ELSEVIER

Earth and Planetary Science Letters 160 (1998) 723–728

EPSL

Determination of predevelopment denudation rates of an agricultural watershed (Cayaguás River, Puerto Rico) using in-situ-produced ^{10}Be in river-borne quartz

Erik Thorson Brown [a,*], Robert F. Stallard [b], Matthew C. Larsen [c], Didier L. Bourlès [d], Grant M. Raisbeck [d], Françoise Yiou [d]

[a] *Large Lakes Observatory, University of Minnesota, Duluth, MN 55812, USA*
[b] *United States Geological Survey, 3215 Marine St., Boulder, CO 80303, USA*
[c] *United States Geological Survey, GSA Center, 651 Federal Dr. Guaynabo, PR 00965, USA*
[d] *Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, CNRS-IN2P3, Bât. 108, F-91405 Campus Orsay, France*

Received 17 November 1997; revised version received 1 June 1998; accepted 1 June 1998

Abstract

Accurate estimates of watershed denudation absent anthropogenic effects are required to develop strategies for mitigating accelerated physical erosion resulting from human activities, to model global geochemical cycles, and to examine interactions among climate, weathering, and uplift. We present a simple approach to estimate predevelopment denudation rates using in-situ-produced cosmogenic ^{10}Be in fluvial sediments. Denudation processes in an agricultural watershed (Cayaguás River Basin, Puerto Rico) and a matched undisturbed watershed (Icacos River Basin) were compared using ^{10}Be concentrations in quartz for various size fractions of bed material. The coarse fractions in both watersheds bear the imprint of long subsurface residence times. Fine material from old shallow soils contributes little, however, to the present-day sediment output of the Cayaguás. This confirms the recent and presumably anthropogenic origin of the modern high denudation rate in the Cayaguás Basin and suggests that pre-agricultural erosional conditions were comparable to those of the present-day Icacos. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: denudation; erosion rates; Puerto Rico; Be-10

1. Introduction

Drainage-basin mass balances represent the classic approach to quantitative examination of weathering [1]. These are inherently time-consuming and problematic because of the highly episodic nature of fluvial transport, and difficulties in quantifying groundwater fluxes. Furthermore, anthropogenic disturbance of watersheds can increase physical erosion rates by orders of magnitude, precluding the use of mass balance for direct estimation of long-term denudation rates [2]. Based on success in utilizing in-situ-produced beryllium-10 (^{10}Be, $t_{1/2} = 1.5$ Ma) in river-borne quartz to determine equilibrium erosion rates in the humid tropics [3], we have developed an approach that uses ^{10}Be to examine pre-agricultural denudation rates in a developed tropical basin.

* Corresponding author. Tel.: +1 (218) 726-8891; Fax: +1 (218) 726-6979; E-mail: etbrown@d.umn.edu

0012-821X/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII S0012-821X(98)00123-X

Denudation may be examined using the accumulation of in-situ-produced cosmogenic nuclides in mineral lattices of rock and soil close to the ground surface [4–6]. Previous field studies [3,7] have shown that the in-situ-produced ^{10}Be concentration of sediment discharged by a river represents the average value for the basin as a whole if: (1) the near-surface distribution of the analyzed mineral phase (typically quartz) is relatively uniform throughout the basin; (2) erosion is sufficiently rapid that loss of cosmogenic nuclides is primarily through erosion rather than radioactive decay (erosion greater than ~1 mm ka^{-1} for ^{10}Be); (3) long-term (millennial scale) sediment storage is minimal. These conditions lead to an expression relating the long-term mean denudation rate of the basin to the measured average concentration ^{10}Be:

$$\bar{\epsilon} = \frac{\bar{P}L}{\bar{N}} \tag{1}$$

Here $\bar{P}$ represents the average production rate (atoms g^{-1} a^{-1}), weighted according to the hypsometric curve of the basin, ϵ is the denudation rate (g cm^{-2} a^{-1}), L is the effective attenuation length of cosmic rays penetrating rock or soil (150 to 170 g cm^{-2}), λ is the radioactive decay constant (a^{-1}), and t is the time since initiation of surface exposure (a). In this work, we utilize production rates calculated for the altitude and latitude of our site based on the semi-empirical polynomials of Lal [4]. We assume a 20% uncertainty in these rates. Various size fractions must be analyzed to calculate a discharge-weighted average concentration [3]. We emphasize that this averaging requires only the relative contributions of the size fractions.

