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Calibrating a long-term meteoric ^{10}Be accumulation rate in soil

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[1] Using 13 samples collected from a 4.1 meter profile in a well-dated and stable New Zealand fluvial terrace, we present the first long-term accumulation rate for meteoric ^{10}Be in soil (1.68 to 1.72 × 10^6 at/(cm^2·yr)) integrated over the past ~18 ka. Site-specific accumulation data, such as these, are prerequisite to the application of meteoric ^{10}Be in surface process studies. Our data begin the process of calibrating long-term meteoric ^{10}Be delivery rates across latitude and precipitation gradients. Our integrated rate is lower than contemporary meteoric ^{10}Be fluxes measured in New Zealand rainfall, suggesting that long-term average precipitation, dust flux, or both, at this site were less than modern values. With accurately calibrated long-term delivery rates, such as this, meteoric ^{10}Be will be a powerful tool for studying rates of landscape change in environments where other cosmogenic nuclides, such as in situ ^{10}Be, cannot be used. **Citation:** Reusser, L., J. Graly, P. Bierman, and D. Rood (2010), Calibrating a long-term meteoric ^{10}Be accumulation rate in soil, *Geophys. Res. Lett.*, *37*, L19403, doi:10.1029/2010GL044751.

1. Introduction

[2] The concentration of meteoric ^{10}Be in soils and sediment can be used as a geochronometer [e.g., *Egli et al.*, 2010; *Pavich et al.*, 1984; *Pavich et al.*, 1986] and a tracer of Earth surface processes [e.g., *Brown et al.*, 1988; *Reusser and Bierman*, 2010; *Valette-Silver et al.*, 1986, *Willenbring and von Blackenburg*, 2010]. Critical to both of these geomorphic applications is constraining the delivery rate of meteoric ^{10}Be to landscapes over geomorphically meaningful time-scales (10^3 to 10^5 yrs). To date, no study has explicitly and deliberately attempted to constrain the long-term accumulation rate of meteoric ^{10}Be in soil. Most geomorphic applications of meteoric ^{10}Be measure concentrations in soil and base their interpretations on globally averaged contemporary delivery rates [e.g., *Jungers et al.*, 2009; *Reusser et al.*, 2008]; yet, contemporary, short-term data clearly indicate that the total flux of meteoric ^{10}Be to the soil surface varies over time and space [e.g., *Graham et al.*, 2003; *Heikkilä et al.*, 2008; *Monaghan et al.*, 1986].

[3] Because of documented long-term changes in primary meteoric ^{10}Be production [*Frank et al.*, 1997], climate (primarily precipitation) [*Dore*, 2005], and the source and volume of allochthonous dust [*Baumgartner et al.*, 1997], there are differences between long- and short-term meteoric ^{10}Be delivery rates. These complexities suggest the importance of calibrating site-specific, long-term delivery rates by measuring the accumulation of meteoric ^{10}Be in geologic archives. Such work has been done in lake deposits, deep-sea sediments, and glacial ice [e.g., *Finkel and Nishiizumi*, 1997; *Frank et al.*, 1997] but not in soils, the basis for most geomorphic studies. Here, we quantify the meteoric ^{10}Be inventory in a 4.1 m depth profile collected from a stable and well-dated alluvial surface on New Zealand's North Island and estimate a long-term accumulation rate for meteoric ^{10}Be in soil.

2. Behavior of Meteoric ^{10}Be

[4] Meteoric ^{10}Be is a valuable tool for studying surface process rates because, once deposited, it adsorbs tenaciously to near-surface materials in all but the most acidic soils [*You et al.*, 1989]. Unlike shorter-lived radionuclides, such as ^{210}Pb and ^{137}Cs [e.g., *Walling et al.*, 2003], the longer half-life of ^{10}Be (1.36 Myr [*Nishiizumi et al.*, 2007]) increases the period of time over which the nuclide accumulates in soils and penetrates to depth before decay, thus extending the timeframe over which the method is applicable. Because measurements of meteoric ^{10}Be are made on bulk samples, the presence or absence of a specific mineral phase is irrelevant, making the isotope useful across a wide variety of landscapes.

