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Single-grain cosmogenic ^{21}Ne concentrations in fluvial sediments reveal spatially variable erosion rates

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Notes

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ABSTRACT

We evaluated the hypothesis that the spatial variation in erosion in a catchment is reflected in the distribution of the cosmogenic nuclide concentrations in sediments leaving the catchment. Using published data and four new ^{10}Be measurements in fluvial sediment collected from the outlets of small river catchments, we constrained the spatial variability of erosion rates in the Gaub River catchment in Namibia. We combined these catchment-averaged erosion rates, and the mean slope values with which they are associated, in a digital elevation model (DEM)–based analysis to predict distributions of cosmogenic ^{21}Ne concentrations in the sediment leaving the Gaub catchment. We compared these synthetic distributions with the distribution of concentrations of cosmogenic ^{21}Ne ($^{21}Ne_C$) in 32 quartz fluvial pebbles (16–21 mm) collected from the catchment outlet. The $^{21}Ne_C$ concentrations span nearly two orders of magnitude (2.6–160 × 10^6 atoms/g) and are highly skewed toward low values. The DEM-based analysis confirms this skew—the measured $^{21}Ne_C$ distribution plots within the envelope of distributions predicted for the catchment. This match between measured and synthetic ^{21}Ne distributions implies that the measured distribution is a signature of the spatial variation in erosion rates.

Keywords: ^{21}Ne, ^{10}Be, cosmogenic nuclides, denudation rates, slope dependence, landscape evolution.

INTRODUCTION

Cosmogenic nuclide analyses of amalgamated sediment samples collected at catchment outlets are widely used to determine catchment-averaged denudation rates (Bierman, 1994; Bierman and Nichols, 2004; Cockburn and Summerfield, 2004; von Blanckenburg, 2005). These studies assume that the sediment sample is an aggregate of grains originating from all parts of a catchment and that each grain records the erosion rate at its source (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). Amalgamated sediment samples thus provide a catchment-averaged erosion rate. This rate masks, however, variations in erosion rates across the catchment, but, just as the cosmogenic nuclide concentration of a grain reflects its history of erosion, so the frequency distribution of nuclide concentrations in a large number of grains leaving a catchment should provide information on the erosional history of the whole catchment. Thus, the frequency distribution of nuclide concentrations in the sediment has the potential to provide not only a mean erosion rate but also a signature of the range of erosion rates across a catchment.

In this study, we examined this possibility by assessing the hypothesis that the spatial variation in erosion in the Gaub River catchment (central western Namibia) is reflected in the frequency distribution of the concentrations of cosmogenic ^{21}Ne ($^{21}Ne_C$) in the sediments leaving the catchment. We used published cosmogenic nuclide data and four new ^{10}Be determinations in river sediments from subcatchments in the Gaub to characterize the spatial variation of erosion across the catchment. These data were then used in a digital elevation model (DEM)–based analysis to predict the $^{21}Ne_C$ concentrations in the sediment leaving the catchment. Finally, the frequency distribution of these concentrations was compared with an empirical distribution obtained by measuring $^{21}Ne_C$ in 32 fluvial quartz pebbles (16–21 mm diameter) randomly collected from the catchment outlet.

FIELD SETTING

The Gaub River is a tributary of the Kuiseb, a major ephemeral system that drains western Namibia. The pebbles for $^{21}Ne_C$ analysis were collected at the outlet of the upper Gaub, an ~1200 km^2 catchment consisting of two low-relief regions, a coastal plain, and an upland plateau separated by the highly dissected, high-relief transition zone marking the Great Escarpment (Fig. 1). The elevation range in the catchment is ~1400 m. The absence of any sizeable colluvial aprons, terraces, or floodplains indicates that there is no significant long-term sediment storage in this catchment and that postdetachment sediment residence times are relatively short in comparison to the time scale of bedrock erosion.

