosmic-ray flux reaching the rock surface and usually results in an underestimation of the true age. Sampling from the highest points should again give the best results. In addition, examination of the study area for remnants of ash or sand, which should be preserved in topographic pockets, where the action of wind is not strong enough to remove them, should provide clues about the presence or absence of such cover in the past.

Vegetation cover blocks cosmic rays and may lead to an underestimation of the true ages. It is considered a minor factor in arid environments, such as that of the Great Basin; however, atmospheric conditions could have been less arid in the past and vegetation may have been different. This effect is therefore very difficult to quantify.

Chemical Weathering

Chemical weathering may affect dating through loss (or gain) of the nuclide of interest, change of the rock's bulk chemical properties and composition, and precipitation of secondary minerals. Precipitation of secondary minerals will affect the dating because of inclusion of non-cosmogenic ^{36}Cl. Sampling of only less weathered rocks should minimize these problems. In the laboratory, one can attempt separation of secondary minerals from primary ones. Whereas this will work for separating out clay minerals and carbonates, it may fail for some non-separable minerals, such as iddingsite, which replaces olivine.

Geometry Change

Geometry change by clast rolling will cause exposure of new surfaces to cosmic radiation and result in an underestimation of true surface age. Sampling from more than one surface of the boulder in question, for example, would yield the necessary information to address this problem. It is, however, expensive and therefore not routinely done in surface exposure dating; instead, multiple boulders from the same landform are sampled.

Geometry change by breaking up along vertical fractures leads to the so called "edge effect" which changes the thermal neutron absorption rate. This process may also lead to an underestimation of the true ages because of diffusion of thermal neutrons out of the rock and into the atmosphere. To minimize this effect, samples should be collected from centers of tops of large, >1 m in diameter, boulders (larger than the attenuation length for thermal neutrons) and from horizontal, flat surfaces.

Elevation Changes

The cosmic ray flux varies as a function of elevation. Thus, in areas of significant changes in surface or landform elevation, the production rates of cosmogenic nuclides will change with time. Processes resulting in elevation change include tectonic activity, isostatic movement and eustatic changes in sea level.

Tectonic subsidence or uplift will lead to change of the cosmic-ray flux reaching the surface. Tectonism may also cause deformation of the landform and destruction of the original surface. Possible effects of tectonic processes are negligible for young, late Quaternary surfaces because of the typically low average rates of tectonic movement. The surface morphology should bear information about any destructive processes caused by tectonics and aid in correct sampling.

Isostatic movement will change the elevation and thus the cosmic-ray flux reaching the studied surface. This factor may be important in areas of glacial or pluvial rebound. Assessment of these effects can be made by using reconstructed (e.g., using independent dating or modeling) isostatic movement rates for the last glaciation-deglaciation cycle. For older surfaces, the cyclicity in the signal due to isostasy is averaged out, due to crustal loading and unloading by glaciers or water, and the effects on cosmogenic nuclide buildup should be negligible.

Eustatic sea-level changes affect the production rates by changing the reference level (i.e., sea level) against which altitudes of sampling sites are determined. To account for sea-level changes, one can use reconstructed sea levels and average these changes over time. For surfaces older than late Quaternary, the cosmogenic signal is averaged out because of "cyclicity" of changes caused by buildup and melting of big polar ice sheets.

We note here that isostatic and eustatic changes have only a minor effect on production rates of cosmogenic nuclides. A

sea level rise by 100 m, typical of Pleistocene fluctuations, will change a high-latitude, near-sea-level production rate from 1.09 to 0.99, a difference of ~10 percent, and a high-altitude production rate from 11.0 to 10.4, a difference of ~6 percent.

Time Range of Applicability

The cosmogenic methods have different theoretical time ranges that depend on their half-lives, from 0 to 15 ky for ^{14}C, to 0 to infinity for stable ^{3}He. Two or three half-lives are considered the theoretical limit of cosmogenic buildup methods based on radioactive nuclides. Beyond this, the buildup curves asymptotically reach secular equilibria between production and decay, i.e., the concentrations do not change with time any more (Fig. 5).

Realistic time ranges depend on geological factors, such as erosion, weathering, and tectonics. Except in environments like Antarctica, most surfaces erode fast enough to affect accumulation of cosmogenic nuclides on time scales shorter than the theoretical limits. To extend the range, erosion must be assessed independently, for instance, by using a second cosmogenic nuclide or by multiple sampling for a single nuclide. A realistic upper limit for ^{36}Cl is 200-500 ka, although ages older than 500 ka have also been obtained. The lower (younger) limit is dictated by the production rates, the analytical technique used, prior exposure to cosmic rays and radiogenic (non-cosmogenic) production. At high altitudes, where the production rates are high, cosmogenic nuclides build up to detectable amounts after only a few hundred years. The utility of the pair ^{10}Be-^{26}Al for simultaneous determination of the erosion rate and exposure age is limited to samples older than ca. 200 ka because of analytical uncertainties (cf. Nishiizumi and others, 1991a), although these nuclides reach measurable quantities after much shorter times, on the order of 10^4 years (Nishiizumi and others, 1989).

METHODOLOGY

Sample Collection

Before sample collection, three questions must be answered: what rock/mineral type to sample, what surface to sample, and how many samples to collect. The sampling strategy depends on the nuclide used, landform studied, its age and geomorphic history and availability of appropriate material.

All types of solid surficial materials can be sampled for one or more of the cosmogenic nuclides discussed herein. The exact petrographical and mineralogical requirements depend on the nuclide used. Whereas ^{36}Cl can be measured in whole rock samples, mineral separation is required for ^{3}He and ^{26}Cl only, and is desired for ^{10}Be and ^{14}C. Because ^{36}Cl is produced from several target elements, virtually all rock types are suitable for this nuclide. Most of the ^{36}Cl in carbonates is produced from Ca, while in silicate rocks the production is divided between Cl, Ca and K. Quartz is the most desirable mineral phase for ^{26}Al because of low total Al concentration. Olivine is considered best for ^{3}He because of its tight crystal structure, which prevents helium loss by diffusion. Quartz is best for ^{10}Be because of its simple chemistry and tight crystal structure, which minimize the effects of contamination by atmospheric ^{10}Be.