[5] The flux of meteoric ^{10}Be to terrestrial environments comes from two sources: ^{10}Be produced in the atmosphere by spallation of nitrogen and oxygen and delivered to earth's surface by precipitation and dryfall (primary component), and ^{10}Be adhered to airborne dust (recycled component) [*Monaghan et al.*, 1986].

[6] Primary production of meteoric ^{10}Be is controlled by solar activity and magnetic field intensity [*Masarik and Beer*, 2009], both of which vary over time [*Beer*, 1994; *Frank et al.*, 1997]. The subsequent distribution of primary meteoric ^{10}Be is controlled by atmospheric circulation, with annual precipitation being a strong predictor of total meteoric ^{10}Be fallout at any one location [*Heikkilä et al.*, 2009].

[7] Delivery of recycled meteoric ^{10}Be is controlled by the flux, and ^{10}Be concentration, of dust. Recycled meteoric ^{10}Be is usually <20% of total meteoric ^{10}Be flux [*Graham et al.*, 2003; *Monaghan et al.*, 1986]; in high-dust environments, such as in regions of loess accumulation, the flux of recycled meteoric ^{10}Be can be far greater [*Baumgartner et al.*, 1997; *Zhou et al.*, 2007]. Ardity sufficient to promote topsoil loss by wind [*Zhou et al.*, 2007] and land-use practices that disrupt topsoil [*Brown et al.*, 1988] increase recycled meteoric ^{10}Be flux from dust.

[8] Because geochemical processes in soils rapidly meld primary and recycled meteoric ^{10}Be, constraining the spatial

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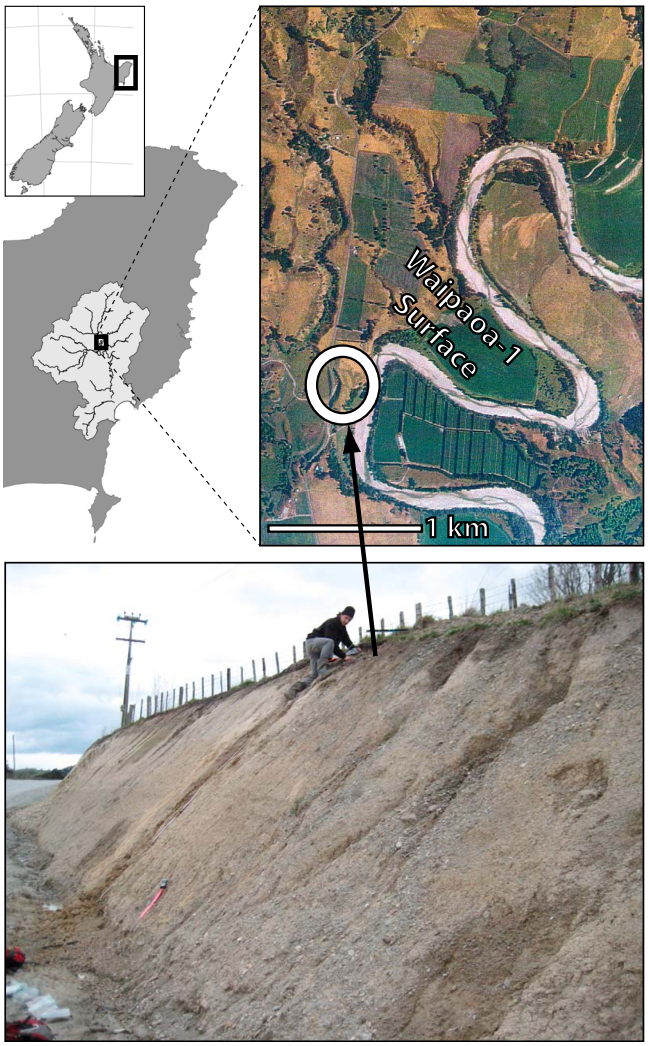

Figure 1. Calibration profile located in the middle Waipaoa River basin, New Zealand, North Island.

and temporal variation in the rate of accumulation of both components is required when measurements of meteoric ^{10}Be are used for modeling surface processes. Most contemporary ^{10}Be flux measurements exclude dust influence to determine the primary ^{10}Be flux. In this study, both components are critical and not explicitly separable.

