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Cosmogenic nuclide analysis

Christopher M. Darvill[1]
[1] Department of Geography, Durham University, South Road, Durham, DH1 3LE, UK
(christopher.darvill@durham.ac.uk)

ABSTRACT: Cosmogenic nuclides can be used to directly determine the timing of events and rates of change in the Earth's surface by measuring their production due to cosmic ray-induced reactions in rocks and sediment. The technique has been widely adopted by the geomorphological community because it can be used on a wide range of landforms across an age range spanning hundreds to millions of years. Consequently, it has been used to successfully analyse exposure and burial events; rates of erosion, denudation and uplift; soil dynamics; and palaeo-altimetric change. This paper offers a brief outline of the theory and application of the technique and necessary considerations when using it.

KEYWORDS: Cosmogenic nuclide, dating, chronology, landscape change, Quaternary

Introduction

Geochronology allows the quantification of rates of landscape change and timing of geomorphic events, bridging the gap between geomorphological evidence and environmental or climatic variability over time. Cosmogenic nuclide analysis involves the measurement of rare isotopes which build-up in rock minerals predictably over time due to bombardment of the upper few metres of the Earth's surface by cosmic rays. In this way, the exposure, burial and altimetric change of surficial rocks and sediments can be assessed. The six most commonly used cosmogenic isotopes, ^{10}Be, ^{26}Al, ^{36}Cl, ^{14}C, ^{3}He and ^{21}Ne, have allowed dating on the scale of hundreds to millions of years, and they can be used to address a wide range of geomorphological problems due to their production in commonly occurring minerals (Dunai, 2010). Unlike some other techniques, cosmogenic nuclide analysis can be applied directly to the rock or sediment in question rather than providing indirect bracketing information, and can be applied to numerous environmental situations. Consequently, the technique has been enthusiastically adopted by the geomorphological community in addressing issues such as the timing of glacial advances, fault-slip rates, bedrock/basin erosion and sediment burial (Cockburn and Summerfield, 2004). However, there are a number of practical and theoretical concerns that need to be considered when applying the technique.

This chapter will briefly explain how cosmogenic nuclides are produced, describe the range of geomorphological applications and highlight some of the practical and theoretical concerns that should be considered. The aim is to help the reader understand if the technique is applicable to their own study; it is a short introduction to a complex and continually-developing subject. For more detail, there exist several extensive reviews of the technique and literature, notably: Gosse and Phillips (2001); Cockburn and Summerfield (2004); Ivy-Ochs and Kober (2008); Dunai (2010); Granger *et al.* (2013). For glacial studies see Balco (2011); burial dating see Granger (2006) and Dehnert and Schlüchter (2008); and landscape denudation studies see Granger (2007).

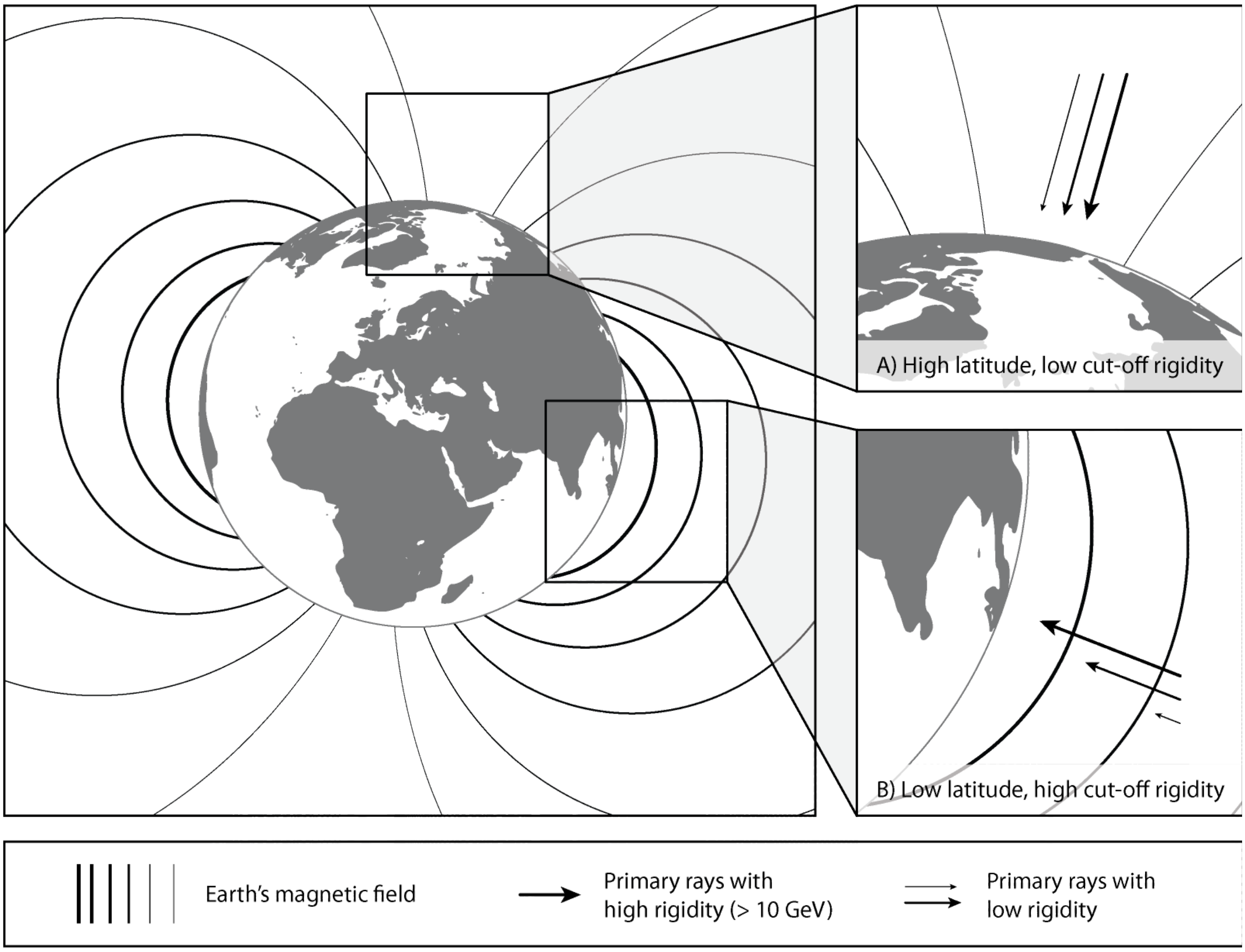

Figure 1: An illustration of the Earth's geomagnetic field and the effect it has on incoming primary cosmic rays. All rays must exceed the cut-off rigidity at a particular latitude (A and B), which is higher towards the equator (B) and lower towards the poles (A). Only rays with higher cut-off rigidities are permitted to enter the atmosphere at the equator, whilst at the poles the convergence of magnetic field lines means that most rays can enter. The consequence is higher production rates of cosmogenic nuclides at higher latitudes.

