SURFACE EXPOSURE DATING: REVIEW AND CRITICAL EVALUATION

Ronald I. Dorn
Geography Department
Arizona State University
Tempe, Arizona 85287

Fred M. Phillips
Geoscience Department
New Mexico Tech
Socorro, New Mexico 87801

Abstract: The past decade has seen the development and application of over a dozen new methods for quantitative age-determinations of geomorphic surfaces. Some surface exposure dating methods are numerical, including the accumulation of cosmogenic radionuclides ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, and ^{41}Ca, accumulation of cosmogenic stable nuclides ^{3}He and ^{21}Ne, ^{14}C dating of organic matter encapsulated in rock coatings, and dendrogeomorphology. Calendar ages are obtained by dendrogeomorphological analysis. Calibrated ages can be obtained by analysis of rock-varnish chemistry, lichenometry, weathering, and soils. Various methods can be used in combination to overcome individual limitations. Whereas conventional methods provide age control on stratigraphic profiles, surface-exposure dating methods are especially suitable for geographic problems, such as analyzing not only temporal, but also spatial variations in the rates of geomorphic processes. [*Key words*: geomorphology, process, geochronology, cosmogenic nuclides, Quaternary, surface exposure dating, rock varnish, weathering, soils.]

INTRODUCTION

A substantial proportion of the earth's land surface changes at rates too slow to detect by studies conducted during the lifetime of a single investigator. In these circumstances, dating of older landforms is necessary to estimate long-term rates of geomorphic processes. At present the vast majority of quantitative age control on landforms is from datable material in a stratigraphic sequence, such as K-Ar dating of lava flows and ^{14}C dating of charcoal intercalated with deposits.

There are circumstances where deposits amenable to dating are found at or near the surface and constrain the ages of landforms. K-Ar dated lava flows have provided extremely valuable data (Naeser, 1971; Lucchitta, 1975, 1984; Dohrenwend et al., 1984, 1986), as have organic deposits (e.g., Benson and Thompson, 1987) to the ~40 ka limit of the radiocarbon method. Other stratigraphic age-determination techniques are increasingly being used: fission-track, amino acid racemization, uranium-series, stable isotopes, electron spin resonance, thermoluminescence, paleomagnetism, and others (Easterbrook, 1988; Rutter et al.,

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1989). Where available, these stratigraphic dating methods have provided insights into the timescales of geomorphic processes. However, suitable material for stratigraphic dating is lacking for the vast majority of the earth's surface. Furthermore, stratigraphic age control is not possible for erosional landforms.

The quantitative study of landscape development has been empirically and theoretically handicapped by relying on stratigraphic ages that are spatially disjunct and provide minimal insight into changes in landform patterns over time. Landscapes are inherently spatial entities; despite this many geomorphologists have been trained to think in terms of stratigraphic columns.

During the past decade, there has been a tremendous expansion in the number of alternative dating methods available to those interested in quantitatively reconstructing rates of landform change over time. These *surface exposure dating* (SED) methods assess how long the surface of a landform has been exposed to the subaerial environment. SED techniques can be divided into form, relative position, weathering, soils, rock coatings, growth of biota, accumulation of cosmogenic nuclides in rocks, and stratigraphic methods (Table 1). SED methods are also grouped into different types of dating results (cf. Colman et al., 1987): numerical; calibrated; relative; and correlated (Table 2).

SED methods offer a complement to stratigraphic (vertical) dating techniques, by constraining the age of a surface. SED techniques allow ages to be assessed as a function of location, instead of just vertically. SED methods also permit sequences of landform development to be placed within the context of dated paleoenvironmental reconstructions (using data from pollen, macrofossils, stable isotopes, soils, paleohydrology, etc.), that in turn place constraints on the processes that could reasonably operate to produce an evolving landscape.

The purpose of this paper is to review trends in surface exposure dating techniques, and to explore the limitations and advantages of the different approaches.

REVIEW OF SURFACE EXPOSURE DATING METHODS

Relative Position and Form

The starting place for any geomorphic study is mapping the position of deposits and erosional features (Table 1). We believe that cross-cutting landforms provide the most unequivocal relative age sequences. Relative positions should be used as benchmarks to test new techniques. It is sometimes possible, however, for the most experienced field observers to misjudge the importance of morphostratigraphic juxtapositions. Gilbert (1890), for example, felt the Stansbury shoreline of Lake Bonneville was cut during a regression, instead of the transgressive feature recognized today (Oviatt et al., 1990).

An intuitively acceptable tool used by many is the general shape of a landform (Coates, 1984). An implicit assumption of many glacial geomorphology studies, for example, is that moraine crests are sharp when young and gradually round in cross-profile with time. This assumption, however, has not yet been tested. Similarly, desert geomorphologists consider rounded ballenas to be remnants of alluvial