The lithology of the catchment is complex; the principal rock units belong to four different groups: pre-Rehoboth, Rehoboth, Sinclair, and Damara (Ziegler and Stoessel, 1993; Becker et al., 1994, 1996). Of these groups, however, only two (Rehoboth and Sinclair) occupy large areas of the catchment (Fig. 1). The Rehoboth Sequence consists of the Gaub Valley and Marienhof Formations, both of which are made up of low- to medium-grade metamorphosed quartzites and schists. These rocks have been intruded by granitoids belonging to the Weener Igneous Complex and Piksteel Intrusive Suite,

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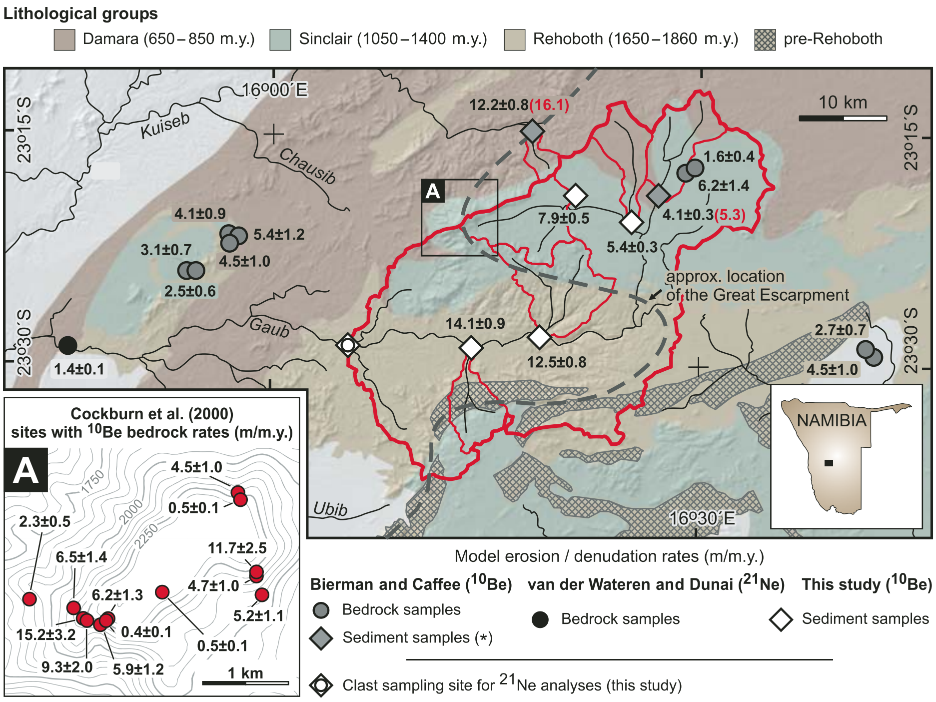

Figure 1. Map of study area with erosion rates (m/m.y.) inferred from cosmogenic nuclide analyses by Cockburn et al. (2000), Bierman and Caffee (2001), van der Wateren and Dunai (2001), and this study. Study catchment boundary is shown by thick red line, and subcatchment boundaries are shown by thin red line. Full calculation procedure for four new erosion rates reported here based on ^{10}Be is given in Appendix DR1 (see text footnote 1). Geological data were obtained from the Geological Survey of Namibia (http://www.mme.gov.na/gsn/). *Bierman and Caffee's (2001) erosion rates based on cosmogenic isotope concentrations in sediment have been recalculated using a production rate for ^{10}Be of 5.1 ± 0.3 atoms g^{-1} yr^{-1} and scaling factors given by Stone (2000) and Codilean (2006). Bierman and Caffee's (2001) original rates are given in red typeface.

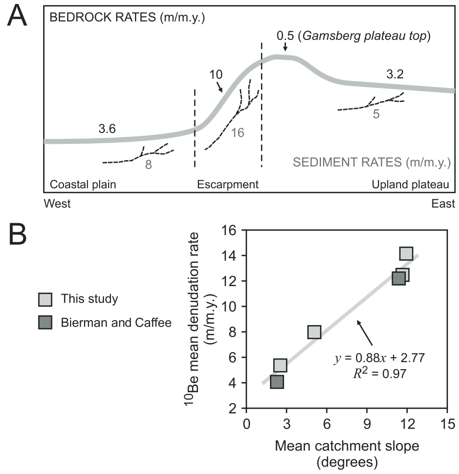

Figure 2. Spatial variability of erosion rates. A: Diagrammatic topographic profile across study area (thick line) summarizing erosion rates (m/m.y.) from cosmogenic nuclide data of Cockburn et al. (2000) and Bierman and Caffee (2001) from spot bedrock samples (above topographic profile) and amalgamated sediment samples (below topographic profile). B: Plot of ^{10}Be model denudation rates obtained for Gaub subcatchments outlined in thin red lines in Figure 1 versus area-weighted mean slopes of these subcatchments. Plot uses rates recalculated from Bierman and Caffee's (2001) data (see Figure 1 caption).

both of Rehoboth age, and by granites belonging to the Gamsberg Granite Suite, part of the Sinclair Sequence. The pre-Rehoboth units (Elim and Moorivier) occur in the southern part of the study area and consist of low- to medium-grade quartzites, schists, and greenschists (Elim Formation) and medium- to high-grade migmatic gneisses, amphibolites, quartzites, and schists (Moorivier Complex). The Damara Sequence is exposed in the north and consists of the metasedimentary rocks of the Swakop Group. Quartz is an abundant component of all these units and crops out throughout the catchment.

