Effects of a tectonically-triggered wave of incision on Riverine Exports and Soil Mineralogy in the Luquillo Mountains of Puerto Rico

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Abstract

We document the long-term response of a tropical mountain stream to tectonics and show how this response exerts a first-order spatial control on the delivery of weatherable minerals to forest soils in its catchment. These minerals, in turn, affect nutrient availability and biogeochemical cycles. The Luquillo Mountains is a rainforest-covered isolated massif on Puerto Rico Island. Instead of displaying typical concave-up long profiles of most mountain streams, the rivers draining the southern flank of these mountains display a systematic downstream increase in gradient. Using concentrations of *in situ-produced* cosmogenic ^{10}Be in quartz from river sediments, we find that the downstream steepening is due to the propagation of an erosion wave along the rivers from the coastal plain upstream, towards the headwaters. Decreased ^{10}Be concentration along the steepened reaches (knickpoint faces or knickzones) results from faster denudation of the valley sides around the steepened reaches. The upper portions of the steepened reaches (knickpoint lips) cluster in elevation around the altitude of a flat-lying, dissected surface traceable around the Luquillo Mountains. Inspection of similar platforms over other parts of Puerto Rico and in the surrounding seas suggests that the dissected surface is an uplifted shore platform formed in the Early Pliocene (~ 4 My ago). Upstream of the knickpoints, rivers possess alluvial reaches still graded to this uplifted platform. They represent relict profiles of the rivers that once drained an island that was surrounded by the now-uplifted platform. We conclude that the knickpoints initiated when the platform started to rise above the Caribbean Sea. The knickpoints then started propagating upstream, defining the front of a slow-moving wave of erosion. ^{10}Be -derived catchment-scale denudation rates measured above and below the knickpoints indicate a 30% to 210% increase in denudation associated to the passage of the knickpoints. Mineralogical analysis of the soils show that soils upstream of the knickpoints overlie deeply depleted saprolite and only contain recalcitrant minerals, whereas soils downstream of the knickpoints experience an input of fresh, weatherable minerals. This influx considerably increases nutrient availability (Porder et al., 2015) in a forest where atmospheric inputs are otherwise the main source of nutrients (McDowell et al., 1990; Zarin and Johnson, 1995; Pett-Ridge, 2009).

1. Introduction

Small mountain rivers have been shown to collectively transport significant amounts of terrestrial materials to the ocean (Restrepo et al., 2000; Rad et al., 2006). Over timescales ranging from a few months to a few decades, fluvial sediment transport can be affected by anthropogenic perturbations of ecosystems such as cultivation and road clearings (MacDonald et al., 1997). Landslides triggered by hurricanes (Zarin and Johnson, 1995) and earthquakes (Dadson et al., 2004) affect sediment delivery over similar timescales. Over centuries and millennia, climate fluctuations modulate the delivery of terrestrial products to the coastal ocean (Goodbred and

Kuehl, 2000). Over longer geologic timescales, tectonic uplift and erosion progressively reshape the topography of river catchments. In an ideal case of topographic equilibrium (Hack, 1960), erosion everywhere in a catchment should exactly counterbalance mountain uplift. In fast turnover landscapes, such equilibrium is roughly achieved over the timescale necessary to even out the effects of climatic oscillations (Brocard et al., 2003). The response time of rivers to changes in tectonic uplift is however generally not instantaneous, and can span hundreds of thousands to millions of years (Attal et al., 2011). Can such slow river response leave a detectable and significant imprint, both spatially and temporally in sediment production and biogeochemical cycles in the catchment of small tropical mountainous rivers? To address this question, we investigated the magnitude of a slowly migrating wave of erosion produced in response to a tectonic uplift initiated several million years ago in the catchment of Río Blanco, a mountain stream located in the Luquillo Critical Zone observatory. We show that this wave of erosion leaves a detectable ^{10}Be signal in riverborne sediments and significantly increase the delivery of weatherable minerals to the soils in a mountain where the subsoil is otherwise strongly depleted in nutrients (Zarin and Johnson, 1995). As a result, this wave of erosion has a first-order effect on the delivery of nutrients to the overlying rainforest.

