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# Geomorphological applications of cosmogenic isotope analysis

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**Abstract**: Cosmogenic isotope analysis involves the measurement of cosmogenic nuclides that have accumulated in the upper few metres of the Earth's surface as a result of interactions between cosmic rays and target elements. The concentrations of these cosmogenic nuclides can provide quantitative estimates of the timing and rate of geomorphic processes. In dating applications the concentration of cosmogenic nuclides is interpreted as reflecting the time elapsed since a surface exposure event. However, over most of the Earth's surface for most of the time the landsurface experiences incremental denudation and in these circumstances cosmogenic nuclide concentrations are related to the rate of denudation. Applications of event dating using cosmogenic isotopes include constructional landforms such as volcanic and depositional features, fault displacement, meteorite impacts, rapid mass movement, bedrock surfaces rapidly eroded by fluvial or wave action or exposed by glacial retreat, and the burial of sediment or ice. Strategies for quantifying rates of incremental change include estimates of denudation rates from site-specific samples and from fluvial sediment samples reflecting catchment-wide rates, and measurements of cosmogenic nuclide concentrations in soils and regolith to quantify rates of rock weathering. The past decade has seen a rapid growth in applications of cosmogenic isotope analysis to a wide range of geomorphological problems, and the technique is now playing a major role in dating and quantifying rates of landscape change over timescales of several thousands to several millions of years.

**Key words**: cosmogenic isotope analysis, cosmogenic nuclides, dating, denudation rates, geomorphology.

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## I Introduction

The Earth is under constant bombardment by cosmic radiation, primarily comprising protons, with a smaller proportion of α-particles, electrons and heavier nuclei. A proportion of this cosmic radiation comes from the Sun, but the more energetic particles (typically $10^8$–$10^{10}$ eV) originate largely from our own galaxy, with the very highest energy particles (up to $10^{20}$ eV) having a source outside the Milky Way. It is the higher energy particles that are primarily responsible for generating the shower of secondary cosmic radiation in the upper atmosphere which reaches the Earth's surface. This secondary cosmic radiation flux, consisting predominantly of neutrons, with a much smaller component of muons, interacts with target elements in minerals in a shallow layer at the Earth's surface to produce, *in situ*, extremely small quantities of cosmogenic nuclides. Measurements of the amounts of these cosmogenic nuclides accumulated over time can provide valuable information on the age and rate of change of the land surface.

Until the development in the late 1970s and early 1980s of accelerator mass spectrometry (AMS) (Klein *et al.*, 1982; Elmore and Phillips, 1987) and high-sensitivity noble gas mass spectrometry, cosmogenic isotope analysis was confined to the relatively much higher concentrations of cosmogenic nuclides found in meteorites and lunar samples that had received a cosmic-ray flux which had not been attenuated by the shielding effects of the Earth's atmosphere. Nonetheless, even prior to developing the capability to measure the exceedingly low concentrations of cosmogenic nuclides produced *in situ* in terrestrial materials, the potential for applying such measurements to geomorphological problems was recognized. In fact, the origins of using cosmogenic nuclides to determine the exposure history of the Earth's surface go back to Davis and Schaffer (1955) who used beta counting to date a late Quaternary surface on a chlorine-rich phonolite. Other early contributions include a largely ignored paper published in German in the early 1970s (Fröhlich and Lübert, 1973) which proposed calculating denudation rates using *in-situ*-produced cosmogenic nuclides (see Tuniz *et al.*, 1998), and the work by Srinivasan (1976) who measured cosmogenic $^{126}$Xe to determine a 'surface residence time' for a sedimentary barite sample (see Cerling and Craig, 1994a).

Following the advances in measurement technology and the increased understanding of the *in situ* production of cosmogenic nuclides that was acquired during the 1980s, there has been a rapid growth in applications of cosmogenic isotope analysis in geomorphology and related fields of Quaternary science. From five or six papers per year in the early 1990s, the number has risen to 20 or more in the past two to three years (Figure 1). These totals are for applications papers only, and exclude a large body of theoretical and technical contributions.

The importance of cosmogenic isotope analysis as a technique in geomorphology arises, in part, from the timescale that it can address. Depending on the local rate of land surface stripping, cosmogenic isotope analysis can provide information on ages of geomorphic events, denudation rates and the operation of specific geomorphic processes over timescales ranging from thousands to millions of years. It thus forms a crucial bridge between investigations over the short term based on modern process rate measurements and historical data, and long-term studies based on techniques such as thermochronology (Burbank *et al.*, 1996; Cockburn *et al.*, 2000). A key advantage of a technique that provides information on denudation over these intermediate timescales

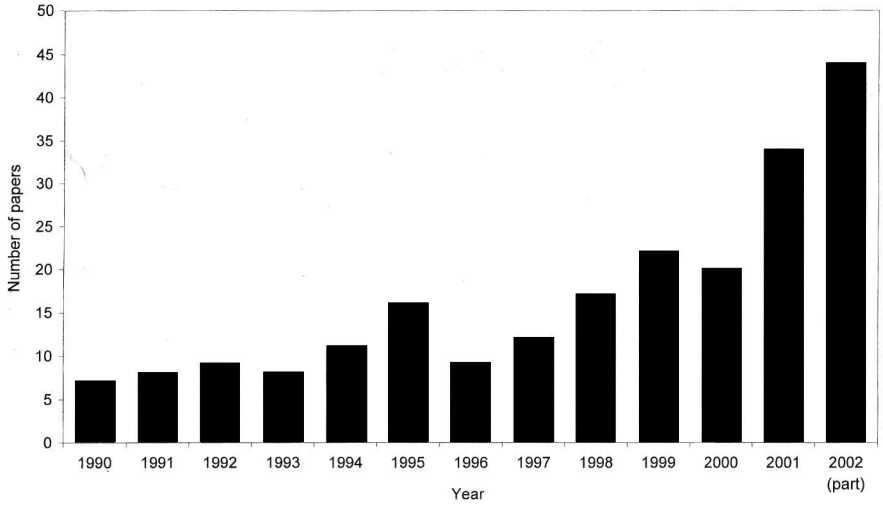


**Figure 1** Growth in number of papers on geomorphological applications of *in situ*-produced cosmogenic nuclides published from 1990 to mid-2002

is that it can effectively average out short-term fluctuations in rates associated with climatic variations or other high frequency perturbations. It also circumvents, to a large extent, the problem of high magnitude–low frequency events which severely limit the potential to extrapolate short-term geomorphic process rate measurements (typically limited to a few years) to the longer term.

Another key advantage is the very wide scope for sampling in addressing a diverse range of geomorphological problems. Unlike information gleaned from geochronological techniques such as radiocarbon or luminescence dating, which are frequently confined to rather specific field situations, cosmogenic isotope data can be acquired from an enormous variety of geomorphologically useful contexts. This is the case because of the almost ubiquitous occurrence in common rock-forming minerals of the target elements for cosmogenic nuclide production (Table 1). The ability to date or quantify rates of landform change directly, rather than inferring chronological information about them indirectly, makes the technique particularly valuable. In short, cosmogenic isotope analysis enables geomorphological studies to be attempted that were previously impossible, it can address key questions about geomorphic process rates, and it provides the means to answer long-standing questions about landscape evolution.

In this review we focus on the geomorphological applications of *in situ*-produced cosmogenic isotope analysis, although many of the studies discussed, especially those involving the dating of landforms, also have great relevance to problems in Quaternary science. We exclude applications based on atmospheric (also known as 'meteoric' or 'garden variety') cosmogenic nuclide production, although this can also provide important insights into environmental processes (e.g., McKean *et al.*, 1993; Stanford *et al.*, 2000), not least in $^{14}C$ dating of organic materials. Our aim is to provide a comprehensive, although not exhaustive, survey to inform researchers unfamiliar with the technique of the potential of *in situ*-produced cosmogenic isotope analysis in advancing

**Table 1** Properties of the main terrestrial cosmogenic nuclides used in geomorphological applications

| Isotope | Half-life (yr) | Main target minerals | Measurement | Comments |
|---|---|---|---|---|
| $^{3}$He | stable | olivine, pyroxene, hornblende, garnet | mass spectrometry | High production rate which is relatively well constrained; low detection limit; long exposure histories can be recorded in suitable host minerals which retain $^{3}$He, but not for quartz from which there is generally rapid diffusion of $^{3}$He; possible inheritance of $^{3}$He where sample has been previously exposed. Best results using samples from rocks with crystalline ages <5 Ma. |
| $^{10}$Be | $1.51 \times 10^{6}$ | quartz, olivine | AMS | Primary target mineral (quartz) is widespread; can be analysed in conjunction with other cosmogenic nuclides formed in quartz ($^{26}$Al in same aliquot, $^{14}$C and $^{21}$Ne in same sample); long half-life provides possibility of recording long exposure histories; low production rate means application is limited where exposure events are recent; relative abundance of atmospheric $^{10}$Be a potential contaminant requiring rigorous sample treatment; production rate well-constrained only for quartz. |
| $^{14}$C | $5.73 \times 10^{3}$ | quartz, calcite | AMS | Target minerals are widespread; short half-life means that recent complex exposure histories can be analysed when paired with a stable cosmogenic nuclide or a cosmogenic radionuclide with a longer half-life; short half-life also limits the potential for inheritance; possibility of contamination by atmospheric $^{14}$C; procedures currently least developed of the commonly used cosmogenic nuclides. |

| | | | | |
|---|---|---|---|---|
| $^{21}$Ne | stable | quartz, olivine, garnet, clinopyroxene | mass spectrometry | Target minerals are widespread; potential for recording the longest exposure histories of any cosmogenic isotope as it is stable and, unlike $^{3}$He, appears to be effectively retained in quartz; however, this also means that inheritance from previous exposure is possible, even over long time spans; as a stable nuclide it is valuable when analysed in conjunction with $^{10}$Be and $^{26}$Al to record complex exposure histories; careful correction for nucleogenic $^{21}$Ne is required, especially for short exposure histories in samples with old crystallization ages, and trapped $^{21}$Ne in inclusions. |
| $^{26}$Al | $7.20 \times 10^{5}$ | quartz | AMS | Target mineral is widespread; can be analysed in conjunction with other cosmogenic nuclides formed in quartz ($^{10}$Be, $^{14}$C, $^{21}$Ne) in same aliquot/sample to investigate complex exposure histories; very low concentration (<200 ppm) of total Al in sample required as it is difficult to measure low $^{26}$Al/$^{27}$Al ratios by AMS. |
| $^{36}$Cl | $3.01 \times 10^{5}$ | K-feldspar, plagioclase, calcite, $^{35}$Cl in fluid inclusions in quartz | AMS | Atmospheric production is low so can be used on whole rock (e.g., basalt and limestone); only viable cosmogenic nuclide for some lithologies; multiple production pathways from multiple elements, together with radiogenic and nucleogenic production, mean that ancillary geochemical analyses are required and that data analysis is more complex than for other cosmogenic nuclides; sulfur contamination in samples is typical and discrimination between $^{36}$Cl and the isobar $^{36}$S by AMS generally requires the higher energies provided by high voltage accelerators. |

*Source*: based on Kurz and Brook (1994), Tuniz *et al.* (1998), Fifield (1999) and Gosse and Phillips (2001).

research in geomorphology and allied fields. Several excellent discussions of the principles and technical details of cosmogenic isotope analysis are already available, most notably the comprehensive review by Gosse and Phillips (2001), but also including contributions by Lal and Peters (1967), Lal (1988), Nishiizumi *et al*. (1993), Finkel and Suter (1993), Cerling and Craig (1994a), Bierman (1994), Kurz and Brook (1994), Tuniz *et al*. (1998), Fifield (1999) and Zreda and Phillips (2000). Discussions of cosmogenic isotope analysis are now also to be found in texts and reference manuals (e.g., Dickin, 1995; Noller *et al*., 2000), an indication that the technique is beginning to move from the purely development stage to more routine applications.