Selection of sampling sites is based largely on the assessed geomorphic stability of the surface and its geometry. We prefer to sample from flat, horizontal surfaces that are likely to have been continuously exposed since the landform formation. In the field, it means that we look for topographic highs with extensive, flat tops. For example, large and tall morainal boulders are preferred to small and short ones and massive parts of lava flows are better than those with pressure ridges. For ^{36}Cl, an additional condition, that samples be far from any edges, should be met. This condition is dictated by possible leakage of thermal neutrons from the sides. This leakage may be difficult to quantify, although Zreda and others (1993) attempted to do so for samples from a lava flow with pressure ridges at the surface.

Samples are collected from the top few centimeters of rock using a hammer and a chisel. This minimizes possible effects of variable production rates with depth. Least weathered parts of the surface are preferred to minimize any inclusion of weathering products and their effect on calculated ages. The samples are put in plastic or cloth sample bags and stored until preparation.

The number of samples is related to geological characteristics of the surface dated, specifically, its history of burial and erosion. Geomorphically stable and young surfaces usually yield consistent ages and three to five samples may suffice. Old landforms, on the other hand, might have had complex geological histories of burial and erosion and require either more samples or multiple nuclides for dating. A depth profile of ^{36}Cl may also be useful in determining effects of surface erosion on calculated exposure ages.

Laboratory Analysis

Two analytical methods for cosmogenic nuclides are commonly employed: (1) accelerator mass spectrometry (AMS), for radioactive nuclides ^{14}C, ^{36}Cl, ^{26}Al and ^{10}Be; and (2) noble gas mass spectrometry, for stable nuclides ^{3}He and ^{21}Ne. In this section, we describe sample preparation and analysis for ^{36}Cl. Analytical methods for ^{10}Be and ^{26}Al have been described by Kohl and Nishiizumi (1992), Brown and others (1991), Klein and others (1982) and Middleton and others (1983), for ^{3}He by Kurz and others (1987) and Craig and Poreda (1986), for ^{21}Ne by Poreda and Cerling (1992) and for ^{14}C by Jull and others (1992).

Table 4. Target Element Concentrations, Macroscopic Cross Sections ($\Sigma\sigma N$), $^{36}Cl/Cl$ Ratios, And ^{36}Cl Surface-Exposure Ages For Samples From Lathrop Wells, Nevada (after Zreda and others, 1993).

Sample ID	K_2O (%)	CaO (%)	Cl ppm	$\Sigma\sigma N$[a] $cm^2\ kg^{-1}$	$^{36}Cl/Cl$[b] 10^{-15}	Age, ky Sample	Surface	Eruption
LWC88-3	1.67	7.48	268	7.54	344 ±15	79 ±3.4		
LWC88-4	1.44	7.41	255	7.49	417 ±19	96 ±4.5	84 ±8	
LWC88-5	1.64	7.57	272	7.44	371 ±20	85 ±4.6		
LWC88-6	1.67	7.40	105	7.39	600 ±35	78 ±4.6		
LWC88-1	1.75	7.33	270	7.53	335 ±26	93[§] ±7.2		
YM88-5	1.72	7.14	268	7.43	270 ±25	73[§] ±6.8		81 ±8
YM88-6L	1.84	7.06	308	7.07	281 ±19	81[§] ±5.4	81 ±7	
YM88-6M	1.88	7.19	292	7.67	270 ±21	77[§] ±6.0		
YM88-8	1.98	7.48	217	6.96	352 ±27	79[§] ±6.1		
LWC89-S	1.59	7.51	1164	8.45	263 ±29	83[#] ±9.2	76 ±10	
LWC89-W	1.61	7.32	233	7.27	326 ±27	68 ±5.7		

Note: The sample ages are for single rock samples, the surface ages are arithmetic averages of the sample ages, and the eruption age is the overall arithmetic mean. All samples are from the surface, at elevation 914 m above sea level, lat 36.4°N, long 243.4°E; the elevation-latitude-depth (ELD) scaling factor (Equ. 3.4.2-1 in Zreda and others, 1991) for all samples is 1.89.

[a] Macroscopic absorption cross section of the rock (Zreda and others, 1991).

[b] After subtraction of the radiogenic $^{36}Cl/Cl$ of 11×10^{-15}.

[c] Corrected for surface geometry (see text for details). Uncorrected surface age is 67 ± 6 ky.

[d] Corrected for meteoric $^{36}Cl/Cl$ (see text for details).

Samples for ^{36}Cl are cleaned of any organic overgrowths, ground to a size fraction smaller than the mean phenocryst size of the rock and leached for 24 hours in 3 percent nitric acid (silicate rocks) or deionized water (carbonate rocks) to remove any meteoric chlorine from micropores or grain boundaries. Silicate rocks are dissolved in a hot mixture of concentrated nitric and hydrofluoric acids, and carbonate rocks in 10 percent nitric acid. Chlorine is liberated from minerals and precipitated as AgCl by addition of $AgNO_3$ to the reaction bottle. The time required for a complete dissolution depends on mineral composition; it is 1-2 days for silicates and a few hours for carbonates. The precipitate is dissolved in NH_4OH and mixed with $BaNO_3$ to remove sulfur; ^{36}S is an interfering isobar and should be removed prior to AMS measurement. After at least 8 hours any $BaSO_4$ precipitated is removed from the solution by centrifugation or filtration. Near sulfur-free AgCl is precipitated by acidifying the remaining base solution, rinsed using deionized water, and placed in an oven at 60°C to dry. Dry samples are loaded into holders made of copper on the outside and lined with AgBr.

The samples are analyzed for ^{36}Cl by accelerator mass spectrometry (AMS) using a tandem Van de Graaff accelerator (Elmore and others, 1979). Analytical error is typically 2-5 percent at the recently upgraded Purdue Rare Isotope Measurement Laboratory (Elmore, personal communication, 1995).

