Publication of exposure ages or erosion rates derived from cosmogenic-nuclide measurements

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This article is intended to provide guidelines for publishing surface exposure ages, surface erosion rates, and catchment-averaged erosion rates derived from cosmogenic-nuclide measurements. This issue is important because during the last decade, cosmogenic-nuclide geochemistry has developed from an experimental technique practiced by only a few specialists to a commonly used tool in a variety of Earth science fields, for example in glacial geology and paleoclimatology (exposure dating of glacial deposits), paleoseismology (exposure dating of surface features formed by earthquakes), geomorphology (measurement of erosion, incision, and sediment transport rates), and tectonics (exposure dating of river terraces, alluvial fans and other deformation markers). All of these applications require not only a measurement of the cosmogenic-nuclide concentration, but also an estimate of present and past nuclide production rates at the sample location, so that the nuclide concentration can be interpreted as an age or erosion rate. Methods for measuring the concentration of cosmogenic nuclides, principally ^{10}Be, ^{26}Al, ^{36}Cl, ^{14}C, ^{3}He, and ^{21}Ne, in rock samples by noble gas mass spectrometry and accelerator mass spectrometry (AMS) are well established. Methods for calculating an exposure age or an erosion rate from such measurements, on the other hand, are still in active development: absolute nuclide production rates and their geographic and temporal variations are not yet precisely known and are continually being refined by ongoing research.

This situation has two effects. First, as production rate estimates have evolved, published exposure ages and erosion rates have been calculated using a variety of inconsistent production rate scaling methods and input parameters (see reviews in Gosse and Phillips, 2001, and Balco et al., 2008). Thus, it is not possible to synthesize the results of many past studies, or even to accurately compare the results of any two studies, unless one recalculates ages or erosion rates from raw measurements using a common production rate scaling method and a common parameter set. Second, currently accepted production rate estimates will in future be superseded by more accurate ones that reflect improved understanding of production rate systematics. Any exposure ages or erosion rate measurements in the existing literature will, without question, have to be recalculated from source data in future.

For these reasons, it is critically important that publications reporting exposure ages or erosion rates include enough information so that the ages or erosion rates can be fully recalculated from the raw measurements of nuclide concentrations and other source data. Publications that do not contain this information cannot be accurately compared with later studies, and their value is lost to future researchers.

In an effort to determine how well the existing literature documents the source data needed to recalculate published exposure ages or erosion rates, we randomly selected (from the results of a GEOREF search) ten recent (post-2006) articles that included erosion rates or exposure ages computed from ^{10}Be measurements.

Not a single one of these articles reported, in either the main text or in appendices lodged at the journal's data repository, enough source data to accurately reproduce its results (Table 1). All ten papers included basic information of location, elevation, and nuclide concentration, but many omitted sample thicknesses and densities, topographic shielding, and the surface erosion rate assumed in exposure age calculations. It is impossible to calculate accurate exposure ages or erosion rates without these data. Furthermore, only four papers identified the reference standard used for ^{10}Be measurements. This is a serious problem, because there are several incompatible standards in use (see Nishiizumi et al., 2007 for details). Without knowing the reference standard, one cannot even accurately reconstruct the ^{10}Be concentration in a sample, let alone an exposure age or erosion rate.

This survey shows that, at present, data reporting in the cosmogenic-nuclide literature is not adequate to ensure that published cosmogenic-nuclide measurements will remain useful to future researchers as production rate estimates evolve. This conclusion is not meant as a criticism of existing research (indeed, all of the authors of this article have most likely reported incomplete source data in past publications) but to make clear to authors, reviewers, and editors that added attention to data reporting is needed to achieve this goal.

Table 1 shows the minimum set of measurements required to calculate exposure ages or erosion rates using any cosmogenic nuclide. These measurements should accompany any published exposure ages or erosion rates. Here we provide only a minimal description: for details, readers are referred to Gosse and Phillips (2001) and Balco et al. (2008). Table 1 applies to surface exposure dating, measurement of point erosion rates from a surface sample, and measurements of catchment-averaged erosion rates from river sediment. It does not apply to 'burial dating' using multiple cosmogenic nuclides.

Besides this minimum data set, publications should also include a description of the geologic and geomorphic setting of the samples, emphasizing evidence pertaining to processes that affect nuclide production rates, including surface erosion and past cover by snow, ice, soil, ash, or vegetation. If any production rate correction is applied to account for these processes, its value and how it was computed should be stated.

So far, the most commonly used cosmogenic nuclide-mineral systems are ^{10}Be and ^{26}Al in quartz. As the composition of quartz is for all practical purposes invariant, the only geochemical information needed is the ^{10}Be and ^{26}Al concentrations. Other nuclides, measured in other minerals or in bulk rock, require more information. Two common examples are as follows:

Whole rock or mineral-separate ^{36}Cl. ^{36}Cl production rates depend on rock and mineral composition. Compositional data required to estimate the ^{36}Cl production rate includes: i) the major element composition of the bulk rock and the target mineral separate; ii) concentrations in the bulk rock of trace elements that are important neutron absorbers, and iii) any measurements or assumptions concerning the water content of the rock. Readers are referred to Phillips et al. (2001), Stone et al. (1998), and Swanson and Caffee (2001) for examples.