The relation between grain size and ^{10}Be concentration provides information about geomorphic processes. High concentrations of ^{10}Be (relative to the discharge-weighted average) for a given size class imply that the material comes from a shallower or more slowly eroding setting than is typical for the basin as a whole. Conversely, relatively low concentrations imply a deeper origin or a more rapidly eroding source. Our previous work in an undeveloped river basin [3] showed that the average ^{10}Be concentration of coarse size fractions of river sediment is much lower than that of the fine fractions. The coarse material appears to have been largely derived from deep within soil profiles, being mobilized by energetic processes such as landslides, while fine material appears to be derived dominantly from near-surface soil.

In most developed basins, anthropogenic erosion primarily removes near-surface soils through processes including surface removal and shallow soil slips [2]. Typical denudation rates for agricultural land, such as those tabulated by Meade et al. [8], when applied over a century, give average depths of anthropogenically induced erosion that are comparable to the apparent attenuation length for cosmogenic nuclide production (~500 mm [9,10]). As discussed in Refs. [3,7,11], this implies that the cosmogenic nuclide concentration of river sediments, and the associated apparent denudation rate, should retain a memory of predevelopment conditions (Fig. 1). In addition, it is likely that such erosion would tend to remove fine material from surface horizons. The fine sediments remaining in the basin, derived from deeper within the soil profile, would have lower ^{10}Be concentrations. However, such erosion would have less effect on the ^{10}Be content of coarse sediments, which are generally present at greater depth in soil profiles.

2. Sampling and methods

The purpose of the present study is the comparison of the relationship between erosional processes and cosmogenic nuclide accumulation at a relatively pristine site with that at an adjacent watershed severely affected by human activity. We examined two sites in northeastern Puerto Rico: the minimally perturbed upper 3.26 km^2 of the Icacos River Basin [3,12] and the nearby Cayaguás River Basin (26.4 km^2), a geologically similar site strongly affected by conversion to agriculture since the mid-19th century (Fig. 2). Both watersheds have granodioritic bedrock and similar relief. Neither has canyons or similar incisions that would be localized sources of deep sediment, low in ^{10}Be.

Agriculture in the Cayaguás watershed resulted in rapid erosion that stripped off the upper layer of unconsolidated soil. Subsequent denudation rates probably decreased with the exposure of more stable saprolite at the surface. Agricultural land use

