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Research paper

Discordance between cosmogenic nuclide concentrations in amalgamated sands and individual fluvial pebbles in an arid zone catchment

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ABSTRACT

Based on cosmogenic ^{10}Be and ^{26}Al analyses in 15 individual detrital quartz pebbles (16–21 mm) and cosmogenic ^{10}Be in amalgamated medium sand (0.25–0.50 mm), all collected from the outlet of the upper Gaub River catchment in Namibia, quartz pebbles yield a substantially lower average denudation rate than those yielded by the amalgamated sand sample. ^{10}Be and ^{26}Al concentrations in the 15 individual pebbles span nearly two orders of magnitude (0.22 ± 0.01 to $20.74 \pm 0.52 \times 10^6$ ^{10}Be atoms g^{-1} and 1.35 ± 0.09 to $72.76 \pm 2.04 \times 10^6$ ^{26}Al atoms g^{-1}, respectively) and yield average denudation rates of ~0.7 m Myr^{-1} (^{10}Be) and ~0.9 m Myr^{-1} (^{26}Al). In contrast, the amalgamated sand yields an average ^{10}Be concentration of $0.77 \pm 0.03 \times 10^6$ atoms g^{-1}, and an associated mean denudation rate of 9.6 ± 1.1 m Myr^{-1}, an order of magnitude greater than the rates obtained for the amalgamated pebbles. The inconsistency between the ^{10}Be and ^{26}Al in the pebbles and the ^{10}Be in the amalgamated sand is likely due to the combined effect of differential sediment sourcing and longer sediment transport times for the pebbles compared to the sand-sized grains. The amalgamated sands leaving the catchment are an aggregate of grains originating from all quartz-bearing rocks in all parts of the catchment. Thus, the cosmogenic nuclide inventories of these sands record the overall average lowering rate of the landscape. The pebbles originate from quartz vein outcrops throughout the catchment, and the episodic erosion of the latter means that the pebbles will have higher nuclide inventories than the surrounding bedrock and soil, and therefore also higher than the amalgamated sand grains. The order-of-magnitude grain size bias observed in the Gaub has important implications for using cosmogenic nuclide abundances in depositional surfaces because in arid environments, akin to our study catchment, pebble-sized clasts yield substantially underestimated palaeo-denudation rates. Our results highlight the importance of carefully considering geomorphology and grain size when interpreting cosmogenic nuclide data in depositional surfaces.

1. Introduction

In situ-produced cosmogenic nuclide analyses in both modern and buried sediment are widely used to quantify modern- and palaeo-denudation rates integrated over a wide range of spatial and temporal scales (e.g., von Blanckenburg, 2005; Dunai, 2010; Portenga and Bierman, 2011). Such studies assume that the sediment sample comprises grains originating from all parts of a catchment and that it records the average denudation rate of the sediment's source (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). The latter assumption implies that the cosmogenic nuclide concentration of the sample, and so the inferred denudation rate, do not depend on grain size. Numerous studies have found no dependence of nuclide concentration on grain size (e.g., Granger et al., 1996; Clapp et al., 2000, 2002; Schaller et al., 2001; Ouimet et al., 2009; Palumbo et al., 2010; see Supplementary Data), but substantial grain size effects have been observed in a few, mostly humid, environments, including Puerto Rico (Brown et al., 1998), the Appalachian Mountains (Matmon et al., 2003), the Olympic Mountains (Belmont et al., 2007), and the Amazon Basin (Wittmann et al., 2011).