Cosmogenic nuclide production

The six most commonly used cosmogenic nuclides are ^{3}He and ^{21}Ne (stable, noble gas isotopes), and ^{10}Be, ^{26}Al, ^{36}Cl and ^{14}C (radioactive isotopes). Others, such as ^{38}Ar, ^{53}Mn and ^{41}Ca can be used but are not as ubiquitously applicable or require further development (Dunai, 2010). The use of any of these nuclides as a dating technique or for erosion/denudation rate studies relies on the accumulation of the isotopes within target minerals, moderated by surface erosion and, in the case of radioactive isotopes, radioactive decay. Their production involves three main stages: the production of (i) primary cosmic rays, (ii) secondary cosmic rays and (iii) nuclides via nucleonic spallation and muogenic reactions (Gosse and Phillips, 2001).

Primary cosmic rays and cut-off rigidity

The Earth is constantly bombarded by cosmic radiation in the form of primary cosmic rays. Most of these are galactic in origin, composed of high energy particles (0.1 – 10 GeV) in the form of protons (87%), α-particles (12%) and heavy nuclei (1%) (Masarik and Beer, 1999). The primary rays can also be of solar origin, with lower energies (< 100 MeV), but these only produce cosmogenic nuclides in the upper atmosphere or during intense solar activity (Masarik and Reedy, 1995).

Galactic primary rays are affected by the Earth's magnetic field and, to a lesser extent, solar activity (Lifton *et al.*, 2005). The *rigidity* of incoming rays relates to the degree to which their momentum is deflected by the Earth's magnetic field, and they must exceed a minimum rigidity (or *cut-off rigidity*) in order to penetrate into the atmosphere. Rigidity is affected by the angle of incidence of the rays and their location relative to geomagnetic field lines, so the cut-off rigidity varies with latitude. For primary particles, this is highest at the equator (fewer rays can penetrate) and lowest at the poles (more rays can penetrate; Dunai, 2010; Figure 1).

Significant variations in long-term primary ray production (1000's – 100,000's of years) affect cosmic radiation flux at the Earth's surface and are caused by changes in the Earth's magnetic field (dominantly the *geocentric axial dipole*, but also *non-dipole components*: Dunai, 2001; Dunai, 2010). This can be reconstructed using proxy records and accounted-for in scaling models (Guyodo and Valet, 1999; Dunai, 2001; Desilets and Zreda, 2003; Lifton *et al.*, 2005). Short-term cyclical changes in solar activity (10's – 100's of years) also affect low energy galactic primary rays, though this is essentially constant over timescales of thousands to millions of years. This modulation generally only affects primary ray flux at high latitudes where cut-off rigidity is low, but has implications for scaling models (see 'Production rates and scaling factors' section; and Lifton *et al.*, 2005).

Secondary cosmic rays and attenuation

Primary rays that penetrate the Earth's magnetic field trigger a reaction with atmospheric gas nuclei that results in a cascade of secondary cosmic rays, composed of high energy nucleons (e.g. protons and neutrons) and mesons (e.g. kaons, pions and muons: Figure 2; and Gosse and Phillips, 2001). Because the production of secondary rays triggers further collisions and interactions and results in a scattering and absorption of energy, the secondary ray intensity decreases down through the atmosphere (roughly exponentially with increasing atmospheric depth below 100 g cm^{-2}: Gosse and Phillips. 2001). This decrease in intensity is called *attenuation* and varies with the density of material through which the secondary rays pass. The *attenuation length* changes according to the energy of the incoming