3. Geologic Setting

[9] We sampled a soil profile within the Waipaoa River Basin, a 2,200 km^2 catchment draining the eastern margin of New Zealand's North Island (Figure 1) [*Mazengarb and Speden*, 2000]. At ~38°S Latitude, this site receives ~110 cm of rain annually [*Hessell*, 1980].

[10] Within the basin, an extensive flat-lying fluvial terrace (termed Waipaoa-1) stands up to ~100 m above the mainstem and many of the tributary channels of the Waipaoa River. This terrace surface is capped by ~10 m of coarse fluvial gravel deposited during the last glacial maximum [*Berryman et al.*, 2000]. Atop the gravel, lie several meters of overbank silty clay-rich flood deposits laid down as this river level was rapidly abandoned in response to a combination of tectonic uplift and a switch in the fluvial system from aggradation to rapid incision, most likely in response to changing climate following the glacial maximum at ~18 ka [*Berryman et al.*, 2000; *Eden et al.*, 2001]. Evidence from other dated terrace surfaces suggests that the cessation of aggradation at ~18 ka was a regional event across the eastern and southern North Island [*Eden et al.*, 2001]. Where we sampled the Waipaoa-1 terrace, it stands ~50 m above the modern channel, is extensive, flat, far from any nearby slopes, well-preserved, and lacks any surface drainage, indicating that little net erosion or deposition have occurred since the emplacement of the overbank deposits shortly after ~18 ka. Land clearance and agriculture have at most reworked the upper several dm of the sampled site.

4. Age of Sampled Profile

[11] The overbank deposits contain age-constrained tephras used to estimate the timing of the Waipaoa-1 terrace abandonment and emplacement of the sediment we sampled. The Rerewhakaaitu Tephra is located at or near the base of the Waipaoa-1 overbank deposits that cap the fluvial gravels [*Berryman et al.*, 2000; *Eden et al.*, 2001; *Froggatt and Lowe*, 1990]. The stratigraphic position of this tephra indicates that it fell coincidently with the initiation of rapid incision [*Berryman et al.*, 2000; *Eden et al.*, 2001]. The overlying flood deposits were emplaced relatively quickly (perhaps over the course of decades; [*Eden et al.*, 2001]) until the river had incised far enough to isolate the terrace surface from further aggradation. The age of the Rerewhakaaitu Tephra is constrained with multiple radiocarbon ages (n = 4) of organic material directly overlying the tephra in a bog core collected nearby [*Lowe et al.*, 1999]. We calibrated the radiocarbon age of 14,700 ± 95 ^{14}C yrs with CALIB REV6.0 [*Stuiver and Reimer*, 1993], yielding a 1σ age range of 17,659 to 18,030 cal. yr.

[12] The Waipaoa-1 terrace is ideal for constraining the long-term delivery rate of meteoric ^{10}Be because: 1) the airfall deposition of the Rerewhakaaitu Tephra within the overbank deposits constrains the integration time of ^{10}Be accumulation, 2) an intact younger capping tephra bed argues against either surface erosion or deposition, 3) the fine texture of the soil and the buffering capacity of the carbonate-bearing source rocks [*Black*, 1980; *Mazengarb and Speden*, 2000] ensure retention of meteoric ^{10}Be and, 4) the ~5 m of overbank deposits above the basal tephra at the location we sampled is thick enough to retain the inventory of meteoric ^{10}Be delivered since 18 ka.