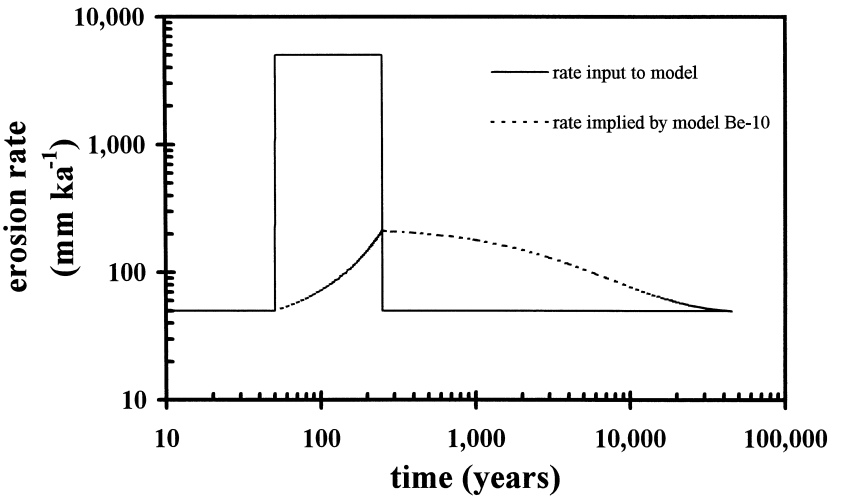

Fig. 1. Model of variations of ^{10}Be-based denudation rates under highly variable erosional conditions. To show the potential of this approach, we present the denudation rate one would calculate from the ^{10}Be content of average sediments (dotted line) exported from a site subject to drastic step-wise changes in erosion (solid line). Initially, the model assumes steady-state conditions with a denudation rate of 50 mm ka^{-1}. This rate is increased to 5000 mm ka^{-1} at year 50, and returns to 50 mm ka^{-1} at year 250. During times of enhanced erosion, the ^{10}Be content of sediments decreases as highly irradiated surface material is removed. On time scales of decades, the associated increases in ^{10}Be-based erosion rates are small relative to increases in the instantaneous denudation rate. This is because the enhanced erosion brings about soil mass losses that are less than the effective attenuation length for ^{10}Be production. Even after periods of enhanced erosion of 50, 75 and 100 years (resulting in 250, 375, and 500 mm of soil loss), the ^{10}Be content of exported sediments corresponds to steady-state erosion rates of 70, 85, and 100 mm ka^{-1}, respectively.

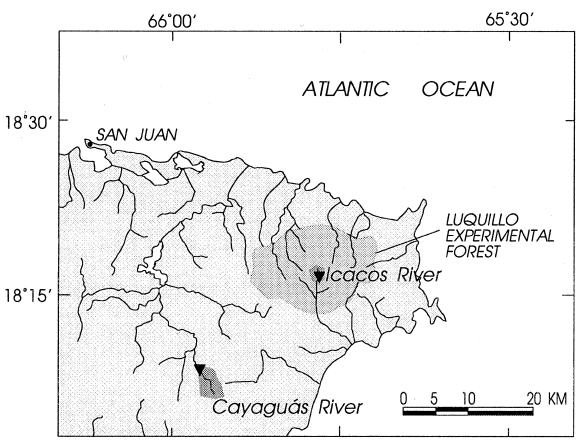

Fig. 2. Map of eastern Puerto Rico showing sampling locations.

peaked in the 1940s; more recently, forests have partially regrown, thereby stabilizing landforms. The present-day solids yield for the Cayaguás watershed is 2000 ± 1000 Mg km^{-2} a^{-1} [13]. Ignoring solute transport, this corresponds to a lowering rate of ∼ 750±350 millimeters per thousand years (mm ka^{-1}). The average Cayaguás solids yield is considerably less than the rate of upland erosion associated with landslides, 10,000–18,000 Mg km^{-2} a^{-1} averaged over seven decades, suggesting that considerable landslide-related material has remained in valley bottoms [13]. Maximum instantaneous rates of surficial erosion off bare soil (construction sites) in nearby watersheds [14] are less than the these landslide yields. Moreover, maximum instantaneous yields are only reached occasionally, and only a small fraction of the basin is bare soil at any time. These observations imply that landslides, rather than surficial erosion, are the predominant erosion mechanism removing soil from uplands. The Cayaguás lowering rates are, in turn, far greater than mean denudation rates for the minimally developed Icacos watershed where values of 75 ± 38 and 43 ± 15 mm ka^{-1} have been reported, based on major constituent analyses of water samples [15] and ^{10}Be distributions [3], respectively. The denudation rate in the Icacos River Basin is close to a model steady-state denudation rate for tropical rivers on young igneous bedrock [2].

In the Icacos Basin, we sampled bed material

Table 1
Sample descriptions and analytical results

Sample ID	Sample description	^{10}Be (1000 atoms g^{-1})	Uncertainty (1σ)
GAB 0.063	Gabion landslide material, 0.063–0.125 mm	36.0	12.7
GAB 0.125	Gabion landslide material, 0.125–0.25 mm	39.9	8.3
GAB 0.5	Gabion landslide material, 0.5–1.0 mm	25.0	3.3
GAB 1.0	Gabion landslide material, 1.0–2.0 mm	13.6	5.3
GAB 2.0	Gabion landslide material, 2.0–4.0 mm	22.4	2.8
GUA 0.063	Guaba river-borne sediment, 0.063–0.125 mm	198	19
GUA 0.125	Guaba river-borne sediment, 0.125–0.25 mm	195	17
GUA 0.25	Guaba river-borne sediment, 0.25–0.50 mm	138	14
GUA 0.5	Guaba river-borne sediment, 0.5–1.0 mm	101	7
GUA 1.0	Guaba river-borne sediment, 1.0–2.0 mm	65.0	11.8
GUA 2.0	Guaba river-borne sediment, 2.0–4.0 mm	57.1	6.4
GUA 4.0	Guaba river-borne sediment, 4.0–8.0 mm	46.6	7.5
CAY 0.063	Cayaguás river-borne sediment, 0.063–0.125 mm	82.8	10.5
CAY 0.125	Cayaguás river-borne sediment, 0.125–0.25 mm	80.6	9.4
CAY 0.25	Cayaguás river-borne sediment, 0.25–0.50 mm	80.3	11.4
CAY 0.50	Cayaguás river-borne sediment, 0.5–1.0 mm	64.0	7.9
CAY 1.0	Cayaguás river-borne sediment, 1.0–2.0 mm	39.9	4.6
CAY 2.0	Cayaguás river-borne sediment, 2.0–4.0 mm	50.7	9.8
CAY 4.0	Cayaguás river-borne sediment, 4.0–8.0 mm	25.9	9.8