Puerto Rico is an island located above an oblique subduction zone; it has experienced rapid changes in tectonic uplift rates throughout its history, faster than the time required by erosion systems to respond and adjust to these fluctuations. As a result, its landscape has been maintained in a state of permanent disequilibrium. Its topography is a patchwork of domains eroding at various rates, separated from each other by knickpoints. Knickpoints are over-steepened reaches of river long profiles generated by along-stream variations in bedrock erodibility, uplift rates, or bedload grain-size. Transient knickpoints are also formed at the front of waves of accelerated erosion that propagate an erosional signal upstream. As hypothesized by Penck (1924), following a climatic, tectonic or base level disturbance, such knickpoints transmit a transient denudation signal across drainage basins in an organized and predictable fashion. In the present study we show how the tectonic evolution of Puerto Rico has influenced the topographic evolution and impacted the environment in the well-studied El Yunque National forest in the Luquillo Critical Zone Observatory.

We show that an episode of uplift that occurred several million years ago has sparked erosion waves that are still propagating across the landscape, generating sharp retreating knickpoints in the topography. These knickpoints provide a fundamental control on sediment and chemical fluxes. Using *in situ*-produced ^{10}Be in riverborne quartz, we evaluate the magnitude of the erosional difference between the relict, slowly eroding uplands and the more rapidly adjusting downstream areas. The upland relict landscape in the Luquillo Mountains has been the site of some of the first studies of catchment-wide denudation rates using detrital ^{10}Be (Brown et al., 1995; 1998). These ^{10}Be measurements were combined with weathering balances to propose some of the first

calculations of long-term weathering fluxes and rates of soil and saprolite formation based on cosmogenic denudation rates (White et al., 1998; Riebe et al., 2003; Ferrier et al., 2010). Here, we build upon these previous measurements by generalizing them across the relict landscape and expanding them below the knickpoints. We observe a decrease in the concentration of cosmogenic ^{10}Be across the knickpoints, confirming that a tectonic event that occurred several millions of years ago still imparts detectable differences in erosion rates in the modern landscape over the timescale of ^{10}Be -derived measurements (typically 10^3 - 10^4 years). By analyzing the mineral composition of the soils near the knickpoints we find that this increase in erosion rate is accompanied by an increase in nutrient-bearing primary minerals. We thus show that knickpoints have a fundamental effect because they separate an upland region where soils are almost completely depleted in primary nutrient-bearing minerals and where previous studies have shown that nutrients are mostly retrieved from the atmosphere and efficient recycling (e.g. Zarin and Johnson, 1995), from a downstream region where soils possess a larger stock of nutrient-bearing minerals and plant-available nutrients.

2. Tectonic evolution and uplift history of Puerto Rico

The island of Puerto Rico sits on the northeastern corner of the Caribbean Plate (e.g. Dolan et al., 1998; ten Brink, 2005; Mann, 2007)(Fig.1a), and, with the Virgin Islands, belong to a common, almost rigid tectonic block (Mann et al., 1995; ten Brink et al., 2009). This block is a fragment of the ancient Greater Antilles island-arc, which collided with the Bahamas Bank in the Early Eocene (e.g. Rojas-Agramonte et al., 2008; Stanek et al., 2009). After collision the arc eroded down to sea level and its residual relief was drowned into coastal sediments (Monroe, 1980a). By Miocene time, the Puerto Rico area had become a slowly-subsiding reef platform (van Gestel et al. 1999). By the end of the Miocene, only pure reef carbonates were deposited (Moussa et al., 1987), suggesting that little to no relief was left. Less than 4 My ago, the Virgin islands-Puerto Rico block experienced a sudden tilting in possibly as few as 14-40 ky (ten Brink, 2005). The northern edge of the Puerto Rico-Virgin islands reef platform sunk 4.5 km into the Puerto Rican trench while its southern ledge was uplifted above sea level and was eroded away, exposing the underlying volcanic basement (Fig.1a)(Birch, 1986; Grindlay et al., 2005; ten Brink, 2005, ten Brink et al., 2009).

Figure 1. Early Pliocene tilting of the Puerto Rican carbonate platform and the formation of shore platforms. A: map showing the present extent of the carbonate cover over the island, with location of the Luquillo Mountains (LM).

B and C are interpreted seismic section redrawn from van Gestel et al. (1998), showing the tilting of the carbonate platform and its beveling below a shore platform around the Virgin Islands (C), and below the Caguana surface north of Puerto Rico (B).