5. Sampling and Analysis Techniques

[13] We sampled the Waipaoa-1 overbank sequence from a recent excavation at 2931760 E, 6297492 N (NZ Grid 1949 (Figure 1)). The sequence consists of fluvial silty clay-rich sediment containing small amounts of reworked tephra. The overbank sediment is capped by a discrete younger tephra bed (presumably the widespread ~3500 cal. ybp Waimihia Tephra) [*Eden et al.*, 2001], the upper ~15 cm of which has developed an organic-rich A/O-horizon. We collected a total of thirteen, 15 to 37 cm thick amalgamated samples. In addition, we collected several undisturbed samples of profile sediment for dry density determination.

[14] We dried and milled samples and isolated meteoric ^{10}Be from ~0.5 g aliquots using a modification of the

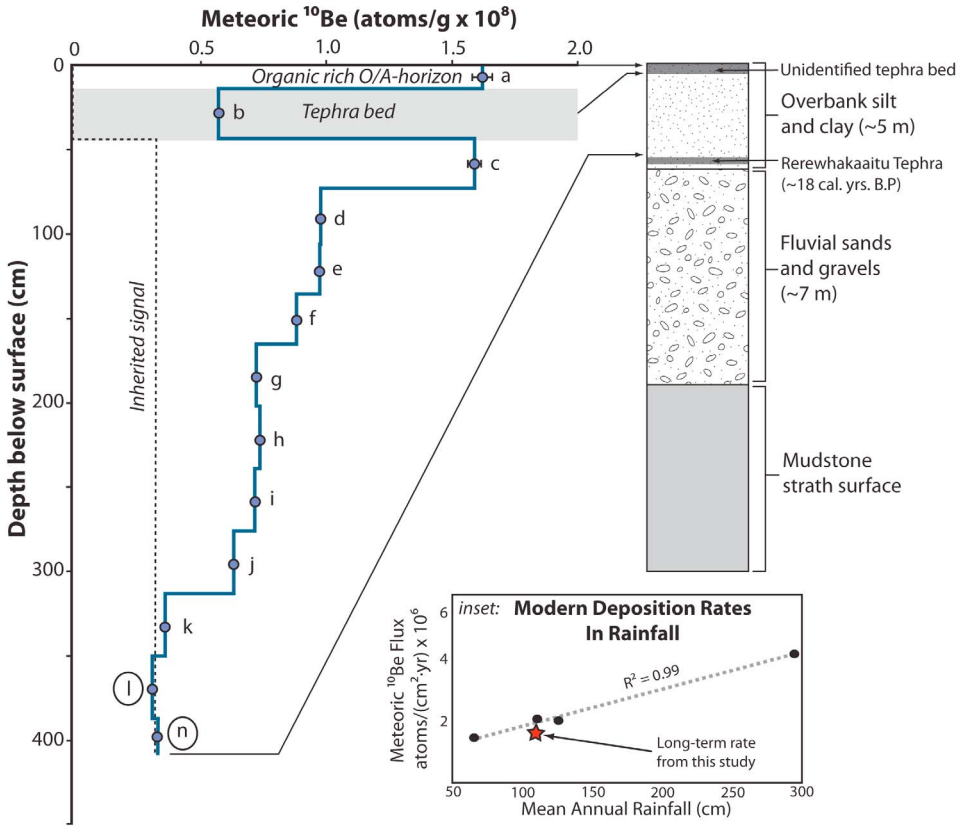

Figure 2. Meteoric ^{10}Be concentration results for the depth profile. Letters to the right of each sample are abbreviations (e.g., "a" represents WA102a in Table S1). The inherited concentration is the average of samples WA102 l, and n (circled). Inset shows relationship of long-term meteoric ^{10}Be delivery rate to contemporary rates measured across the North and South islands of New Zealand [*Graham et al.*, 2003].

method of *Stone* [1998], then calculated meteoric ^{10}Be concentrations from ^{10}Be/^{9}Be ratios measured at Lawrence Livermore National Laboratory. Data were normalized to the 07KNSTD3110 standard with an assumed ratio of $2850 \cdot 10^{-15}$ [*Nishiizumi et al.*, 2007]. All measured sample isotopic ratios were corrected using process blanks prepared from acid-leached fluvial sediment collected in the Waipaoa Basin; blank corrections ranged from 2.1 to 0.3% of measured ratios.