Table 1. Surface Exposure Dating Methods

Methods	Examples of use
1. Relative position	Glacial moraines (Gibbons et al., 1984)
	Intermontane basins (Gile et al., 1981)
	Cliff retreat (Gerson, 1982)
2. Form	Fault scarps (Bucknam and Anderson, 1979)
	Alluvial fans (Hunt and Mabey, 1966)
	Surface roughness (Gaddis et al., 1990)
	Abandoned seacliffs (Orme, 1962; 1966).
3. Weathering	
A. Minerals	Hornblende (Hall and Martin, 1986)
	Quartz (Pope, 1991)
B. Whole rock	Rinds (Colman and Pierce, 1981)
	Seismic waves (Crook, 1986)
	Obsidian (Pierce et al., 1976)
	Post-depositional modifications (Kiernan, 1990)
4. Soils	Individual properties (Birkeland, 1984; Mahaney, 1990)
	Indices (Switzer et al., 1988)
	Catena (Birkeland and Burke 1988)
	Meteoric ^{10}Be (Pavich et al., 1986)
	U-series $CaCO_3$ (Ku et al., 1979)
	^{14}C $CaCO_3$ (Chen and Polach, 1986)
	$CaCO_3$ accumulation models (Marion, 1989)
	Uranium-trend (Muhs et al., 1989)
5. Rock Coatings	
A. Calcium carbonate coatings (Turner, 1977; Dragovich, 1986)	
B. Rock pigment (Loy et al., 1990)	
C. Oxalate-rich crusts (Watchman, 1991)	
D. Silica skins (Curtiss et al., 1985; Watchman, 1990)	
E. Rock varnish	^{14}C organic matter (Dorn et al., 1989)
	Cation-ratios (Dorn, 1989)
	Uranium-series (Knauss and Ku, 1980)
	Microstratigraphic, sequences (Dorn, 1988)
	Transition metal concentration (Dorn et al., 1992)
	Trace element trends (Bard, 1979)
	Paleomagnetism (Clayton et al., 1990)
	Tephrachronology (Harrington, 1990)
	Carbonate formation over varnish (Dragovich, 1986)
	Percent cover black varnish (Derbyshire et al., 1984)
	Clasts covered with orange bottom varnish (McFadden et al., 1989)
6. Growth of biota	Lichenometry (Mahaney, 1990)
	Dendrogeomorphology (Shroder and Butler, 1987)

(continued on next page)

Table 1. (continued) Surface Exposure Dating Methods

Methods	Examples of use
7. Cosmogenic isotopes	^{3}He (Kurz et al, 1990; Cerling, 1990)
	^{21}Ne (Graf et al., 1991)
	^{10}Be and ^{26}Al (Nishiizumi et al., 1989)
	^{14}C (Jull et al., 1989; Lal et al., 1990)
	^{36}Cl (Phillips et al., 1990; Zreda et al., in press)
	^{41}Ca (Klein et al., 1990)
8. Stratigraphic dating methods that can be used to date surfaces	
A. Uranium series	Tufa (Lao and Benson, 1988)
	Corals (Bloom et al., 1974)
B. K-Ar	(Dohrenwend et al., 1984; Lucchitta, 1984).

deposits where the original surface has eroded. These and other models of morphological evolution (Table 1) are often reasonable, but in places they can be misleading. We do not consider form to be as clear an age indicator as relative position. In both Ireland and California, for example, abandoned seacliffs of distinctive form are often associated with marine terrace deposits of known Quaternary age so that, where the latter have been removed by erosion, the form and relative position of bevelled and truncated seacliffs allow former shorelines to be placed in a sequence of coastal development (Orme, 1962, 1966).

Weathering and Soils

Weathering has long been viewed as a viable relative dating indicator, but it has taken on a new vigor in recent years. Colman and Pierce (1981), Chin (1981), Knuepfer (1988) and others have calibrated the development of lithology-specific weathering rinds. Alterations of hornblende (Hall and Martin, 1986), quartz (Ericson et al., 1986; Pope, 1990), and other minerals (Yatsu, 1988) may be calibrated by established numerical ages. Regolith dating, in the southeastern United States (Pavich, 1985) and Australia (Idnum and Senior, 1978; Gulson et al., 1986; Bird and Chivas, 1988) is also making great strides.

Soils have long been used to assign relative ages to landforms (e.g., Birkeland, 1984). More recently, soil indices have been used to assign calibrated ages (e.g., Switzer et al., 1988; Harden and Matti, 1989). The accumulation of $CaCO_3$ in soil profiles have also been calibrated (Machette, 1985). However, these efforts are based on the isolation of chronosequences. Not only is it extremely difficult to control all of Jenny's (1941) soil-forming factors (McFadden, 1988), but current models of soil genesis are under fire (Johnson and Watson-Stegner, 1987; Johnson et al., 1990; Johnson, 1990). Clearly, many of the assumptions involved in soil dating require rethinking.

Uranium-series dating of soil carbonate rinds (Ku et al., 1979), by accumulation of organic matter in carbonate rinds (Chen and Polach, 1986), by uranium-trend

Table 2. Surface Exposure Dating (SED) Methods, Organized by the Quaternary Dating Terminology of Colman et al. (1987).

Numerical ages	Calibrated ages	Relative ages	Correlated ages
Accumulation cosmogenic radionuclides (^{36}Cl, ^{26}Al, ^{10}Be, ^{14}C, ^{129}I, ^{41}Ca)	Ratio of mobile to immobile cations in rock varnish	Morphology Relative position	Fluctuations in stable isotopes and Mn:Fe ratios in rock varnish
	Harden soils index	Seismic waves in granite rock	Oxygen isotopes in regolith
Accumulation of cosmogenic stable nuclides (^{3}He, ^{21}Ne)	Accumulation of $CaCO_3$ in soils Weathering rinds	Individual soil properties (e.g., Fe-oxide, clay accumulation)	Identification of tephra encapsulated in rock varnish
^{14}C dating of organic matter in rock coatings	Weathering of minerals (e.g., hornblende, quartz)	"PDM" methods: pit depth, pitting ratios, hammer blow, surface boulder frequency, grussification	Paleomagnetic variations in rock varnish layers
^{14}C dating of organic matter in carbonate rinds	Lichenometry		
Uranium-series dating of rock varnish, soils carbonate		Cosmogenic isotopes in soils	
Dendrogeomorphology		Percent cover of varnish on rocks	

dating (Muhs et al., 1989), and by meteoric ^{10}Be (Pavich et al., 1986; Monaghan et al., 1990) are promising methods for providing numerical ages for soils.

Growth of Biota

The pioneering work of Beschel (1950) established that the maximum diameter of the largest lichen thallus on a surface is proportional to time since colonization (approximating post-depositional time). If numerical age control can be obtained in an area, it may be possible to calibrate the growth rate of lichens. Objections to the method include complications arising from climatic change, ecological factors, erratic behavior of lichen growth, and difficulty in lichen identification and measurement. Lichenometry has been used to assign relative and calibrated-ages for Holocene deposits in arctic and alpine environments (Benedict, 1967; Porter, 1981; Gellatly, 1982; Winchester, 1984; Mahaney, 1990).