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A possible grain size effect can also be observed in cosmogenic nuclide data from the Gaub River catchment in the arid central-western Namibia (Codilean et al., 2008) (Fig. 1). Codilean et al. (2008) established the spatial pattern of denudation in the Gaub using in situ-produced cosmogenic ^{10}Be (^{10}Be$_c$) in amalgamated sand samples (0.25–0.50 mm), showing that the spatial distribution of denudation is reflected in the shape of the frequency distribution of cosmogenic ^{21}Ne (^{21}Ne$_c$) concentrations in 32 quartz pebbles (16–21 mm) randomly collected from the catchment outlet (Fig. 1C). Although the spatial pattern of denudation implied by the ^{21}Ne$_c$ in the pebbles is consistent with Codilean et al.'s (2008) ^{10}Be$_c$ data from amalgamated sand samples (Fig. 1), when amalgamated the ^{21}Ne$_c$ concentrations in the pebbles yield a substantially lower average denudation rate of ~1 m Myr^{-1} as compared to the ~12 m Myr^{-1} determined using the ^{10}Be$_c$ in the sand (Bierman and Caffee, 2001; Codilean et al., 2008). Identifying the cause of this apparent discrepancy between the ^{10}Be$_c$ in the sand and ^{21}Ne$_c$ in the pebbles is hindered by the fact that it involves two separate isotopic systems. If the low ^{10}Be$_c$ in the sand (relative to the ^{21}Ne$_c$ in the pebbles) is not a grain-size effect, it could indicate radioactive decay of ^{10}Be$_c$ during long-term sediment storage, in both the colluvial and fluvial systems, at depths sufficient for cosmogenic nuclide production to cease. Conversely, the relatively high ^{21}Ne$_c$ concentrations in the pebbles, relative to the ^{10}Be$_c$ in the sand, could indicate the presence of excess non-cosmogenic ^{21}Ne that has not been identified during measurement (cf. Niedermann, 2002).

To establish the cause of this apparent grain size bias in the Gaub River catchment, we measured cosmogenic ^{10}Be and ^{26}Al (^{26}Al$_c$) in 15 of Codilean et al.'s (2008) 32 pebbles (Fig. 1C). In the case of a mismatch between the ^{10}Be$_c$ and ^{21}Ne$_c$ in the pebbles, measurements of ^{26}Al$_c$ will determine whether this is the result of radioactive decay of ^{10}Be$_c$ during long-term sediment storage, or the presence of excess non-cosmogenic ^{21}Ne. In addition, to better constrain the spatial pattern of denudation and to confirm that the sediment leaving this catchment is a mixture of grains originating from all parts of the catchment, we complemented Codilean et al.'s (2008) ^{10}Be$_c$ amalgamated sand data with a further eight samples: seven from tributaries and a further sample from the catchment outlet (Fig. 1A).

2. Field setting

The Gaub is a tributary of the ~15,500 km^2 Kuiseb River, one of the major ephemeral rivers systems draining western Namibia. The study catchment has an area of ~1200 km^2 and the geomorphology is that of a high elevation passive margin with an extensive low-relief upland region and a highly dissected, high-relief zone marking the Great Escarpment. Quartzites and granites of the Rehoboth group (1650–1860 Myr) and Sinclair group (1050–1400 Myr) are the dominant rock types in the study catchment (Ziegler and Stoessel, 1993). Quartz is an abundant component of all lithological units and quartz-vein outcrops are ubiquitous throughout the catchment (Fig. 2).

Overall, denudation rates in central-western Namibia are low, with the steeper escarpment area eroding more rapidly than either the more gently sloping coastal plain or the upland plateau. Cosmogenic nuclide-based bedrock erosion rates average around ~3 m Myr^{-1} on the coastal plain and upland plateau (Bierman and Caffee, 2001; van der Wateren and Dunai, 2001), and the steeper escarpment area is eroding in the proximity of the study catchment at a rate of ~10 m Myr^{-1} (Cockburn et al., 2000). Denudation rates based on ^{10}Be$_c$ analysis of sediment are higher than their bedrock counterparts but exhibit a similar regional pattern: ~8 and ~6 m Myr^{-1} on the coastal plain and upland plateau respectively, and ~16 m Myr^{-1} on the escarpment (Bierman and Caffee, 2001; Bierman et al., 2007; Codilean et al., 2008).