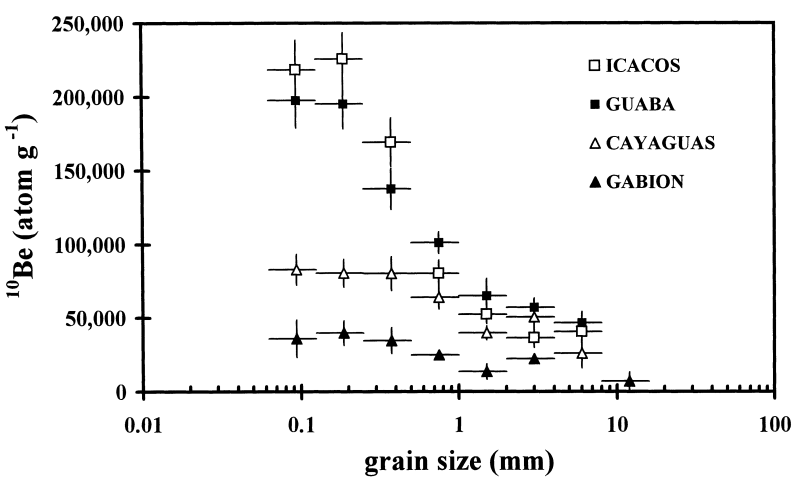

Fig. 3. Variability of grain-size dependence of ^{10}Be concentrations in quartz isolated from stream sediments collected in various erosional environments. Horizontal error bars represent grain size fractions. Data are presented for samples from the mainstream of the unperturbed Icacos River, from a tributary of the Icacos in which little evidence of landslide activity has been observed (the Guabá), from material in the Icacos basin recently mobilized by mass wasting (Gabion Slide), and from the Cayaguás River, which has been disturbed by human activity. Data for the samples from the Icacos mainstream and for two of the samples from the Gabion slide are from Ref. [3].

from a tributary of the Icacos River, the Guabá, that drains an area with little evidence of recent landslide activity. We also collected sediments eroded from the face of a nearby landslide ('Gabion Slide' of Ref. [3] or 'Road-Related Slide 51' of Ref. [16]). Samples were sieved into various size fractions, each of which was separately analyzed. These data (Table 1), coupled with our previously reported results from soils within the basin and from the Icacos mainstream [3], provide a basis for evaluating ^{10}Be distributions in size fractions of stream sediment samples from the Cayaguás (Fig. 3).

Because ^{10}Be produced in the atmosphere may present a source of contamination for these samples, rigorous cleaning procedures were followed [17–19]. After dissolution of cleaned quartz in HF and addition of 0.350 mg ^{9}Be carrier, Be was purified by solvent extraction. All ^{10}Be determinations were made at the Tandétron Accelerator Mass Spectrometry Facility, Gif-sur-Yvette, France [20,21]. Analytical uncertainties (1σ) are based on counting statistics and conservative assumptions of 5% variability in machine response and 50% uncertainty in blank correction. Although the blank correction was less than 5% for most samples, it was the major source of analytical uncertainty for some low-concentration landslide samples (Table 1).