## II Cosmogenic isotope analysis

The main principles that govern the use of cosmogenic isotopes in geomorphology are conceptually simple: a cascade of cosmic radiation continuously bombards the Earth, of which a small proportion reaches the surface where nuclear interactions with terrestrial materials, such as soil or rock, produce cosmogenic nuclides. Strong attenuation of the cosmic-ray flux restricts production to the upper few metres of the Earth's crust; thus the concentration of *in situ*-produced cosmogenic nuclides in a surface sample provides a quantitative record of near-surface exposure. Lal (1988) identified 12 cosmogenic isotopes that are produced in terrestrial materials. Six of these have been significant in geomorphological investigations – $^{3}$He, $^{10}$Be, $^{14}$C, $^{21}$Ne, $^{26}$Al, $^{36}$Cl (Table 1) – whereas others, such as $^{39}$Ar and $^{41}$Ca (e.g., Loosli, 1983; Fink *et al*., 1990), will require further development for geomorphological applications.

Knowledge of production mechanisms and time-integrated production rates form the basis for the application of cosmogenic isotope analysis in geomorphology. Significant advances have been made since the pioneering work of Lal and Peters (1967), and reducing remaining uncertainties in production systematics remains a major research priority (Gosse *et al*., 1996; Dunai, 2000, 2001a, b, 2002; Stone, 2000, 2002; Desilets *et al*., 2001). Three principal mechanisms produce most cosmogenic nuclides: neutron spallation (the dominant process at the surface for all cosmogenic nuclides), thermal neutron capture and muonic interactions (which become of increasing relative importance with depth owing to the longer penetration lengths of these particles (Heisinger *et al*., 2002a, b) ). Production rates have been determined both empirically using natural and artificial targets (e.g., Nishiizumi *et al*., 1989, 1996; Cerling and Craig, 1994b; Niedermann *et al*., 1994; Kubik *et al*., 1998; Stone *et al*., 1998a; Dunai and Wijbrans, 2000) and theoretically (e.g., Lal, 1991; Masarik and Reedy, 1995; Masarik 2002; see also Gosse and Phillips, 2001: 1519). Production rates vary with location and time and must be scaled to account for a number of factors including depth within a target (Lal, 1991; Brown *et al*., 1992), altitude (atmospheric shielding) and latitude (primarily the spatial influence of the geomagnetic field) (Lal, 1991; Dunai, 2000; Stone, 2000), topographic shielding and sample surface slope (exposure geometry) (Dunne *et al*., 1999). Temporal influences that need to be addressed include variations in the cosmic-ray flux (Gosse and Phillips, 2001), several geomagnetic field parametres that vary with time (Kurz *et al*., 1990; Licciardi *et al*., 1999; Dunai, 2001b; Masarik *et al*., 2001), intermittent shielding by surface materials including regolith, sediments, snow and vegetation (Nishiizumi *et al*., 1989; Gosse *et al*., 1995a), loss of cosmogenic nuclides

through diffusion from the host mineral (Trull *et al.*, 1991; Brook *et al.*, 1993), the effects of fire (Bierman and Gillespie, 1991; Zimmerman *et al.*, 1994) and possible changes in the elevation of sampled sites (Lal, 1991; Brown *et al.*, 1991). The net result of all these effects is that very careful sampling protocols are required based on a detailed understanding of the geomorphic processes operating at sampled sites (Gosse and Phillips, 2001) and quantitative modelling of production rates for each isotope and application (Lal, 1991; Dunai, 2000; Stone, 2000). Current levels of uncertainty are approximately 10–20%, most of which results from production rate scaling for latitude and altitude (see Gosse and Phillips, 2001, for detailed discussion).

Cosmogenic nuclides accumulate in surface rocks as a function of production over time moderated by denudation and, for radioisotopes, radioactive decay. In some cases, relative concentrations in a suite of samples can be enough to solve a geomorphological problem. More often, translating measured abundances of cosmogenic nuclides into useful geomorphic data depends on the use of a suitable interpretative model based on an appreciation of probable site history. Various models have been devised, some being unique to individual applications. The simplest and most widely used model involves estimating the surface exposure age of a sample assuming that it has been suddenly exposed from a depth sufficient for it not to contain a pre-existing (inherited) cosmogenic nuclide component, and that it has not subsequently experienced denudation or burial. Under these circumstances a stable nuclide will continue to accumulate indefinitely and therefore have no theoretical upper age limit, although the zero denudation assumption is likely to be violated over longer timescales (~>$10^5$ yr) and this imposes an upper limit to exposure dating. Radionuclides eventually attain an equilibrium concentration where production is balanced by radioactive decay. This point defines the theoretical upper age limit for cosmogenic radionuclide exposure dating, assuming zero denudation, and is reached after approximately four times the half-life of the radionuclide being used (Table 1). If the assumption of zero denudation is not met, or the nuclide concentration has become saturated, the model will yield an 'apparent' or minimum age. In cases where there has been progressive denudation rather than a sudden 'exposure event', the cosmogenic nuclide concentration can be used to estimate a rate of denudation assuming that the system is in secular equilibrium with respect to production, denudation, and decay (for radionuclides) (see Section V, 1). This model effectively quantifies the 'dwell time' of the upper 1–2 m of the surface. Such estimates are model-dependent since assumptions have to be made about secular equilibrium and the temporal variability in the denudation rate and are model maxima if these assumptions are not met (Bierman, 1994; Cerling and Craig 1994a).

## III Range of applications

In summarizing here the wide range of applications of cosmogenic isotope analysis to geomorphological phenomena, it is important to highlight the two ways of modelling cosmogenic nuclide concentrations by drawing a distinction between dating geomorphological 'events' and measuring incremental change. A geomorphological event in this context is a change in the landscape that, in relation to the background rate of modification of the landscape, represents an 'instantaneous' occurrence of sufficient magnitude to expose material that has previously been effectively shielded from cosmic

radiation. Common examples would be exposure of a fresh bedrock face by a deep landslide, or by glacial retreat. Obviously once the 'event' has occurred 'normal' geomorphic processes can lead to progressive denudation of the 'event surface'. The depth of such modification, and therefore the effect on cosmogenic nuclide concentration, is likely to be negligible in most instances for young events (typically ~1–3 × $10^4$ yr) in comparison with the depth through which significant cosmogenic nuclide production occurs.

By incremental change we envisage the mode of landscape activity that occurs over most of the Earth's landscape for most of the time – that is, the progressive weathering and stripping away of material in increments that are small in comparison with the characteristic attenuation length (typically ~0.6 m for rock) of cosmogenic nuclide production in Earth surface materials. Although there are important exceptions, it is usually more appropriate to regard the cosmogenic nuclide concentration of a sample as reflecting the net effect of cosmogenic nuclide production and the prevailing rate of denudation (and radioactive decay in the case of radionuclides), than to think of a land surface as having been initiated at a specific instance in the past and thereby seeing the landscape as comprising elements with specific 'ages'. We prefer the term 'denudation' to 'erosion' when referring to the overall removal of surface materials resulting from a combination of processes, or where the specific processes are undefined; we use 'erosion' where the process is predominantly or solely one of entrainment and transport of solid material by water, ice or wind. The distinction between dating events and recording rates of incremental change has been used as the basis for organizing this review (Table 2).

## IV Dating events

### 1 Constructional landforms

*a Volcanic landforms:* The construction of new surfaces on volcanic landforms, which normally occurs 'instantaneously' in the context of long-term rates of landscape change, provides a clear example of a geomorphic event that can be dated through the accumulation of cosmogenic nuclides. Moreover, the ability to date volcanic rocks independently using radiometric techniques has provided an important means of determining cosmogenic nuclide production rates (Craig and Poreda, 1986; Kurz 1986a, 1986b, 1987; Phillips *et al*., 1986; Marti and Craig, 1987; Kurz *et al*., 1990; Nishiizumi *et al*., 1990; Poreda and Cerling, 1992; Laughlin *et al*., 1994). With these improved cosmogenic nuclide production rate data, surface exposure dating of lava flows is now able to provide independent corroboration of radiometric ages where post-eruptive denudation has been insignificant (Staudacher and Allègre, 1993), and has the potential to be used in preference to conventional radiometric methods in specific cases, especially for young flows and for samples with a low potassium content or inherited argon (Sarda *et al*., 1993; Zreda *et al*., 1993; Laughlin *et al*., 1994; Shepard *et al*., 1995).

Where there are reliable radiometric ages for lava flows, the difference in radiometric and apparent surface exposure age can be used to identify burial events and quantify the rate of post-eruptive denudation (Cerling, 1990). For instance, on Réunion Staudacher and Allègre (1993) found that the cosmogenic exposure age of ~62 ± 4 ka for a lava flow was only slightly younger than its 65 ka K-Ar age, thus constraining the rate

**Table 2** Applications of *in situ*-produced cosmogenic nuclides in geomorphology

| Nature of process | Category of process | Applications with examples |
|---|---|---|
| Event (age) | Construction of land surfaces: volcanic | **1. Volcanic landforms** (e.g., lava flows, cinder cones): dating of extrusive rocks; chronology of construction of volcanic landforms.<br>Craig and Poreda (1986), Kurz (1986b, 1987), Phillips *et al.* (1986), Marti and Craig (1987), Cerling (1990), Nishiizumi *et al.* (1990), Kurz *et al.* (1990), Poreda and Cerling (1992), Anthony and Poths (1992), Staudacher and Allègre (1993), Sarda *et al.* (1993), Zreda *et al.* (1993), Laughlin *et al.* (1994), Shepard *et al.* (1995), Reynolds *et al.* (1995), Eppes and Harrison (1999), Licciardi *et al.* (1999), Fenton *et al.* (2001). |
| | Construction of land surfaces: depositional | **2. Alluvial river terraces:** changes in sediment delivery through time; climatic or tectonic controls on sediment delivery.<br>Molnar *et al.* (1994), Anderson *et al.* (1996), Repka *et al.* (1997), Phillips *et al.* (1998), Hancock *et al.* (1999), Schaller *et al.* 2002), Schildgen *et al.* (2002).<br><br>**3. Alluvial fans/debris flows:** age constraints on seismic activity through offsetting by faults.<br>Ritz *et al.* (1995), Bierman *et al.* (1995), Liu *et al.* (1996), Siame *et al.* (1997, 2002), Brown *et al.* (1998a), van der Woerd *et al.* (1998, 2002), Cerling, (1990); Klinger *et al.* (2000), Zehfuss *et al.* (2001), Fenton *et al.* (2001), Hetzel *et al.* (2002a, b), Jackson *et al.* (2002).<br><br>**4. Lacustrine shoreline deposits:** chronology of tectonic deformation, palaeohydrology and climatic change.<br>Trull *et al.* (1995)<br><br>**5. Ice-marginal moraines:** glacial history; climatic change.<br>Brown *et al.* (1991), Brook *et al.* (1993, 1995a, b), Brook and Kurz (1993), Gosse *et al.* (1995a, b), Phillips *et al.* (1990, 1996, 1997), Zreda and Phillips (1995), Ivy-Ochs *et al.* (1996, 1997), Fabel *et al.* (1997), Jackson *et al.* (1997, 1999), Chadwick *et al.* (1997), Steig *et al.* (1998), Davis *et al.* (1999), Fabel and Harbor (1999), Gualtieri *et al.* (2000), Shanahan and Zreda (2000), Tschudi *et al.* (2000), Marsella *et al.* (2000), Phillips *et al.* (2000) Barrows *et al.* (2001, 2002), Briner *et al.* (2001; 2002), Licciardi *et al.* (2001), Owen *et al.* (2001, 2002a, b, c), Kaplan *et al.* (2001), Miller *et al.* (2002), Schäfer *et al.* (2002a, b), Bourlès *et al.* (2002), Bowen *et al.* (2002), Phillips and Bowen (2002), James *et al.* (2002)<br><br>**6. Marine shoreline deposits:** relative sea-level change.<br>Perg *et al.* (2001). |