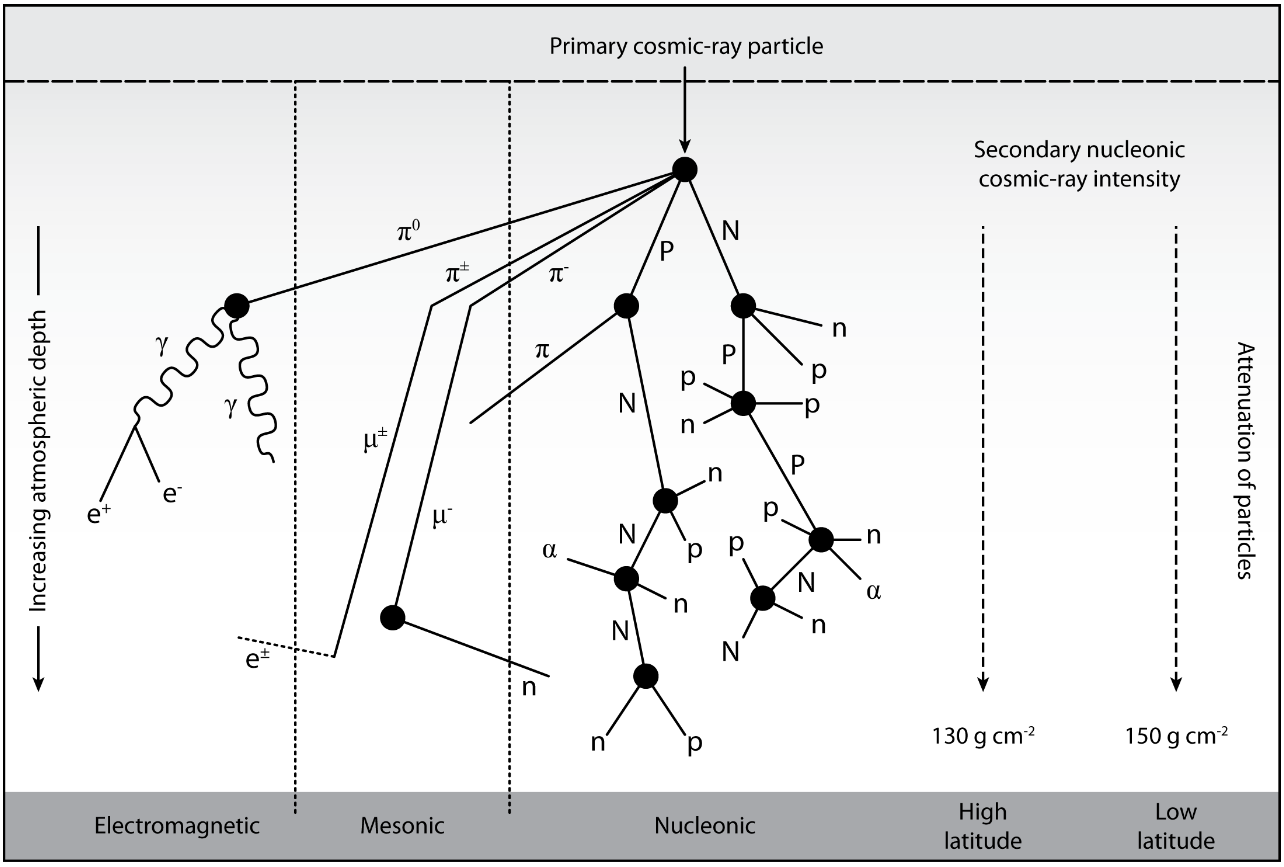

Figure 2: The cascade of secondary ray particles produced in the atmosphere by incoming primary cosmic rays (adapted from Dunai, 2010). Cosmic rays have greater attenuation lengths at the equator (150 g cm^{-2}) than at the poles (130 g cm^{-2}; see discussion in the text).

Table 1: The six major cosmogenic nuclides used in geomorphological research, their target elements and the reaction pathways through which they are formed. From Ivy-Ochs & Kober (2008) and Dunai (2010).

Isotope	Main target elements	Reactions
^{3}He	Many, including Li	**Spallation** (100%) **Thermal neutron capture** (on Li via ^{3}H)
^{21}Ne	Mg, Al, Si	**Spallation** (>96.4%)
^{10}Be	O, Si	**Spallation** (96.4%) **Muons** (3.6%)
^{26}Al	Si	**Spallation** (95.4%) **Muons** (4.6%)
^{36}Cl	K, Ca, Cl (Fe, Ti)	**Spallation** (95.4% from K; 86.6% from Ca; 100% from Fe and Ti) **Thermal neutron capture** (from Cl and K) **Muons** (4.6% from K; 13.4% from Ca;
^{14}C	O, Si	**Spallation** (82%) **Muons** (18%)

cosmic rays and thus varies with latitude. At lower latitudes, the rays have higher energies (because the cut-off rigidity is higher) so must pass through more of the atmosphere to reduce the cosmic ray flux. Consequently, attenuation length varies between roughly 130 g cm^{-2} at high latitudes and 150 g cm^{-2} at low latitudes (Dunai, 2000).

Thus, before cosmic rays interact with the Earth's surface, they have already been significantly influenced by the geomagnetic field (primary rays), latitude (primary and secondary rays), and altitude (secondary rays). This has important implications for calculations of cosmogenic nuclide production (see 'Analysis and age determination' section).

Spallation, capture and muonic reactions

On encountering the Earth's surface, secondary ray particles are also attenuated with depth according to rock density and their attenuation length. These particles trigger a number of reactions in target minerals that can result in the production of cosmogenic nuclides (see Table 1 and also Figure 5). Spallation reactions involve fast and high energy neutrons and produce most cosmogenic nuclides (^{3}He, ^{21}Ne, ^{10}Be, ^{26}Al, ^{14}C, ^{36}Cl), but neutron flux attenuates to <1% below 3 m from the surface (Figure 3). Thermal neutrons result from a slowing-down of some neutrons during the atmospheric cascade, and trigger capture reactions which can be important for the production of some nuclides, particularly ^{36}Cl if natural Cl is available. Because these low energy neutrons can leak back out of a rock, thermal neutron flux peaks at roughly 20 cm from the surface; an important consideration if sampling for ^{36}Cl. Muons have a lower mass than neutrons and are not highly reactive, so can penetrate much deeper into rock. Consequently, they account for roughly 2.5% of cosmogenic reactions at the surface, but 100% of reactions below 1000 g cm^{-2} (normally around 3 m) as the spallogenic reactions decrease (Heisinger *et al.*, 2002a, 2002b; Braucher *et al.*, 2013).

Analysis and age determination

Procedure

With the preceding understanding of how cosmogenic nuclides are produced, this section explains how their analysis can be used in geomorphic studies. Rocks and sediments containing the required target mineral are sampled in the field using the protocol given in Table 2. Samples are then

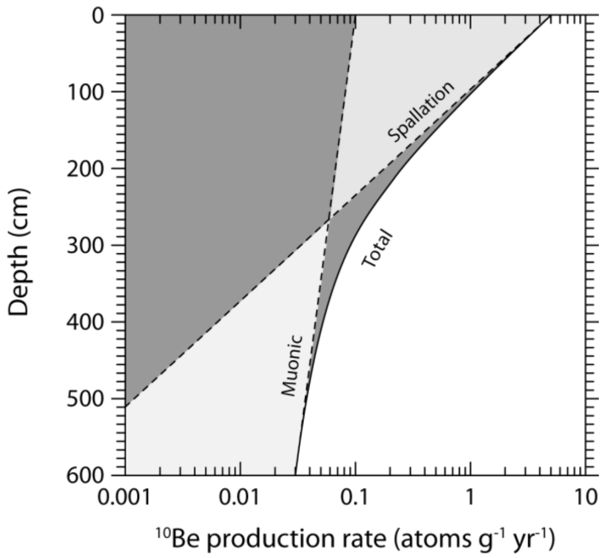

Figure 3: Production of ^{10}Be with depth in quartz arenite (adapted from Gosse and Phillips, 2001). Deeper into the rock, muonic reactions play a greater role in total production of cosmogenic nuclides than nucleonic spallation.