Dendrogeomorphology was developed into a workable and systematic methodology by Shroder (1980) and students (Giardino et al., 1984; Shroder and Butler, 1987). Tree-ring dating is now used in a wide variety of geomorphic problems, including fluvial, periglacial, glacial, hillslope, volcanic, and paleoseismic concerns. Dendrogeomorphology provides the most reliable and precise minimum-age estimates for landforms, short of historic photographic evidence. However, in most regions it is useful over a time span of at most a few thousand years.

Rock Coatings

As in lichens and trees, the time-clock for rock coatings starts when initial colonization takes place. This can be quite rapid in certain microenvironments and yet take thousands of years in other places (cf. Dorn, 1989). Most of the current effort in dating rock coatings has concentrated on accelerator mass spectrometry (AMS) radiocarbon dating of organic matter encapsulated by rock varnish (Dorn et al., 1992), silica skins (Watchman, 1985; Dorn et al., 1991), and rock pigment (Loy et al., 1990). AMS ^{14}C dating has also been tried on calcium carbonate rock coatings (Turner, 1977; Dragovich, 1986) and oxalate-rich crusts (Watchman, 1991).

In all cases, these methods assume that radiocarbon dates provide minimum ages for the surface exposure of the underlying landform. While it is hypothetically possible that older organic matter was either trapped or encapsulated in the coatings, the most reasonable model is that the source of the organic matter was the adjacent vegetation matter. This has been tested for rock varnish (Dorn and DeNiro, 1985), where radiocarbon dates on organic matter in rock varnish are consistently younger than control ages (Dorn et al., 1992)

Rock varnish may also be evaluated by calibrating the decrease in the 'cation ratio' (Ca+K)/Ti using independent established numerical ages (Dorn, 1983, 1989; Glazovskiy, 1985; Harrington and Whitney, 1987; Jacobson, 1989; Pineda et al., 1988, 1990; Zhang et al., 1990). It is beyond the scope of this review to comment on new criticisms of the cation-ratio method, but most of these critiques are due to different investigators sampling different types of rock varnishes. Uranium-series dating of varnish holds great promise (Knauss and Ku, 1980). Sequences of stable isotopes (Dorn and DeNiro, 1985), micromorphologies (Dorn, 1986), and microchemical laminations (Dorn, 1990; Jones, 1991) may allow cross-correlation between landforms in an area that has experienced relatively uniform paleoenvironmental fluctuations. Relative ages can also be obtained by the concentration of transition metals (Dorn et al., 1992), percent of black varnish cover on rocks (Derbyshire et al., 1984), percent of orange varnish on the underside of rocks (McFadden et al., 1989). Additional experimental rock-varnish dating methods include paleomagnetism (Clayton et al., 1990), tephrachronology (Harrington, 1988), and K-Ar dating of varnish Mn-Oxides (Becker et al., 1991).

Cosmogenic Isotopes

The newest and most powerful SED techniques are based on the *in situ* build-up of cosmogenic nuclides in rocks exposed at the earth's surface. Several earth-science applications for the accumulation of cosmogenic isotopes were predicted by Lal and Peters (1962, 1967), but it was not until the advent of accelerator mass spectrometry (AMS) that routine measurement of terrestrial cosmogenic nuclides became feasible (Elmore and Phillips, 1987). Cosmogenic radionuclides such as ^{36}Cl (Phillips et al., 1986, 1990; Zreda et al., 1990), ^{10}Be and ^{26}Al (Nishiizumi et al., 1986, 1989), ^{14}C (Jull et al., 1989; Lal et al., 1990), ^{41}Ca (Klein et al., 1990), and others (Lal, 1988) are measured by AMS. Stable cosmogenic isotopes like ^{3}He (Kurz, 1986a,b; Lal, 1987; Kurz et al., 1990; Cerling, 1990) and ^{21}Ne (Graf et al., 1991) can be measured by conventional (but difficult) mass spectrometry.

These nuclides build up in rocks due to the interactions of cosmic rays with atoms in minerals by high-energy spallation, neutron-capture reactions and muon-induced nuclear disintegrations (Lal, 1988). The rate of accumulation is dependent on factors that can be measured (altitude, geomagnetic latitude, rock chemistry, geometry of exposure to cosmic rays), on time, and on the cosmic ray flux. The cosmic ray flux does vary with time (e.g., radiocarbon production; Stuiver et al., 1986), but *in situ* isotopes reflect the long-term average, integrating short-term fluctuations.

For stable isotopes such as ^{3}He, exposure time to cosmic rays is assessed assuming a linear accumulation with time. For radionuclides, it must include the effects of both build-up and decay. Zreda et al. (1991) outline the build-up equation for cosmogenic ^{36}Cl accumulated in a given sample after t years of exposure to cosmic rays and with negligible erosion. This is expressed as:

$$R-R_o = \frac{E_n\, L_n\, D_n\, (\psi_K\, C_K + \psi_{Ca} C_{Ca} + \Psi_n) + E_\mu - L_\mu - \Psi_\mu -}{\lambda\, N} (1-e^{-\lambda t}) \qquad (1)$$

where:

R— atomic ratio of ^{36}Cl to stable Cl;

R_o— background of ^{36}Cl/Cl ratio supported by U and Th derived neutrons;

ψ_K, ψ_{Ca}— production rates due to spallation of ^{39}K and ^{40}Ca, respectively in atoms per kg of rock per year per unit concentration of K or Ca.

C_K, C_{Ca}— concentration of K or Ca;

Ψ_n— production due to thermal neutron activation of ^{35}Cl, in atoms per kg of rock per year;

Ψ_μ— production due to negative muon capture by ^{40}Ca, in atoms per kg of rock per year;

E,L,D— correction factors for elevation above sea level (E), geographical longitude and latitude (L), and depth below surface (D), for distribution of neutrons (n) and muons (μ), respectively;

t— time of exposure, in years;

N— stable Cl concentration, in atoms per kg of rock;
λ— decay constant for ^{36}Cl ($2.30 * 10^{-6}$ per year).