3. Discussion and conclusions

The ratio of the ^{10}Be concentration in fine relative to coarse fractions reflects the style of erosion within the undeveloped watersheds. We assume that the ratio increases with an increasing contribution of processes, such as landslides, that bring large quantities of coarse material to the surface from substantial depth. We determined ratios of ~5 to 6 for the Icacos Basin as a whole, but only ~3.5 in the Guabá subbasin where fewer active landslides have been observed (Fig. 3). Coarse sediment in the Guabá must be from shallower soil horizons than in the Icacos as a whole. The ^{10}Be size relation for the Cayaguás is flatter still, with a ratio of ~2 to 3, indicating that the fines and coarse material come from an even narrower range of depths in the soil. Although the analytical uncertainties for the low-concentration samples (~10^4 at. g^{-1}) from the Gabion Slide make quantitative comparisons difficult, the Cayaguás is intermediate in character between the Icacos and the Slide. Assuming that Cayaguás soils were once like those of the Icacos, this is consistent with removal of the original highly irradiated fine-grained surface soil, perhaps by landslides, leaving thin soil that had been at the base of thicker profiles and containing a mix of coarse and fine materials. This preferential removal of fine material could be enhanced by size fractionation during fluvial transport.

In the Icacos watershed, flux-weighted average ^{10}Be concentrations of sediments from both the mainstem [3] and the Guabá subbasin indicate an average denudation rate of 43 ± 15 mm ka^{-1}, consistent with values derived from mass balances. A steady-state denudation rate calculated from ^{10}Be in Cayaguás sediments corresponds to ~85 mm ka^{-1}, a denudation rate much lower than that presently observed through measurements of sediment discharge: 750 mm ka^{-1}. This contradiction demonstrates that erosion in the Cayaguás watershed has not been steady and continuous, and is consistent with a recent anthropogenic origin of the current high rate of denudation. The model in Fig. 1 indicates that after a century of rapid erosion, the apparent denudation rate of ~85 mm ka^{-1} could be as much as a factor of two greater than the pre-agricultural rate, thus implying original conditions comparable to those presently observed in the Icacos. The similarity of ^{10}Be concentrations in the coarse fractions of bed material from the Icacos and the Cayaguás rivers (Fig. 3) suggests similar irradiation and erosional histories in the two basins. If pre-anthropogenic erosional conditions had been identical in the two basins, the two- to three-fold lowering of ^{10}Be concentrations in fine-size fractions of Cayaguás stream sediments (relative to the present-day Icacos) implies an average basin-wide loss of soil and saprolite of approximately 500 mm.

The methods discussed in this work provide an efficient quantitative approach for determination of the extent of erosion induced by human activity and for examination of erosional processes on geologically significant time scales. Because the effective attenuation length for cosmogenic nuclide production is comparable to (or greater than) typical basin-wide average erosional losses induced by human activity over the past century, cosmogenic nuclide concentrations can reflect pre-anthropogenic erosional conditions in perturbed basins. In addition, the ratio of cosmogenic nuclide concentrations in fine and coarse sediments can be used to determine the style of erosion acting in a basin.

Acknowledgements

We thank J. Lestringuez and D. Deboffle for their expert assistance with AMS measurements. The assistance in sample collection and processing of A.

Torres, and I. Concepción is gratefully acknowledged. Comments of two anonymous reviewers have improved the manuscript. This study has been partially supported by the program 'Dynamique et Bilan de la Terre' of INSU and is part of the 'Global Change Hydrology — Water, Energy and Biogeochemical Budgets Program' of the USGS Water Resources Division. Tandétron operation is supported by the CNRS, CEA and IN2P3. ***[MK]***

References

[1] G.E. Likens, F.H. Bormann, R.S. Pierce, J.S. Eaton, N.M. Johnson, Biogeochemistry of a Forested Ecosystem, Springer, New York, 1977, 146 pp.

[2] R.F. Stallard, Relating chemical and physical erosion, Rev. Mineral. 31 (1995) 543–564.

[3] E.T. Brown, R.F. Stallard, M.C. Larsen, G.M. Raisbeck, F. Yiou, Denudation rates determined from the accumulation of in situ produced ^{10}Be in the Luquillo Experimental Forest, Puerto Rico, Earth Planet. Sci. Lett. 129 (1995) 193–202.

[4] D. Lal, Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models, Earth Planet. Sci. Lett. 104 (1991) 424–439.

