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EXPRESS LETTER

Quantitative determination of long-term erosion rates of weathered granitic soil surfaces in western Abukuma, Japan using cosmogenic ^{10}Be and ^{26}Al depth profile

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We present erosion rates of granitic soil surfaces in the western Abukuma upland, Japan using depth profiles of *in-situ* produced cosmogenic ^{10}Be and ^{26}Al based on physical parameters for both neutron and muon interactions. Samples were obtained below the severely weathered zone, from 30 to 190 cm depth below surface (bs). We confirmed that, in this environment, deeper layers from at least 80 cm bs must be analyzed to achieve highly accurate measurement of erosion rate because near-surface layers are potentially influenced by pedogenic processes. The depth profiles obtained suggest a surface-lowering rate of 49–74 m/Myr for a mountain ridge composed of granitic soil. This newly obtained erosion rate is much higher than previously reported granitic or metamorphic bedrock, as well as quartz vein, erosion rates from several climatic environments including humid regions, suggesting that granitic soil surface is more susceptible to erosion.

Keywords: weathered granitic soil surface, erosion rate, cosmogenic ^{10}Be and ^{26}Al, depth profile, sampling depth

INTRODUCTION

Quantitative long-term erosion rates are an important contribution for understanding landscape evolution, which is controlled by tectonic or climatic forces, and are required to constrain geomorphology models of landscape evolution. However, direct observation of erosion rates is complicated by (1) the long temporal scale, which is on the order of millions of years, (2) the difficulty in identification of the onset and termination of erosional events, and (3) the inherent removal of surficial material (Matsukura, 2008).

In-situ produced terrestrial cosmogenic nuclides (TCNs) have been used for directly determining erosion rates for close to 20 years (e.g., Gosse and Phillips, 2001). *In-situ* TCNs are produced in the upper few meters of the Earth's surface due to interactions between target atoms and secondary cosmic rays that reached the earth surface via cascading processes (Lal, 1991). *In-situ* TCN (^{10}Be and ^{26}Al in this study) production is controlled by high-energy neutron spallation and muon interactions, which have significantly different attenuation lengths that decrease exponentially with attenuation of the secondary cosmic ray flux at depth (e.g., Kim and Englert, 2004). Distributions of *in-situ* TCNs at depth allow us to estimate erosion rates without complex assumptions, and highly accurate values can be obtained with appropriate sample site selection. Therefore, TCN depth profiles provide a highly appropriate means for quantifying long-term values for unconsolidated surfaces (e.g., Braucher *et al.*, 2009).

Rates of surface erosion and fluvial incision determined with depth profiles have been reported from a variety of climatic, topographic, lithologic, and tectonic environments (e.g., Siame *et al.*, 2004; Kim and Englert, 2004). However, there are only a few previous studies that applied to Japanese geology (Matsushi *et al.*, 2006; Mahara *et al.*, 2010).

We focus on deducing erosion rates of granitic soil surfaces. Granitic soil surfaces are distributed widely throughout Japan due to the temperature and relatively humid conditions (e.g., Mahara *et al.*, 2010). Therefore, erosion rates of granitic soil surfaces are widely applicable to Japan. However, only one previous study on erosion rates of granitic surface soil in Japan was deduced from a TCN (^{10}Be, ^{26}Al and ^{36}Cl) depth profile with a

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Table 1. Measured $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ ratios and concentrations of ^{10}Be and ^{26}Al

Sample ID	Depth (cm)	Quartz (g)	^{10}Be/^{9}Be (10^{-12})	error	^{26}Al/^{27}Al (10^{-12})	error	^{10}Be conc. (10^{4}) (atoms/gSiO$_2$)	error	^{26}Al conc. (10^{5}) (atoms/gSiO$_2$)	error
ABK0902-1	32.1	18.4831	0.081	0.007	0.385	0.041	7.95	1.03	4.34	0.479
ABK0902-2	56.2	16.4744	0.065	0.004	0.299	0.014	6.47	0.669	3.65	0.206
ABK0902-3	86.8	19.071	0.058	0.003	0.236	0.015	4.66	0.438	2.74	0.201
ABK0902-4	106.1	17.7037	0.051	0.003	0.180	0.016	4.06	0.495	2.28	0.223
ABK0902-5	125.3	16.4322	0.049	0.005	0.175	0.012	4.04	0.715	2.07	0.163
ABK0902-6	144.6	16.3398	0.043	0.003	0.160	0.012	3.17	0.433	1.79	0.144
ABK0902-7	176.8	12.8377	0.036	0.002	0.126	0.011	2.74	0.493	1.55	0.151
ABK0902-8	189.6	13.3671	—	—	0.154	0.019	—	—	1.53	0.199
ABK-BLK			0.022	0.001	0.002	0.001				