The build-up curve is steep (Fig. 1), so radionuclides can be detected after only a few thousand years. 'Saturation' is reached for radionuclides after about 4 times the half life. So saturation for ^{36}Cl (with a 1/2-life of 300,000 years) is reached after about 1 Myr, ^{26}Al (1/2-life 710,000 years) after about 2-1/2 Myr, ^{10}Be (1/2-life 1.6 myr) after about 5-6 Myr, and ^{14}C after about 20,000 years. The effective dating limits of the *in situ* radionuclides are from a few thousand years to several millions of years. For samples less than 10 ka, ^{3}He and ^{14}C are best (Jull et al., 1989; Kurz et al., 1990). For samples greater than 10 ka, the time range is a function of when saturation occurs.

EVALUATION OF SURFACE EXPOSURE DATING METHODS

Levels in Sampling

The first step in developing a strategy for surface exposure dating is to assess the scope of the problem in different levels in sampling.

Level 1. Before-sampling assessments. Before sampling, the focus of the study needs to be defined. If the project revolves around the nature and rate of weathering, methods sensitive to weathering of surfaces (e.g., rock coatings and weathering rinds) would be sampled along with less sensitive indicators (cosmogenic isotopes) in a different fashion than if the project was to assess landform evolution. Styles of rock weathering, weathering processes, and rates of surface degradation are critical issues in SED techniques. Quantitative data on these issues are desperately needed. However, the rest of this discussion will revolve around the assumption that the project is to assess the chronology of landform development, rather than rates of weathering.

If numerical age information is needed, if dendrogeomorphological techniques are inappropriate due to time-scale or biotic environment, and after the morphostratigraphic relationships are well understood, the new SED methods of dating rock coatings and cosmogenic isotopes should be considered. The rest of this discussion will focus on these circumstances.

Level 2. Iterative sampling. In using all SED methods, an iterative sampling procedure is the best approach. The current approach used by those applying new cosmogenic isotope and new rock coating SED methods is to sample the 'best preserved' surfaces from the largest boulders. This is a subjective process that involves avoiding such situations as fire spalling and places where the geometry of boulders may change. Experiments are ongoing on sampling the best and worst places for sampling in order to determine the end members (cf. Phillips et al., in preparation; Dorn, 1989; Krinsley et al., 1990; P. Kubik, personal communication). After an initial set of samples are taken and analyzed, second and third rounds of collection will help resolve issues of rock weathering and geometry changes. It

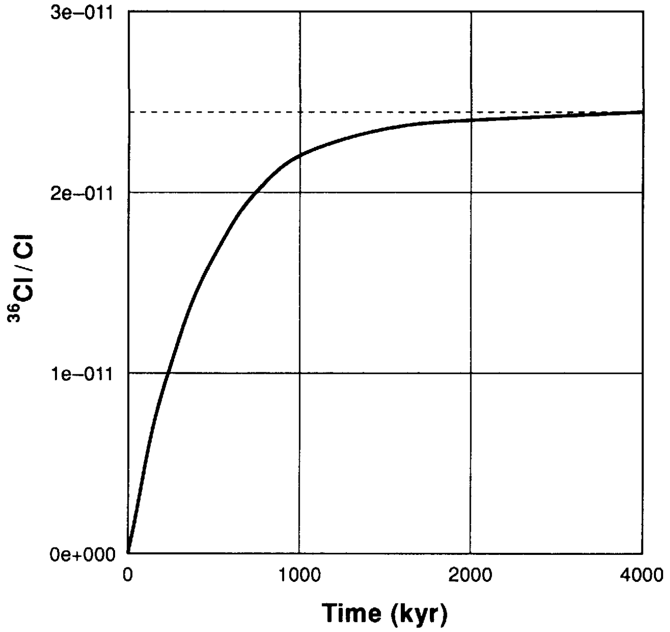


Fig. 1. Calculated ^{36}Cl buildup with time in a hawaiite lava exposed at 3,500 m elevation on Mauna Kea. The dashed line is ^{36}Cl/Cl ratio in secular equilibrium with the cosmic ray flux.

may also be advantageous to use low-cost methods like varnish cation-ratios to screen which samples would be best for the more expensive cosmogenic dating methods.

Level 3. Weighing advantages and disadvantages of different methods. Within the cosmogenic isotopes, there are methods that have different advantages. ^{10}Be and ^{26}Al extraction from quartz (Nishiizumi et al., 1989) requires time-consuming preparation, but paired isotopes with different half-lives from the same material yield additional information on exposure histories of rocks. By using more isotopes with widely varying half-lives, the most information on rates of rock-surface erosion and landform history can be gained (Lal, 1991).

A single radionuclide such as ^{36}Cl, extracted from whole rocks (Phillips et al., 1990; Zreda et al., 1991) is much easier to prepare than ^{10}Be and ^{26}Al, and would be most appropriate where many measurements are needed, where a prior exposure history is unlikely, and where rock-surface erosion is minimal.

Stable nuclides such as ^{3}He (Kurz et al., 1990; Cerling, 1990) or ^{21}Ne (Marti and Craig, 1987; Graf et al., 1991) have the advantage of not requiring accelerators for measurement, but they record a cumulative history of exposure.

Rock varnish and other rock coating dating methods are less suitable than cosmogenic methods of dating landforms for most geomorphic purposes, because they can dissolve with environmental changes (Dorn, 1989; Watchman, 1991). They are also problematic where the surfaces of rocks are not stable, because rock coatings are lost if even a millimeter of rock is eroded. On the other hand, rock coatings can be superior in circumstances where a prior exposure history is likely for the rock under the coating, for example, in dating the cessation of aeolian abrasion on a boulder or in dating petroglyphs, or most other human artifacts.