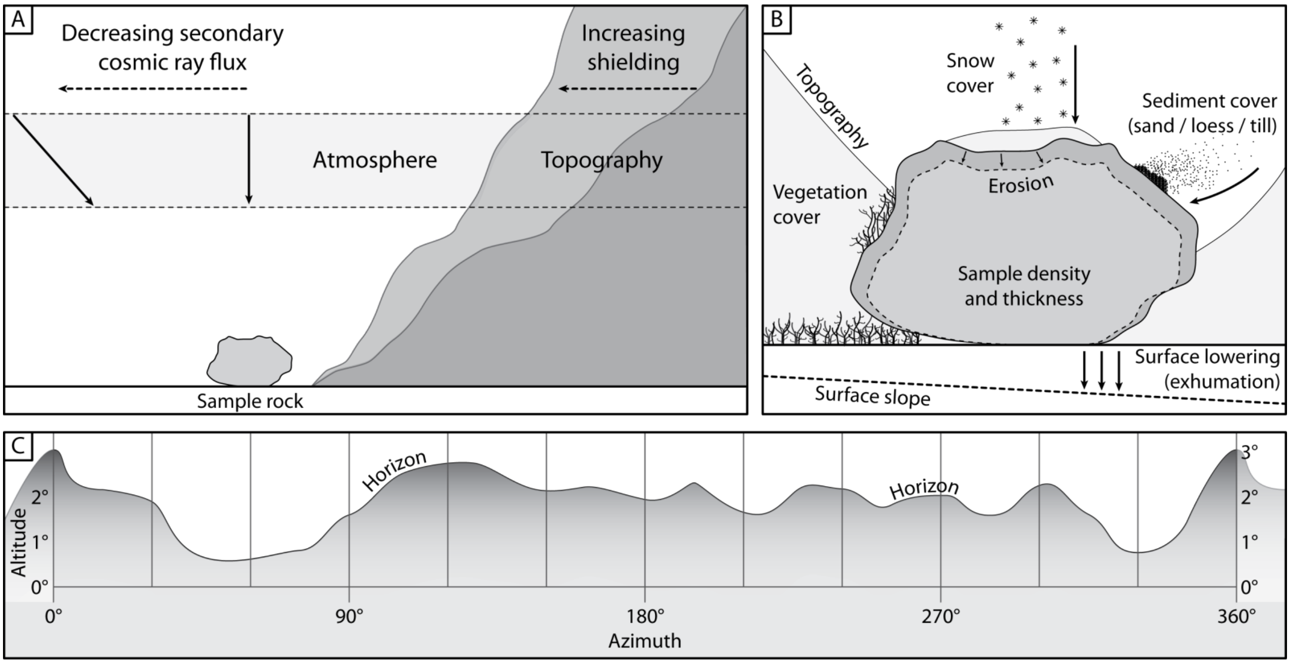

Figure 4: An illustration of factors affecting shielding. (A) Cosmic ray flux decreases if it passes through a greater amount of atmosphere (i.e. at a lower angle of incidence) and steeper local topography will decrease the incoming flux at a site. (B) Various local factors which will alter the shielding of a sample. It is also important to consider that these factors may change over time. (C) Topographic shielding is calculated by determining the degree to which a sampling site is exposed to a full hemisphere of open sky. One approach is to measure the altitude of the horizon at regular intervals (e.g. every 30°) for a full 360° and then calculate the exposure (Balco et al., 2008).

mechanically crushed and physically and chemically separated to isolate first the target mineral and then the target nuclide within that mineral (Wilson *et al.*, 2008). This is a complex and time-consuming process, the cost of which is often a significant limiting factor on the number of analyses achievable. Nuclide concentration is then measured, in the form of a ratio (e.g. $^{9}Be/^{10}Be$) in an accelerator mass spectrometer to measure the amount of nuclide within that sample. This can be converted into a concentration which can be used to calculate an age (Gosse and Phillips, 2001; Dunai, 2010), which has been greatly aided by the development of calculator tools such as those of Vermeesch (2007) and Balco *et al.* (2008). However, it is still important to understand how both the geomorphological context of the sample (e.g. shielding, erosion rate and inheritance) and the selection of different production rate parameters can affect the age calculation and may limit its usefulness.

Geomorphological context

The choice of cosmogenic nuclide used is determined by the timescale of interest (nuclide half-life) and the rock types available (target minerals; Ivy-Ochs and Kober, 2008). It is important to demonstrate that a sample of rock or sediment will relate unambiguously to the geomorphological process or event being studied, requiring an initial understanding of the environment and relative history, such as through geomorphological mapping. Changes to that environment over time will influence how nuclides have accumulated within the sample, so it is also necessary to consider the impact of shielding, erosion, inheritance and elevation-change over time (expanded in following sections; and Gosse and Phillips, 2001).

Shielding

The cosmic ray flux can be reduced at a particular location by local obstructions to the full horizon, such as the surrounding topography, surface slope and local rock formations (Gosse *et al.*, 1995; Dunne *et al.*, 1999). This topographic shielding blocks some of the incoming rays, altering the local production rate and, if uncorrected, can produce erroneously young ages. Incident cosmic radiation has a non-linear dependence on the angle from the horizon,

Table 2: A sampling checklist for cosmogenic nuclide analysis (adapted from author's own protocol and: Gosse and Phillips (2001), Hubbard and Glasser (2005), Hein et al. (2009) and Dunai (2010).

1. Equipment	• Marker pens • Hand-held GPS • Digital camera • Tape measure • Maps/aerial photos of the area • Compass • Abney level or (compass) clinometer • Sample bags (cloth bags are more robust than plastic) • Hammer and chisel / core-drill / rock-cutting saw (boulders or bedrock) • Scales (for weighing samples, otherwise estimate) • Spade, pick-axe, hand-trowel (depth-profiles) • Spirit level and spray paint (depth profiles)

2. Considerations	Context	**The geomorphic context of the samples(s) must be understood.** It is important to be clear about the link between the sample and geomorphic process or event being studied. For single samples, avoid any situations where the stability of the boulder or surface is in question (e.g. signs of rolling, shifting or slumping). For depth profiles, be sure that the geomorphic surface is stable and that it is the original surface being studied.
	Sample history	Are the following likely to have affected the sample? • Soil cover • Snow cover • Ice/glacier cover • Vegetation • Ash cover • Water/lake cover Could the history be complex? Avoid complexity if possible.
	Ethics	Minimise the effects that sampling will have on the environment.

