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Research Paper

In situ cosmogenic ^{10}Be production-rate calibration from the Southern Alps, New Zealand

A.E. Putnam [a,*], J.M. Schaefer [b], D.J.A. Barrell [c], M. Vandergoes [d], G.H. Denton [a], M.R. Kaplan [b], R.C. Finkel [e,f], R. Schwartz [b], B.M. Goehring [b], S.E. Kelley [a]

[a] Department of Earth Sciences and Climate Change Institute, University of Maine, Orono, ME 04469, USA
[b] Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA
[c] GNS Science, Dunedin, New Zealand
[d] GNS Science, Lower Hutt, New Zealand
[e] Earth and Planetary Science Dept, University of California, Berkeley, CA 94720, USA
[f] ASTER, Centre Européen de Recherche et Enseignement des Géosciences de l'Environnement, Aix-en-Provence 13100, France

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ABSTRACT

We present a ^{10}Be production-rate calibration derived from an early Holocene debris-flow deposit at about 1000 m above sea level in the central Southern Alps, New Zealand, in the mid-latitude Southern Hemisphere. Ten radiocarbon ages on macrofossils from a soil horizon buried by the deposit date the deposit to 9690 ± 50 calendar years before AD2008. Surface ^{10}Be concentrations of seven large boulders partially embedded in the stable surface of the deposit are tightly distributed, yielding a standard deviation of ~2%. Conversion of the ^{10}Be measurements to sea level/high-latitude values using each of five standard scaling methods indicates ^{10}Be production rates of 3.84 ± 0.08, 3.87 ± 0.08, 3.83 ± 0.08, 4.15 ± 0.09, and 3.74 ± 0.08 atoms g^{-1} a^{-1}, relative to the '07KNSTD' ^{10}Be AMS standard, and including only the local time-integrated production-rate uncertainties. When including a sea level high-latitude scaling uncertainty the overall error is ~2.5% (1σ) for each rate. To test the regional applicability of this production-rate calibration, we measured ^{10}Be concentrations in a set of nearby moraines deposited before 18 060 ± 200 years before AD2008. The ^{10}Be ages are only consistent with minimum-limiting ^{14}C age data when calculated using the new production rates. This also suggests that terrestrial in situ cosmogenic-nuclide production did not change significantly from Last Glacial Maximum to Holocene time in New Zealand. Our production rates agree well with those of a recent calibration study from northeastern North America, but are 12–14% lower than other commonly adopted values. The production-rate values presented here can be used elsewhere in New Zealand for rock surfaces exposed during or since the last glacial period.

1. Introduction

Surface-exposure dating using in situ cosmogenic nuclides has developed into a revolutionary tool for understanding Earth surface processes. Improvements in laboratory procedures and accelerator mass spectrometry (AMS) have greatly enhanced the analytical precision of the method, but the application of surface-exposure dating to problems requiring sub-millennial-scale accuracy remains hampered by systematic uncertainties associated with terrestrial cosmogenic nuclide production rates. The rate at which a cosmogenic nuclide is produced in a rock at the earth's surface is required to convert a measured nuclide concentration into an exposure age (or erosion rate). The production rate of a particular cosmogenic nuclide can be evaluated by measuring the nuclide concentration in a rock whose exposure time has been well determined by independent means. In order to translate a production rate measured at one location to that at another location, local influences must be taken into account. Local influences on cosmogenic nuclide production include spatial and temporal variations in atmospheric pressure (e.g., Stone, 2000; Gosse and Phillips, 2001; Ackert et al., 2003; Licciardi et al., 2006; Staiger et al., 2007), time-dependent fluctuations of Earth's magnetic field (e.g., Nishiizumi et al., 1989; Dunai, 2001; Pigati and Lifton, 2004; Desilets and Zreda, 2003; Desilets et al., 2006; Lifton et al., 2005, 2008), and potential effects of solar modulation (Lifton et al., 2005). Exposure ages are thus calculated using a production rate obtained

* Corresponding author. Tel.: +1 207 581 2166; fax: +1 207 581 1203.
E-mail address: aaron.putnam@umit.maine.edu (A.E. Putnam).

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from independently age-constrained calibration points, scaled to account for atmospheric pressure, geomagnetic, and solar modulation effects.

In this paper, we focus on ^{10}Be, which is the nuclide used most widely for exposure-dating applications. Over the last two decades, a network of production-rate calibration sites has been established (summarized in Balco et al., 2008), concentrated in the middle latitudes of the Northern Hemisphere and ranging up to 2000 m altitude. To produce a reference value, each local production rate has been scaled to sea level and high latitude (SLHL) using theoretical models that rely on neutron-monitor data (Dunai, 2001; Desilets et al., 2006; Lifton et al., 2005) or on a combination of neutron detectors and nuclear disintegration data (e.g., Lal and Peters, 1967; Lal, 1991). In general, scaling models predict a threefold production-rate increase from sea level to 1500 m altitude, and a twofold increase from the equator to the poles at sea level. Uncertainties of the 'global ^{10}Be calibration dataset' are about 9–12%, if one considers uncertainties in both local production rates and in scaling (Balco et al., 2008).