[5] P.R. Bierman, Using in situ produced cosmogenic isotopes to estimate rates of landscape evolution: a review from the geomorphic perspective, J. Geophys. Res. 99 (1994) 13885–13896.

[6] T.E. Cerling, H. Craig, Geomorphology and in-situ cosmogenic isotopes, Annu. Rev. Earth Planet. Sci. 22 (1994) 273–317.

[7] D.E. Granger, J.W. Kirchner, R. Finkel, Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediment, J. Geol. 104 (1996) 249–257.

[8] R.H. Meade, T.R. Yuzyk, T.J. Day, Movement and storage of sediment in rivers of the United States and Canada, in: M.G. Wolman, H.C. Riggs (Eds.), Surface Water Hydrology, The Geology of North America, O-1, Geol. Soc. Am., Boulder, CO, 1990, pp. 255–280.

[9] E.T. Brown, E.J. Brook, G.M. Raisbeck, F. Yiou, M.D. Kurz, Effective attenuation lengths of cosmic rays producing ^{10}Be and ^{26}Al in quartz: implications for exposure age dating, Geophys. Res. Lett. 19 (1992) 369–372.

[10] E.T. Brown, D.L. Bourlès, F. Colin, G.M. Raisbeck, F. Yiou, S. Desgarceaux, Evidence for muon-induced in situ production of ^{10}Be in near surface rocks from the Congo, Geophys. Res. Lett. 22 (1995) 703–706.

[11] P. Bierman, E.J. Steig, Estimating rates of denudation using cosmogenic isotope abundances in sediment, Earth Surf. Process. Landforms 12 (1996) 125–139.

[12] M.C. Larsen, P.D. Collar, R.F. Stallard, Research plan for investigation of water, energy, and biogeochemical budgets in the Luquillo Mountains, Puerto Rico, USGS Open-File Rep. 92-150, 1993, 19 pp.

[13] M.C. Larsen, An extreme case of mass wasting in the humid tropics: the agriculturally developed Cayaguás Watershed, Puerto Rico, Geol. Soc. Am., Abstr. Prog. 28 (1996), A-80.

[14] A.C. Gellis, R.M.T. Webb, W.J. Wolfe, S.C.I. McIntyre, Land use, upland erosion, and reservoir sedimentation, Lago Loiza, Puerto Rico, Geol. Soc. Am., Abstr. Prog. 28 (1996) A-79.

[15] W.H. McDowell, C.E. Asbury, Export of carbon, nitrogen, and major ions from three tropical montane watersheds, Limnol. Oceanogr. 39 (1994) 111–125.

[16] M.R. Guariguata, M.C. Larsen, Preliminary map showing locations of landslides in El Yunque Quadrangle, Puerto Rico, USGS Open-File Rep. 89-257, 1993, 1 sheet.

[17] E.T. Brown, J.M. Edmond, G.M. Raisbeck, F. Yiou, M.D. Kurz, E.J. Brook, Examination of surface exposure ages of moraines in Arena Valley, Antarctica using in situ produced ^{10}Be and ^{26}Al, Geochim. Cosmochim. Acta 55 (1991) 2269–2283.

[18] E.T. Brown, R.F. Stallard, G.M. Raisbeck, F. Yiou, Determination of the denudation rate of Mount Roraima, Venezuela using cosmogenic ^{10}Be and ^{26}Al, Eos 73 (1992) 170.

[19] C.P. Kohl, K. Nishiizumi, Chemical isolation of quartz for measurement of in situ-produced cosmogenic nuclides, Geochim. Cosmochim. Acta 56 (1992) 3583–3587.

[20] G.M. Raisbeck, F. Yiou, D. Bourlès, J. Lestringuez, D. Deboffle, Measurements of ^{10}Be and ^{26}Al with a Tandetron AMS facility, Nucl. Instrum. Methods B 29 (1987) 22–26.

[21] G.M. Raisbeck, F. Yiou, D. Bourlès, E. Brown, D. Deboffle, P. Jouhanneau, J. Lestringuez, Z.Q. Zhou, The AMS facility at Gif-sur-Yvette: Progress, perturbations and projects, Nucl. Instrum. Methods Phys. Res. B 92 (1994) 43–46.