Little is known about the subsequent landscape evolution of Puerto Rico. The interior of the island displays vast expanses of flat, high-standing sub-horizontal erosional surfaces at various stages of dissection (Fig.2). Semmes (1919) first recognized these and interpreted them as remnants of a large peneplain exhumed from beneath the Oligocene-Miocene carbonates. He ascribed lateral changes in elevation and attitude of the plain remnants to later tectonic deformation. Lobeck (1922) disputed the role of tectonic deformation and instead proposed two distinct, parallel, imbricated peneplain levels surrounding the highest peaks (Fig.2). Briggs (1966) and Monroe (1980b) noticed the progressive dearth of terrestrial inputs to the Miocene reef platforms, which was attributed to the formation of the peneplains (Monroe, 1980b) or to the decline in the size of the feeding hinterland (van Gestel et al., 1998). Meyerhoff (1927) inferred that both levels are Pliocene in age, noticing that the Oligo-Miocene platform is tilted 4° to the north and that it is beveled by an erosional surface slanting 1° to the north (the Caguana surface, Fig.1b). These now-uplifted platforms are important benchmarks for understanding the topographic evolution of Puerto Rico in general, and of the Luquillo Mountains in particular. They demonstrate that the Luquillo Mountains are young and have been uplifted incrementally over the past 4 My. The mountains we observe today are not in a state of dynamic equilibrium; instead, they are a patchwork of relict surfaces and deeply dissected, quickly eroding areas.

Figure 2. Relict surfaces of Puerto Rico

A: Topographic slopes of Puerto Rico, with faults that disrupt the relict surfaces, and the modern extent of the Oligo-Miocene sedimentary cover along the northern side of the island (Ol-Mi). Notice the extensive flat surfaces that are still largely preserved over the central highlands, incised by deep, south-north oriented canyons.

B: Main ‘peneplains’ identified by Lobeck (1922), and Meyerhoff (1927), modified.

3. Methods

3.1 Digital extraction of erosional platforms and knickpoints

We reconstructed the extent and attitude of the erosional platforms identified in past works. We first identified the remnants of these surfaces over the entire island using the USGS 1-arc-second National Elevation Dataset (NED) digital elevation model. We removed high frequency topographic details by resampling the initial 30-meters DEM with a 210m-wide circular filter that extracts the highest points in the topography. The slope map of this resampled topography (Fig.2a) was used to delineate the expanses of perched flat land. In many instances, the remnants matched the levels described by Lobeck (1922) and Meyerhoff (1927) (Fig.2b). They represent either one single surface disrupted by faults (Lobeck, 1922) or imbricate surfaces of differing age separated by sinuous escarpments (Meyerhoff, 1927). We modeled the simplest case of a single surface disrupted by faults to evaluate the maximum amount of deformation necessary to reproduce the observed spread in elevations. A cubic spline interpolation was passed over all the mapped platform remnants and was allowed to break freely across major tectonic faults (Fig.3a). The resulting envelope was used to study how the relict surface projects around the Luquillo Mountains (Fig.3b).

Rivers and ridge profiles of the Luquillo Mountains were extracted from a one-meter LiDAR DEM (doi: 10.5069/G9BZ63ZR). Due to the coverage patchiness, the DEM was resampled at 5 meters and void areas were patched with a 10-meters DEM generated by interpolation of 10-m-elevation contour lines (Pike et al, 2010).

Figure 3: Definition of El Yunque Island based on the areal extent of the flat erosional surfaces of Puerto Rico. A: Surface envelope fit over the remnant of the Barranquitas-Cayaguas surface, with location of cross-section 4B. Contour spacing: 100 m. Mountains protruding over the surface envelope displayed in black (CC: Central Cordillera, LM: Luquillo Mountains). GNFZ: Great Northern Fault zone.

B: Topographic projection across the Luquillo Mountains showing the Barraquitas-Caguana platform reconstructed using ridge #1, and the protruding 'El Yunque island' (ridges #2 and #3). Note spatial correlation between the platform, prominent notches in ridges, and major river knickpoints over streams flowing on the quartz diorite. Location of ridges and rivers on figure 5.