Note: BeO$^-$ currents for ^{10}Be AMS measurements were ~5 μA, and each sample was counted for 40 min. ABK-BLK is chemical blank. Dashes in table indicate no data.

simple erosion model based on Lal (1991) (Mahara *et al.*, 2010). While this work indicates that TCN cosmogenic depth profiles are useful for estimating erosion rates in Japan, the depth of the profile was limited to a relatively shallow ~70 cm bs, introducing the ambiguity that the results may be influenced by near-surface pedogenic processes. A previous study conducted in New Zealand indicates that both ^{10}Be and ^{26}Al from shallow depths do not fit to any erosion model (Kim and Englert, 2004). Therefore, in this study, we employ an extended TCN depth profile of ^{10}Be and ^{26}Al (to ~190 cm) in an attempt to avoid pedogenic effects and determine a minimum depth, considering both neutron and muon interactions, required to obtain reliable erosion rate of granitic soil surfaces.

STUDY AREA, SAMPLING STRATEGY AND METHODS

The sampling site is located in the western Abukuma upland, Japan (140°32′ E and 37°23′ N), at an altitude of 480 m above sea level (Fig. 1A). The study area is primarily a Pliocene to Early Pleistocene granitic soil erosion surfaces derived from Early Cretaceous bedrock (e.g., Yamamoto, 2005 references therein). No volcanic activity has been recorded in this area since the Late Neogene, and there are no known active faults (Yamamoto, 2005). Annual rainfall in this region is reported to be 1200 mm/yr by the Japan Meteorological Agency.

To collect a sufficient amount of ^{10}Be and ^{26}Al in quartz (~15 g) for AMS measurements, we selected a quartz-rich vein penetrating obliquely into a typical granitic soil mountain ridge outcrop for sampling (Fig. 1B). Production of TCNs in the quartz vein is controlled by erosion of the overlying granitic soil due to vertical attenuation of cosmic rays. Therefore, the erosion rate deduced from TCNs in the quartz vein is equivalent to that of the overlying granitic soil surface. We obtained eight quartz-rich rocks between 30 cm and 190 cm bs (Fig. 1B). There is no evidence of tectonic events, such as faulting or folding, as well as no unconformities cutting across the sampled strata. The vegetated surface and heavily-weathered near-surface layers (~10–15 cm) were not sampled.

Samples were crushed into a 0.5 to 1 mm size fraction, and quartz grains were subsequently separated by chemical etching following the method of Kohl and Nishiizumi (1992). The purified quartz samples were dissolved with HF and were spiked with a Be carrier (~0.4 mg). Aliquots for Be and Al were separated by a series of column chromatography and then oxidized for AMS measurements (^{10}Be/^{9}Be and ^{26}Al/^{27}Al) at The University of Tokyo following the method of Matsuzaki *et al.* (2007). Standard materials of KNB5-1 and KN5-1 are used for AMS measurements of Be and Al, respectively (Nishiizumi *et al.*, 2007). Stable ^{27}Al was measured by ICP-AES at Nihon University.

The model describes predicted depth distributions with long-term simple erosion and exposure history calculated from the following equation that assumed no inheritance;

$$
\begin{aligned}
C(x,t) = {} & \frac{P_0 \cdot P_{spal.}}{\dfrac{\rho\cdot\varepsilon}{\Lambda_{spal.}}+\lambda}\cdot e^{\frac{-\rho\cdot x}{\Lambda_{spal.}}}\cdot\left(1-e^{-\left(\lambda+\frac{\varepsilon\cdot\rho}{\Lambda_{spal.}}\right)t}\right)\\
& +\frac{P_0 \cdot P_{stop}}{\dfrac{\rho\cdot\varepsilon}{\Lambda_{stop}}+\lambda}\cdot e^{\frac{-\rho\cdot x}{\Lambda_{stop}}}\cdot\left(1-e^{-\left(\lambda+\frac{\varepsilon\cdot\rho}{\Lambda_{stop}}\right)t}\right)\\
& +\frac{P_0 \cdot P_{fast}}{\dfrac{\rho\cdot\varepsilon}{\Lambda_{fast}}+\lambda}\cdot e^{\frac{-\rho\cdot x}{\Lambda_{fast}}}\cdot\left(1-e^{-\left(\lambda+\frac{\varepsilon\cdot\rho}{\Lambda_{fast}}\right)t}\right).
\end{aligned}
\tag{1}
$$