COSMOGENIC ^{10}Be AND ^{21}Ne DATA

Cosmogenic isotope-based erosion rate data from central-western Namibia show that the steeper and more dissected escarpment zone is eroding more rapidly than the gently sloping coastal plain and upland plateau (Fig. 2A). This relationship between erosion rate and slope was assessed by determinations of ^{10}Be concentrations in four sediment samples (grain size: 250–500 µm) from the outlets of four small (~46–92 km^2) Gaub subcatchments, two of which drain the escarpment zone and two of which drain the upland plateau (Fig. 1). The quartz pebbles intended for ^{21}Ne measurements were collected from a 200-m-long reach at the outlet of the Gaub (Fig. 1). This reach consists of an ephemeral semi-alluvial channel that is 15–25 m wide. We randomly collected both rounded and subangular quartz pebbles but then excluded those with an opaque milky appearance, which is generally associated with abundant fluid inclusions and high concentrations of noncosmogenic ^{21}Ne (cf. Hetzel et al., 2002). Field observations indicated that opaque milky quartz veins can be found throughout the Gaub, and so, by excluding these milky quartz pebbles, we did not bias the randomness of our sampling. Quartz separates were prepared following standard procedures, and Be and Ne isotope measurements were carried out at the Scottish Universities Environmental Research Centre (SUERC) (see the GSA Data Repository).[1]

The ^{10}Be model catchment-wide denudation rates are shown in Figure 1, and the spatial pattern of denudation rates is summarized in Figure 2A (see footnote 1). The ^{10}Be rates based on small-catchment sediment samples confirm the strong relationship between erosion rate and mean catchment slope (Figure 2B).

The Ne isotope results are summarized in Table 1 and Figure 3 (see footnote 1). Ne isotopic ratios confirm the absence of significant noncosmogenic Ne in the pebbles (Fig. 3A), and we consider all the nonatmospheric ^{21}Ne to be cosmogenic. Cosmogenic ^{21}Ne concentrations span two orders of magnitude (2.6–160 × 10^6 atoms/g), and their distribution is highly skewed toward low values (Fig. 3B).

DEM ANALYSIS

For comparison with the empirical ^{21}Ne$_C$ concentration distribution in the pebbles, we used a 30 m DEM obtained from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) stereo images to predict ^{21}Ne$_C$ concentration distributions in the sediment leaving the study catchment. We took bedrock erosion to be spatially variable as a linear function of slope (Fig. 2), and calculated the total nuclide concentration acquired by a "grain" prior to detachment, following Lal (1991). Given the lack of evidence for sediment storage in the catch-

[1]GSA Data Repository item 2008038, Appendix DR1 (full description of all laboratory procedures), Table DR1 (full description of the ^{10}Be data), and Table DR2 (full description of the ^{21}Ne data), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. SUMMARY OF NE ISOTOPE DATA

ID	Weight (mg)	^{21}Ne ($\pm 1\sigma$) ($\times 10^6$ atoms/g)
A0	533.7	58.32(1.79)
A1	529.0	8.79(0.27)
A2	590.6	7.11(0.23)
A3	555.7	10.94(0.35)
A5	556.8	7.15(0.22)
A6	559.5	32.20(1.02)
A8	558.8	8.16(0.25)
B1	566.0	32.28(1.97)
B2	573.9	35.03(1.09)
B6	554.6	7.79(0.24)
B9	539.3	10.88(0.37)
C0	541.2	15.79(0.49)
C1	550.9	12.90(0.40)
C3	549.6	66.06(2.02)
C4	558.5	161.18(5.05)
C7	559.7	13.71(0.42)
C9	550.8	17.36(0.53)
D0	534.6	6.56(0.20)
D1	570.4	19.05(0.63)
D3	585.7	40.46(1.24)
D7	558.6	37.13(1.15)
D8	560.4	10.68(0.39)
D9	540.3	4.30(0.15)
E1	528.3	8.42(0.26)
E3	540.6	71.88(2.21)
E7	527.8	31.64(0.98)
E8	570.9	107.73(3.35)
F2	542.0	2.63(0.08)
F5	541.6	66.21(2.03)
F7	542.9	90.21(2.79)
F8	555.6	10.60(0.33)
F9	554.7	8.67(0.27)