3.2. Processing and measurement of in situ cosmogenic ^{10}Be in quartz

Cosmogenic ^{10}Be is produced in quartz grains within the immediate subsurface of the Earth, over the few uppermost meters of soil that quartz grain traverses during their final exhumation before being transported downslope. The residence time of a quartz mineral grain in this sub-surface zone of ^{10}Be production depends on the rate at which the overlying material is removed. Therefore, the ^{10}Be concentration in river sediment is inversely related to the mean erosion rate in the upstream drainage basin (Lal, 1991). Over time, a steady state may exist where the input of ^{10}Be produced equals the export of ^{10}Be in sediment leaving the catchment (Lal, 1991; Brown et al., 1995; Granger et al., 1996). The catchment of Río Icacos in Luquillo Mountains is one of the first sites where the method was tested (Brown et al., 1995). The Río Blanco quartz diorite is very homogeneous and rich in quartz (23% wt. quartz, Smith et al., 1998), making it ideally suited for such studies. We collected river-borne quartz in sand-and-gravel bars of streams at various locations above and below the river knickpoints. Samples were taken 50-200 meters downstream of major tributary junctions to ensure thorough mixing of the bedload material (Binnie et al., 2006). The samples were prepared at the University of Pennsylvania Cosmogenic Isotope Laboratory. Sediment grain sizes were separated using a phi-scale sieve set. Fractions coarser than 2 mm were crushed and sieved to obtain a 0.25-0.5 mm powder.

Stream	Grain size range ⁽¹⁾	Easting	Northing	Quartz ⁽²⁾ feeding area (A _Q)	A _Q Average elevation	Quartz used	[¹⁰ Be]	Topographic shielding factor ⁽³⁾	P _μ ⁽⁴⁾	P _{spal} ⁽⁴⁾	Quartz enrichment factor ⁽⁵⁾	Integrated soil density ⁽⁶⁾
	(ϕ) unit	(°)	(°)	(km ²)	(m)	(g)	(10 ⁴ at g ⁻¹)		(at g ⁻¹ yr ⁻¹)	(at.g ⁻¹ yr ⁻¹)		(g cm ⁻³)
ES-UK	[-1 -3] c	-65.8050	18.2967	0.99	763	63.8	5.93 ± 0.29	0.92*	0.23	4.36	1	2.7
	[4 3] f					55.6	22.51 ± 0.29	0.98	0.23	4.66	1.27	1.6
IC-UK	[-1 -4] c	-65.7853	18.2758	3.19	685	18.5	4.34 ± 0.51	0.92*	0.22	4.11	1	2.7
	[3 2] f					60.7	17.05 ± 0.55	0.97	0.22	4.35	1.27	1.6
	[4 3] f					23.9	16.23 ± 0.49	0.97	0.22	4.35	1.27	1.6
SAB-UK	[0 -3] c	-65.8004	18.2742	2.82	713	10.5	6.06 ± 1.00	0.92*	0.22	4.20	1	2.7
	[4 3] f					11.4	22.1 ± 1.4	0.97	0.22	4.44	1.27	1.6
CUY-UK	[-1 -3] c	-65.8060	18.2662	1.83	700	24.3	1.6 ± 2.8	0.92*	0.22	4.16	1	2.7
	[3 2] f					41.1	11.52 ± 0.78	0.96	0.22	4.40	1.27	1.6
	[4 3] f					46.6	33.32 ± 0.94	0.96	0.22	4.40	1.27	1.6
PRI-UK	[-1 -3] c	-65.7741	18.2573	1.06	673	34.1	4.85 ± 0.41	0.92*	0.22	4.07	1	2.7
	[3 2] f					18.3	15.2 ± 1.0	0.98	0.22	4.36	1.27	1.6
SAB-TDK1	[-3 -4] c	-65.7958	18.2704	0.37	634	34.3	2.51 ± 0.25	0.92*	0.21	3.96	1	2.7
	[4 3] f					7.0	9.72 ± 1.25	0.96	0.21	4.15	1.27	1.6
SAB-TDK2	[-3 -4] c	-65.7993	18.2708	0.21	611	46.5	2.31 ± 0.21	0.92*	0.21	3.89	1	2.7
	[4 3] f					11.3	7.73 ± 0.77	0.94	0.21	3.98	1.27	1.6
SAB-TDK3	[-1 -3] c	-65.7964	18.2693	0.11	548	35.5	1.98 ± 0.23	0.92*	0.21	3.72	1	2.7
	[4 3] f					12.8	9.83 ± 0.83	0.93	0.21	3.76	1.27	1.6
IC-TDK1	[-1 -2] c	-65.7830	19.2694	0.13	606	48.6	3.28 ± 0.20	0.92*	0.21	3.88	1	2.7
	[4 3] f					49.9	13.27 ± 0.38	0.94	0.21	4.02	1.27	1.6
IC-TDK2	[-3 -4] c	-65.7834	18.2629	0.19	596	18.6	2.11 ± 0.35	0.92*	0.21	3.85	1	2.7
	[4 3] f					18.7	10.72 ± 0.36	0.96	0.21	4.03	1.27	1.6
IC-TDK3	[-3 -4] c	-65.7816	18.2596	0.03	600	18.2	2.39 ± 0.27	0.92*	0.21	3.86	1	2.7
	[4 3] f					60.9	11.80 ± 0.30	0.97	0.21	4.09	1.27	1.6
CUY-TDK	[4 3] f	-65.7990	18.2615	0.27	598	13.4	10.88 ± 0.52	0.94	0.21	3.99	1.27	1.6