3a. Single samples overview	1. Rock lithology needs to contain the target mineral required for the cosmogenic nuclide being used 2. Aim for at least three samples per landform (sequence) being dated 3. If sampling boulders, aim for the tallest boulders possible 4. Do not sample edges and corners of boulders and rock outcrops 5. If possible, avoid signs of post-depositional erosion 6. Aim to take a sample roughly 5cm deep, but be aware that for ^{36}Cl, a thicker sample will better record the nuclides produced by thermal neutron capture 7. Sample weight will depend on lithology and age, so size/weight of sample will be an estimate. It is consequently better to aim for a larger sample than is likely to be necessary. **Record features according to Part 4 below**
3b. Depth profile sampling overview	1. Profile should be at least 1.5 - 2.5 m deep, measured from regional surface level 2. Excavate a clean, relatively flat surface and describe stratigraphy of the section 3. Measure soil depth from surface if necessary 4. Use spirit level to mark sampling depths from surface across width of the profile 5. Sample at least 6 depths every 10-50 cm, capturing closely-spaced samples towards the top of the profile and at least one deep sample (> 3 m if possible) 6. Aim to sample at least 1 kg of amalgamated pebbles or sand samples – use clasts < 3 cm to avoid single clasts dominating the nuclide signature 7. Collect clasts/sediment lithologies containing the target mineral required 8. Measure or estimate thickness of samples 9. If possible, measure average bulk density of each sedimentary unit. 10. If sampling surface clasts, aim for larger (20 - 30 cm) clasts of a suitable lithology that are embedded within the landscape surface and can be linked unambiguously to the depth profile. They will be treated individually as single samples. **Record features according to Part 4 below**

<table>
<tr><td rowspan="8">4.
Record</td><td>Time</td><td>Note the date and time.</td></tr>
<tr><td>Location</td><td>Record latitude, longitude and elevation using GPS.</td></tr>
<tr><td>Context</td><td>Describe the sample site and how it relates to the surrounding geomorphic environment. Is the sample site (un)usual?</td></tr>
<tr><td>Labelling</td><td>Label samples with:
• Sample name
• Top surface
• Burial line if partially submerged.

If a single sample is taken in fragments, label in such a way as to be able to reconstruct the complete sample in the laboratory.
For depth-profile amalgams, label all bags carefully, including depths.
Label all samples with top surface, sample name and burial line if they are partially submerged.</td></tr>
<tr><td>Photos</td><td>Take:
• Photos of the sample site from as many angles as possible, both near- and far-field, including a scale!
• Photos of the rock before and after sampling (single samples) or sediment face (depth profile), including a scale!
• A 360° panorama from sample site looking outward.
Include sample names in the photos for reference.
Note all photograph numbers and what they are showing.</td></tr>
<tr><td>Physical characteristics</td><td>Describe and photograph the following:
• Size
• Shape
• Lithology
• Colour
• Grain size
• Lichen cover
• Glacial polish
• Striations
• Visible cracks (width and depth)
• Emergent veins (measure height)
• Weathering pits
• Rock-varnish
• Ventifacts
• Any other characteristics relevant to exposure history or geomorphic event/process being studied
For a depth profile, full, detailed stratigraphic log of the sedimentary exposure, noting imbrication and cementation</td></tr>
<tr><td>Topographic shielding</td><td>Record the angular elevation of the horizon from the sample at regular intervals for a full 360°
See Figure 4.</td></tr>
<tr><td>Sample strike/dip</td><td>Likely only an issue with single samples – measure the strike and dip of the surface from which the samples has been taken if it is not level</td></tr>
<tr><td></td><td>Thickness and fragments</td><td>• Record the thickness of a single sample, or the thicknesses of fragments to aid reconstruction in the laboratory.
• Measure or estimate the thickness of depth profile amalgam samples – this will help inform the depth error of samples.</td></tr>
</table>

so it requires a high degree of shielding to significantly affect the cosmic ray flux. However, shielding is important for age calculation, and is measured in the field (Figure 4). In addition, samples from protruding objects can lose some high energy neutrons back to the atmosphere, resulting in a lower spallation rate (Masarik and Wieler, 2003). For this reason, the edges of rocks are avoided (Gosse and Phillips, 2001). Post-depositional shielding must also be considered, such as annual or semi-permanent snow, sand, loess, soil or vegetation cover. This is difficult to incorporate into an age calculation, so sampling should avoid signs of post-depositional shielding.

Erosion

Over time, the surface of a rock or sedimentary unit will be eroded. This has two consequences: first, the top layer in which cosmogenic nuclides are produced will be progressively removed, and secondly, the contemporary surface may have been exposed later than the event being dated (Gosse and Phillips, 2001). These two factors will combine to produce an erroneously young age for the sample. This can be accounted for, to a degree, by measuring the protrusion of more resistant mineral bands (such as quartz veins) or the depth of surface pitting on rocks and using this as a proxy for erosion rate (Gosse and Phillips, 2001). Alternatively, a depth-profile through sediment can be used to model the erosion rate (see ‘Single samples vs depth-profiles’ section; and Hein *et al.*, 2009). Few independent measures of erosion rate exist, so as a compromise, two age estimates are often given for a single sample: one assuming no erosion has occurred and the other under a constant, *estimated* rate of erosion. The former provides a minimum age for the deposit, irrespective of the amount of erosion. Older exposure ages become increasingly susceptible to the erosion rate, hence this cautionary approach.

Inheritance

Another assumption of cosmogenic nuclide analysis is that the sample has not been previously exposed to cosmic rays prior to the event in question, and it thus contains no prior cosmogenic nuclide signature (Anderson *et al.*, 1996). However, pre-exposure to the atmosphere (e.g. reworking of clasts) and a lack of erosion of the rock surface to sufficient depth may fail to reset the cosmogenic ‘clock’ (Guido *et al.*, 2007). The presence of an inherited nuclide component will provide an anomalously old age for a sample. In single nuclide analysis, outliers can be identified using statistical analyses such as relative probability distributions and reduced chi-squared tests,