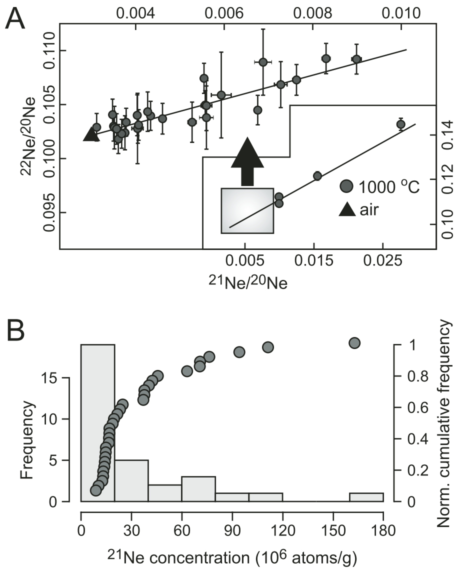

Figure 3. Summary of ^{21}Ne data. A: Neon three-isotope plot showing isotopic ratios for 32 samples. Uncertainties are shown at 2σ. Line represents cosmic-ray spallation line (Niedermann et al., 1993). B: Frequency and cumulative frequency distribution plots of measured $^{21}Ne_C$ concentrations.

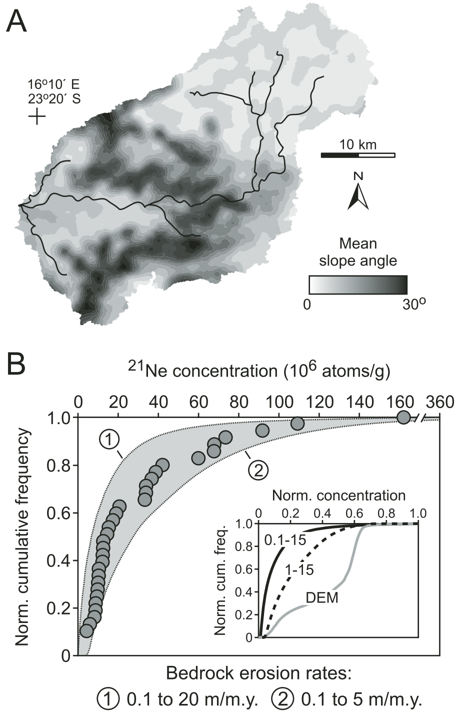

Figure 4. Results of digital elevation model (DEM) analysis. A: Map of spatial distribution of mean slope in study area. B: Cumulative frequency distribution plots comparing 32 $^{21}Ne_C$ concentrations (gray circles) with calculated envelope of possible $^{21}Ne_C$ concentration distributions for bedrock erosion rates that vary as a linear function of slope. In order to encompass a range of reasonable erosion rates for this region, erosion rates were set to vary with slope between 0.1 and 5 m/m.y. and between 0.1 and 20 m/m.y. Inset shows normalized cumulative distribution of elevation values in study catchment ("DEM": hypsometric curve) and two $^{21}Ne_C$ distributions obtained using different ranges of bedrock erosion rates that vary linearly with slope. Note how the two $^{21}Ne_C$ distributions are markedly different from hypsometric curve (and also different from each other), illustrating sensitivity of cosmogenic nuclide concentration distribution to spatial distribution and range of erosion rates in catchment. We used a normalized sea-level high-latitude production rate for ^{21}Ne of 19 atoms g^{-1} yr^{-1} (Niedermann, 2000) and scaling factors given by Dunai (2000) and Codilean (2006).

ment, we assumed that our grains did not acquire sufficient cosmogenic nuclides during transport (i.e., between detachment and leaving the catchment) to mask the cosmogenic nuclide "signal" acquired prior to detachment. In other words, we assumed that the $^{21}Ne_C$ distribution of the grains sampled at the outlet reflected erosion rates throughout the catchment.