**Table 2** Continued

| Nature of process | Category of process | Applications with examples |
|---|---|---|
| Event (age) (cont.) | Exposure through tectonic displacement | **7. Development of fault scarps:** palaeosesimicity; earthquake recurrence intervals; regional tectonic studies.<br>Zreda and Noller (1998), Handwerger *et al.* (1999), Mitchell *et al.* (2001). |
| | Episodic denudation of the land surface | **8. Meteorite impacts:**<br>Nishiizumi *et al.* (1991a), Phillips *et al.* (1991). |
| | | **9. Rapid mass movement** (e.g., landslides, rock falls, debris avalanches, toppling boulders): magnitude–frequency relationships of rapid mass movement processes; correlation with climatic change or seismic events.<br>Kubik *et al.* (1998), Ivy-Ochs *et al.* (1998), Ballantyne *et al.* (1998), Bell *et al.* (1998), Cerling *et al.* (1999), Hermanns *et al.* (2000, 2001), Barnard *et al.* (2001) |
| | | **10. Catastrophic flooding:** lake overflows; glacial lake outbursts; landslide dam failures.<br>Cerling (1990), Cerling and Craig (1994b), Cerling *et al.* (1994). |
| | | **11. Formation of strath terraces:** palaeohydrology; chronology and rate of incision of associated channel. Burbank *et al.* (1996), Leland *et al.* (1998), Barnard *et al.* (2001), Pratt *et al.* (2002). |
| | | **12. Formation of wave-cut platforms:** chronology of relative sea-level change.<br>Stone *et al.* (1996). |
| | Exposure of land surface through removal of ice cover | **13. Exposure of bedrock surfaces, or glacial or fluvioglacial depositional forms:** chronology of retreat of ice margin; confirmation and dating of limits of glaciation from trimlines; chronology of climatic change.<br>Nishiizumi *et al.* (1989, 1991b), Brook *et al.* (1996), Bruno *et al.* (1997), Ballantyne *et al.* (1998), Stone *et al.* (1998b), Briner and Swanson (1998), Bierman *et al.* (1999), Fabel *et al.* (2002), Stroeven *et al.* (2002), Gosse and Willenbring (2002), Gualtieri and Brigham-Grette (2001), Kelly *et al.* (2002), Stone (2002). |
| | Burial processes | **14. Deposition of sediment in caves:** chronology of cave development; rate of incision of associated subaerial fluvial systems.<br>Granger *et al.* (1997; 2001a). |
| | | **15. Burial of surfaces / horizons in depositional sequences:** changes in sediment delivery through time; climatic or tectonic controls.<br>Granger and Smith (2000), Granger and Muzikar (2001). |

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|---|---|---|
| | | **16. Burial of glacial ice:** glacial and climatic history.<br>Schäfer *et al.* (2000), Marchant *et al.* (2002). |
| Incremental change (rate) | Progressive denudation of the land surface | **17. Denudation of bedrock, regolith and depositional surfaces** by mechanical and/or chemical denudational processes at specific points on the land surface (site-specific rates): in some cases extrapolation of site-specific rates to larger areas possible; rates of denudation of different landscape elements (e.g., river channels, valley-side slopes, interfluves); assessment of factors controlling denudation rates on specific landforms (e.g., slope, climate, lithology).<br>Nishiizumi *et al.* (1986, 1991b), Kurz (1986b), Albrecht *et al.* (1993), Brown *et al.* (1995a), Bierman and Turner (1995), Seidl *et al.* (1997), Small *et al.* (1997, 1999), Heimsath *et al.* (1997, 1999, 2000, 2001a, b), Weissel and Seidl (1998), Cockburn *et al.* (1999, 2000), Fleming *et al.* (1999), Cockburn and Summerfield (2000), Summerfield *et al.* (1999a, b), Belton *et al.* (2000), Granger *et al.* (2001b), van der Wateren and Dunai (2001), Bierman and Caffee (2001, 2002) |
| | | **18. Regional denudation** representing aggregate effects of denudational processes across drainage areas (areally averaged denudation rates derived from bulk sediment samples): assessment of factors controlling denudation rates for drainage areas as a whole.<br>Brown *et al.* (1995a, 1998b), Granger *et al.* (1996, 2001b), Small *et al.* (1999), Clapp *et al.* (2000, 2001, 2002), Bierman and Caffee (2001), Riebe *et al.* (2000, 2001a, b, c), Kirchner *et al.* (2001), Schaller *et al.* (2001), Nichols *et al.* (2002) |
| | Ablation of ice surfaces | **19. Rates of ablation on glaciers:** long-term glacier mass balance studies.<br>Lal *et al.* (1987, 1990), Lal and Jull (1990, 1992), Jull *et al.* (1994a) |
| | Vertical movements within regolith or other deposits | **20. Vertical translocation of material in soils:** modes and rates of soil development.<br>Heimsath *et al.* (1997, 1999, 2000, 2001a, b), Phillips *et al.* (1998), Phillips (2000). |
| | | **21. Vertical translocation of material in laterites/duricrusts:** modes and rates of formation.<br>Brown *et al.* (1994), Liu *et al.* (1994), Braucher *et al.* (1998a, b; 2000), Schroeder *et al.* (2001). |
| | | **22. Vertical translocation of material within slope materials:** nature and rates of slope processes.<br>Small *et al.* (1999), Heimsath *et al.* (2002). |
| | | **23. Vertical translocation of material within aeolian deposits:** dynamics of aeolian deposits.<br>Klein *et al.* (1986), Shepard *et al.* (1995). |
| | | **24. Vertical translocation of material within desert pavement systems:** formation of desert pavements.<br>Wells *et al.* (1995), Shepard *et al.* (1995). |
| Palaeo-altimetry | | **25. Change in elevation through time** inferred through change in production rate: estimating past elevations and rate of uplift of the land surface to constrain tectonic models.<br>Brown *et al.* (1991), Brook *et al.* (1993, 1995a), Ivy-Ochs *et al.* (1995), Bruno *et al.* (1997), Schäfer *et al.* (1999), Van der Wateren *et al.* (1999), Gosse and Stone (2001), Kober *et al.* (2002). |

of denudation rate since eruption to less than ~3 m $Ma^{-1}$, and confirming that the flow was not covered by scoriae or ash during subsequent eruptions. Other specific applications of cosmogenic isotope analysis to volcanic landforms have included using cosmogenic $^{3}He$ concentrations to investigate zonation and magma evolution of the Potrillo volcanic field, New Mexico, USA (Anthony and Poths, 1992; Eppes and Harrison, 1999), constraining surface flow stratigraphy and rates of eruption for Sierra Negra, the largest of the western Galapagos shield volcanoes (Reynolds *et al*., 1995), dating the displacement of volcanic features to constrain the age of caldera collapse on Réunion (Staudacher and Allègre, 1993), and quantifying rates of Quaternary fault movement in the Grand Canyon region, USA (Fenton *et al*., 2001; see Section IV, 2).

*b Depositional landforms:* Applications of cosmogenic isotope analysis to depositional landforms range from glacial moraines and erratics, to fluvial terraces, alluvial fans and debris flows, and lacustrine and marine shorelines. Compared with other methods for dating depositional landforms, such as conventional $^{14}C$ dating and luminescence techniques, the advent of *in situ* cosmogenic isotope methods has greatly expanded both the temporal range that can be addressed and the variety of sites that can be studied.

The dating of moraines and other glacial deposits through surface exposure ages has been a major application of cosmogenic isotope analysis, with most studies being focused on the chronology of the associated glacier fluctuations and their broader climatic and environmental implications, rather than with the dating of glacial landforms *per se*. Locations for such studies are worldwide, ranging from the British Isles (Bowen *et al*., 2002) to eastern Russia (Gualtieri *et al*., 2000), the western USA (Zreda and Phillips, 1995; Gosse *et al*., 1995a, b; Phillips *et al*., 1996, 1997, 1990; Chadwick *et al*., 1997; Licciardi *et al*., 2001; James *et al*., 2002), western Canada (Jackson *et al*.,1997, 1999), eastern Canada (Steig *et al*., 1998; Davis *et al*., 1999; Marsella *et al*., 2000; Kaplan *et al*., 2001; Miller *et al*., 2002), East Africa (Shanahan and Zreda, 2000), southeast Australia and Tasmania (Barrows *et al*., 2001, 2002), the Himalayas and Tibetan Plateau (Phillips *et al*., 2000; Owen *et al*., 2001, 2002a, b, c; Taylor and Mitchell, 2002; Schäfer *et al*., 2002a), and Antarctica (Brown *et al*., 1991; Brook and Kurz, 1993; Brook *et al*., 1993, 1995a, b; Fabel *et al*.,1997). A focal issue for a number of these and other studies of glacial deposits has been the chronology of glacial fluctuations marking the Late Glacial Maximum and the global synchrony, or otherwise, of the Younger Dryas (Ivy-Ochs *et al*., 1996, 1999; Tschudi *et al*., 2000; Briner *et al*., 2001, 2002; Phillips and Bowen, 2002; Bourlès *et al*., 2002; Schäfer *et al*., 2002b). However, in attempting to date the rapid climatic fluctuations represented by the last glacial to post-glacial transition, and in particular to identify any leads and lags in the climatic system between the northern and southern hemispheres, the current resolution of cosmogenic isotope analysis is being pushed to its limits, especially in view of uncertainties in cosmogenic nuclide production rates resulting from regional differences over time in the geomagnetic field and in mean atmospheric pressure (Stone, 2000; Gosse and Stone, 2001).