Data Analysis

The analytical data are reduced to ages using Equations 5 or 5a. Usually, surface exposure ages are treated as minimum ages. If the variance of cosmogenic ages for multiple samples from a single surface is large, the oldest sample age is considered closest to the landform age. On the other hand, if the individual ages are consistent, the average age is reported. There are no other requirements for data analysis if only one nuclide is used. In a two-nuclide approach (Lal, 1991), the two data sets can be analyzed together to simultaneously constrain the age and erosion rate. However, individual measurements of nuclide concentrations are not sufficiently precise to use the multiple nuclide approach with confidence.

Because cosmogenic methods are still under development, there are no standards for reporting uncertainties or assessment of confidence. Typically, the only error reported is the analytical uncertainty associated with the determination of the cosmogenic nuclide concentration. The assessment of confidence is, therefore, based on the spread in individual sample ages from the same surface. Data are reported and presented in different ways by different individual investigators, usually depending on the context of their work. This may render difficult the comparison of dating results obtained using different nuclides and from different locations.

Reporting and Presentation

The data may be presented in tabular form or/and graphically. The following necessary information for calculation of surface exposure ages should be reported:

(1) The assumed production rates of the nuclide from all target elements.

(2) The production scaling factor and geographic latitude

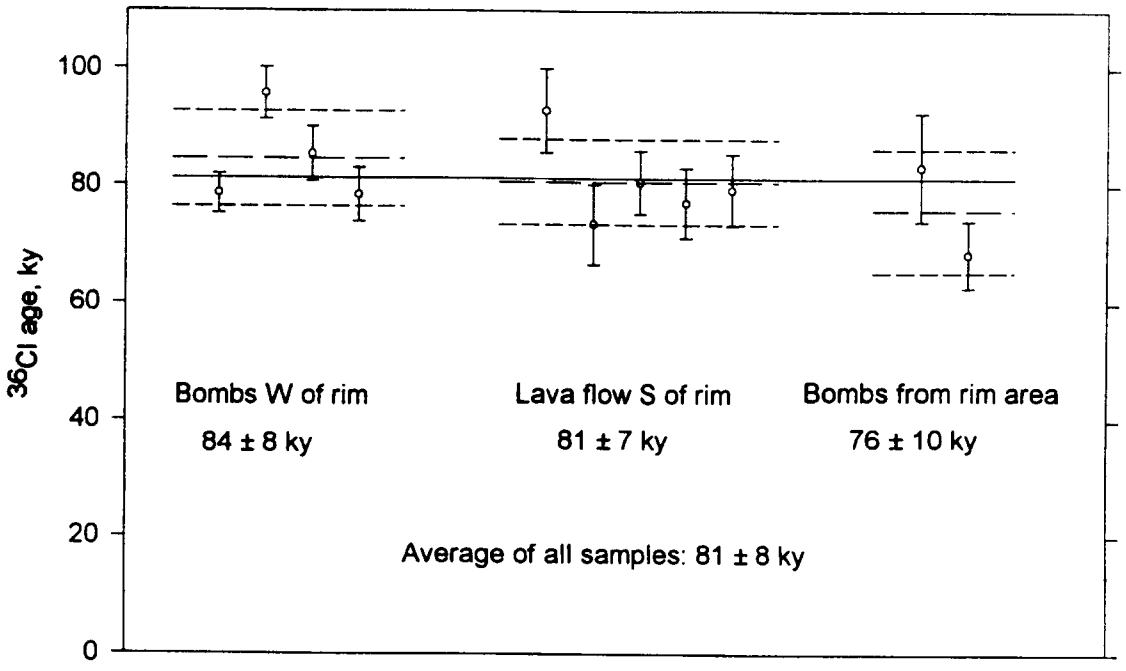

Figure 6. ^{36}Cl ages of samples from Lathrop Wells. Error bars represent ^{36}Cl measurement errors. Long dashes are means of three groups of samples; short dashes represent intervals within one standard deviation calculated for each group; solid line is mean of all 11 samples. From Zreda and others, 1993. Reprinted with permission of the publisher, The Geological Society of America, Boulder, Colorado.

and elevation.

(3) Concentrations of all target elements for the nuclide, if needed for age calculations.

(4) For ^{36}Cl only, concentrations of all major elements, Cl, B and Gd, which are necessary for calculation of the macroscopic thermal neutron absorption cross section (Zreda and others, 1991).

(5) Initial or background concentration of the nuclide.

(6) Measured nuclide concentration in the sample.

Figure 6 and Table 4 are examples of data presentation taken from Zreda and others (1993). Here, the mean of 11 samples was considered the best estimate for the eruption time because of close agreement among the individual sample ages.

APPLICATIONS

Surface exposure dating by cosmogenic nuclide accumulation has only recently been developed to the point at which geological applications are possible. The approach is still considered experimental because of uncertainties in the production rates and in isotope systematics of these systems. Several applications of cosmogenic nuclides in the area of Quaternary geochronology have been reported in the last few years. They include (1) development of chronologies of Quaternary glaciations, (2) dating of late Quaternary volcanic eruptions, (3) dating paleolake shorelines, and (4) dating a terrestrial impact crater. Quantitative estimates of rates of erosion and other processes modifying landforms also have been reported. Below, we discuss appropriate geologic settings for surface exposure dating using cosmogenic nuclide accumulation and present examples of geochronological applications. In addition, we discuss two applications of cosmogenic nuclides to paleoseismology.