Table 1, ¹⁰Be concentrations and environmental parameters used for the calculation of catchment-wide erosion rates

(1) Grain size phi scale of analyzed sediment: grain diameter $D = D_0 \times 2^{-\phi}$ with $D_0 = 1$ mm, used to define a coarse (c) and fine (f) fraction. (2) Quartz feeding area corresponds to the extent of the quartz-diorite. (3) Topographic shielding factor of the fine fraction is the average shielding in the quartz-feeding area. For the coarse fraction, it is the average shielding of boulder-strewn gullies. (4) Production rates for neutrons (P_{spal}) and muons (P_{μ}) is calculated using the CRONUS calculator for a polar sea-level ¹⁰Be production rate of 5.1 at.g⁻¹.y⁻¹ (Balco et al., 2008), topographic shielding (3) and a vegetation shielding of 7%. The quartz enrichment factor of the coarse fraction is zero and 1.27 (see main text). (6) Soil density of the coarse fraction is the density of dense quartz diorite, while the soil density for the fine fraction is that of the soil above fully weathered saprolite.

Quartz isolation, purification and dissolution, ion exchange extraction and precipitation of beryllium were performed following an adaptation of the technique of Kohl and Nishiizumi (1992). A ^9Be carrier (Scharlau BE03450100 carrier batch 2Q2P – 14/10/10) with a measured $^{10}\text{Be}/^9\text{Be}$ ratio of $1.5 \cdot 10^{-15}$ was added to each sample. Beryllium hydroxide was precipitated at pH 8-9, oxidized to BeO over an open butane-propane flame and mixed with Nb powder. The $^{10}\text{Be}/^9\text{Be}$ ratio was measured by accelerator mass spectrometry (AMS) at PRIME lab, Purdue University. Results were normalized to the 07KNSTD standard (Nishiizumi *et al.*, 2007) with an assumed $^{10}\text{Be}/^9\text{Be}$ ratio of $2.79 \cdot 10^{-11}$ (Balco, 2009). The $^{10}\text{Be}/^9\text{Be}$ ratios of the procedural blanks were 2.0 to $4.0 \pm 0.6 \cdot 10^{-15}$. Reported one-sigma uncertainties (Table 1) encompass uncertainties on Purdue AMS measurement, uncertainty on the primary standard, and uncertainties on the blank correction.

3.3. Soil Mineral Analysis

Soil samples from 20 sites on the quartz diorite in the watersheds of Río Blanco and Río Espíritu Santo were used for a comparison of soil mineralogical composition upstream and downstream of the knickpoints. Samples were collected on ridges at a depth of 0 to 20 cm. A few grams of the soil < 2 mm fraction was ground in a ball-mill to a size of 10 microns. Samples were analyzed for Ca, Mg and K-bearing primary minerals using X-ray diffraction. Twelve samples were measured on a D8 Advance diffractometer (Bruker Corp., Billerica, MA, analysis by X-Ray Wizards, LLC). Ten other samples were analyzed by X-ray diffraction in a Pananalytical X'Pert Pro instrument (Zhou, 2011). Percent crystallinity, phase identification and phase quantities were determined via Reitveld Refinement (RIR) using the TOPAS software for the first 12 samples, and using the software X'Pert HighScore Plus, version 2.2 (2.2.0) for the ten other samples (Zhou, 2011).