The simplest model for dating glacial moraines and similar glacial depositional forms assumes that blocks of bedrock with no prior exposure to cosmic radiation are either entrained at the glacier base, or fall on to the glacier surface and are rapidly incorporated as englacial debris. Subsequently these boulders are exposed at the surface when the ice cover is removed. Various factors, however, can produce more complex

scenarios and these can result in a moraine of a particular age having constituent boulders with a range of cosmogenic surface exposure ages, and indeed moraines with identical cosmogenic exposure ages not being correlative (Hallet and Putkonen, 1994). One of these factors is inheritance, where individual boulders already contain a significant inventory of cosmogenic nuclides through exposure to cosmic radiation prior to incorporation as englacial or subglacial debris. Others are the differential weathering and erosion of boulders of contrasting lithologies, and the progressive exposure of boulders in a moraine through the removal of overlying finer material. Inheritance, which appears to characterize 10–20% of moraine boulders (Gosse and Phillips, 2001; Briner *et al*., 2001), produces exposure ages greater than the age of the moraine, whereas erosion gives rise to younger ages. The variation in exposure age as a result of erosion, which is obviously more significant on older moraines, has been modelled by Zreda *et al*. (1994), but a common strategy for dating a moraine is simply to discount individual boulders with exposure ages significantly younger or older (typically by several standard deviations) than the overall mean age (e.g., Zreda *et al*., 1999; Briner *et al*., 2002). In spite of these issues of data interpretation, the potential of cosmogenic isotope analysis to identify complex moraine sequences and to challenge previous chronologies of glacial landform development based on correlation through stratigraphic position is clear (Fabel and Harbor, 1999; Zreda and Phillips, 1995).

The question of inheritance is also prominent in applications of cosmogenic isotope analysis to other depositional landforms such as fluvial terraces (Molnar *et al*., 1994), alluvial surfaces (Liu *et al*., 1996) and shoreline deposits (Trull *et al*., 1995). In dating fluvial terraces in Wyoming and Utah, Anderson *et al*. (1996) addressed the problem by analysing two amalgamated samples of 30 clasts each, one from the surface and one from the subsurface at a depth sufficient for the sample to have been shielded from post-depositional cosmic-ray exposure. This enabled them to constrain cosmogenic nuclide accumulation prior to deposition. Developments of this approach involving multiple-sample depth profiles have been used to date suites of fluvial (Repka *et al*., 1997; Hancock *et al*., 1999) and marine (Perg *et al*., 2001) terraces, while Phillips *et al*. (1998) have modelled different vertical profile patterns of cosmogenic $^{21}$Ne concentrations in stream terraces and alluvial fan deposits in New Mexico to assess the effects on exposure age of inheritance, changes in bulk density, erosion and burial. Where the age of a river terrace is independently known then the measured cosmogenic nuclide concentrations can be corrected for post-depositional production and the remaining cosmogenic nuclide inventory used to estimate the catchment-wide rate of denudation at the time of terrace formation (Schaller *et al*., 2002). More generally, cosmogenic surface exposure dating of fluvial terraces has significant potential for recording episodic incision and aggradation in fluvial systems over timescales of $10^4$–$10^5$ yr (Schildgen *et al*., 2002) and thereby providing much needed chronological constraints on models of episodic erosion and complex response.

## 2 Tectonic displacement

A major application of cosmogenic isotope analysis has been the dating of fault movements to infer slip rates and earthquake recurrence intervals. The advantage of cosmogenic exposure dating here is that timescales typically up to 50 ka can be

addressed and seismic activity is therefore being monitored over geologically useful time spans. In the majority of studies surface exposure dating of displaced depositional features has been used to provide age constraints on fault movement. Offsets on alluvial fans have been used in central Asia (Ritz *et al*., 1995; Brown *et al*., 1998a; Hetzel *et al*., 2002a, b ), the southwest USA (Bierman *et al*., 1995; Fenton *et al*., 2001; Zehfuss *et al*., 2001), Argentina (Siame *et al*., 1997) and Jordan (Klinger *et al*., 2000), on piedmont alluvial surfaces in Argentina (Siame *et al*., 2002) and on fluvial terraces at several locations along the Kunlun fault in Tibet (Van der Woerd *et al*., 1998, 2002). In Otago, New Zealand, Jackson *et al*. (2002) have inferred the rate of propagation of an anticline above a blind reverse fault from the trend in cosmogenic $^{10}$Be exposure ages of large silcrete boulders on the crest of the resulting uplifting ridge.

Fault displacement histories can also be inferred from cosmogenic nuclide inventories in bedrock fault scarps (Zreda and Noller, 1998). Measuring *in situ*-produced $^{14}$C in limestone, Handwerger *et al*. (1999) have estimated an age of ~4600 yr for the most recent movement of a fault in northern Utah, while Mitchell *et al*. (2001) have compared measured accumulations of cosmogenic $^{36}$Cl concentrations on a limestone scarp face in northern Israel with modelled accumulations through time based on different fault displacement scenarios. In this latter study the best matches between modelled and measured $^{36}$Cl concentrations indicated episodic behaviour of the fault and variations in mean displacement rate over the past 14 ka.

## 3 Episodic denudation

*a Meteorite impacts:* Perhaps the clearest example of an 'instantaneous' denudational event that exposes bedrock previously shielded from cosmic radiation is the creation of a crater by an impacting bolide. One of the most significant early applications of cosmogenic isotope analysis was the dating of the Meteor Crater impact site in Arizona, USA. Previous age estimates had ranged from 25 ± 5 ka, based on stage of soil development, to 49 ± 3 ka from thermoluminescence data. Two independent studies employing $^{36}$Cl (Phillips *et al*., 1991) and $^{10}$Be and $^{26}$Al (Nishiizumi *et al*., 1991a) confirmed the thermoluminescence dating, with Phillips *et al*. (1991) finding a mean age of 49.7 ± 0.85 ka for four ejected boulders, and Nishiizumi *et al*. (1991a) establishing an overall lower bound on the crater age of 49.2 ± 1.7 ka. Cosmogenic isotope analysis is clearly applicable to dating recently formed terrestrial impact structures, and thereby improving estimates of impact recurrence intervals, although erosional, weathering and burial effects make sampling and data interpretation more complex for older craters.

*b Rapid mass movement:* An important issue in geomorphology is gaining an accurate assessment of the significance in landscape development of high magnitude–low frequency events. Rapid mass movement represents a suite of processes which are difficult to monitor directly because of their low frequency, although they may represent an important mode of hillslope transport in a number of geomorphic settings. Dating of these events through cosmogenic isotope analysis is not only yielding valuable insights into their role *vis-à-vis* other geomorphic processes, but also providing key quantitative data on slope failure processes and recurrence intervals, and for natural hazard assessment.

Examining post-glacial landsliding on the Isle of Skye, Ballantyne *et al*. (1998) analysed cosmogenic $^{36}Cl$ in two blocks exposed during slope failure, but originating well below the original surface (in order to eliminate any inherited cosmogenic $^{36}Cl$). The measured surface exposure age of 6.5 ± 0.5 ka post-dates deglaciation by several thousand years and slope failure was therefore thought to be caused by joint extension and rock bridge shearing and/or seismic activity, rather than related to periglacial conditions. In attempting to relate rock failure events to seismic activity, Hermanns *et al*. (2000, 2001) have used cosmogenic $^{21}Ne$ to date eight superimposed rock avalanche deposits on the Puna Plateau in the central Andes, ranging in age from 152 to 31 ka, to investigate the influence of active faulting on slope oversteepening and subsequent gravitational collapse. In another study Bell *et al*. (1998) estimated the period elapsed since the last major seismic event at sites in California and Nevada by determining minimum- and maximum-limiting ages (using, respectively, rock-varnish microlaminations and cosmogenic $^{36}Cl$) of precariously balanced boulders that could be toppled by strong ground motion.

An important aspect of rapid mass movement events is their significance in environmental management. Through the relatively long timescales that it is able to address, cosmogenic isotope analysis can provide valuable benchmark data for comparison with historical or modern rates. For instance, in the Garwhal Himalaya, northern India, Barnard *et al*. (2001) have compared estimates of the enhancement of modern rates of landsliding and erosion caused by human activity (mostly through the removal of slope toes at road cuts) with longer-term rates of landsliding and river incision derived from cosmogenic $^{10}Be$ and $^{26}Al$ dating of strath terraces and two large (>10 million $m^3$) mid–late Holocene slides. They concluded that in their study area anthropogenic influences are accelerating rates of denudation. Debris flows can play a significant role in modifying river channels through creating rapids or natural dams, and their frequency is important in the management of regulated rivers. Using a range of historical data and a variety of chronological techniques in association with cosmogenic $^{3}He$ exposure dating of olivine phenocrysts in basalt clasts, Cerling *et al*. (1999) have been able to estimate recurrence intervals for debris flows entering the Grand Canyon reach of the Colorado River at tributary junctions.

In addition to the application of cosmogenic surface exposure dating to rapid mass movement events of previously unknown age, independently dated events are potentially valuable sites for calibrating cosmogenic nuclide production rates since major landslides instantaneously expose rock previously buried below the depth of cosmic ray penetration. For example, the age of the Köfels landslide in Austria (9800 ± 100 yr dendro-calibrated relative to 1995) has been tightly constrained by $^{14}C$ dating of buried wood, and this has been used to determine the production rates of cosmogenic $^{10}Be$ and $^{26}Al$ (Ivy-Ochs *et al*., 1998; Kubik *et al*., 1998).

*c Catastrophic flooding:* As with major landslides, sites experiencing rapid erosion of bedrock or large boulders through deep scouring by catastrophic floods can be valuable for cosmogenic nuclide production rate studies when there is independent dating of flood events. For instance, erosion by the Bonneville flood in the Snake River Plain at the end of the last glacial (~17.6 ka BP) has been used by Cerling (1990) and Cerling and Craig (1994b) to provide calibration sites for cosmogenic $^{3}He$ production. Cosmogenic surface exposure dating also has the potential to provide ages for

previously undated catastrophic flooding events, as illustrated by the study of Cerling *et al*. (1994) who used cosmogenic $^{3}$He and $^{21}$Ne in basalt boulders and scoured bedrock to date the Big Lost River flood through Box Canyon in south-central Idaho. A range of ages amongst the samples was ascribed to inheritance of pre-flood cosmogenic nuclide production, but together the data indicated a maximum age of ~20.5 ± 1.9 ka for the Big Lost River flood. This is essentially identical to the $^{3}$He age of 20.5 ± 0.8 ka for the Owens River flood in California (Cerling, 1990; Cerling and Craig, 1994b). Both ages correlate with the beginning of the Missoula floods in the northwest USA and together they may indicate the start of glacial melting in the western USA (Cerling *et al*., 1994).

*d Strath terraces:* While catastrophic floods can scour bedrock to depths of many metres in a single event, lateral erosion of bedrock valley walls and progressive vertical incision of bedrock channels by 'normal' flood events can create flights of strath terraces whose height above the present channel and surface exposure age (time elapsed since abandonment) can together yield long-term mean rates of channel incision. Such incision rates are a key variable characterizing regional-scale rates of denudation and landscape change, especially in active orogenic settings. For instance, in the middle gorge of the Indus River near Nanga Parbat in the northwest Himalayas, cosmogenic $^{10}$Be and $^{26}$Al surface exposure ages of well-preserved strath terraces up to 410 m above the present channel indicate incision rates of 1–12 m ka$^{-1}$ with an acceleration of rates 15 ka ago (Burbank *et al*., 1996; Leland *et al*., 1998). To the southeast in the Garwhal Himalaya , Barnard *et al*. (2001) have inferred a fluvial incision rate of 4 m ka$^{-1}$ from two cosmogenically dated terraces above the Alaknanda River in their study focused on rates of landsliding. Strath terraces often exhibit patchy alluvial cover implying a complex history involving temporary burial after their initial formation. Careful field assessment prior to sampling is therefore necessary in order to assess the suitability of a simple surface exposure model (Molnar *et al*., 1994; Anderson *et al*., 1996). Where a simple exposure history does not apply surface exposure ages of flights of strath terraces cannot be used directly to estimate channel incision rates, but may yield other useful information. For instance, Pratt *et al*. (2002) found similar surface cosmogenic ($^{10}$Be and $^{26}$Al) exposure ages of around 7 ka BP for fluvially eroded surfaces in central Nepal across a height range of 43–124 m above the channel of the Marsyandi River and interpreted this to be the result of filling of the valley by sediment at least 80 m thick during a period of more active landsliding triggered by enhanced early Holocene monsoonal precipitation.