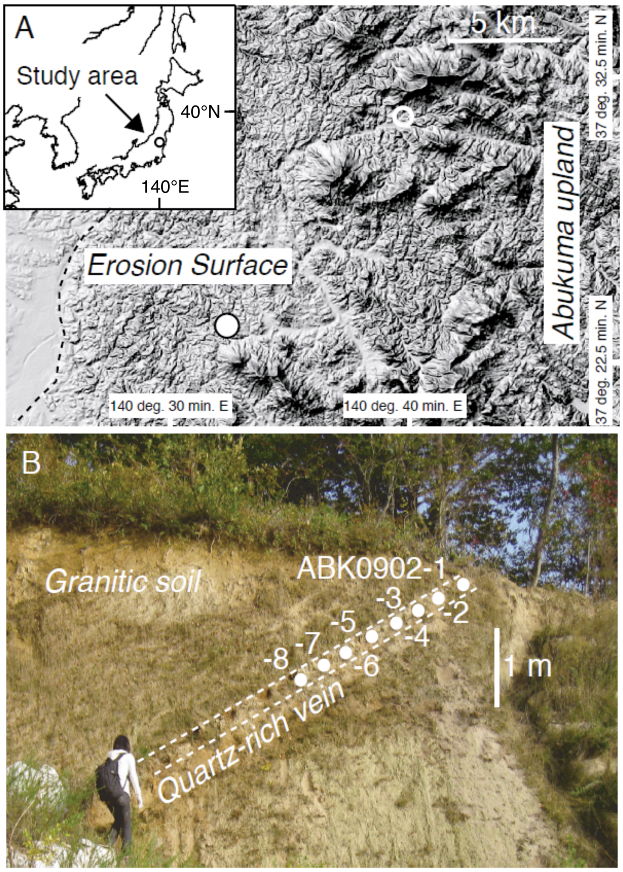

Fig. 1. (A) Location of the study site at 140°32′ E and 37°23′ N at an altitude of 480 m at sea level, in western Abukuma, Japan. The figure shows the shaded-relief map of this study area based on 50-mesh elevation data. The white-filled circle indicates the sampling site in this study, and the white circle is the site of Mahara et al. (2010). (B) The photo describes sampling site of TCN measurements. White dash lines show the area of quartz-rich vein and white-filled circles are sampling points.

Here $C(x, t)$ is concentrations of TCNs in quartz at exposure time t (yr) and depth x (cm), P_0 is the production rate (atoms/g Quartz/yr) of TCNs in quartz at the surface. ε is the erosion rate (cm/yr) at the surface, ρ is density of the formation (2.2 g/cm^3) as wet granitic soil, λ is the radioactive decay of TCNs (^{10}Be: 5.10×10^{-7}; ^{26}Al: 9.83×10^{-7}), $P_{spal.}$ (0.9815), P_{slow} (0.012), P_{fast} (0.0065) are contribution rates of each mechanical production of TCNs at the surface ($P_{spal.} + P_{slow} + P_{fast} = 1$), and $\Lambda_{spal.}$ (160 g/cm^2), Λ_{slow} (1500 g/cm^2) and Λ_{fast} (5300 g/cm^2) are the effective attenuation lengths (Braucher *et al.*, 2003; Gosse and Phillips, 2001; Heisinger *et al.*, 2002). Production rates of TCNs in quartz were calculated using the protocol described in Stone (2000). For the present case, ^{10}Be and ^{26}Al production rates are 7.17 and 44 atoms/g/yr, which are scaled from sea-level-and-high-latitude values of 5.1 and 31.1 atoms/g/yr (Stone, 2000), respectively.

We use the sum of chi-squared (χ^2) (Eq. (2)) for best fitting of the model (Siame *et al.*, 2004; Braucher *et al.*, 2009).

$$\chi^2 \equiv \sum_{i=1}^{N}\left(\frac{C_i - C\left(x_i,\varepsilon,t\right)}{\sigma_i}\right)^2. \qquad (2)$$

Here x_i is the depth, ε and t are given erosion rate and exposed year, respectively. C_i is measured concentration of TCNs at x_i, σ_i is the analytical uncertainty at x_i, and $C(x_i, \varepsilon_i, t)$ is the calculated concentration of TCNs from Eq. (1). N is the total number of samples in the profile.