4. Results: Origin of the uplifted platforms around the Luquillo Mountains

The relict low-relief platforms that cover much of Puerto Rico bevel both the tilted Mio-Pliocene carbonates and their volcanic basement (Meyerhoff, 1927 and Fig.1b). A similar beveling can be observed today on the marine platform that surrounds the Virgin Islands (van Gestel *et al.*, 1998; Fig.1c). The Virgin Island shore platform is essentially an extensive erosional shore platform that surrounds residual islands, with patchy reefs and detrital sediments blanketing its basal erosional surface. The similarity suggests that the upland relict surfaces of Puerto Rico are former shore platforms rather than peneplains. The Virgin Islands platform is 40- to 50-km-wide and would have had to expand landwards

by at least a centimeter per year to reach its modern extent since the Early Pliocene tilting of the reef platform. Such a rate is compatible with reported rates of long-term sea-cliff retreat (Bradley and Griggs, 1976; de Lange and Moon, 2005), rather than with the tens of millions of years necessary to form peneplains (e.g. Baldwin et al., 2003). The ‘blanket sands’ of Puerto Rico also support this marine origin: these patches of mature quartz-dominated sands are commonly found over the relict surfaces (Figs. 1a and 3b). They did not form by concentration of insoluble residues following the weathering of their substrate as they commonly rest on non-quartz bearing substrates such as pure carbonates (Briggs, 1966; Miotke, 1972; Jones et al. 1982) and serpentinites (Weaver, 1962; Jones et al. 1982). Instead, they must have been transported all over the platforms by an agent able to widespread dispersion, most likely by the sea.

Figure 4. Delimitation of El Yunque Island using platform remnants identified around the Luquillo Mountains. Major river knickpoint lips over the quartz diorite do not match geological boundaries; instead, their elevation coincides with that of the platform. IP: Initiation point chosen for the modeling of knickpoint propagation.

The platforms may originate in one single level disrupted by faults (Semmes, 1919), or belong to at least two different imbricate levels (Lobeck, 1922). The surface envelope that we passed over the platform remnants is allowed to break freely across major tectonic faults (Fig.3a). In places, faults are found to coincide with abrupt changes in the elevation and attitude of the reconstructed envelope, such as

across the Great Northern Fault Zone along the Luquillo Mountains. At other places, the surface display more diffuse and sinuous scarps that could correspond to belts of diffuse tectonic deformation (folds, or arrays of minor faults), or degraded risers separating imbricate surfaces of differing ages. In the Luquillo area, the situation is simpler. Lobeck (1922) stated that ‘the peneplane remnants fringe nicely [the peaks] in the west and form a narrow shelf on the south’. In our reconstruction, the platform appears as a simple slab that rises towards the ESE with an inclination of 0.7° and projects across the Luquillo Mountains at an elevation of 500 to 650 m (Fig.3b). If the relict surface is a shore platform, then the center of the massif defines an ancient ‘El Yunque’ island 10 km in diameter and 500 m high, similar in size and height to the modern Virgin Islands (Fig.4). Flat topographic shoulders and notches are also found at the elevation of the projected platform (Fig.3b) all around the mountains. These smaller topographic features correspond to the ‘narrow shelf’ of Lobeck (1922).

5. Results: Origin of the knickpoints along the Río Blanco drainage

The rivers that descend the southern flank of the Luquillo Mountains drain the Río Blanco quartz diorite stock (Fig.4). Halfway from their headwaters the rivers display pronounced steepened reaches, called knickpoints, or more properly knickzones, or knickpoint faces, the knickpoint (or knickpoint lip) being the upper break in slope from shallow to steep (Fig.5). Above the knickpoints (KPs), the rivers have concave-up alluvial reaches with low gradients and limited stream power (Pike, 2010). The KPs lips are located far upstream from the quartz diorite stock border, on homogenous, almost isotropic bedrock. A survey of joint spacing along the knickpoint face indicates the presence of several families of regularly-spaced joints with a characteristic spacing of 1.5 to 2.5m. This same spacing determines the size of the corestones encountered in the saprolite above the knickpoints (Brantley et al., 2011). There is therefore no significant along-stream change in bedrock erodibility susceptible to explain the formation of these 600m-tall knickzones. On the other hand, the elevation of the knickpoint lips closely cluster around the 600-m altitude of the uplifted shore platform (Fig.3b). The most straightforward explanation therefore is that these KPs represent the front of an incision wave produced by the uplift that brought the 600 m-platform from sea-level up to its modern elevation during the past 4 My. The KPs are transient features: they are migrating upstream and separate an upstream landscape which is still graded to the former platform level, from a downstream landscape adjusting to the current coast level.