*e Wave-cut platforms:* Analogous to the cutting of new surfaces into bedrock by fluvial channel incision is the formation of wave-cut platforms through the erosive effects of wave action on shoreline bedrock outcrops. The exposure histories (formation ages) of these landforms are important both in tracking relative sea-level change, and, where the global sea-level change is independently constrained, quantifying rates of active tectonic, or glacio-isostatic, surface uplift. Although radiocarbon dating and other radiometric techniques have been widely employed, notably to raised coral reefs, cosmogenic isotope analysis is valuable where the bedrock, or associated deposits, are not suitable for these other dating methods. Stone *et al*. (1996) have presented data for the 'Main Rock Platform' in western Scotland with cosmogenic $^{36}$Cl apparent ages or 'effective irradiation times' based on a simple exposure model. They note, however, that

this will not represent the true age if marine transgressions or other temporary shielding effects are not taken into account. Nonetheless, even with these uncertainties, their study demonstrates that apparent ages alone place the formation of the Main Rock Platform firmly in the termination phase of the last glacial.

## 4 Removal of ice cover

Conceptually, one of the simplest applications of cosmogenic isotope analysis is dating the removal of an ice cover from bedrock surfaces, moraines or glacial erratics. It is not surprising therefore, that much emphasis was placed on this kind of study in the initial applications of cosmogenic surface exposure dating. For instance, Nishiizumi *et al*. (1989) used glacially polished rocks exposed by the (radiocarbon-dated) retreat of Tioga stage glaciers in the Sierra Nevada to calibrate $^{10}$Be and $^{26}$Al production rates (see also Clark *et al*., 1995). Cosmogenic isotope exposure dating of glacial retreat across bedrock surfaces has subsequently been applied in Antarctica (Nishiizumi *et al*., 1991b), eastern Canada and the Arctic (Bierman *et al*., 1999; Gualtieri and Brigham-Grette, 2001) and the Swiss Alps (Kelly *et al*., 2002). Many studies of the chronology of glacial retreat have combined data on bedrock forms with the exposure of glacial depositional landforms, the assumption being that careful sampling from features such as moraines and erratics can also provide reliable constraints on the timing of glacial retreat (e.g., Ivy-Ochs *et al*., 1997; Steig *et al*., 1998; Schäfer *et al*., 1999; Zreda *et al*., 1999; Marsella *et al*., 2000; Kaplan *et al*., 2001; Karhu *et al*., 2001; Owen *et al*., 2001, 2002b; Bourlès *et al*., 2002; Bowen *et al*., 2002; Oberholzer *et al*., 2002; James *et al*., 2002; Stone *et al*., 2002) (see Section IV, 1 *b*).

An exposure age for the removal of ice cover through glacial retreat or wasting will only be valid if the thickness of shielding ice (several multiples of the attenuation length for ice) has been sufficient to effectively shut down cosmogenic nuclide production. Moreover, the depth of scouring by glacial erosion prior to a glacial retreat episode has to be great enough to remove the vertical zone of bedrock in which cosmogenic nuclides produced during any earlier exposure episode would be residing. If this were not the case, the cosmogenic nuclide concentration measured would include an inherited component. In some studies, such as that for Tumbling Glacier, Baffin Island (Davis *et al*., 1999), samples collected just beyond an actively retreating ice front have indeed been found to contain minimal cosmogenic nuclide concentrations. But instances where this is not the case can provide valuable insights into the effectiveness of glacial erosion during individual episodes of glacial advance. For example, assuming that any inherited cosmogenic nuclide component related only to the most recent interglacial, Briner and Swanson (1998) calculated an erosion rate of 0.09–0.35 mm yr$^{-1}$ for the Cordilleran Ice Sheet at Mt Erie in the Puget Sound region of Washington State, USA from excessive cosmogenic $^{36}$Cl concentrations compared with the well-constrained radiocarbon deglaciation age. In studying the possible preservation of preglacial topography in areas subject to frozen bed conditions under the Fennoscandian Ice Sheet in Sweden, Fabel *et al*. (2002) and Stroeven *et al*. (2002) have found that cosmogenic nuclide concentrations in erratic boulders gave consistent deglaciation ages, thus confirming ice sheet overriding as opposed to ice-free conditions, but concentrations of $^{10}$Be and $^{26}$Al in preserved tors within the landscape suggested minimal erosion over several glacial cycles. Similarly, Bierman *et al*. (1999) and Gosse and Willenbring (2002)

have found complex exposure histories and evidence of inheritance indicating differential erosion under the Laurentide Ice Sheet.

The vertical extent of former glaciers and ice sheets is an important variable required for determining past ice volumes and for palaeoclimatic reconstructions. Geomorphic indicators of previous ice levels range from clearly defined trim lines to more equivocal weathering limits which may reflect other zones of process transition, such as post-glacial differential weathering or englacial boundaries between wet-based eroding ice and noneroding frozen-bed ice. Cosmogenic exposure dating of bedrock surfaces across these transition zones can help to distinguish between different processes of formation, as well as providing information on the chronology of changes in ice volume (Brook *et al*., 1996; Stone *et al*., 1998b).

## 5 Burial events

*a Sediment burial:* In addition to the chronological information that can be derived from cosmogenic nuclide concentrations in deposits formed on the land surface, valuable information can also be garnered in circumstances where sediments previously exposed to cosmic radiation are rapidly buried beyond the zone of cosmogenic nuclide production. This is because the differential decay of cosmogenic nuclides with different half-lives will indicate the time elapsed since burial, and hence the date of deposition. A particularly useful situation in which such rapid sediment burial occurs is in caves, and in the first use of this application Granger *et al*. (1997) measured cosmogenic $^{10}$Be and $^{26}$Al concentrations to date burial times of alluvium deposited in abandoned caves above the present level of the New River, Virginia, USA, and to constrain the rate of downcutting of the river during the Quaternary. Granger *et al*. (2001a) also constrained the evolution of Mammoth Cave in Kentucky by dating a series of sediments deposited by the Green River. They were able to show that the river's incision history was in step with major climatic changes and drainage reorganizations associated with fluctuations in the margin of the Laurentide Ice Sheet.

The cosmogenic nuclide inventories in sediments buried within depositional forms such as river terraces can also provide valuable chronological information. For example, although determining the cosmogenic nuclide concentration of surface samples can yield valid ages for well-preserved river terraces (see Section IV, 1, *b*), this strategy cannot be applied to older, degraded terraces which may have experienced several metres of erosion. In such cases, however, the differential decay of two radioactive cosmogenic isotopes (commonly $^{26}$Al and $^{10}$Be) collected from depth can be used to estimate the age of terrace formation assuming that post-burial cosmogenic nuclide production is known (Granger and Smith, 2000). Such production can continue at a depth of several metres because of the deep penetration of fast muons (Granger and Smith, 2000; Granger and Muzikar, 2001).

*b Burial of glacial ice:* An unusual, but key, application of cosmogenic isotope data to constrain the chronology of a burial event is provided by the controversy over the age of a subsurface body of glacial ice in Beacon Valley, Southern Victoria Land, Antarctica. The significance of this buried ice is that if it is of Miocene age (minimum 8.1 Ma BP) – as has been inferred from stratigraphic relationships to overlying tills

dated by $^{40}Ar/^{39}Ar$ analyses of presumed *in situ* volcanic ash – it confirms the persistence of a cold, hyper-arid climate in the area throughout the Pliocene and refutes the notion of an unstable East Antarctic Ice Sheet during this period (Sugden *et al*., 1995). The ability of ice in the near subsurface to survive sublimation over the time spans proposed has been questioned (Hindmarsh *et al*., 1998), as has the interpretation that the volcanic ash deposits are undisturbed and thus provide a chronological constraint on the age of the ice. Through an analysis of the concentrations of cosmogenic $^{3}He$ and $^{21}Ne$ in two surface dolerite erratics and one shielded erratic from within the ice, Schäfer *et al*. (2000) demonstrated that sublimation rates could not have exceed more than a few metres per million years and that the ice must be at least several million years old. Marchant *et al*. (2002) have addressed the question of whether the volcanic ash is *in situ*, especially in view of the presence of well-developed polygonal patterned ground developed in the till. Two profiles of cosmogenic $^{3}He$ concentrations through the till deposit show it to have formed through sublimation of the underlying ice and indicate the long-term stability of the till layer in areas unmodified by pattern ground formation.

## V Incremental change

### 1 Site-specific denudation rates

As pointed out in Section III, most of the Earth's surface is subject to the incremental change associated with bedrock weathering, hillslope processes, and sediment and solute transport, rather than discrete geomorphic events involving the instantaneous exposure of rock through the removal of several metres of overburden. Consequently, rather than thinking of an 'event exposure age', in most cases it is more meaningful to interpret concentrations of cosmogenic nuclides as reflecting these rates of incremental denudation.

The key to quantifying denudation rates using surface concentrations of cosmogenic nuclides is changes in production with depth, since denudation involves bringing up to the surface rock that was previously buried. In a steadily eroding rock outcrop, the cosmogenic nuclide concentration approaches saturation, or secular equilibrium, as a result of constant production on the one hand and losses by denudation as well as radioactive decay (in the case of radionuclides) on the other. After initial exposure secular equilibrium will be reached when sufficient time has elapsed for denudation to remove a depth of rock two or three times the attenuation length (see Section III), assuming denudation has been occurring in small increments relative to the attenuation length. Under these circumstances a measured surface concentration can be accurately modelled in terms of a constant denudation rate representing an integrated rate for the minimum period of time required to reach secular equilibrium (Nishiizumi *et al*., 1986; Kurz, 1986b; Lal, 1991). This model is commonly referred to as the 'steady-state erosion model', with the term 'steady-state' often used to refer to both secular equilibrium and the particular style of denudation required to satisfy the model. If the system has not yet reached saturation, then the model will overestimate the denudation rate, whereas if erosion is occurring episodically (i.e. in increments that are large relative to the attenuation length), or the exposure history is complex and has included periods of burial, then the model may either overestimate or underestimate the true rate (Lal, 1991;

Small *et al*., 1997). In favourable circumstances, the ratio of two radionuclides with different half-lives can be used to test the assumptions of the steady-state erosion model. The ratios of $^{10}$Be and $^{26}$Al are commonly used in such cases to test for complex exposure histories involving burial episodes and/or episodic or highly temporally variable denudation rates, with the behaviour associated with particular isotope ratios being depicted on an erosion-island graph (Klein *et al*., 1986; Lal, 1991). Measurement uncertainties mean that the test for episodic denudation may be inconclusive, progressively more so for denudation rates >1 m Ma$^{-1}$ (Small *et al*., 1997). Nonetheless, even though errors resulting from an inappropriate application of the steady-state erosion model can be greater than both measurement and production rate errors, a more accurate denudation rate estimate can be obtained by calculating the mean from many individual steady-state erosion rate measurements (Small *et al*., 1997).