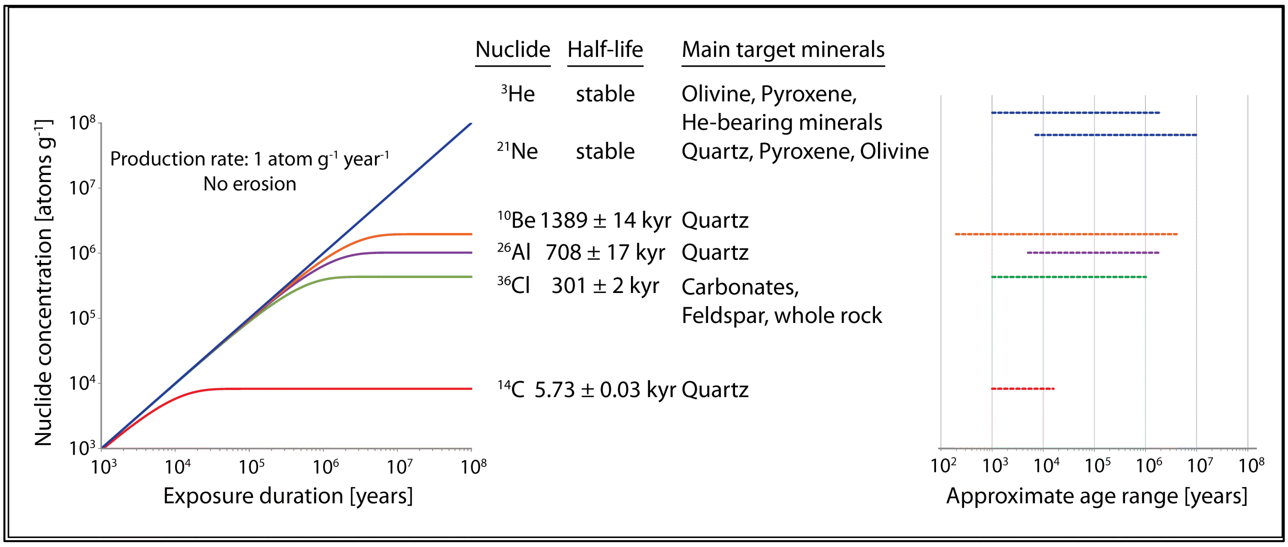

Figure 5: A summary of the properties of the six most commonly-used cosmogenic nuclides. Age ranges are approximate and are heavily controlled by laboratory methodology and local factors such as erosion. The plot shows that ^{14}C has the shortest useable age range because of its relatively rapid decay, whilst longer-lived radionuclides (e.g. ^{10}Be) can be used for much broader age ranges. Data from Ivy-Ochs and Kober (2008) and Dunai (2010). ^{10}Be half-life is from Chmeleff et al. (2010) and Korschinek et al. (2010).

but require numerous samples to have been taken (Barrows *et al.*, 2002). In depth-profiles, a nuclide concentration from a sufficiently deep sample (e.g. greater than roughly 3 m) can only have been created by inheritance, and this can be taken into account during age calculation (see 'Single samples vs depth profiles' section; Repka *et al.*, 1997; Hancock *et al.*, 1999). Some applications use multiple isotopes both to identify nuclide inheritance but also to quantify erosion rates.

Using multiple isotopes

Because radioactive cosmogenic nuclides decay over time, they have the potential to provide information on both the exposure time (the amount of accumulated isotope) and the degree of burial, shielding or erosion of the surface (the amount of the accumulated isotopes that have decayed; Dehnert and Schlüchter, 2008). Consequently, the technique is particularly powerful when multiple isotopes are used which have significantly different rates of production and different decay half-lives (Figure 5; Lal, 1991; Gosse and Phillips, 2001). For example, a combination of ^{10}Be (½ life: 1389 ± 14 kyr) and ^{26}Al (½ life: 708 ± 17 kyr) can show whether a rock has experienced a simple or complex exposure history because a period of shielding will allow almost twice as much ^{26}Al to decay than ^{10}Be, resulting in discordant age estimates (Lal, 1991; Balco *et al.*, 2005; Dehnert and Schlüchter, 2008).

Single samples vs depth-profiles

Single samples are more commonly used than depth-profiles for dating (Figure 6). Single samples can potentially yield a date per analysis and are often simpler to sample in the field. However, it can be difficult to quantify the effects of shielding, erosion and inheritance, creating scatter in data sets from single geomorphological features that increases with landform age (Balco, 2011). Larger datasets can statistically reduce this uncertainty, but require more analyses to be performed (Rinterknecht *et al.*, 2006).

Conversely, depth-profiles can provide a wealth of information in addition to an age. Several samples are analysed from various depths through a sedimentary unit, whereby the surface concentration relates to the age

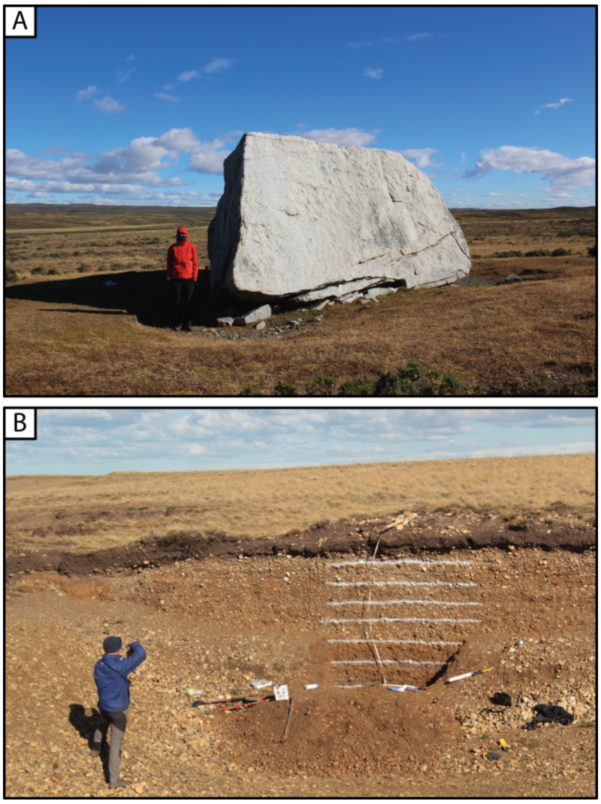

Figure 6: Two different approaches to sampling for cosmogenic nuclide dating. (A) Single sample, such as a large, intact erratic boulder. (B) Depth profile, such as through glaciofluvial outwash. (Photographs taken by the author, southern South America).

of the unit, and samples at increasing depth will contain progressively decreasing nuclide concentrations according to the normal attenuation of cosmic radiation (Anderson *et al.*, 1996; Repka *et al.*, 1997). Modelling of the nuclide concentration data, such as using a chi-squared best-fit, can produce an age for the unit, but also information on average inheritance, surface erosion/deflation, and changes in deposition, thereby resulting in a more robust age estimate. The use of multiple isotopes in a profile can also yield both exposure and burial ages (Granger and Muzikar, 2001; Häuselmann *et al.*, 2007; Balco and Rovey, 2008; Hein *et al.*, 2009). However, a depth-profile requires a number of analyses (e.g. >5) to yield only one actual age estimate, and may prove problematic if using fractions greater than sand-size (Hidy *et al.*, 2010). It is also necessary to find or create a deep exposure within the sedimentary unit at a suitable geomorphological location, which may not always be possible. Consequently, depth profiles only tend to be used instead of single samples where the sediment being dated lends itself to this form of analysis (e.g. fluvial/glaciofluvial/alluvial terraces) and/or where post-depositional processes are thought to undermine ages from single samples (Hein *et al.*, 2009, 2011a).