One way to improve the accuracy of surface-exposure chronologies is to obtain high-precision ^{10}Be production rates from local calibration sites. This is of particular importance for Southern Hemisphere applications of the ^{10}Be method, where there is an abundance of in situ cosmogenic ^{10}Be measurements (e.g., Shulmeister et al., 2005; Schaefer et al., 2006, 2009; Sutherland et al., 2007; Barrows et al., 2007; Ackert et al., 2008; Kaplan et al., 2008), but no calibration sites for this nuclide. Thus, ^{10}Be ages calculated from the southern latitudes depend on production rates from sites in the Northern Hemisphere that are extrapolated to the Southern Hemisphere using different scaling schemes. Therefore, ages calculated in the Southern Hemisphere incorporate difficult-to-quantify uncertainties stemming from how these scaling models describe nuclide production at locations distant from given calibration points (e.g., Dunai, 2001; Lifton et al., 2005, 2008; Desilets et al., 2006)

Here we document a ^{10}Be production-rate calibration site from the Southern Hemisphere middle latitudes. This site at Macaulay River, South Island, New Zealand, comprises a bouldery debris-flow deposit that overran a vegetated alluvial terrace in the early Holocene. We report high-precision measurements of ^{10}Be concentrations in boulders protruding from the top of this debris-flow landform. We determine the age of the deposit by ^{14}C dating of macrofossils from buried vegetation and soil that directly underlie the debris-flow deposit. The date of burial of these organic materials defines the age of the debris flow and the commencement of ^{10}Be accumulation in surface boulders. From these data we derive an SLHL in situ production rate for ^{10}Be at this location. We then examine the validity of this production-rate estimate by obtaining ^{10}Be measurements from boulders partially embedded in the surface of a nearby moraine sequence (Boundary Stream) deposited during the Last Glacial Maximum (LGM). Radiocarbon-dated sediments within a pond dammed by ice-marginal deposits afford a minimum-limiting age of these moraines. Using this approach, we discuss the implication for variations of the ^{10}Be production rate over the last glacial–interglacial transition in New Zealand.

2. Geologic description

New Zealand is the emergent part of a largely submerged block of continental rock straddling the boundary between the Australian and Pacific plates. Through South Island, the Alpine Fault marks the plate boundary, where plate motion is expressed as strike-slip displacement with a minor reverse component. Uplift southeast of the Alpine Fault has produced the Southern Alps. The study areas are on the eastern side of the Southern Alps (Fig. 1), within well-indurated Mesozoic sedimentary rocks dominated by 'greywacke' sandstone and 'argillite' mudstone. The highest parts of the Southern Alps support valley glaciers today, but during the LGM, and earlier glaciations, valley glaciers extended throughout the mountain range and out onto adjacent foreland regions.

2.1. Overview of the Macaulay valley

The Macaulay River is a tributary of Lake Tekapo (Fig. 1), the catchment of which was fully glaciated during the LGM. Well upstream of the LGM terminal moraine complex, the Macaulay valley contains ice-sculpted bedrock valley sides, trimlines, hanging tributary valleys and patches of recessional lateral moraine. The river floodplain and terraces, as well as fans built by tributary streams occupy the valley floor. A prominent set of moraines in the middle reaches of the Macaulay valley ($\sim$1020 m above sea level (a.s.l.)), informally referred to here as the 'mid-Macaulay moraines', are in a position intermediate between LGM moraines down-valley, and modern glaciers and late-Holocene moraines farther up-valley. The mid-Macaulay moraines have previously been assessed as early Holocene in age (e.g., McSaveney and Whitehouse, 1989).

2.2. Previous work on the mid-Macaulay moraines

A buried organic horizon exposed in the western bank of the Macaulay River near the down-valley end of the mid-Macaulay moraines has been a subject of scientific interest for several decades. In 1963, A.C. Beck first described the buried organics and collected a sample of wood (NZ-548) that was subsequently dated using ^{14}C (Grant-Taylor and Rafter, 1971; NZ-548, 8460 $\pm$ 120 ^{14}C yr BP). The stratigraphy was interpreted as 'peat on fan debris and overlain by moraine'. In response to the publication of this date and its geologic interpretation, Burrows (1972) drew attention to the unsorted bouldery deposit that overlies the organic horizon, and the hummocky, boulder-strewn landform developed on this deposit (boulder field in Figs. 1 and 2). Burrows considered that the deposit lacks the fine silt matrix that he regarded as typical of basal till, and noted that the boulder field has a faintly expressed arrangement of ridges that could be interpreted as radiating out from the adjacent northwestern side of the valley; he preferred the interpretation that the deposit is landslide debris. Burrows also noted his impression in the field that the landslide terrain, at its northern margin, laps onto morainal landforms and is therefore younger than the moraines. Beck (1972) endorsed Burrows' reinterpretation of the deposit, and concurred that the ^{14}C date represents a minimum age for the mid-Macaulay moraines.

McSaveney and Whitehouse (1989) reported a visit to the Macaulay valley in 1980 during which they found that river erosion had refreshed the riverbank exposures. They described and discussed the stratigraphic exposures and adjacent landforms, and presented a radiocarbon date (NZ-6473, 8690 $\pm$ 120 ^{14}C yr BP) of wood collected from buried soil about 80 m upstream of the original sample site. McSaveney and Whitehouse (1989) agreed with Burrows' (1972) overall interpretation of the locality, including the general nature of the mid-Macaulay moraines, but disputed the genesis of the deposit (diamicton) overlying the buried soil. They considered that the diamicton lacks characteristic features diagnostic of rapidly emplaced landslide ('rock avalanche') debris, and therefore concluded that the diamicton is till, emplaced in part by subglacial processes (basal till) and in part by passive ice downwasting (ablation till). They noted that they could not discount an alternative interpretation that the diamicton was emplaced by two debris-flow events, the earlier of which deposited the material they interpreted as basal till, and the latter depositing the material regarded as ablation till.