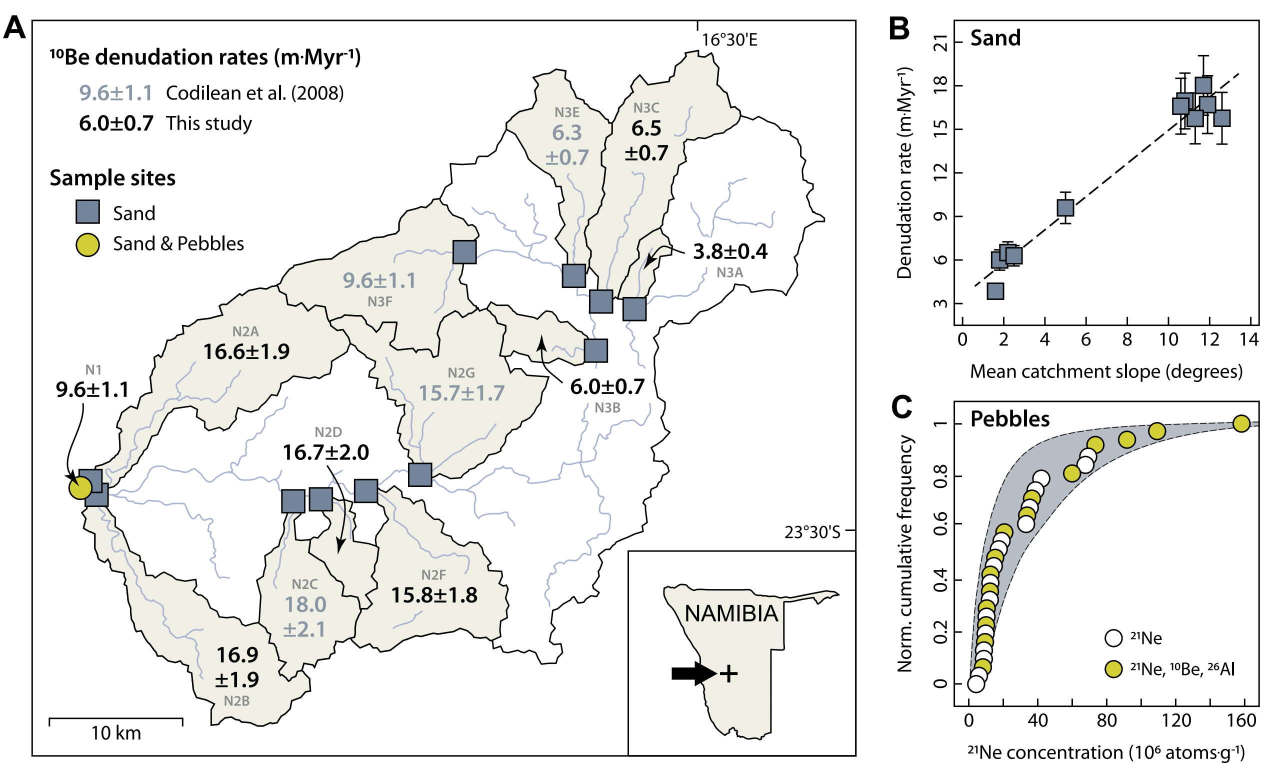

Fig. 1. Field setting and cosmogenic nuclide data. (A) Map of study area showing denudation rates (m Myr^{-1}) inferred from ^{10}Be$_c$ analyses in amalgamated sand samples by Codilean et al. (2008) and this study. (B) Plot of the ^{10}Be$_c$ catchment-wide denudation rates obtained for the 11 Gaub sub-catchments in (A) versus the mean slopes of these sub-catchments. (C) Cumulative frequency distribution plot showing Codilean et al.'s (2008) ^{21}Ne$_c$ concentrations in the 32 pebbles. Circles in yellow indicate the pebbles that were selected for ^{10}Be$_c$ and ^{26}Al$_c$ measurements (this study). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)