The KPs must have initiated at breaks-in-slopes that initially formed downstream across the platform. The most likely sites of formation of such breaks are the fault scarps that accommodated the uplift of the Luquillo Mountains with respect to the surrounding land. They would have been situated in the zone of interference between the Great Northern Fault Zone that bounds the mountains to the

southwest (Fig. 3a) and the Fajardo Fault zone that bounds the mountains to the southeast. Similar knickpoints likely developed over the volcanoclastic rocks as well. However, although detectable in places, knickpoints are less well expressed over the volcanoclastic rocks (Pike et al., 2010). The mechanical properties of the quartz diorite may explain their better expression over the quartz diorite. Quartz diorite is more massive, less fractured than the volcanoclastic rocks. Quartz diorite may have slowed down the propagation of the knickpoints and prevented them from degrading by diffusion, rather helping maintaining or even developing extremely steep faces as they migrate upstream. Conversely, over the volcanoclastics, knickpoints may have propagated faster and more diffusively towards the headwaters, and are now either gone or completely degraded.

Figure 5. Long profiles of the tributaries of Río Blanco sampled for the measurement of detrital ^{10}Be .

CUY: Cubuy, IC: Icacos, PRI: Prieto, SAB: Sabana. DK-x: tributaries of aforementioned streams (x), sampled downstream of the knickpoint lips.

Insert: χ graph (Perron and Royden, 2012), with χ calculated for a reference drainage area A_0 of 1 km^2 and an intrinsic concavity of 0.5. The χ scale is a drainage area-weighted upstream distance. Transient KPs retreating at a celerity solely controlled by drainage area on a homogeneous substrate plot at the same χ distance. The graph highlights how K_{IC} is left behind other KPs.

6. Results: Erosion rates inferred from ^{10}Be measurements in river-borne quartz

Previous ^{10}Be -based studies have shown that cosmogenic isotopes can be used to track increases in river incision rate across headward-retreating knickpoints (e.g. Weissel and Seidl, 1998; Brocard et al., 2003; Jansen et al., 2011), as well as the resulting increase in catchment-wide denudation rate (e.g. Reinhardt et al., 2007; Willenbring et al., 2013). To quantify the magnitude of the change in erosion rate induced by the passage of the knickpoints, we measured the concentration of in-situ produced cosmogenic ^{10}Be in river-borne quartz. We generalized previous measurements by Brown *et al* (1995) along Río Icacos to the entire relict landscape by sampling the five largest streams above the knickpoints. Seven tributaries that exclusively drain the dissected landscape downstream of the knickpoint lips were sampled to document erosion rates below the knickpoints (Fig.6a). Conversion of ^{10}Be concentration (Table 1) into denudation rates and selection of scaling factors for ^{10}Be production rates are detailed in Appendix.

Figure 6. Location of sampling sites for the measurement of ^{10}Be -derived erosion rates across the knickpoint lips.

6a. Location of river borne quartz samples and upstream contributing areas. Relief: 1m-precision LiDAR DEM. Simplified contour interval: 25m. CUY: Cubuy, CUY-BK: Cubuy downstream of knickpoint, ES: Espiritú Santo, IC: Icacos, IC-DK: Icacos downstream of knickpoint, PRI: Prieto, SAB: Sabana, SAB-DK: Sabana downstream of knickpoint.

6b. ^{10}Be -derived erosion rate estimates across the knickpoints, using coarse (c) and fine (f) sediment size fractions. Plot shows the effect of various parameter values, as explicated in Table 3. NC: no shielding corrections, soil density of 2.1 g cm^{-3} . Additions of topographic shielding (TC), vegetation shielding (VC), spatially variable soil density (SD), spatially variable soil quartz enrichment (QE), and time-dependent production rate (T). Box (B, 1995) represents the spread of erosion rates across the entire range of grain sizes from Brown *et al.* (1995), plotted for TC+VC+SD+QE+T.