Cosmogenic noble gases. First, non-cosmogenic ^{3}He and ^{21}Ne occur in nearly all minerals. There exists a large literature on resolving cosmogenic from non-cosmogenic components (summarized, for example, by Niedermann (2002) for ^{21}Ne and ^{3}He, and by Blard and Farley (2008) for ^{3}He). Publications involving these nuclides should descibe how this was carried out. Second, production rates of noble gases in many target minerals depend on the composition; in these cases one should report the major element composition of the mineral in question. Third, production rates of noble gases in some (mainly accessory) minerals are affected by the size and geometry of the mineral grains, their concentration of neutron absorbers, and their proximity to neutron sources and sinks; in this case, additional compositional data, similar to that described above for ^{36}Cl measurements, may be required to calculate production rates. Dunai et al. (2007) and Farley et al. (2006) discuss this further.

A final related issue is that several recent papers on exposure dating have used the term "^{10}Be years" (also "^{36}Cl years", etc.) as a unit for exposure ages calculated from concentrations of these nuclides. The presumed purpose of these terms is to connote that the exposure ages are model-dependent and may differ from true calendar years. This practice has most likely been suggested by the term "^{14}C years," or "radiocarbon years" used to report radiocarbon ages. However, this analogy is misleading and has the potential to cause serious confusion. "^{14}C years" is a defined term that is simply a way of restating the measured ^{14}C activity of a sample in a chronologically meaningful fashion. The definition is described in many references (Stuiver and Polach, 1977; Mook and van der Plicht, 1999; van der Plicht and Hogg, 2006) and has been used consistently throughout the Earth science literature for several decades. The ^{14}C activity of a sample can always be uniquely recovered from its age in ^{14}C years using this definition.

In contrast, there exists no accepted (or proposed) definition of "^{10}Be years." Ages reported in "^{10}Be years" in different papers have been calculated using different reference ^{10}Be production rates, different production rate scaling schemes, and different assumptions about the depth dependence of nuclide production. Thus, i) "^{10}Be years" reported in different publications are, in general, inconsistent and cannot be directly compared, and ii) the ^{10}Be concentration of a sample cannot be uniquely recovered from an age given in "^{10}Be years." As noted above, scaling schemes and production rate estimates remain the subject of active research, so no lasting definition of a unit such as a "^{10}Be year" is possible at present. Furthermore, nuclide production rates used in calculating exposure ages are determined at calibration sites whose true exposure age has been independently estimated in calendar years, so correct propagation of units and uncertainties yields an exposure age in calendar years. Thus, cosmogenic-nuclide exposure ages should simply be stated in units of years.

Once again, this discussion is not intended as a criticism of existing research, but to highlight the importance of comprehensive data reporting in cosmogenic-nuclide studies. The purpose of using a term such as "^{10}Be years" – to indicate that an age is model-dependent and may need to be recalculated in future when new information becomes available – is best served if authors are certain to include all the raw measurements needed to fully reproduce the age calculations. If this information is present, then the exposure ages can be recalculated in future to take advantage of improved production rate estimates. If it is not, the results of the study cannot be updated, improved, or incorporated into broader syntheses, and their value will be lost to future researchers.

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Table 1: Basic measurements required to calculate an exposure age or erosion rate from a cosmogenic-nuclide measurement. The final column shows which data were reported in ten recent papers that included exposure ages or erosion rates calculated from ^{10}Be measurements (see text). An estimate of the surface erosion rate was only counted as lacking when it was omitted in exposure-dating applications.

Measurement	Typical units	Required precision	Comments	Number of papers reporting (out of 10)
Site location	Degrees latitude, longitude (or the equivalent in a defined coordinate system)	$\sim$50 m	Precision of handheld GPS is more than adequate. For catchment-averaged erosion rates, the location must be precise enough that the upstream drainage area can be clearly determined from a map or digital elevation model.	10
Site elevation	m	$<$5 m	Should be referenced to sea level: vertical datums commonly used to reference GPS measurements differ from sea level in some parts of the world (Antarctica, for example). Handheld GPS is generally not accurate enough; precision GPS, barometric leveling from a benchmark, or a large-scale topographic map is required. The means of determining the elevation should be stated.	10
Sample thickness	cm	$\sim$1 cm	Not relevant for catchment-averaged erosion rates	4
Sample density	$g \cdot cm^3$	$\sim 0.1\ g \cdot cm^3$	If not measured, state assumed value. For catchment-averaged erosion rates, usually taken to be the density of the predominant rock type in the catchment.	3
Topographic or geometric shielding factor	Dimensionless	n/a	For sites with significant ($>\sim$ 5 %) shielding, one should report enough geometric information that the shielding factor could be recalculated with an improved method. Usually not relevant for catchment-averaged erosion rates.	5
Erosion rate (or lack of erosion) assumed in exposure age calculation	$cm \cdot yr^{-1}$	As accurately as possible, depending on available evidence	Should state any evidence on which the erosion rate estimate is based. Not relevant for an erosion rate calculation.	7
Nuclide concentration and measurement uncertainty	$atoms \cdot g^{-1}$	N/A	Should include a description of the size (both in absolute terms and relative to the total number of atoms measured in the sample) and uncertainty of laboratory and/or mass-spectrometric blank corrections. Actual measured nuclide concentrations are required: concentrations normalized to sea level and high latitude, which appear in some older publications, are not sufficient. The measurement uncertainty in the nuclide concentration should be clearly distinguished from any production rate uncertainty later propagated into an age or erosion rate estimate.	10
Name and assumed isotope ratio of reference standard	N/A	N/A	Always required. Particularly important for ^{10}Be and ^{26}Al measurements.	4