Alpine Moraines

Mountain glaciers erode bedrock and previously accumulated deposits, transport the debris down the valley, and deposit some of the material as moraines. The essential assumption made here is that glacial erosion is deep enough to excavate material previously completely shielded from cosmic rays and thus having near zero initial concentration of cosmogenic nuclides. As soon as the moraine is deposited, its surface is bombarded by energetic cosmic rays that interact with certain nuclei within the rock matrix to produce cosmogenic isotopes. Since the production rates of these nuclides are known (Table 3), their accumulation in moraine material can be used to calculate surface exposure ages (Phillips and others, 1991). Phillips and colleagues used this idea to date late Pleistocene moraines in the Sierra Nevada, California (Phillips and oth-

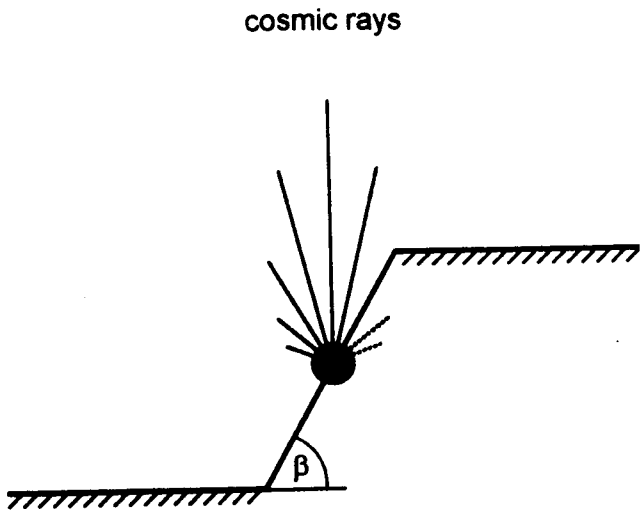

Figure 7. Incident cosmic ray intensity at a fault face inclined at an angle ß. The cosmic-ray intensity depends on the direction according to Equation 6; the highest intensity is in the vertical direction (longest line), whereas the horizontal contribution is zero. Fault face is exposed to cosmic rays over the angle 180-ß (solid lines) and shielded from cosmic rays over the remaining angle ß (dashed lines).

ers, 1991; Zreda, 1994) and the White Mountains, California and Nevada (Zreda and others, 1995a). They measured cosmogenic ^{36}Cl in boulders exposed on moraine crests, calculated surface exposure ages (assuming negligible erosion) and thus developed numerical chronologies of glaciations in these areas. It was possible to correlate moraines deposited at different locations during the same time intervals and distinguish moraines with ages differing by as little as a few ky. The early work of Phillips and others (1991) was followed by similar studies using ^{36}Cl (Zreda and others, 1995a; Zreda, 1994; Phillips and others, 1993), ^{10}Be and/or ^{26}Al (Brown and others, 1991; Brook and others, 1993; Nishiizumi and others, 1993) and ^{3}He (Brook and others, 1993). These studies helped develop Pleistocene glacial chronologies at other locations and revealed complex histories of landforms.

Volcanic Surfaces

Cosmogenic methods may be very useful for dating young, alkaline volcanics, whose low potassium content renders them unsuitable for K-Ar and $^{39}Ar/^{40}Ar$ dating. An attempt to date young volcanics was made at Lathrop Wells, Nevada by Zreda and others (1993). They measured ^{36}Cl in samples collected from three types of volcanic deposits: a lava flow, volcanic bombs, and the cinder cone (Table 4)(Fig. 6).

Lava flows are almost ideal for surface exposure dating because they (1) originate deep in the subsurface, which assures no prior exposure to cosmic rays, (2) form virtually instantan-eously, and (3) have surface structures that help assess their geomorphic stability. Because of these characteristics, and also because they can be dated by other means, lava flows have been used to calibrate cosmogenic methods based on ^{3}He (Kurz and others, 1990; Cerling and Craig, 1994) and ^{36}Cl (Zreda and others, 1991; Phillips and others, 1993; Zreda, 1994).

Volcanic bombs share some characteristics of lava flows, but because they are loose deposits, their geomorphic stability cannot be assessed with great certainty. Zreda and others (1993) reported cosmogenic ^{36}Cl ages of volcanic bombs at Lathrop Wells, Nevada; the ages are indistinguishable from the ^{36}Cl age of the associated lava flows.

Cinder cones are less well suited for exposure dating because they are composed partly of easily erodible, soft material. Their suitability for dating should be assessed in the field, based on local topographic and petrographic characteristics. Zreda and others (1993) found that samples from the rim at Lathrop Wells are only slightly younger than lava flow and bomb samples and attributed the difference to either analytical uncertainties or erosion of the cinder cone rim.

Paleoshorelines

Two types of materials from ancient lake shorelines are suitable for surface exposure dating: (1) clasts transported by streams and redeposited at the shore; and (2) tufa deposits precipitated directly from the lake water. Fluvial deposits may have previously accumulated cosmogenic nuclides due to exposure in outcrops or during stream transport. This inherited component must be independently assessed before the measured concentrations can be used to calculate the true shoreline age (Zreda, 1994). At the time of deposition, carbonate tufas have initial ^{36}Cl concentrations equal to the lake composition, and this component should be subtracted from the measured 36Cl concentration to arrive at the accumulated value.

Fluvial and alluvial deposits are examples of geological materials comparable to ancient shoreline deposits. Because they all have similar geomorphic characteristics and the same problems, similar precautions should be observed. A limited study of glaciofluvial sediments from the eastern flanks of the Wind River Range was conducted by Zreda (1994). The terrace deposits were numerically correlated with glacial deposits in the nearby mountains, which established a temporal connection between these two types of deposits.

Impact Craters

Impact craters are an appropriate geomorphic setting for surface exposure dating by cosmogenic nuclide buildup. These features are formed instantly and are deep enough to assure that the rocks at the bottom had been shielded from cosmic

radiation prior to the impact. In addition, they have simple stratigraphy, often reversed due to redeposition of ejected material on the rim. Meteor Crater, on the southwest margin of the Colorado Plateau, Arizona, is an example of a well-preserved meteor impact crater. The impact exposed previously shielded siliceous dolomites to cosmic radiation. The crater thus provides a nearly perfect scenario for applying surface exposure dating methods. Multiple boulders from the crater rim were sampled and the samples analyzed for ^{36}Cl (Phillips and others, 1991) and ^{10}Be and ^{26}Al (Nishiizumi and others, 1991b). The inferred ages, 50 ± 1 and 49 ± 2 ky, respectively, are in excellent agreement with thermoluminescence age of 49 ± 3 ky (Sutton and others, 1985). This study is important in that it provides support for the accuracy and reliability of the cosmogenic dating methods.