RESULTS AND DISCUSSION

The measured ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios ranged from 3.6 to 8.1×10^{-14} and 1.26 to 3.85×10^{-13}, respectively, which is reasonably higher than typical blank measurements of $(2.2 +/- 0.1) \times 10^{-14}$ and $(0.02 +/- 0.01) \times 10^{-13}$, respectively, allowing accurate measurements from these relatively small amounts of TCNs (Table 1).

We deduced the site erosion rate by combining the above model based on Eqs. (1) and (2) and the measured ^{10}Be and ^{26}Al activities. Figure 2 illustrates the measured ^{10}Be and ^{26}Al together with the modeled nuclides distributions, that steady-state concentrations have been reached, and the erosion rate from layers between 30 to 190 cm bs is 61 (+6/–4 in 1σ) m/Myr for ^{10}Be and 62 (+4/–3 in 1σ) m/Myr for ^{26}Al. These results exhibit exceptionally good fit to the erosion rate model at all sampled depths.

We also reanalyzed ^{10}Be and ^{26}Al reported by Mahara *et al.* (2010) using Eq. (1). They reported a steady state erosion rate from a different surface at 496 m above sea level in northern Abukuma but only sampled from 0 cm to 70 cm bs (Fig. 1A). Multiple exposure age-erosion rate pairs deduced from Eq. (1) fit the measured values between 0 and 70 cm bs, which may suggests that steady-state concentrations have not been reached (Braucher *et al.*, 2009). Determination of erosion rates from only shallow depth layers (from 0 to 30 cm bs), where nuclides are produced mainly by neutron spallation, may be problematic because exposure age-erosion rate pairs with differing values may exhibit similar figures of depth profiles (Braucher *et al.*, 2009). In the current study, we also calculated erosion rates based on Eq. (1) using only two samples from shallow layers (up to ~60 cm; ABK0902-1 and -2). We also obtained different acceptable model curves for ^{10}Be (0.08 Myr, 44 m/Myr) and ^{26}Al (0.085 Myr, 47 m/Myr) (Fig. 2). Therefore, evaluations of steady-

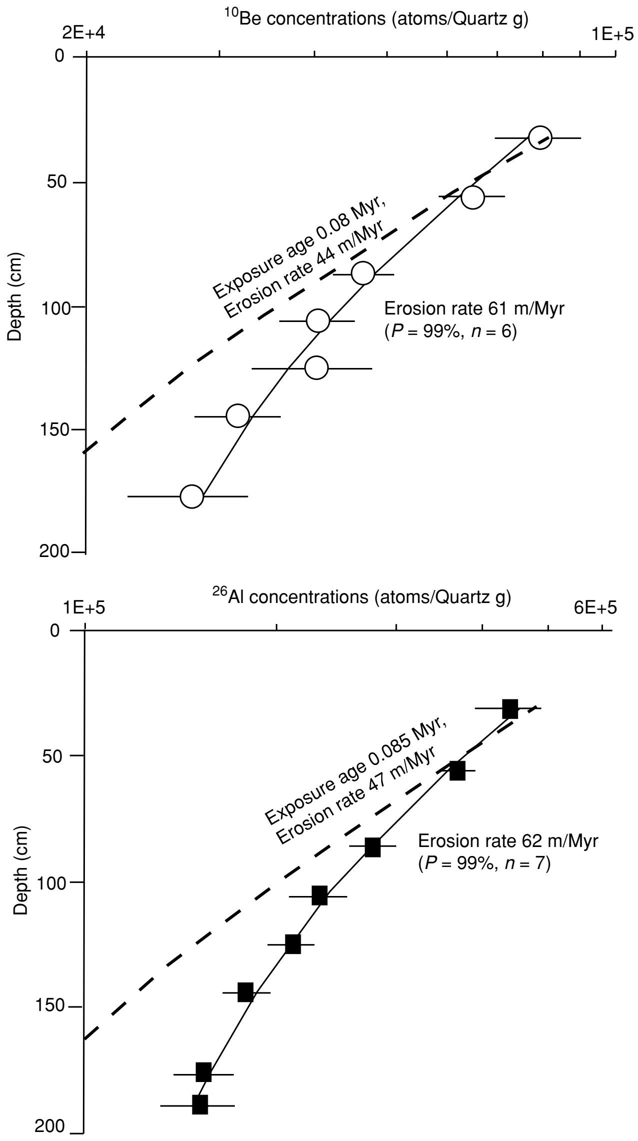

Fig. 2. The ^{10}Be and ^{26}Al depth profile. Circles and squares indicate measured concentrations of ^{10}Be and ^{26}Al for each depth, respectively. Error bars show analytical uncertainties (1σ). The curves show the best-fit model based on Eq. (1) and (2). The dash curves show the examples of the assumption by only two data at shallower layers (ABK0902-1 and -2). n indicates the degree of freedom in the model.