Geomorphic Scenarios

Our philosophy is not to claim that one SED method is inherently superior to another. We believe that each approach has advantages appropriate to different projects. In order to illustrate this, we will review different SED methods in different geomorphic scenarios.

Scenarios #1 and #2 in Figure 2 are where all SED methods would ideally yield the same age signal: time since erosion or deposition. The landforms that would meet this situation include most glacial moraines, erosional marine terraces remnants such as uplifted sea stacks, talus cones, and landslides.

In scenario #3, there is a possibility of dating buried landforms without having stratigraphically datable material like tephra. If clasts were once exposed at the surface, and if a former surface can be identified (e.g., surface of buried glacial till, old sand dune, surface of buried alluvial fan), the radionuclides that had built up would have decayed but the stable isotopes would not decay. Multiple isotopes could be used to assess how long the rocks have been buried, and also how long they were exposed at the surface. Alternatively, if the original surface is still exposed elsewhere, cosmogenic nuclide measurements on buried and exposed rocks could be interpreted together to yield the time of burial.

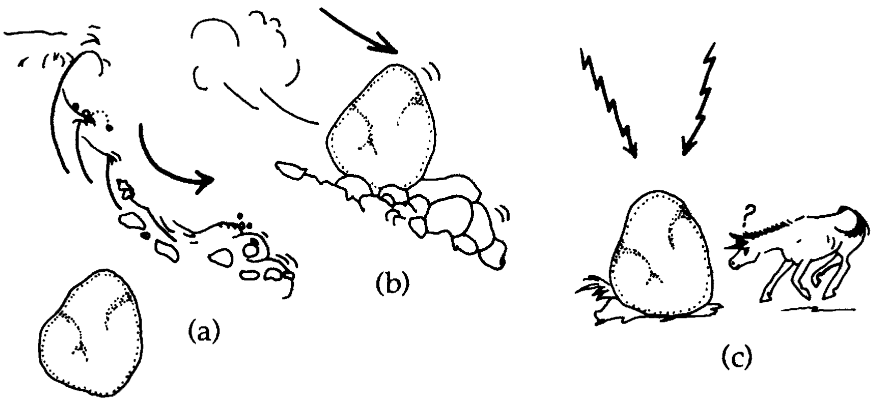
Rocks with a complex history of exposure-burial-reexposure in scenario #4 can be dated. This would require, however, the analysis of multiple isotopes with different half-lives. Scenario #4 would be the most expensive to assess accurately, since many different isotopes would be required to determine the exposure history.

Scenario #5 would be of little value in evaluating the timing of a particular geomorphic event, since the accumulation of cosmogenic nuclides would reveal the cumulative exposure. This information, however, would be of unique value in tracing the long-term history of particle movement.

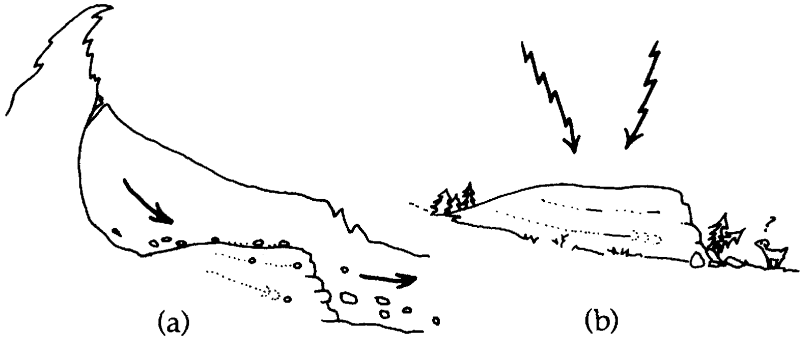
Scenarios #6 and #7 illustrate a complication and an advantage to cosmogenic isotopes. Minor abrasion events that may remove a few cm of rock would not influence a cosmogenic age for the deposition/erosion of the clast, because the 1/2-depth of cosmic ray penetration is on the order of one-third of a meter (Zreda et al., 1991). On the other hand, cosmogenic isotopes would be of little use in determining the timing of these abrasion events.

One of the long-term uses of dating rock coatings in geomorphic research will be to resolve the circumstances of scenarios #5 and #6 in Figure 2. Unlike cosmogenic isotopes that can tolerate tens of centimeters of spalling, even the slightest spalling of a rock surface resets the varnish clock. Geomorphic events like aeolian abrasion, fluvial transport, wave action, cryoturbation, and mass wasting are often severe enough to remove the upper few centimeters off a rock and reset the varnish signal, but they are often not great enough to erode enough rock to reset the cosmogenic clock. This is also true for archaeological disturbances. Cosmogenic nuclides in petroglyph panels or surface quarry sites would reflect the

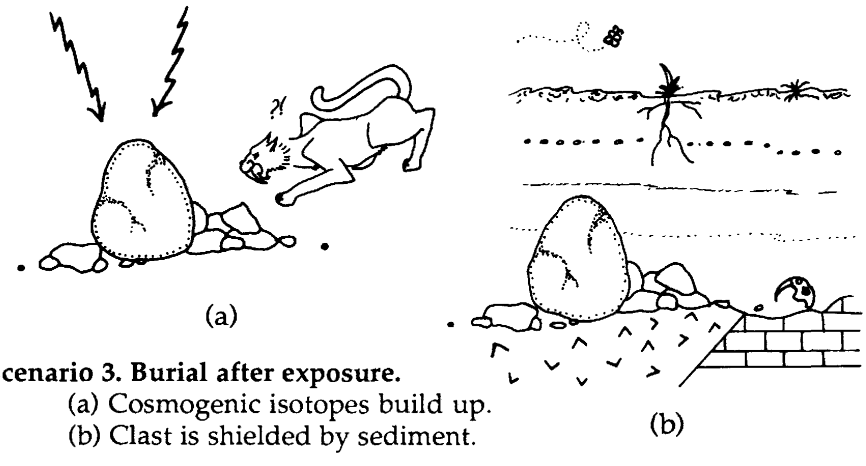
Fig. 2. Possible exposure histories for rocks sampled for age determination by cosmogenic isotopes. The number assigned to each scenario corresponds to discussion in the text.