Fault Faces

Fault scarps are a manifestation of past seismic activity. Whereas those developed in soils or other loose materials can be dated by ^{14}C on organic matter clearly associated with the faulting event, many scarps that formed in bedrock cannot be dated by that technique. Fortunately, bedrock fault faces are potentially a suitable geological setting for cosmogenic nuclide dating.

During a faulting event, previously buried rocks are exposed to cosmic rays at the fault face (Fig. 7). Because such faces usually form at a steep angle with the Earth's surface, they receive less cosmic radiation than horizontal surfaces do. A suitable correction can be calculated using the radial distribution of the cosmic ray intensity, approximated as (Nishiizumi and others, 1989):

$$f(\alpha) = \sin^{2.3}\alpha \qquad (6)$$

where a is the incident angle of the cosmic ray particle. The total amount of radiation reaching a fault face (forming an angle β with the Earth's surface) from all directions in a vertical plane is obtained by integration of $f(\alpha)$ as follows (cf. Zreda and Phillips, 1994):

$$f(\beta) = \int_{\beta}^{\pi} f(\alpha)d\alpha = \int_{\beta}^{\pi} \sin^{2.3}\alpha d\alpha \qquad (7)$$

and production rates of cosmogenic nuclides are reduced by a factor $f(ß)/f(0)$.

Another concern in cosmogenic dating of faults is a possibility of polygenetic character of fault faces. Many faults were active more than once in the past and these multiple events produced cumulative movements along the same face. It is important to recognize these different phases of the fault formation and design sampling accordingly. In polygenetic faults, each part of the face has been exposed to cosmic radiation for a different period of time. From cumulative exposure durations at these different parts of the face and respective total accumulated movements, it is possible to reconstruct differential movements along the fault. A study of ^{36}Cl exposure ages of a fault scarp along the Hebgen Lake fault zone, Montana demonstrates the utility of this approach (Zreda and others, 1995b; Zreda and others, 1996; Zreda and Noller, 1998).

LIMITATIONS AND MAXIMUM UTILITY

There are several advantages of *in situ* cosmogenic methods: (1) they can be used to date landforms and determine rates of surficial processes, (2) they are applicable to the Quaternary period, (3) they can be used on a variety of geological materials, and (4) analytical methods for their determination are well established.

The major advantage of the cosmogenic nuclide methods is that they allow numerical dating of landforms, including those constructed out of redistributed material. Previously, such surfaces could not be dated because conventional radiometric geochronometers, such as K-Ar, are not reset by processes of mobilization and geomorphic redeposition. As an example, consider alpine moraines deposited 20 ka, during the late Wisconsin glacial maximum. They were constructed out of pre-existing material and this material itself is as old as the mountains out of which it was eroded by the glacier. The geomorphic redistribution of this material and deposition as moraines does not reset geochronological clocks based on radioactive decay, such as K-Ar or $^{39}Ar/^{40}Ar$, but it does start the in situ cosmogenic clocks by exposing the previously buried material to cosmic rays. If erosion is negligible, one can obtain the exposure age of the moraines from just one cosmogenic nuclide. On eroding surfaces, a second nuclide may be necessary to also determine the average erosion rate.

A major geological advantage of the methods is that they are applicable to the Quaternary period. They expand our ability to date sediments and surfaces beyond the 50 ka limit of the ^{14}C method and, consequently, have become invaluable tools for Quaternary geologists, geochronologists and geomorphologists.

In contrast to the conventional ^{14}C dating method, which requires organic carbon, cosmogenic methods can use many different types of material. Typically, rock or soil samples are collected because they are in abundance in most geological contexts. For some nuclides, such as ^{26}Al and ^{3}He, specific minerals must be present, whereas others, such as ^{36}Cl, can be measured on whole rocks as well.

The quality of analytical data for cosmogenic nuclides is usually very good. It has been assessed by repeated measurements on the same rock samples. For example, multiple samples prepared at New Mexico Institute of Mining and Technology from the same rock yielded consistent ^{36}Cl ages, well within the analytical uncertainty of the AMS measurement.

These were not splits of the same sample, but samples prepared at different times and using different dissolution methods.

Disadvantages common to all cosmogenic buildup methods include: (1) limited availability of sampling sites and/or samples; (2) limited knowledge of production rates; (3) complex exposure history due to geological factors; (4) long and involved sample preparation; and (5) limited accessibility of analytical equipment.

Availability of samples varies from one geologic context to another. Moraines, for instance, may not contain large boulders suitable for dating and one may have to collect samples from small boulders or the moraine matrix. Such samples may be more affected by erosion of previous soil cover than large boulders are and they give ages that differ from the landform age. Extensive lava flows are easy to sample and almost any location not covered by tephra or other loose material may be suitable. However, they may lack suitable minerals for selected nuclides. For paleoseismic studies, best geological settings would be uneroded fault scarps and fault faces with visible slickensides. Such settings are not readily available everywhere, but there are locations where cosmogenic studies could be conducted.

Another disadvantage is that the cosmogenic methods are still under development. For instance, there are disagreements regarding production rates. Differing calibrations were reported for ^{36}Cl (Zreda and others, 1991; Swanson and others, 1993; Zreda, 1994) and ^{3}He (Kurz and others, 1990; Brook and others, 1993; Cerling and Craig, 1994). It is likely that they reflect problems with scaling factors for elevation and latitude or inaccurate independent age estimates. Such problems should be solved in the near future.

Sample preparation for some nuclides is very involved and includes separation of suitable minerals. The analyses are routine, but can only be done at specialized facilities, at limited times. In consequence, a typical turn around time is on the order of months. The overall cost is relatively high; sample preparation costs are about $500 and the spectrometric analyses are about $500 per sample; these costs vary among the nuclides.