Site-specific denudation rates based on the steady-state erosion model have been estimated for a wide range of locations and geomorphic settings (Table 3). These rates are naturally biased towards low values because of preferential sampling of bare bedrock surfaces that are usually the most slowly eroding and resistant components of the local landscape. Variations in rates can also be evident depending on microtopography and other detailed characteristics of the specific sampling site selected. Extrapolation of these rates across the landscape can, therefore, be problematic, and uncertainties can arise from the difficulties in strictly fulfilling the assumptions of the steady-state erosion model. Notwithstanding these caveats, the studies listed in Table 3 represent a major advance in quantifying rates of denudation integrated over geomorphologically useful periods of time ($10^3$–$10^6$ years) compared with the previous paucity of data relevant to these timescales. That uncertainties over the appropriate erosion model in any particular case, together with analytical and production rate errors, may produce total errors in denudation rate estimates in some cases exceeding 50% must be placed in the context of the lack of data for similar timescales provided by other techniques. Whilst such large errors would be unacceptable in cosmogenic surface exposure studies attempting, for instance, to resolve uncertainties in the timing of late glacial events, they may not be problematic in studies where establishing approximate rates of denudation is sufficient to test often long-standing notions about rates and modes of landscape change. For example, cosmogenic-nuclide based estimates of escarpment retreat rates of 10–100 m Ma$^{-1}$ over the past $10^4$–$10^6$ yr for the Great Escarpment in southern Africa contrast with a mean rate of retreat of the order of 1000 m Ma$^{-1}$ implied by King's classic model of landscape evolution for the area (Fleming *et al*., 1999; Cockburn *et al*., 2000). Similarly, although cosmogenic nuclide concentrations have demonstrated some exceedingly slow rates of denudation of ~5 m Ma$^{-1}$ or less for erosion surfaces and inselbergs in Australia, southern Africa and Antarctica (Nishiizumi *et al*., 1991b; Bierman and Turner, 1995; Cockburn *et al*., 1999; Cockburn and Summerfield, 2000; Summerfield *et al*., 1999a, b ; Belton *et al*., 2000; Bierman and Caffee, 2001), these rates would still be too high to preserve intact erosion surfaces over the time intervals of up to 50 Ma or more that have been proposed.

## 2 Catchment-averaged denudation rates

An obvious potential limitation of site-specific sampling in providing data relevant to denudation rates at a broader scale is the 'nonrandom' nature of sample selection.

Where sampling is from bedrock outcrops in terrain that is predominantly blanketed by regolith, denudation rates are likely to be less than the regional average since exposed bedrock is likely to be present because it is eroding less rapidly than its surroundings. In principle, however, the process of denudation, from the weathering of bedrock to the transport of material on slopes and the transmission of sediment in river channels, provides a natural sampling mechanism whereby each of many thousands of individual mineral grains in a river sediment sample will carry its own history of exposure to cosmic radiation. By averaging together these individual exposure histories through the analysis of a single sample of sediment from a river channel it is possible to estimate the mean rate of denudation for the catchment area upstream of the sampling site. This principle was first suggested by Lal and Arnold (1985), and was tested by Brown *et al*. (1995a) in the Icacos basin in Puerto Rico, where a denudation rate of ~43 m $Ma^{-1}$ was estimated. This study, together with that of Granger *et al*. (1996), identified a range of factors that have to be addressed in making such denudation rate estimates; these include variations in production rates throughout the basin (especially as a function of elevation), variations in bedrock mineralogy, the storage and remobilization of sediment, differential weathering of different calibre grains, regolith mixing through bioturbation, physical weathering and slope processes, and the mixing of sediment from areas of different erosion rates. In evaluating the method, Granger *et al*. (1996) compared denudation rates estimated from cosmogenic nuclide concentrations in present-day river sediment with rates derived from sediment volumes in well-dated alluvial fans in two small catchments in northeast California. The close correspondence between the two sets of estimates confirmed that in small catchments with little sediment storage cosmogenic nuclide concentrations in river sediment can provide a good estimate of basin-wide long-term denudation rates. In a general assessment of the viability of this basin-averaged approach to cosmogenic isotope analysis, Bierman and Steig (1996) concluded that it provides an effective means of estimating denudation rates in basins in isotopic steady state and where the sampled sediments are well mixed. However, care has to be taken where quartz grains are being analysed (as is frequently the case for cosmogenic $^{10}Be$ and $^{26}Al$) since the relative resistance of quartz to dissolution means that its residence time in regolith will be longer than the average for all mineral grains (Small *et al*., 1999), although the resulting bias is probably modest compared with the other uncertainties in cosmogenic denudation rate estimates (Riebe *et al*., 2001a).

The ability to use cosmogenic nuclide concentrations to characterize basin-wide as well as site-specific denudation rates has provided the opportunity to compare areally averaged denudation rates with those for specific landform elements and subcatchments within basins. For instance, Granger *et al*. (2001b) showed that in the Diamond Mountains batholith in California, exposed granite bedrock has been eroding more slowly than the average rate for catchments in which they are found. Similarly, Bierman and Caffee (2001) found that denudation rates for bedrock samples in Namib Desert were lower than catchment-averaged rates from channel sediment samples. In the Yuma Wash basin in southwest Arizona, Clapp *et al*. (2002) used channel sediment samples to compare sediment generation rates for subcatchments as well as the basin as a whole. They found that in the upland subcatchments cosmogenic nuclide concentrations reflect rates of sediment generation from bedrock weathering, whereas sediment in the main channel also includes the long-term effects of sediment storage

**Table 3** Site-specific denudation rates determined from *in situ*-produced cosmogenic nuclides in bedrock samples

| Source | Location | Lithology | Field setting and comments | Isotope | *n* | Rate (mm ka$^{-1}$) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Mean | Range |
| Nishiizumi *et al.*, 1991b | Allan Hills, southern Victoria Land, Antarctica | sandstone | Samples from boulders and bedrock outcrops from Beacon Supergroup | $^{10}$Be, $^{26}$Al | 9 | 0.7 | 0.3–1.3 |
| | Sör Rondane Mts, Droning Maud Land, Antarctica | ? | Mean rate and range exclude two samples with complex exposure history | | 6 | 0.17 | 0.06–0.45 |
| | Wright Valley, southern Victoria Land, Antarctica | sandstone | Bedrock from horizontal platforms | | 7 | 0.9 | 0.5–1.3 |
| Summerfield *et al.*, 1999a | Dry Valleys region, southern Victoria Land, Antarctica | granite, sandstone | Rectilinear slope samples | $^{21}$Ne | 4 | 0.56 | 0.26–1.02 |
| | | | Plateau surface samples | | 4 | 0.15 | 0.13–0.16 |
| Brown *et al.*, 1995a | Icacos River, Luquillo Mts, Puerto Rico | quartz-diorite | Bedrock ridge crest samples | $^{10}$Be | 2 | 25 | – |
| Small *et al.*, 1997 | Wind River, Wyoming, USA | granite, gneiss | Tor and large boulder samples from summit flats (2–10° slope) showing no evidence of prior glaciation | $^{10}$Be, $^{26}$Al | 7 | 7.5 | 3–12 |
| | Beartooth, Montana, USA | granite | | | 5 | 10.5 | 6–19 |
| | Front Range, Colorado, USA | granite, schist | | | 4 | 7.4 | 6–9 |
| | Sierra Nevada, California, USA | granite | | | 3 | 3.0 | 2–5 |
| Small *et al.*, 1999 | Wind River Range, Wyoming, USA | granite, gneiss | Samles from regolith profiles and buried bedrock | $^{10}$Be, $^{26}$Al | 18 | 13.7 | 12.16 |
| Heimsath *et al.*, 1997, 1999 | Marin County, northern California, USA | greenstone, greywacke, sandstone, chert | Isolated bedrock outcrops on hillslopes | $^{10}$Be, $^{26}$Al | 3 | 24.7 | 15–39 |
| | | | From subsoil bedrock samples on hillslopes estimated assuming steady-state soil thickness | | 11 | 46.5 | 21–105 |
| Heimsath *et al.*, 2001a | Coast Range, Oregon, USA | sandstone, siltstone | From subsoil bedrock on samples on hillslopes estimated assuming steady-state soil thickness (although field evidence suggests temporal variation in local soil depth) | $^{10}$Be, $^{26}$Al | 31 | 122.5 | 15–359 |
| Granger *et al.*, 2001b | Diamond Mts, California, USA | hornblende, granodiorite | Bedrock samples from exposures along catchment ridges | $^{10}$Be, $^{26}$Al | 3 | 8.2 | 6–12 |
| | Fort Sage Mts, California, USA | biotitie-granite | | | 1 | 19 | – |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Weissel and Seidl, 1998 | Macleay River System, eastern New South Wales, Australia | granite | Gorgehead erosion | $^{10}$Be, $^{26}$Al | 6 | ~100 | 52–195 |
| | | | Plateau surface above gorge | | 1 | 4.0 | – |
| Bierman and Turner, 1995; Bierman and Caffee, 2002 | Eyre Peninsula, south-central Australia | granite | Bedrock samples from inselberg summits including boulders and slabs on summit surface | $^{10}$Be, $^{26}$Al | 27 | 0.8 | 0.3–2.5 |
| | | | Exposed boulders and bedrock samples from inselberg flanks | | 21 | 2.1 | 0.5–5.0 |
| Heimsath *et al.*, 2000 | Upper Bega Valley, New South Wales, Australia | granite, granodiorite | From subsoil bedrock saprolite samples on slopes at base of escarpment estimated assuming steady-state soil thickness | $^{10}$Be, $^{26}$Al | 14 | 28.6 | 9–57 |
| | | | From sides and tops of tors | | 7 | 15.8 | 9–26 |
| Heimsath *et al.*, 2001b | Breadho River Valley, southeastern Highlands, New South Wales, Australia | granite | Tors on plateau hillslopes | $^{10}$Be, $^{26}$Al | 10 | 10.0 | 4–28 |
| Bierman and Caffee, 2002 | Northern Territory, Australia | granite | Bedrock samples from tops of large boulders and inselberg summits | $^{10}$Be, $^{26}$Al | 7 | 1.96 | 0.7–3.7 |
| | | | Bedrock samples from low lying rock platforms and flanks of inselbergs | | 6 | 2.6 | 1.2–3.8 |
| Cockburn *et al.*, 1999 | Central Namib Desert, Namibia | granite | Bedrock samples from bornhardts, some evidence of complex exposure | $^{10}$Be, $^{26}$Al | 6 | 5.1 | 3–7 |
| Cockburn *et al.*, 2000 | Gamsberg, central Namibian escarpment, Namibia | granite-gneiss | Samples from ridges extending below escarpment face | $^{10}$Be, $^{26}$Al | 6 | 7.2 | 2–15 |
| | | sandstone | Escarpment face samples | | 4 | 7.2 | 5–12 |
| | | | Gamsberg (escarpment) summit | | 4 | 0.44 | 0.35–0.50 |
| Bierman and Caffee, 2001 | Central Namib Desert, Namibia | granite, gniess, quartz veins, schist | Bedrock samples from tops and flanks of inselbergs and smaller rocky outcrops | $^{10}$Be, $^{26}$Al | 47 | 3.5 | 1.1–7.5 |
| Van der Wateren and Dunai, 2001 | Central Namib Desert, Namibia | quartz veins | Exposed veins on gravel and sand-covered pediment surface | $^{21}$Ne | 4 | 0.46 | 0.11–1.04 |
| | | | River cut bedrock surfaces, 6 m and 0 m above present dry channel, respectively | | 2 | 0.9 | 0.41–1.4 |
| Fleming *et al.*, 1999 | Drakensberg Escarpment | basalt | Escarpment face | $^{36}$Cl | 2 | 55 | 48–62 |
| | | | Flat-lying escarpment summit | | 3 | 6 | 1–10 |

**Notes**: rates are mean values from all isotopes used. Uncertainties on denudation rates from analytical and production rate errors are typically 5–20%. Most denudation rate estimates assume a 'steady-state' erosion model.

and reworking. Further west in the Mojave Desert Nichols *et al*. (2002) have measured cosmogenic $^{10}$Be and $^{26}$Al in sediment samples to document rates and processes of piedmont modification.