Production rates and scaling factors

In order to establish an age from the accumulation of a particular cosmogenic nuclide, the rate at which that nuclide is produced at the sampling site must be estimated, given that the *in situ* production of cosmogenic nuclides varies with latitude, altitude and the thickness and density of a sample (Lal, 1991; Dunai, 2000; Stone, 2000), and will be affected by shielding. Production rates of different nuclides at different locations are most commonly established using well-dated event features, where the dates are independently established using an alternative technique such as radiocarbon-dated moraines (Putnam *et al.*, 2010b; Kaplan *et al.*, 2011), argon-dated volcanic lavas (Dunai and Wijbrans, 2000; Foeken *et al.*, 2012), varve records (Balco and Schaefer, 2006) or tree-ring chronologies (Kubik *et al.*, 1998); as well as inter-comparison between different nuclides at such sites (Balco and Shuster, 2009; Schimmelpfennig *et al.*, 2011).

These production rates are usually published in a normalised form to Sea-Level and High Latitude (SLHL). Then, either the most appropriate regional production rate can be applied directly or a reference production rate can be used, which consists of an average of these different regional studies (Balco *et al.*, 2008). Whichever approach is adopted, *scaling factors* must be carefully considered in order to appropriately scale the production rate from the regional or global rate (given at SLHL) to the local site from where the sample was taken, taking into account the variable production at different latitudes and altitudes (Lal, 1991). Six main scaling models exist, which deal with variations in production rates in different ways (Lal, 1991; Stone, 2000; Dunai, 2001; Desilets and Zreda, 2003; Lifton *et al.*, 2005; Desilets *et al.*, 2006). There is not a great deal of difference between the models; they mainly manipulate the effects of atmospheric pressure, the geomagnetic field and solar variability in different ways (Balco *et al.*, 2008; Dunai, 2010), and age calculators often produce a range of ages to show the effects of using each model. However, there must be consistency between the scaling factors used, including when comparing ages between different studies that may have used different production rates and scaling factors (Balco, 2011).

Age range and applications

Stable nuclides accumulate over time according to their production rate and will eventually reach equilibrium with respect to the erosion rate of the rock surface. By contrast, the production of a radioactive nuclide will eventually equal both the erosion rate and the amount of nuclide lost through radioactive decay. The state of equilibration is called *saturation* and limits the maximum timescales over which the nuclides can be used to date (Figure 5). The minimum age limit is determined by the measurement procedure (Ivy-Ochs and Kober, 2008).

A summary of the uses of cosmogenic nuclide analysis in different settings is given in Table 3. The applications are grouped into different geomorphological environments: glacial, hillslope, fluvial, coastal/lacustrine, volcanic, dryland, karst, extra-terrestrial and tectonic. Broadly, these constitute three different types of analysis: events (exposure and burial dating), rates (erosion/denudation, uplift and soil dynamic rates) and direct palaeo-altimetry. A limited number of exemplar publications are given as a starting point for further environment-specific investigation.

Recent advances

Cosmogenic nuclide analysis is an exciting and developing tool in geochronology and there is scope to improve the technique in coming years. Recent work has focussed on improving production rate estimates, critically analysing data in relation to geomorphological processes and extending the age range of the technique.

Uncertainties in reference production rates are being reduced by improving the number, quality and global distribution of regional calibration sites. This has been greatly aided by the CRONUS-Earth (2005-2010) and CRONUS-EU (2004-2008) initiatives and forthcoming projects such as SPICE (Fenton

Table 3: Summary of the range of applications for which cosmogenic nuclide dating have been used. This is an update to the table produced by Cockburn and Summerfield (2004) but is still a limited selection given the huge increase in literature over the last decade. It should therefore be used as the starting point for further reading.

Environment	**Study**	**Type of dating**	**Example studies**
Glacial	Moraines	Exposure Event	Phillips *et al.* (1990); Brown *et al.* (1991); Brook *et al.* (1993); Brook *et al.* (1995); Gosse *et al.* (1995); Phillips *et al.* (1996); Jackson *et al.* (1997); Barrows *et al.* (2001); Owen *et al.* (2001); Barrows *et al.* (2002); Briner *et al.* (2002); Owen *et al.* (2002); Schäfer *et al.* (2002); Kaplan *et al.* (2004); Schaefer *et al.* (2006); Barrows *et al.* (2007); Putnam *et al.* (2010a); Ballantyne (2012); Rinterknecht *et al.* (2012b); Rinterknecht *et al.* (2012a)
	Bedrock features	Exposure Event	Nishiizumi *et al.* (1989); Nishiizumi *et al.* (1991a); Stone *et al.* (1998); Bierman *et al.* (1999); Fabel *et al.* (2002); Stroeven *et al.* (2002); Marquette *et al.* (2004); Harbor *et al.* (2006); Phillips *et al.* (2006); McCormack *et al.* (2011); Briner *et al.* (2012b); Hippe *et al.* (2013)
	Ice-sheet thinning	Exposure Event	Stone *et al.* (2003); Bentley *et al.* (2006); Bentley *et al.* (2010); Todd *et al.* (2010); Hein *et al.* (2011b); Mackintosh *et al.* (2011)
	Glaciofluvial features	Exposure Event	Hein *et al.* (2009); Hein *et al.* (2011a)
	Buried ice	Burial Event	Schäfer *et al.* (2000); Marchant *et al.* (2002)
	Ablation	Exposure Rate	Lal *et al.* (1987); Lal & Jull (1990); Lal *et al.* (1990); Lal & Jull (1992); Jull *et al.* (1994)
Hillslope	Mass movement	Exposure Event	Ballantyne *et al.* (1998); Kubik *et al.* (1998); Barnard *et al.* (2001); Sanchez *et al.* (2010); Akçar *et al.* (2012a)
	Slope translocation	Exposure/Burial Rate	Small *et al.* (1999); Heimsath *et al.* (2002); Heimsath *et al.* (2005); Nichols *et al.* (2007)
	Surface burial	Burial Event	Granger & Smith (2000); Granger & Muzikar (2001); Kong *et al.* (2009); Hu *et al.* (2011); Matmon *et al.* (2012)
	Surface denudation (local)	Exposure Rate	Nishiizumi *et al.* (1986); Brown *et al.* (1995); Heimsath *et al.* (1997); Small *et al.* (1997); Heimsath *et al.* (1999); Cockburn *et al.* (2000); Heimsath *et al.* (2000;2001b); Heimsath *et al.* (2001a); Norton *et al.* (2011); Hippe *et al.* (2012)
	Surface denudation (regional)	Exposure Rate	Brown *et al.* (1995); Riebe *et al.* (2000); Bierman & Caffee (2001); Kirchner *et al.* (2001); Riebe *et al.* (2001a;b); Schaller *et al.* (2001); Nichols *et al.* (2005); Norton *et al.* (2008); Aguilar *et al.* (2013)