REFERENCES

Albrecht, A., Herzog, G. F., Klein, J., Dezfouly-Arjomandy, B., and Goff, F., 1993, Quaternary erosion and cosmic-ray-exposure history derived from ^{10}Be and ^{26}Al produced in situ, An example from Pajarito plateau, Valles caldera region: Geology, v. 21, 551-554.

Andrews, . N., Fontes, J.-Ch., Michelot, J.-L., and Elmore, D. 1986, In situ neutron flux, ^{36}Cl production and groundwater evolution in crystalline rocks at Stripa, Sweden: Earth and Planetary Science Letters, v. 77, 49-58.

Andrews, J. N., Davis, S. N. Fabryka-Martin, J. Fontes, J.-Ch. Lehman , B. E. Loosli, H. H., Michelot, J.-L. Moser, H., Smith, B., and Wolf, M., 1989, The in situ production of radioisotopes in rock matrices with particular reference to the Stripa Granite: Geochimica et Cosmochimica Acta, v. 53, 1803-1815.

Bentley, H. W., Phillips, F. M., and Davis, S. N., 1986, Chlorine-36 in the terrestrial environment: in Fritz , P., Fontes, J. Ch., eds., Handbook of Environmental Isotope Geochemistry, v. 2, The Terrestrial Environment, B, Elsevier, New York, p. 427-480.

Brook, E. J., and Kurz, M. D., 1993, Surface-exposure chronology using in situ cosmogenic ^{3}He in Antarctic quartz sandstone boulders: Quaternary Research, v. 39, p. 1-10.

Bierman, P., and Gillespie, A., 1991, Range fires: a significant factor in exposure-age determination and geomorphic surface evolution: Geology 19, p. 641-644.

Brown, E., Edmond, J. M., Raisbeck, G. M., Yiou, F., Kurz, M., and Brook, E. J., 1991, Examination of surface exposure ages of Antarctic moraines using in situ produced 10-Be and 26-Al: Geochimica et Cosmochimica Acta, v. 55, p. 2269-2284.

Cerling, T. E., and Craig, H., 1994, Cosmogenic ^{3}He production rates from 39°N to 46°N latitude, western USA and France: Geochimica et Cosmochimica Acta 58, 249-255.

Conversi, M., 1950, Experiments on cosmic-ray mesons and protons at several altitudes and latitudes: Physics Reviews, v. 79, p. 749-767.

Craig, H., and Poreda, R., 1986, Cosmogenic ^{3}He in terrestrial rocks: the summit lavas of Maui: Proceedings of the National Academy of Science, USA, v. 83, p. 1970-1974.

Davis Jr., R., and Schaeffer, O. A., 1955, Chlorine-36 in nature: Annals of New York Academy of Science, v. 62, p. 105-122.

Dep, L., Elmore, D., Fabryka-Martin, J., Masarik, J., and Reedy, R. C., 1994a, Production rate systematics of in-situ produced cosmogenic nuclides in terrestrial rocks: Monte Carlo approach of investigating ^{35}Cl(n,p)^{36}Cl: Nuclear Instruments and Methods in Physics Research, v. B92, p. 321-325.

Dep, L., Elmore, D., Sharma, P., Bourgeois, M., Lipschutz, M. E., Vogt, S., and Phillips, F. M., 1994b, Depth profiles of in-situ produced cosmogenic ^{10}Be, ^{26}Al and ^{36}Cl in an erratic boulder from a Bishop Creek moraine, Sierra Nevada, CA, American Geophysical Union 1994 Fall Meeting: Program & Abstracts, EOS, v. 75 (44) Supplement.

Dep, L., Elmore, D., Sharma, P., Bourgeois, M., Lipschutz, M. E., Vogt, S., and Phillips, F.M., 1994c, Depth dependence of cosmogenic neutron-capture-produced ^{36}Cl in a terrestrial rock: Nuclear Instruments and Methods in Physics Research, v. B92, p. 301-307.

Elmore, D., Fulton, B. R., Clover, M. R., Marsden, J. R., Gove, H. E., Naylor, H., Purser, K. H., Kilius, L. R., Beukins, R. P., and Litherland, A. E., 1979, Analysis of 36Cl in environmental water samples using an electrostatic accelerator: Nature, v. 277, p. 22-25.

Elmore, D., and Phillips, F. M., 1987, Accelerator mass spectrometry for measurement of long-lived radioisotopes: Science, v. 236, p. 543-550.

Fabryka-Martin, J. T., 1988, Production of Radionuclides in the Earth and Their Hydrogeologic Significance, With Emphasis on Chlorine-36 and Iodine-129: Ph.D. dissertation, University of

Arizona, University Microfilms, Ann Arbor.

Fabryka-Martin, J. F., Fowler, M. M., and Biddle, R., 1991, Study of neutron fluxes underground: Isotope and Nuclear Chemistry Division Quarterly Report October 1-December 31, 1990, p. 82-85.

Feige, Y., Oltman, B. G., and Kastner, J., 1968, Production rates of neutrons in solids due to natural radioactivity: Journal of Geophysical Research, v. 73, p. 3135-3142.

Hendricks, L. D., and Edge, R. D., 1966, Cosmic-ray Neutrons Near the Earth: Physics Reviews, v. 145, p. 1023-1025.

Jha, R., and Lal, D., 1982, On cosmic ray produced isotopes in surface rocks: in Natural Radiation Environment, K. G., Vohra, K. G., and others, eds., Proceedings of Second Special Symposium on Natural Radiation Environment, Halsted Press, p. 629-635.

Jull, A.T., Wilson, A. E., Burr, G. S., Toolin, L. J., and Donahue, D. J., 1992, Measurements of cosmogenic ^{14}C produced by spallation in high-altitude rocks: Radiocarbon, v. 34, p. 737-744.