As well as exploring the spatial variability of denudation rates, catchment-averaged rates derived from cosmogenic nuclide concentrations (which reflect denudation over periods of $10^3$–$10^6$ years) can usefully be compared with rates derived from modern measurements of river sediment yield. For instance, Brown *et al*. (1998b) used cosmogenic $^{10}$Be in fluvial sediments to assess differences between modern and pre-development rates of denudation in Puerto Rico, and found evidence for a significant anthropogenic enhancement of modern sediment discharges. In the Negev Desert, Israel, Clapp *et al*. (2000) compared the 33-yr sediment budget of a small, intensively studied basin with cosmogenic $^{10}$Be and $^{26}$Al estimates of the longer-term sediment flux and found that the modern rates of sediment transport exceed the longer-term average by 53–86%, thus indicating current evacuation of sediment accumulated during previous periods of enhanced sediment generation. By contrast, in the more humid setting of western Europe, Schaller *et al*. (2001) found catchment-averaged denudation rates from cosmogenic $^{10}$Be in quartz for catchments in the Allier, Meuse, Neckar and Regen basins to be 1.5–4 times greater than those derived from modern river loads. They suggest that this may be due to under-representation in the modern record of high magnitude–low frequency events, to inheritance of an elevated Pleistocene signal or to nonuniform erosion and preferential sourcing of modern sediment from the deeper (and therefore less cosmogenically exposed) zones of the subsurface. A similar relationship between modern and longer-term rates was found by Kirchner *et al*. (2001) in their assessment of erosion rates over a range of timescales in mountainous granitic catchments in Idaho, USA. Here they estimated that mean rates over the past ~10 ka derived from cosmogenic $^{10}$Be concentrations in river sediment are on average 17 times greater than modern stream fluxes, a difference that they interpret as arising from the underestimation of rare but catastrophic erosional events in short-term stream-load monitoring. Clearly even these few studies both caution against simple generalizations about anthropogenic enhancements of modern sediment discharges and question the reliability of short-term records of river sediment load as indicators of longer-term process rates.

The growing application of catchment-averaged denudation rates from cosmogenic nuclide concentrations has gone beyond the simple documentation of rates and comparison of different timescales to the testing of assumptions about the efficacy of factors controlling denudation and landscape development. For example, measurements of cosmogenic $^{10}$Be and $^{26}$Al in stream sediments in the Sierra Nevada have demonstrated a strong augmentation of denudation rates in the proximity of fault scarps (Riebe *et al*., 2000), but a lack of correlation with climate (Riebe *et al*., 2001b). Moreover, by combining estimates of long-term rates of mechanical denudation from cosmogenic nuclide concentrations in sediment with estimates of solute loss from the enrichment of insoluble elements in regolith, Riebe *et al*. (2001c) have shown a strong correlation between rates of mechanical and chemical denudation, but a lack of correlation between chemical denudation rates and climate.

## 3 Accumulation and ablation of ice surfaces

A specific application of cosmogenic isotope analysis of relevance to glacial geomorphology involves the use of $^{10}$Be and $^{14}$C produced *in situ* in ice by neutron spallation of oxygen nuclei as recorders of glacier accumulation and ablation rates (Lal *et al*., 1987; Lal and Jull, 1990; Jull *et al*., 1994a). This is analogous to the use of cosmogenic isotopes to record sediment deposition and denudation, except that it is the accumulation or loss of ice that is being recorded by cosmogenic nuclide concentrations. However, differentiating the *in situ* component from atmospheric cosmogenic nuclides trapped in air during the firn–ice transition and those deposited by wet precipitation is complex. This is particularly so for $^{10}$Be since atmospheric sources exceed the *in situ* component by an order of magnitude and this kind of application is therefore limited to special cases (Lal and Jull, 1992). For instance, using $^{14}$C Lal *et al*. (1990) estimated ice ablation rates of 58 ± 7 and 76 ± 8 mm yr$^{-1}$ for two locations in the Allan Hills main ice field, Antarctica, these rates being in agreement with those determined using stakes. Similarly, the $^{14}$C-based estimates by Lal *et al*. (1987) of accumulation rates for the Greenland Ice Sheet were also found to be in line with recent model estimates.

## 4 Regolith and soil development

The depth-dependence of cosmogenic nuclide production rates provides a valuable means of quantitatively monitoring those processes in soil and regolith in which there is a vertical component to the movement of material relative to the surface. Using this approach, data from cosmogenic isotope analysis have started to provide the means to evaluate models of soil and regolith development that were previously untestable with reference to the usually lengthy timescales over which the relevant processes operate. An elegant example is provided by the testing by Wells *et al*. (1995) of a model of stone (desert) pavement formation. In contrast to the idea of stone pavements resulting from a progressive concentration of gravel at the surface as a result of the swelling and shrinkage of surrounding fines, or through the removal of fines through deflation or sheet wash, the similarity of surface exposure ages derived from cosmogenic $^{3}$He concentrations in their pavement gravel and adjacent bedrock samples demonstrated continuous exposure of both components. As also shown in a similar study by Shepard *et al*. (1995), these data are inconsistent with the gradual emergence of individual gravel clasts over an extended period of time (the 'lag' hypothesis), but accord with a model of stone pavement formation involving vertical inflation through the infiltration of fines from above.

The very extended time periods over which duricrusts, lateritic weathering profiles and associated weathering materials typically develop mean that the processes that form them cannot be adequately encompassed by short-term measurements or monitoring. Cosmogenic nuclides, however, provide a powerful means of investigating the long-term development of such weathering forms through their ability to record progressive burial or exposure of components of weathering profiles. For instance, Brown *et al*. (1994) used $^{10}$Be and $^{26}$Al measurements in quartz veins and pebbles in West African lateritic crusts both to determine erosion rates for the weathering profile surfaces and to distinguish between profiles that are being eroded from those that are experiencing burial. Other work on Brazilian and African lateritic profiles has used

cosmogenic $^{10}$Be and $^{26}$Al to differentiate between autochthonous and allochthonous components of lateritic systems – and hence the role of *in situ* weathering and colluvial transport in their development, and to constrain models of stone-line formation (Braucher *et al*., 1998a, b, 2000). Cosmogenic isotope analysis has also been applied to calcretes using $^{36}$Cl, with the study by Liu *et al*. (1994) indicating, through an increase in age with depth, that at their site in southern Arizona calcretes develop by upward accumulation and that water movement is very limited once induration has occurred. The potential of cosmogenic isotope analysis to reveal complex components of weathering profile development is illustrated by the study of Schroeder *et al*. (2001) in the piedmont zone of Georgia, USA. Here a significantly younger age (maximum ~8000 yr) for $^{14}$C bound in gibbsite compared with near surface residence times for quartz, based on $^{10}$Be and $^{26}$Al inventories, of at least 90 ka points to significant recrystallization of secondary minerals during weathering front propagation into bedrock.

## 5 Soil production, erosion and landscape development

The rate at which soil (regolith) is produced is a key geomorphological parameter because it is the entrainment and transport of unconsolidated material rather than the direct erosion of bedrock that dominates in most environments. Soil depth is a function of the rate of soil production and the rate of removal by physical erosion and solutional loss. But it has long been recognized that the rate of soil production is itself also influenced by soil depth (Gilbert, 1877), although the precise nature of this relationship has been disputed. The relationships between slope, soil depth, rate of soil production and rate of hillslope erosion are fundamental to understanding the surface processes controlling landscape evolution, and the ability of cosmogenic isotope analysis to provide quantitative insights into these processes and their relationships is likely to provide one of its most significant contributions to geomorphology. Already these applications are being exploited. For instance, in a study of regolith production on hillslopes in an alpine environment in Wyoming, USA using $^{10}$Be and $^{26}$Al concentrations from depth profiles, Small *et al*. (1999) have established that the rate of regolith production has been nearly twice as rapid under ~0.9 m of regolith than that previously determined from erosion rates on bare rock surfaces from similar (although not identical) alpine environments in the western USA (Small *et al*., 1997).

Making the assumption that bedrock conversion to soil attains a steady state under a constant soil thickness, Heimsath *et al*. (1997, 1999) used cosmogenic $^{10}$Be and $^{26}$Al concentrations in bedrock at the base of the soil column to evaluate the relationship between soil production rate and soil depth. For their field area in northern California they found an exponential decline in production rate with increasing soil depth from 77 mm ka$^{-1}$ with no soil cover, to 7.7 mm ka$^{-1}$ under a soil depth of 1 m. Although from their data they could not rule out a maximum in soil production rate under a thin soil cover (a long-standing notion in geomorphology (Carson and Kirkby, 1972)) they were able to confirm that peak soil production does occur very close to zero soil depth. Results from a similar study in southeastern Australia confirmed the exponential decline in rates of soil production with increasing soil depth (Heimsath *et al*., 2000).

Extending this approach to an intensively studied field site in the Oregon Coast Range, Heimsath *et al*. (2001a) concluded from a $^{10}$Be- and $^{26}$Al-derived analysis of soil

production rates that although there may be an approximately constant rate of landscape erosion over parts of the Oregon Coast Range, smaller-scale processes such as drainage competition and stochastic erosional events, especially by biogenic processes, lead to significant temporal and spatial variations in soil depth. Further applications in southeastern Australia illustrate how cosmogenic isotope data can be used to quantify long-term relationships between rates of soil production, bedrock incision, and regional erosion and regolith stripping (Heimsath *et al*., 2000, 2001b).

Another strategy for estimating soil accumulation and erosion rates is provided by depth profiles of cosmogenic nuclide concentrations in soils (Phillips *et al*., 1998; Phillips, 2000). Anomalously low erosion rates using this method can be produced from the inheritance of cosmogenic nuclides from old soils incorporated into colluvium, while bioturbation can produce depth profiles of cosmogenic nuclide concentration that are very similar to those associated with rapid soil accumulation. Fortunately, the distinctive profile produced through the rapid radioactive decay of *in situ*-produced $^{14}C$, when coupled with measurements of stable (e.g., $^{21}Ne$) or longer-lived isotopes (e.g., $^{10}Be$), can resolve the effects of both bioturbation and inheritance (Phillips, 2000). The potential for cosmogenic isotope data to elucidate specific processes operating in soils on hillslopes, especially when combined with other techniques, has been illustrated by Heimsath *et al*. (2002). They used cosmogenic nuclide concentrations of $^{10}Be$ and $^{26}Al$ to measure the overall downslope flux of soil material, in combination with single-grain OSL dating to track the movement of individual quartz grains in order to quantify the grain-scale mechanisms involved in the process of soil creep.