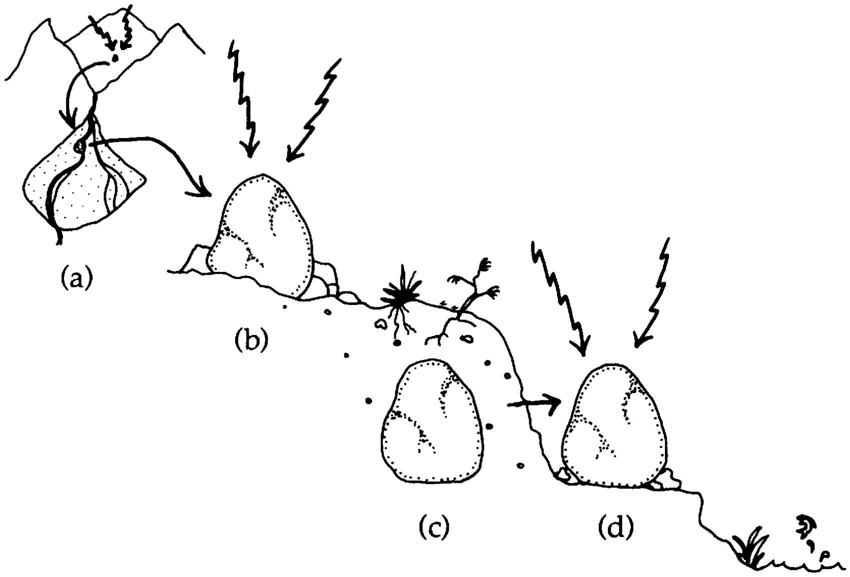
Scenario 1. Deposit with no prior exposure history.
(a) Deep burial before landslide.
(b) Exposure during landslide.
(c) Cosmogenic isotopes build up after landslide.



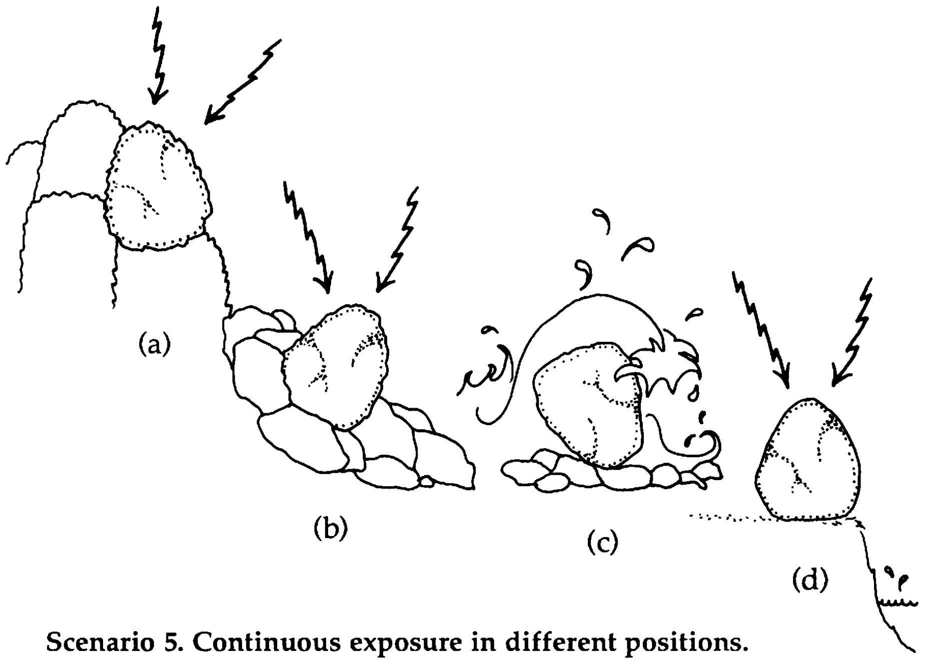
Scenario 2. Erosion with no prior exposure history.
(a) Glacier erodes stoss and lee landform.
(b) Cosmogenic isotopes build up after deglaciation.



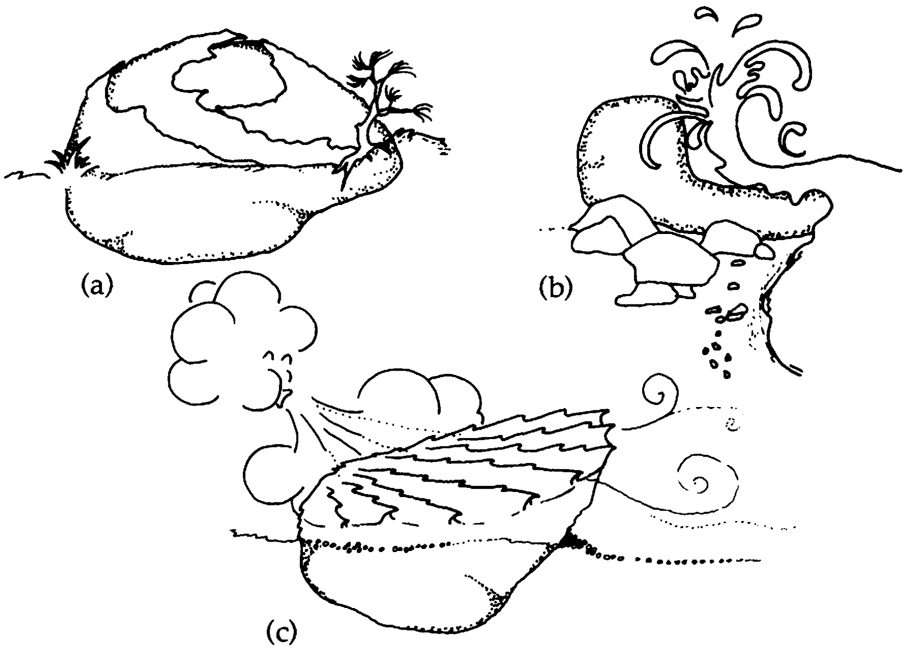
Scenario 3. Burial after exposure.
(a) Cosmogenic isotopes build up.
(b) Clast is shielded by sediment.