Jull, A.J.T., Lifton, N., Phillips, W.M., and Quade, J., 1994, Studies of the production rate of cosmic-ray produced ^{14}C in rock surfaces: Nuclear Instruments and Methods in Physics Research, v. B92, p. 308-310.

Klein, J., Middleton, R., and Tang, H., 1982, Modifications of an FN tandem for quantitative ^{10}Be measurement: Nuclear Instruments and Methods in Physics Research, v. 193, p. 601-616.

Kohl, C. P., and Nishiizumi, K., 1992, Chemical isolation of quartz for measurement of in situ-produced cosmogenic nuclides: Geochimica et Cosmochimica Acta, v. 56, p. 3583-3587.

Kubik, P. W., Korschinek, G., Nolte, E., Ratzinger, U., Ernst, H., Teichmann, S., and Morinaga, H., 1984, Accelerator mass spectrometry of ^{36}Cl in limestone and some paleontological samples using completely stripped ions: Nuclear Instruments and Methods in Physics Research, v. B5, p. 326-330.

Kuhn, M. W., Davis, S. N., Bentley, H. W., and Zito, R., 1984, Measurements of thermal neutrons in the subsurface: Geophysical Research Letters, v. 11, p. 607-610.

Kurz, M. D., Gurney, J. J., Jenkins, W. J., and Lott, D. E., 1987, Helium isotope variability within single diamonds from the Orapa kimberlite pipe: Earth and Planetary Science Letters, v. 86, p. 57-68.

Kurz, M., 1986, Cosmogenic helium in a terrestrial igneous rock: Nature, v. 320, 435-439.

Kurz, M., Colodner, D., Trull, T. W., Moore, R. B., and O'Brien, K., 1990, Cosmic ray exposure dating with in situ produced cosmogenic ^{3}He: results from young Hawaiian lava flows: Earth and Planetary Science Letters, v. 97, p. 177-189.

Lal, D., 1987, Cosmogenic nuclides produced in situ in terrestrial solids: Nuclear Instruments and Methods in Physics Research, v. B29, p. 238-245.

Lal, D., 1991, Cosmic ray labelling of erosion surfaces: in situ production rates and erosion models: Earth and Planetary Science Letters, v. 104, p. 424-439.

Lal, D., and Peters, B., 1967, Cosmic ray produced radioactivity on Earth: in Fluegge, S., and Sitte, K., eds., Encyclopedia of Physics, Cosmic Rays II, Springer-Verlag, Berlin, v. 46/2, p. 551-612.

Leavy, B. D., 1987, Surface-exposure Dating of Young Volcanic Rocks Using the in situ Buildup of Cosmogenic Isotopes: Unpublished Ph.D. dissertation, Geoscience Department, New Mexico Institute of Mining and Technology.

Liu, B., Phillips, F. M., Fabryka-Martin, J. T., Fowler, M. M., and Biddle, R. S., 1994, Cosmogenic ^{36}Cl accumulation in unstable landforms: I. Effects of the thermal neutron distribution: Water Resources Research, v. 30, p. 3115-3125.

Mazaud, A., Laj, C., Bard, E., Arnold, M., and Tric, E., 1991, Geomagnetic field control of ^{14}C production over the last 80 ky: implications for the radiocarbon time-scale: Geophysical Research Letters, v. 18, p. 1885-1888.

Middleton, R., Klein, J., Raisbeck, G. M., and Yiou, F., 1983, Accelerator mass spectrometry with ^{26}Al: Nuclear Instruments and Methods in Physics Research, v. 218, p. 430-438.

Montgomery, C. G., and Montgomery, D. D., 1939, The intensity of neutrons of thermal energy in the atmosphere at sea level: Physics Reviews, v. 56, p. 10-12.

Mughaghab, S. F., and Garber, D. I, 1973, Neutron Cross Sections, v. 1, Resonance Parameters, Brookhaven National Laboratory.

Nishiizumi, K., Lal, D., Klein, J., Middleton, R., and Arnold, J. R., 1986, Production of ^{10}Be and ^{26}Al by cosmic rays in terrestrial quartz in situ and implications for erosion rates: Nature, v. 319, p. 134-136.

Nishiizumi, K., Winterer, E. L., Kohl, C.P., Klein, J., Middleton, R., Lal, D., and Arnold, J.R., 1989, Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks: Journal of Geophysical Research, v. 94, p. 17,907-17,915.

Nishiizumi, K., Kohl, C. P., Arnold, J. R., Klein, J., Fink, D., Middleton, R., 1991a, Cosmic ray produced 10Be and 26Al in Antarctic rocks: exposure and erosion history: Earth and Planetary Science Letters, v. 104, p. 440-454.

Nishiizumi, K., Kohl, C. P., Shoemaker, E. M., Arnold, J. R., Klein, J., Fink, D., and Middleton, R., 1991b, ^{10}Be-^{26}Al Exposure ages at Meteor Crater, Arizona: Geochimica et Cosmochimica Acta, v. 55, p. 2699-2703.

Nishiizumi, K., Kohl, C. P., Arnold, J. R., Dorn, R., Klein, J., Fink, D., Middleton, R., and Lal, D., 1993, Role of in situ cosmogenic nuclides ^{10}Be and ^{26}Al in the study of diverse geomorphic processes: Earth Surface Processes and Landforms, v. 18, p. 407-425.

O'Brien, K., Sandmeier, H. A., Hansen, G. E., and Campbell, J. E., 1978, Cosmic ray induced neutron background sources and fluxes for geometries of air over water, ground, iron, and aluminum: Journal of Geophysical Research, v. 83, p. 114-120.

Phillips, F. M., Leavy, B. D., Jannik, N. D., Elmore, D., and Kubik, P. W., 1986, The accumulation of cosmogenic chlorine-36 in rocks: A method for surface exposure dating: Science, v. 231, p. 41-43.

Phillips, F. M., Zreda, M. G., Smith, S. S., Elmore, D., Kubik, P. W., Dorn, R. I., and Roddy, D. J., 1991, Age and geomorphic history of Meteor Crater, Arizona, from cosmogenic ^{36}Cl and ^{14}C in varnish: Geochimica et Cosmochimica Acta, v. 55, p. 2695-2698.