## VI Palaeoaltimetry

A fundamental difficulty in testing models of long-term landscape development is the lack of data on land surface palaeoelevation. Without such data it is not possible to quantify changes in topography (in terms of elevation with respect to the geoid) over time and therefore test this key component of landscape evolution models. Since cosmogenic nuclide production rates are a function of altitude – or, more strictly, atmospheric pressure – accumulation is sensitive to changes in the elevation of a sample during exposure (Lal, 1991). Inferring palaeoaltimetry from measured concentrations of cosmogenic nuclides is therefore an exciting possibility (Gosse and Stone, 2001), but true palaeoaltimetry requires independent data on the exposure age and erosion rate of a sample, since only by constraining these two unknowns can a change in surface elevation of a sample since it was first exposed be calculated. Nonetheless, it is possible to evaluate particular combinations of surface exposure age and elevation change during the period of exposure. Such an application has been used in the Transantarctic Mountains, Antarctica to test the assertion of substantial surface uplift of supposed late Pliocene age Sirius Group glacial deposits and associated landscape elements at rates of up to 1000 m $Ma^{-1}$ over the past ~3 Ma (Brown *et al*., 1991; Brook *et al*., 1995a; Ivy-Ochs *et al*., 1995; Bruno *et al*., 1997; Schäfer *et al*., 1999; Van der Wateren *et al*., 1999). The cosmogenic data can be interpreted as showing that either the Sirius Group deposits are of late Pliocene age, or there has been substantial surface uplift over the past 3 Ma, but not both. In other words the cosmogenic data provide a one-way test since, within the relevant timescale, high cosmogenic nuclide concentrations are incompatible with high

surface uplift rates, whereas low concentrations do not require high surface uplift rates (because of the possibility of erosion reducing cosmogenic nuclide concentrations) (Brook *et al.*, 1995a).

Incorporating the effect of surface uplift increases apparent exposure times, and this effect has been used to reconcile apparent differences between independent age constraints and cosmogenic exposure age estimates (Schäfer *et al.*, 1999; Kober *et al.*, 2002). More accurate palaeoaltimetry from cosmogenic nuclide data in the future will require a better understanding of the atmospheric pressure–altitude relationship for production than is currently available (Gosse and Stone, 2001), but will also require unusual circumstances where the exposure history is independently constrained.

## VII Facilities for cosmogenic isotope analysis

The future expansion of applications of cosmogenic isotope analysis to geomorphology and Quaternary science will depend to a significant extent on the availability of facilities for sample preparation and isotope measurement. There are a growing number of such facilities worldwide, with a concentration in the USA but including Australia, Canada, France, Germany, Japan and Switzerland. In the UK there are dedicated AMS target preparation laboratories for $^{10}Be/^{26}Al$ and $^{36}Cl$ in the Department of Geography at Edinburgh University, but the widespread adoption of cosmogenic isotope analysis in the UK, as elsewhere, will require a substantial increase in target preparation capability. Sample preparation for the stable noble gas cosmogenic isotopes is less demanding and can be accomplished with standard laboratory facilities.

In terms of the measurement of cosmogenic isotopes, the high-sensitivity noble gas mass spectrometres capable of measuring $^{3}He$ and $^{21}Ne$ are relatively widely available, but there are difficulties in using such machines where they have also been used for measuring irradiated samples for $^{40}Ar/^{39}Ar$ dating, and the number of machines dedicated to cosmogenic $^{3}He$ and $^{21}Ne$ is limited. For the measurement of cosmogenic radioisotopes, the tandem electrostatic accelerators most commonly used range in maximum terminal voltage from less than 3 MV to 16 MV. The lower voltage accelerators (~3 MV or less) are commonly used routinely for $^{14}C$, but they can also be used to measure $^{10}Be$ and $^{26}Al$. Intermediate-sized machines (5–9 MV) can potentially measure the full range of cosmogenic isotopes, although the higher energies available from the largest machines (10 MV or more) are particularly advantageous for the measurement of $^{36}Cl$ (Fifield, 1999). With a maximum terminal voltage of 5 MV, the Joint Infrastructure Fund (NERC)-financed AMS at the Scottish Universities Environmental Research Centre AMS Facility, East Kilbride, is in the intermediate category and will have a capability across the range of cosmogenic isotopes commonly used in Earth and environmental science applications. Although there are currently over 40 AMS facilities worldwide (Tuniz *et al.*, 1998), several specialize in radiocarbon dating, and relatively few currently undertake significant numbers of measurements across a range of cosmogenic isotopes for Earth and environmental science applications (Table 4).

**Table 4** AMS facilities involved in the measurement of cosmogenic isotopes for Earth and environmental science applications

| Facility | $V_T$ (MV) | Principal cosmogenic isotopes measured | Comments |
|---|---|---|---|
| Accelerator Laboratory, ANU, Canberra, Australia | 15.5 | $^{10}$Be, $^{14}$C, $^{26}$Al, $^{36}$Cl, | High voltage accelerator with an especially good capability for $^{36}$Cl. Experience with environmental and geomorphic applications. |
| AMS Facility, SUERC, East Kilbride, UK | 5 | $^{10}$Be, $^{14}$C, $^{26}$Al, $^{36}$Cl, | Dedicated to Earth and environmental science applications. |
| Gif-sur-Yvette Tandetron Accelerator, France | 3 | $^{10}$Be, $^{26}$Al | Used for several applications employing $^{10}$Be. |
| CAMS, UC/LLNL, California, USA | 10 | $^{10}$Be, $^{14}$C, $^{26}$Al. | A facility with a high-voltage AMS that has produced a large quantity of $^{10}$Be and $^{26}$Al measurements and has worked with a wide range of collaborators. |
| ANTARES, ANSTO, Lucas Heights, Australia | 10 | $^{10}$Be, $^{14}$C, $^{26}$Al | A facility which has become significantly involved in geomorphological and Quaternary science applications since the mid-1990s. |
| PRIME Lab, Purdue University, USA | 8 | $^{10}$Be, $^{14}$C, $^{26}$Al, $^{36}$Cl, | A facility which has worked with a diverse range of collaborators both with the USA and elsewhere. |
| NSF-Arizona AMS Facility, University of Arizona, USA | 2.5 | $^{10}$Be, $^{14}$C | A major $^{14}$C facility that has been involved in developing the application of *in situ*-produced $^{14}$C. |
| VERA, Vienna, Austria | 3 | $^{14}$C , $^{26}$Al | Primarily known for $^{14}$C measurements. |
| ETH/PSI AMS Facility, Zurich, Switzerland | 6 | $^{10}$Be, $^{14}$C, $^{26}$Al, $^{36}$Cl, | One of the first facilities to be involved in a range of geomorphological and Quaternary science applications. |

**Notes**: The listing is not exhaustive. Facilities undertaking measurements of $^{14}$C only are not included. $V_T$, maximum terminal voltage; ANSTO, Australian Nuclear Science and Technology Organisation; ANTARES, Australian National Tandem Accelerator for Applied Research; ANU, Australian National University; CAMS, Centre for AMS; ETH/PSI, Swiss Federal Institute of Technology/Paul Scherrer Institute; NSF, National Science Foundation; PRIME Lab, Purdue Rare Isotope Measurement Laboratory; UC/LLNL, University of California/Lawrence Livermore National Laboratory; SUERC, Scottish Universities Environmental Research Centre; VERA, Vienna Environmental Research Accelerator.

## VIII Conclusions and future directions

Over the past decade there has been a remarkable growth in applications of cosmogenic isotope analysis in geomorphology and Quaternary science. This has arisen very largely from the capability to provide chronological constraints where none were possible before, both in terms of the timescales that can be addressed and because the technique can be applied to a range of minerals that are virtually ubiquitous on the Earth's surface. However, this is still a rapidly developing technique and there are exciting prospects for the immediate future.

One of these, which underpins all applications of cosmogenic isotope analysis, is improved data on production rates and a better understanding of the spatial and temporal factors that control them. The importance of establishing a community-wide consensus on cosmogenic isotope production rates used in the estimation of exposure ages and denudation rates is now regarded as a major priority, with the ultimate objective of producing cosmogenic exposure ages with errors of 5% or less. Coupled with the analysis of a larger number of samples for a particular problem, and the measurement of several isotopes in the same sample, this greater accuracy will provide the kind of tight chronological constraints necessary to answer key questions in recent Earth history.

Another area of active research involves muon production (Heisinger *et al*., 2002a, b, c). The greater attenuation length of muon interactions compared with spallation means that muogenic production requires more time to reach secular equilibrium with respect to losses from denudation and radioactive decay. Consequently muogenic production is less sensitive to short-timescale perturbations in denudation, and therefore yields rates averaged over longer periods of time than the spallation-produced component. This opens the possibility of comparing denudation rates over different timescales from vertical sequences of samples (Stone *et al*., 1994; Brown *et al*., 1995b; Heisinger and Nolte, 2000).

The issue of how rates of denudation might vary over different timescales can be taken much further by combining cosmogenic isotope analysis with other techniques that address both shorter and longer time ranges (Kirchner *et al*., 2001). Such information has important practical implications since denudation rates over 'cosmogenic' timescales can provide a valuable benchmark for recent anthropogenic perturbations of drainage basins. The multi-timescale approach has already been applied in the Nanga Parbat area of the western Himalayas where the rate of incision of the Indus River estimated from cosmogenic exposure ages of strath terraces was compared with longer-term denudation rates derived from fission-track thermochronology (Burbank *et al*., 1996). The combination of cosmogenic isotope analysis and thermochronology has also been applied to landscapes in far less active tectonic settings (Belton *et al*., 2000; Cockburn *et al*., 2000; Brown *et al*., 2002). Such comparative studies have to be undertaken with care when using site-specific sampling for cosmogenic isotope analysis given the much larger spatial scale to which thermochronology applies, but sampling from key landscape elements, such as escarpment faces and summits, can be fruitfully integrated with data on regional patterns of denudation derived from thermochronology (Cockburn *et al*., 2000).

Finally, expanded applications of catchment-averaged denudation rates studies are also likely in the future. The ability to document the exposure, transport and burial of

sediment in fluvial systems over timescales of $10^3$–$10^6$ yr opens up a whole suite of possibilities for developing an understanding of drainage basin processes over the timescales relevant to significant landscape change (Granger, 2002). Particularly valuable for addressing the more recent part of this time range will be the wider use of *in-situ*-produced $^{14}C$ (Jull *et al.*, 1989, 1992, 1994b; Handwerger *et al.*, 1999; Lal and Jull, 2001). Recent technical advances (Lifton *et al.*, 2001; 2002) are now making it possible to pair this short-lived radioisotope with cosmogenic nuclides with much longer half-lives in order to provide far more sensitivity in the detection of complex exposure histories.

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