6. Long-Term Meteoric ^{10}Be Delivery Rate

[15] In general, meteoric ^{10}Be concentrations decrease regularly down section (Figure 2 and Table S1 of the auxiliary material), with a maximum concentration of $16.27 \pm 0.40 \times 10^7$ atoms/g in the uppermost sample, and a minimum concentration of $3.12 \pm 0.07 \times 10^7$ atoms/g near the bottom of the profile.[1] When deposited, the overbank sediment carried some meteoric ^{10}Be, its inherited concentration. Following the abandonment of the Waipaoa-1 terrace and the emplacement of the overbank sequence, additional atmospherically-derived meteoric ^{10}Be accumulated, adsorbed to fine sediment, was bioturbated, and translocated downward through macropores, resulting in the profile shape we see today (Figure 2). We consider the relatively uniform and low concentration of meteoric ^{10}Be in the bottom ~0.6 m of the profile (samples WA102l and n (Figure 2)) as representative of the inherited component of the total inventory of meteoric ^{10}Be in the profile, and subtract the thickness-weighted average concentration of these two samples from all others, except WA102a and b. Because these two uppermost samples were sourced primarily from airfall tephra, we assume they contained no meteoric ^{10}Be when deposited.

[16] We use equation (1) to calculate a total inventory of meteoric ^{10}Be (N; $3.02 \pm 0.05 \times 10^{10}$ atoms/cm^2) deposited and adsorbed since the abandonment of the Waipaoa-1 terrace.

$$N = \sum (n_{tot} - n_{inh}) \cdot \rho \cdot l \qquad (1)$$

where, n_{tot} = the measured concentration of meteoric ^{10}Be (atoms/g), n_{inh} = the inherited component of the total concentration ($3.21 \pm 0.06 \cdot 10^7$ atoms/g), ρ = the dry density of the depth increment (g/cm^3), and l = the increment thickness (cm). The dry density of the overbank silt and clay (WA102c to n) is 1.68 ± 0.03 g/cm^3 based on repeat measurements (n = 4) of undisturbed samples we collected. We use a literature value for the dry density of tephra (1.05 ± 0.12 g/cm^3 [*Houlbrooke et al.*, 1997]) for the uppermost tephritic increments (WA102a and b).

[17] We arrive at a geologic delivery rate (q; atoms/(cm^2·yr)), corrected for decay and inheritance, for the meteoric ^{10}Be accumulated within the measured profile

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044751.

(N; atoms/cm^2) over the duration of time since the abandonment of the Waipaoa-1 surface (t; yrs) and emplacement of the overbank sediment with equation (2):

$$q = N \cdot \lambda / \left(1 - e^{\lambda t}\right) \quad (2)$$

We assume $\lambda = 5.1 \cdot 10^{-7}$ yr^{-1}, the decay constant for ^{10}Be [*Nishiizumi et al.*, 2007]. The calibrated 1σ age range of 17,659 to 18,030 cal. yrs translates into a 1σ range of decay-corrected deposition rates for meteoric ^{10}Be of 1.72 to 1.68 × 10^6 atoms/(cm^2·yr).

[18] Our analysis accounts for all errors associated with AMS measurement, radiocarbon measurement and calibration, and density; however, several possible sources of error are difficult to quantify. If the overbank deposits we sampled were emplaced after the age-constraining basal tephra, the integration time of ~18 ka would be an overestimate. If surface erosion over the last 18 ky removed material, the measured ^{10}Be inventory would be an underestimate. If the radiocarbon age of the basal tephra is younger than the deposit, the period of accumulation we use would be too short.