Phillips, F. M., Zreda, M. G., and Elmore, D., 1993, A recalibration of cosmogenic chlorine-36 production rates using lava-flow samples from the western Snake River Plain volcanic field: Geological Society of America Annual Meeting Abstract A-373.

Phillips, F. M., Zreda, M. G., Elmore, D., and Sharma, P., 1996, A reevaluation of comogenic ^{36}Cl production rates in terrestrial rocks: Geophysical Research Letters (in press).

Poreda, R. J., and Cerling, T. E. 1992, Cosmogenic neon in recent lavas from the western United States: Geophysical Research Letters, v. 19, p. 1863-1866.

Raisbeck, G. M., and Yiou, F., 1984, Production of long-lived cosmogenic nuclei and their applications: Nuclear Instruments and Methods in Physics Research, v. 233 (B5), p. 91-99.

Rama and Honda, M., 1961, Cosmic-ray-induced radioactivity in terrestrial materials: Journalä of Geophysical Research, v. 66, p. 3533-3539.

Rossi, B., 1952, High Energy Particles: Prentice Hall, New Jersey, 569 p.

Simpson, J. A., 1951, Neutrons produced in the atmosphere by the cosmic radiations: Physics Reviews, v. 83, p. 1175-1188.

Staudacher, T., and Allègre, C. J., 1993, The cosmic ray produced $^{3}He/^{21}Ne$ ratio in ultramafic rocks: Geophysical Research Letters, v. 20, p. 1075-1078.

Stuiver, M., Pearson, G. W., and Braziunas, T., 1986, Radiocarbon age calibration of marine samples back to 9000 cal yr B.P.: Radiocarbon, v. 28, p. 980-1021.

Sutton, S. R., 1985, Thermoluminescence measurements on shock-metamorphosed sandstone and dolomite from Meteor Crater, Arizona: 2. Thermoluminescence age of Meteor Crater: Journal of Geophysical Research, v. 90, p. 3690-3700.

Swanson, T. W., Caffee, M., Finkel, R., Harris, L., Seven, G., Zreda, M. G., and Phillips, F. M., 1993, Establishment of new production parameters for chlorine-36 dating based on the deglaciation history of Whidbey Island, Washington: Geological Society of America Abstracts with Programs, p. A-461.

Trull, T. W., Kurz, M. D., and Jenkins, W. J., 1991, Diffusion of cosmogenic ^{3}He in olivine and quartz: implications for surface exposure dating: Earth and Planetary Science Letters, v. 103, p. 241-256.

Yamashita, M., Stephens, L. D., and Patterson, H. W., 1966, Cosmic-ray-produced neutronsä at ground level: Neutron production rate and flux distribution: Journal of Geophysical Research, v. 71, p. 3817-3834.

Yiou, F., Raisbeck, G. M., Bourles, D., Lorius, C., and Barkow, N. I. 1985, 10Be in ice at Vostok, Antarctica during the last climate cycle: Nature, v. 316, p. 616-617.

Yokoyama, Y., Reyss, J.-L., and Guichard, F., 1977, Production of radionuclides by cosmic rays at mountain altitudes: Earth and Planetary Science Letters, v. 36, p. 44-50.

Zreda, M. G., 1994, Development of the Cosmogenic ^{36}Cl Surface Exposure Dating Method and its Application to the Chronology of Late Quaternary Glaciations: Unpublished Ph.D. dissertation, Geoscience Department, New Mexico Tech.

Zreda, M. G., and Elmore, D., 1995, Dating paleoseismic events at Crater Flat, Nevada by cosmogenic ^{36}Cl accumulation in ash deposited in ground fractures: American Chemical Society - Accelerator Mass Spectrometry Symposium, Anaheim.

Zreda, M.G., and Noller, J. S., 1998, Ages of prehistoric earthquakes revealed by cosmogenic chlorine-36 in a bedrock fault scarp at Hebgen Lake: Science, v. 282, p. 1097-1099.

Zreda, M. G., and Phillips, F. M., 1994, Surface exposure dating by cosmogenic chlorine-36 accumulation: in Beck, C., ed., Dating in Exposed and Surface Contexts, University of New Mexico Press, p. 161-183.

Zreda, M. G., Phillips F. M., and Smith, S. S., 1990, Cosmogenic 36Cl Dating of Geomorphic Surfaces: Hydrology Program Report 90-1, New Mexico Tech.

Zreda, M. G., Phillips, F. M., Elmore, D. Kubik, P. W., Sharma, P., and Dorn, R. I.,, 1991, Cosmogenic ^{36}Cl production rates in terrestrial rocks: Earth and Planetary Science Letters, v. 105, p. 94-109.

Zreda, M. G., Phillips, F. M., Kubik, P. W., Sharma, P., and Elmore, D., 1993, Eruption age at Lathrop Wells, Nevada from cosmogenic chlorine-36 accumulation: Geology, v. 21, p. 57-60.

Zreda, M. G., Phillips, F. M., and Elmore, D., 1994, Cosmogenic 35Cl accumulation in unstable landforms 2, simulations and measurements on eroding moraines: Water Resources Research, v. 30, p. 3127-3136.

Zreda, M. G., Phillips, F. M., Kubik, P. W., Sharma, P., and Elmore, D., 1995a, Glacial chronology of the eastern White Mountains, California-Nevada by the cosmogenic ^{36}Cl method: in revision for Quaternary Research.

Zreda, M. G., Noller, J. S., Lettis, W. R., 1995b, Dating of late Quaternary bedrock fault scarp at Hebgen Lake, Montana using cosmogenic chlorine-36: American Geophysical Union 1995 Fall Meeting, EOS 76 Supplement.

Zreda, M. G., Noller, J. S., Lettis, W. R., 1996, Cosmogenic dating of fault faces - a new tool for paleoseismology: Goldschmidt Conference, Heidelberg, April 1996.