	Soil translocation	Exposure/Burial Rate	Brown *et al.* (1994); Heimsath *et al.* (1997); Heimsath *et al.* (1999); Heimsath *et al.* (2000;2001b); Heimsath *et al.* (2001a); Heimsath *et al.* (2005); Burke *et al.* (2007); Schaller *et al.* (2009); Riebe & Granger (2013)
Fluvial	Alluvial river terraces	Exposure Event	Molnar *et al.* (1994); Repka *et al.* (1997); Hancock *et al.* (1999); Hetzel *et al.* (2002); Schildgen *et al.* (2002); Darling *et al.* (2012)
	Alluvial fans / debris flows	Exposure/Burial Event	Siame *et al.* (1997); Brown *et al.* (1998); Nishiizumi *et al.* (2005); Dühnforth *et al.* (2007); Frankel *et al.* (2007); Blisniuk *et al.* (2012)
	Floods	Exposure/Burial Event	Cerling *et al.* (1994); Margerison *et al.* (2005); Reuther *et al.* (2006); Amidon & Farley (2011)
	Strath terraces	Exposure Event	Burbank *et al.* (1996); Leland *et al.* (1998); Pratt *et al.* (2002); Ruszkiczay-Rüdiger *et al.* (2005); Schaller *et al.* (2005)
Coastal/ lacustrine	Shoreline deposits	Exposure Event	Trull *et al.* (1995); Perg *et al.* (2001); Matmon *et al.* (2003); Owen *et al.* (2007); Kurth *et al.* (2011)
	Wave-cut platforms	Exposure Event	Stone *et al.* (1996); Alvarez-Marrón *et al.* (2008)
	Lacustrine sediments	Burial Event	Kong *et al.* (2009); Davis *et al.* (2011)
Volcanic	Volcanic landforms	Exposure/Burial Event	Craig & Poreda (1986); Kurz (1986); Kurz *et al.* (1990); Poreda & Cerling (1992); Laughlin *et al.* (1994); Licciardi *et al.* (1999); Goethals *et al.* (2009); Schimmelpfennig *et al.* (2009); Schimmelpfennig *et al.* (2011); Medynski *et al.* (2013)
Dryland/ aeolian	Aeolian erosion and denudation	Exposure/Burial Rate	Bierman & Caffee (2001); Vermeesch *et al.* (2010); Fujioka & Chappell (2011); Ruszkiczay-Rüdiger *et al.* (2011)
	Desert pavements	Exposure Event	Wells *et al.* (1995); Marchetti & Cerling (2005); Matmon *et al.* (2009)
Karst	Sediment deposition in caves	Burial Event	Granger *et al.* (1997); Granger *et al.* (2001); Stock *et al.* (2004); Stock *et al.* (2006); Anthony & Granger (2007); Matmon *et al.* (2012)
Extra-terrestrial	Meteorite impacts	Exposure Event	Nishiizumi *et al.* (1991b); Phillips *et al.* (1991)
Tectonic	Fault scarp development	Exposure Event	Zreda & Noller (1998); Mitchell *et al.* (2001); Daëron *et al.* (2004); Palumbo *et al.* (2004); Schlagenhauf *et al.* (2010); Akçar *et al.* (2012b)
	Change in elevation	Palaeo-altimetry	Brook *et al.* (1995); Van der Wateren *et al.* (1999); Gosse & Stone (2001); Riihimaki & Libarkin (2007)

et al., in press). For example, recent ^{10}Be calibration studies from northeastern North America (Balco *et al.*, 2009), New Zealand (Putnam *et al.*, 2010b) Patagonia (Kaplan *et al.*, 2011), Norway (Fenton *et al.*, 2011; Goehring *et al.*, 2012), Greenland (Briner *et al.*, 2012a) and western Greenland/Baffin Island (Young *et al.*, 2013) gave more accurate results than previous work (Young *et al.*, 2013). They also yielded production rates that are lower than those produced in previous studies, which is particularly important given that some studies are now using ^{10}Be to attempt to resolve sub-millennial glacial events and their inter-hemispheric relationships.

There has been a recent drive in the critical assessment of the way in which cosmogenic nuclide data is handled and statistically manipulated. Given the particular rise of cosmogenic nuclide exposure dating in glacial geomorphological studies, Balco (2011) cautioned against extending the technique beyond its limitations, particularly with regards to resolving shorter timescale events. More specifically, Heyman *et al.* (2011) compiled a vast number of published exposure ages from around the world to demonstrate that shielding, erosion and exhumation of boulders often cause incorrect ages – to a greater degree than inheritance, so that ages are more likely to be underestimates. This has been developed further using statistical techniques to manipulate cosmogenic nuclide data to examine geomorphological processes (Putkonen and Swanson, 2003; Putkonen and O'Neal, 2006; Applegate *et al.*, 2012; Mackey and Lamb, 2013).

Studies are continuing to extend the age range of cosmogenic nuclide analysis. Younger age constraints remain limited to hundreds of years at best by methodological constraints (Davis *et al.*, 1999; Akçar *et al.*, 2012a; Putnam *et al.*, 2012; Kaplan *et al.*, 2013), but the upper age range is being extended into the multiple millions of years using different cosmogenic isotopes (Schäfer *et al.*, 1999; Balco *et al.*, 2005; Dunai *et al.*, 2005; Stock *et al.*, 2005; Häuselmann *et al.*, 2007; Alvarez-Marrón *et al.*, 2008; Balco and Rovey, 2010; Hein *et al.*, 2011a).

In conclusion, cosmogenic nuclide analysis is likely to remain one of the primary tools used in geomorphological studies. However, the generation of meaningful data requires clear understanding of the geomorphological history of samples and the limitations of the technique.

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