7. Discussion

[19] Using precise AMS measurements (<2%, 1σ) of a deep soil profile from a stable depositional surface of constrained age, we provide the first explicit long-term, soil-based calibration of meteoric ^{10}Be deposition integrated over a geologically relevant time interval. The soil we sampled (Figure 2 and Table S1) contains meteoric ^{10}Be derived from three distinct sources: 1) meteoric ^{10}Be inherited prior to the emplacement of the overbank deposits, 2) atmospherically-derived primary meteoric ^{10}Be, and 3) dust-derived recycled ^{10}Be. Our approach quantifies and subtracts the inherited component from the total inventory (N; equation (1)) allowing us to estimate the temporally averaged meteoric ^{10}Be delivery rate (q; equation (2)) since the exposure we sampled was emplaced. The delivery rate we calculate reflects contributions of both primary and recycled meteoric ^{10}Be.

[20] Contemporary data suggest that meteoric ^{10}Be deposition rates in New Zealand correlate well with precipitation (Figure 2, inset) and that the majority of meteoric ^{10}Be accumulated in the profile we measured is atmospherically-derived (primary). Measurements of meteoric ^{10}Be in modern precipitation collected over two years at four sites spanning New Zealand show a range in deposition rates from 1.7 to 5.2 × 10^6 atoms/(cm^2·yr), with total flux strongly correlating to annual precipitation [*Graham et al.*, 2003]. When these values are normalized to mean annual rainfall at each site and 700 MV of solar activity [*Masarik and Beer*, 2009; *Usoskin et al.*, 2005], the between-site variability collapses to 1.4 to 2.1 × 10^4 atoms/cm^3 of rainfall. Based on ^{7}Be and dust concentration measurements, *Graham et al.* [2003] estimate that only about 10% of the contemporary meteoric ^{10}Be fallout is recycled from dust. If the atmospherically-produced primary component is considered separately, modern meteoric ^{10}Be deposition rates (Figure 2, inset) in New Zealand range from ~1.4 to ~4.2 × 10^6 atoms/(cm^2·yr).

[21] If these modern ^{10}Be deposition values represent long-term conditions, and long-term dust flux remained ~10% of the total meteoric ^{10}Be deposition, then our measured long-term total meteoric ^{10}Be deposition rate of ~1.70 × 10^6 atoms/(cm^2·yr) suggests that precipitation at the Waipaoa site averaged ~77 cm/yr. This estimate is ~30% lower than contemporary measurements [*Hessell*, 1980], suggesting that precipitation averaged over ~18 ky was lower than today. Alternatively, some of the difference may be due to a recent increase in meteoric ^{10}Be recycled from dust. Contemporary dust is primarily generated by human activities. If the long-term dust flux on the largely unglaciated North Island is negligible and meteoric ^{10}Be concentrations in contemporary rainfall are otherwise representative of long-term conditions, paleo-precipitation would be ~91 cm/year over 18 ky, still about 17% drier than modern climate records indicate. Regional paleoclimate records are consistent with this interpretation of the meteoric ^{10}Be data, as they suggest that the eastern North Island was substantially drier prior to an ENSO-driven precipitation increase approximately 4 ka [*Gomez et al.*, 2004].

8. Implications

[22] Our findings demonstrate the feasibility of calibrating long-term meteoric ^{10}Be accumulation rates using deep, stable, well-dated soil profiles. Such soil-based calibrations are important because soils constitute the source material for most surface process studies including fluvial sediment analysis [e.g., *Reusser and Bierman*, 2010]. Terrestrial calibration of meteoric ^{10}Be delivery rates compliments other methods. Polar ice cores reliably record ^{10}Be fluxes over time at high latitudes [e.g., *Finkel and Nishiizumi*, 1997]; however, these fluxes can differ dramatically from those at lower latitudes because of atmospheric production and mixing processes [e.g., *Heikkilä et al.*, 2009]. Deep-sea and most lake sediment records are filtered by drainage basin and biologic processes making delivery rates over time difficult to deconvolve accurately [e.g., *Aldahan et al.*, 1999]. Because deposition rates of meteoric ^{10}Be to the soil surface change over time and space as rainfall, dust flux, and geomagnetic shielding all vary, performing additional geologic calibrations at a variety of latitudes, in different precipitation regimes, and over different integration times will improve the accuracy and precision of surface process studies using this isotope system.

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