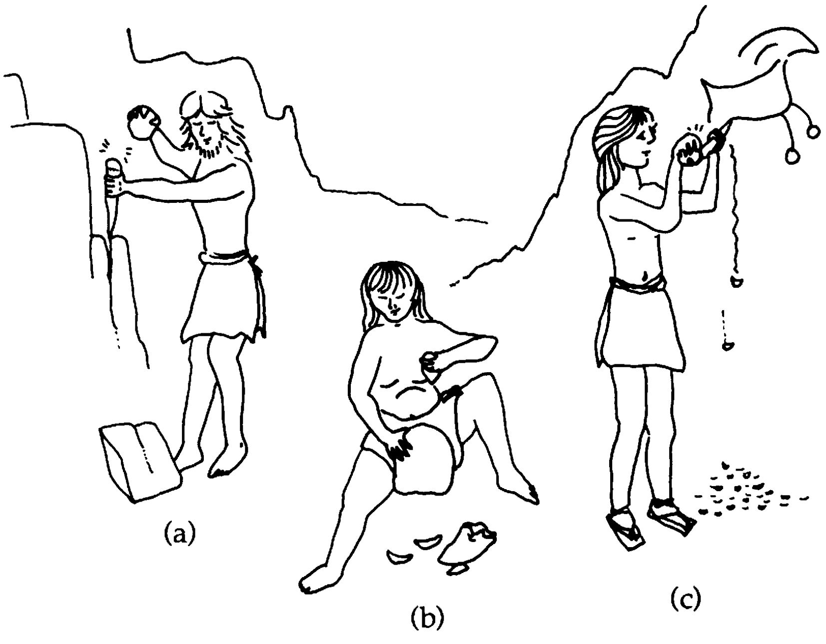
Scenario 4. Multiple cycles of exposure and burial.
(a) Alluvial-fan system where clast moves from exposure in the drainage basin to
(b) exposure on the upper fan or
(c) burial on the upper fan and then transport-erosion, then
(d) exposure lower down on the fan.



Scenario 5. Continuous exposure in different positions.
(a) Bedrock exposure on hillslope crest, then movement to
(b) slope where clast is still exposed, then transport to
(c) fluvial system where clast is
(d) deposited and is still exposed.



Scenario 6. Centimeter-scale erosion of exposed landform.
(a) Scaling caused by lightning, fire, salt weathering.
(b) Wave erosion of large boulder.
(c) Ventifact produced by aeolian abrasion.



Scenario 7. Humans abrade surfaces of exposed rocks
to produce surface artifacts (a-b) and petroglyphs (c).

geomorphic exposure history. Yet what is of interest to the archaeologist is the timing of engraving or flaking. In contrast, rock coatings provide the timing of last abrasion, not the entire exposure history of the rock.

A major concern for surface exposure dating is how rapidly the constructional surfaces of landforms erode. This topic has been little explored in geomorphology, but recent research on surface exposure dating seems to indicate that some parts of a geomorphic surface erode while other parts remain intact. For example, radiocarbon dates on charcoal buried by lava flows on Hawaii (Rubin et al., 1987) are quite similar to varnish radiocarbon (Dorn et al., 1989) and ^{3}He (Kurz et al., 1990) ages. K-Ar dates on lava flows are similar to ^{36}Cl (Phillips et al., 1986; Leavy et al., 1987) and varnish cation-ratios (Dorn, 1989). Recent research in Antarctica indicates that some surfaces have not eroded in millions of years (Brown et al., 1991; Nishiizumi et al., 1990). Certainly, brush fires, lightning, salt, frost and other weathering agents spall many rocks (e.g., Blackwelder, 1927; Yatsu, 1988), but remnants of erosional and depositional geomorphic surfaces can remain intact for hundreds of thousands to millions of years. The circumstances and rates of preservation of land surfaces require further systematic study.

In constrast to soils, rock varnish and cosmogenic isotopes, the weathering of rocks and minerals does not require that a constructional surface remain intact. The surface itself may erode, but the rocks and minerals at depth remain buried and continue to weather. If these weathering trends can be calibrated, weathering trends may provide calibrated age-determinations.

Cost-Benefit of New SED Methods

There are some basic questions that the geomorphic consumer may be asking about cosmogenic isotopes produced by muon-induced spallation, before going blind scraping thin films off rocks.

(1) How much does it cost? It is difficult to calculate cosmogenic 'dates' on a price-per-sample basis at this time, but AMS analysis, chemicals, and associated analyses cost on the order of \$600–\$1200 per sample. At present, the 'real' cost of a single varnish ^{14}C date is about \$800 in sample preparation time, electron microscope time, laboratory supplies, and buying a commercial AMS radiocarbon date. A varnish cation-ratio age-determination (if a calibration exists) runs ~ \$125 (depending on the number of replicate chemical analyses).

The costs involved in generating quantitative measurements of weathering rinds and minerals are probably the least of any calibrated SED method. The costs involved in developing a soils index based solely on field data (Switzer et al., 1988) are probably on the same order. However, if a calibrated-soils age requires the opening of a deep trench and detailed laboratory analyses (e.g., Harden, 1987), the labor costs alone are substantially more than a cosmogenic-nuclide or rock-varnish age-estimate.

(2) Can I send my sample off? Not yet. Sample collection has not yet been refined to a cook-book procedure. Commercial laboratories have yet to become established to process samples for accelerator analysis, but it is just a matter of time.