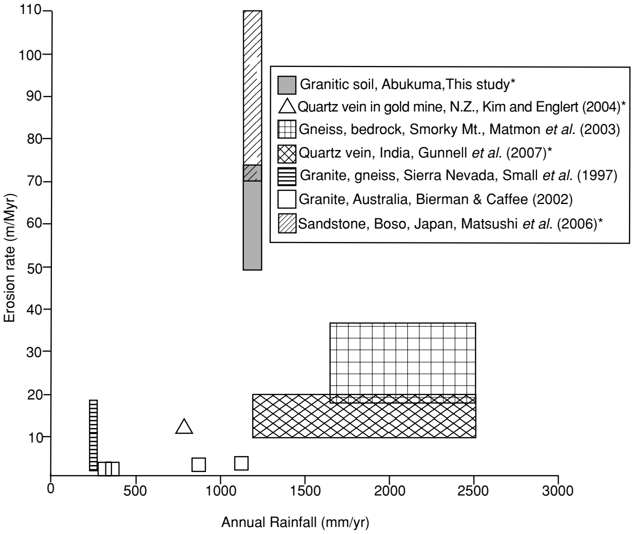

*Fig. 3. The figure shows erosion rate vs. annual rainfall. *; deduced from depth profile. We refer to Christopherson (2003) for information about annual rainfall at India, New Zealand and Sierra Nevada.*

state assumptions using samples obtained from shallower depth cannot deduce reliable erosion rate. A ^{10}Be and ^{26}Al depth profile determined from not only shallow-depth layers, but layers at a deeper depth of at least than 80 cm bs is needed to achieve highly accurate measurement of erosion rates of granitic soil surfaces.

In order to investigate the model's sensitivity to density variations, in addition to the best-fit value of 2.2 g/cm^3, we also calculated exposure ages and erosion rates using densities of 2.5 and 2.0 g/cm^3. The resulting steady-state erosion rates were ~49 m/Myr (^{10}Be) and ~50 m/Myr (^{26}Al) assuming 2.5 g/cm^3, and ~72 m/Myr (^{10}Be) and ~74 m/Myr (^{26}Al) assuming 2.0 g/cm^3. These erosion rates are consistent with the rate obtained from 2.2 g/cm^3 (57–67 m/Myr; including in 1σ).

Our result (49–74 m/Myr) also indicates that granitic soil surfaces are more erosion resistant than the mudstone and sandstone surfaces (720 ± 110 and 70–110 m/Myr, respectively) distributed in the Boso Peninsula, Japan, which exhibits a similar climatic setting (Matsushi *et al.*, 2006). The erosion rate of granitic soil surface for this study area is approximately twice as high as previous studies in several climatic regions (Fig. 3) (New Zealand, Kim and Englert, 2004; Smokey Mt., U.S.A., Matmon *et al.*, 2003; India, Gunnell *et al.*, 2007; Sierra Nevada, U.S.A., Small *et al.*, 1997; Australia, Bierman and Caffee, 2002). Although our result is limited to only one site, the present study shows granitic soil surfaces are eroded much faster than fresh granitic bedrock surfaces. Our results also suggest that lithology is one of the important factors to produce differences in erosion rate (mudstone >> sandstone > granitic soil > granitic or gneiss bedrock, quartz vein).

CONCLUSIONS

We determined the long-term, steady-state erosion rate of a granitic soil surface in western Abukuma, Japan to be 49–74 m/Myr using a cosmogenic ^{10}Be and ^{26}Al depth profile from 30 to 180 cm bs, considering both neutron and muon interactions. This erosion rate is lower than that for the mudstone and sandstone sites in Boso Peninsula, Japan, but higher than granitic or gneiss bedrock surfaces. The material comprising a particular landform is one of the most important factors controlling the magnitude of surficial erosion rate. We also confirm that a TCN depth profile based on physical parameters for both neutron and muon interactions provides an appropriate means for obtaining accurate steady-state, long-term erosion rates of granitic soil surfaces, which are very common in Japan. Additionally, we conclude that the accurate determination of erosion rates of granitic soil surfaces requires the sampling of deeper layers, at least 80 cm bs.

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