We produced $^{21}Ne_C$ concentration maps for a range of bedrock erosion rates that varied linearly with slope, and we sampled 200,000 grains from each map. We allowed multiple grains to originate from the same source and used a sampling technique whereby the probability of a grain being selected was directly proportional to the erosion rate at its source. The results of the DEM analysis are given in Figure 4.

DISCUSSION AND CONCLUSIONS

The $^{21}Ne_C$ production rates range in the study catchment between ~25 and ~68 atoms g^{-1} yr^{-1}, meaning that most of the measured $^{21}Ne_C$ concentrations require erosion rates that are lower than those obtained using ^{10}Be in the amalgamated sediment samples (Bierman and Caffee, 2001; this study). This apparent inconsistency between the $^{21}Ne_C$ in the pebbles and ^{10}Be in the amalgamated sediments reflects the fact that the ^{10}Be values are from amalgamated sand samples and are therefore mean values that do not reveal the possible range of concentrations in the individual clasts in a sand sample. Thus, our ^{10}Be data show that the catchment-averaged erosion rate obtained from ^{10}Be in sediment for one of the upland plateau subcatchments is 7.9 ± 0.5 m/m.y., while the same subcatchment's spot bedrock erosion rates (i.e., the rates that would be recorded by individual clasts in an amalgamated sediment sample) were measured by Cockburn et al. (2000) to be as low as 0.5 ± 0.1 m/m.y. and as high as 11.7 ± 2.5 m/m.y. All the measured $^{21}Ne_C$ concentrations in the pebbles, including the maximum values, can be generated by measured bedrock erosion rates alone (Cockburn et al., 2000; Bierman and Caffee, 2001; van der Wateren and Dunai, 2001; see also Fig. 1), and they do not require postdetachment cosmogenic nuclide acquisition during, for example, pebble transport through the drainage system. In short, we take our measured $^{21}Ne_C$ distribution to be a valid measure of the distribution of $^{21}Ne_C$ in sediments leaving the study catchment.

The DEM-based analysis predicts highly skewed cosmogenic nuclide concentration distributions that are similar to that obtained from the $^{21}Ne_C$ measurements (Fig. 4B). The good fit between the data and the predicted distributions strongly suggests that the shape of the $^{21}Ne_C$ distribution is a signature of the slope dependence of, and hence spatial variation in, erosion rates in the study area.

A catchment in which erosion rate is slope-dependent is not in topographic steady state. In a catchment that is in both topographic and isotopic steady state (i.e., bedrock erosion is uniform throughout the catchment and postdetachment nuclide acquisition is negligible), the frequency distribution of cosmogenic nuclide concentrations will mirror the distribution of elevation values in the catchment because of the strong dependence of nuclide production on altitude (Lal, 1991; see Fig. 4B, inset). Deviation from either topographic or isotopic steady-state conditions results in changes in the shape of the detrital cosmogenic nuclide concentration distribution due to either nonuniform production of sediment throughout the catchment (deviations from topographic steady state) or significant postdetachment nuclide acquisition during sediment transport (deviations from isotopic steady state). If a landscape is not in topographic steady state and erosion is proportional to slope, steeper areas erode more rapidly and contribute a greater proportion, relative to their surface area, of the sediment leaving the catchment. Moreover, this more rapid erosion also means that the resultant sediment will have relatively low nuclide concentrations, skewing the distribution of cosmogenic nuclide concentrations leaving the catchment toward lower values. This type of skew is precisely that evident in both the $^{21}Ne_C$ data and the predicted distributions in sediments derived from the complex topography of the Gaub River.

The two predicted distributions shown in the inset in Figure 4B further illustrate that the skew of the cosmogenic nuclide concentration distribution is sensitive to the range of erosion rates in a catchment. Thus, a deviation in the cosmogenic nuclide concentration distribution from the steady-state shape (i.e., one mirroring the distribution of elevation values) indicates the absence of topographic steady state and can potentially provide clues to the range of erosions rates in a catchment.

Our combination of DEM-based analysis and measurement of $^{21}Ne_C$ in individual pebbles demonstrates that the spatial nonuniformity of erosion rates in a catchment affects the distribution of cosmogenic nuclide concentrations in sediments leaving the catchment. Our findings further indicate that the shape of this distribution is sensitive to the range of erosion rates that are present in the catchment. The erosion rates derived from ^{10}Be measurements on fluvial sand and the $^{21}Ne_C$ concentrations in the 32 pebbles both also indicate that erosion rates in the Gaub River catchment are slope-dependent and that this catchment is not in topographic steady state.

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