(3) Can I do it myself? "Yes." Replication, a key component of any scientific endeavor, has been achieved for cation-ratio dating (Dorn, 1983; Glazovskiy, 1985; Harrington and Whitney, 1987; Pineda et al., 1988; Zhang et al., 1990). ^{3}He dating has been accomplished by several groups (Kurz, 1986a,b, 1990; Lal, 1987; McConville and Reynolds, 1989; Cerling, 1990), as has *in situ* ^{14}C dating (Jull et al., 1989; Lal et al., 1990). Varnish radiocarbon dating, ^{36}Cl, and ^{26}Al and ^{10}Be, still await replication by different groups.

Most geomorphologists are aware of the hazards of improper sample collection procedures, the necessary laboratory pre-treatment, and the need for careful laboratory analysis. Given time, SED methods will probably be treated like radiocarbon dating is today.

(4) Is it really better than the existing product? (In this case, the existing products are form, relative position, weathering, growth of biota, and soils.) If relative ages are required, "no." Landform morphology, relative position, and soil properties have long been used as indicators of relative landform age. These approaches are "low-tech," relying on inexpensive aerial photography and relatively simple laboratory procedures.

If numerical ages are required, "no" if dendrogeomorphology is suitable, "yes" if it is not available. However, the aforementioned relative dating methods can be used as "litmus tests" of reasonability to help identify potentially anomalous cosmogenic, varnish, and weathering "ages."

If calibrated ages are required, "maybe," if a trusted calibration exists for weathering rinds, weathering of minerals, rock-varnish cation ratios, or soil properties. These approaches are certainly less expensive than numerical SED techniques. However, the development of each calibration is limited to a particular area (Switzer et al., 1988; Dorn, 1989). The development of a calibration, therefore, is economical only when a large number of landform ages are to be derived in a project.

In order to evaluate this issue further, one of the weakest of the new surface exposure dating methods (cation-ratio dating of rock varnish) is compared with a more traditional approach of using soils in geomorphic research. Soils are much better understood than varnish, having been studied intensively by thousands of soil scientists over the past century. Still, fundamental problems persist in the use of soils as a dating technique, where the theoretical basis is Jenny's (1941) chronofunction; these are less severe for cation-ratio dating of rock varnish.

(1) There are few ways to test the constancy of climate, biota, topography, parent material, and factors other than time influencing soil development (Jenny, 1941). McFadden (1988, p. 175) notes it "is difficult to identify a soil chronofunction that is not likely to reflect the influences of at least two soil-forming factors." A soil scientist has no way of knowing that a particular soil trench experienced the same vegetation cover, even during the same climatic period, let alone the great vegetation changes that occurred from the latest Pleistocene to the Holocene. For example, an isolated pinyon pine tree could have been present over a soil pit for thousands of years, increasing the local acidity, and only recently died, leaving no pinyon pine in the local area. Because varnish is a cumulic deposit and not a diagenetic medium that is constantly mixing like soils, it is possible to assess the

environmental history of the varnish, including whether the varnish has experienced past episodes of erosion (Krinsley et al., 1990; Dorn and Krinsley, 1991).

(2) The number of soil profiles that can be examined for a particular geomorphological unit is necessarily low, usually no more than 3 soil pits per site due to the large effort in opening and analyzing soil pits. With much less effort and less dollar cost in labor, 15 or more boulders can be analyzed for cation-ratio dating of rock varnish from a site. This higher "*n*" provides an opportunity to assess anomalies that are an inherent part of any biogeochemical system such as soils and rock varnish.

CONCLUSION

Where numerical ages are needed beyond the time range of dendrogeomorphology, we believe that the accumulation of cosmogenic nuclides in rocks will become the SED method of choice for geomorphologists, just as radiocarbon dating is commonly used today. Unlike varnish, soils, lichenometry, and weathering, cosmogenic isotope dating is based on physics and is not dependent on changing biological or geochemical variables. Field sampling is relatively straightforward, relying on the investigator to select rock surfaces that reflect the depositional or erosional geomorphic event. Laboratory processing is tedious and requires care (e.g., Kurz, 1986b; Nishiizumi et al., 1989; Zreda et al., 1991), but so is sample preparation for virtually any laboratory analysis. The time range is ideal for geomorphological purposes, from 10^2 to 10^7 years BP.

Some might argue that the use of cosmogenic nuclides will be limited by time on tandem accelerators. It is imperative that geomorphologists with uses for surface-exposure dating have access to these new methods, and accelerator time is a key issue for national funding agencies. However, who would have predicted that radiocarbon would play such a vital role in geomorphology? As demand increases and more accelerators are used for mass spectrometry, an ongoing trend, the number of samples that can be run will gradually increase. Also, ^{3}He and ^{21}Ne can be analyzed by conventional, albeit difficult, mass spectrometry.

We believe the greatest inherent limitations of cosmogenic nuclides are geomorphological. The exposure history of rocks that are sampled will ultimately control the use of cosmogenic isotopes in geomorphology. This is best illustrated by reviewing different scenarios for the exposure histories of sampled rocks (Fig. 2).

Ever since the inception of geomorphology, we have typically been constrained to use indirect, correlative methods for determining the age and rates of changes of landforms. The most exciting aspect of the new surface exposure dating techniques is that, by measuring rock properties that are unique to the very surface of the earth, they permit the direct determination of landform chronology. In a sense this has, for the first time, put geomorphology on an equal footing with many other fields of earth science where direct chronology has long been taken for granted. The new methods are not a panacea; the measurements will reveal only what the actual surface history of the sample has been, and not necessarily the facts we might most like to know. Nevertheless, the first applied studies and cross-checks between methods are very encouraging (Brown et al., 1991; Dorn et al., 1991; Phillips et al., 1991). The challenge now is to discover where the new methods can most effectively be applied to advance the science of geomorphology.

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