By analyzing grain-size fractions at each one-phi increment from -3 to 4 (8 mm to 0.063 mm), Brown *et al.* (1995) showed that above the knickpoint of Río Icacos ^{10}Be concentration decreases systematically with increasing grain size. Because landslides are regarded as the largest providers of bedload in the Luquillo Mountains (Larsen, 2012; Stallard, 2012), Brown *et al.* (1995) attributed the grain-size dependency to a change in clast provenance whereby the finer fractions stemming from shallow soils (60-80 cm below the surface), the coarser fractions being delivered by the landslides from deeper, shielded horizons. In this model, landslides have a 10 ky return frequency at any place in the catchment. We observed that landslides distribution is not homogenous and that landslides concentrate in coves incised into the 10s-of-meters-thick saprolite that covers the relict landscape. The Icacos River is, above its knickpoint, a shallow-gradient, sandy river (Pike *et al.*, 2010). The coarsest grains released to the stream by the saprolite are individual quartz crystals that reach a maximum size of 2 mm. The saprolite also hosts large corestones several meters across made of saprock and fresh bedrock (Turner *et al.*, 2003; Brantley *et al.*, 2011; Buss *et al.*, 2013). The corestones are exhumed along the coves, slip downslope and

pile up over the streams. They are too large to be transported and decay in place, shedding rindlet fragments that make up the entirety of the small flux of quartz-bearing gravel delivered to the stream. The fact that the spatial provenance of the sediment changes with grain-size dependency of the source material has important implications for the calculation of erosion rates: it introduces a systematic bias on the ^{10}Be production rate first because gravels tend to be exhumed at sites topographically more shielded than the sand; second, because the attenuation of cosmic rays is sensitive to the ground density, which varies from 2.7 g cm^{-3} in fresh quartz diorite to 1.6 g cm^{-3} in the Icacos soils. There is no significant reduction of quartz grains by dissolution during the weathering (Schultz and White, 1999). As a result, quartz strongly concentrates in the soil (Ferrier et al., 2010) due to the preferential entrainment, dispersal and dissolution of clay minerals. This effect induces a correction of up to 30% of the ^{10}Be -denudation rates in the soils, but it does not apply to the exhumation of gravel exfoliated from the corestones. A part or the whole of the grain-size dependency could therefore be due to these changes in provenance; it will affect the absolute value of the calculated erosion rates, as well as, more importantly, the relative variation of the erosion rates across the knickpoints.

To capture the full range of ^{10}Be concentration expectable, we analyzed a fine sand (0.63-0.125 mm) and a gravel fraction at each site (8 mm, or above when available, Table 1). Along the Icacos River we found similar concentrations to those of Brown et al. (1995) (Fig.6b), confirming that the Icacos River is a well-mixed and damped system. A similar strong grain-size dependency was found along all streams. The ^{10}Be concentration is very stable in the fine fraction across the relict landscape, indicating homogeneity of erosional processes and rates. The gravel fraction shows more variability, probably due to the more restricted extent of the source areas (corestone zones), and possibly to more episodic delivery. Río Cubuy (CUI) stands as an outlier probably because the measured watershed is the only one that includes a fraction of adjusting landscape (Fig.6) that may contaminate the relict landscape bedload signal. Downstream of the knickpoints, the concentration is systematically lower in both the fine and coarse fractions, reflecting a net increase in denudation rates and an increase in the spatial heterogeneity of denudation.

We conducted an analysis of the sensitivity of the calculation of the increase in erosion rate to the choice of the correction factors (Appendix). We first calculated erosion rates assuming an average soil density of 2.1 g cm^{-3} (model NC, Table A1), then explored the effect of topographic shielding by ascribing an 8% shielding typical of coves to the gravel, and site-specific catchment-derived shielding values for the sand (model topographic correction, TC). We added the effect of shielding by vegetation (7%, model TC-VC), and then explored the effect of variations in ground density, ascribing a soil density of 2.7 g cm^{-3} to the gravel and 1.6 g cm^{-3} to the sand (model TC-VC-DV). We finally added the effect of

differential quartz enrichment (model TC-VC-DV-QE), and the effect of temporal variations in production rate using the schemes proposed by CRONUS (Table A2-1). These effects of lateral variations in the physical parameters at steady-state greatly reduce the divergence in erosion rate introduced by the choice of the grain size (Fig.6b). Divergences are not completely eliminated however, indicating that a non-steady-state ^{10}Be accumulation model still must be used to finally reconcile these values (Brown et al, 1995). Above the knickpoints, our results yield an average erosion rate of the relict landscape of 53.0 ± 1.6 to $83.9 \pm 6.4 \text{ m My}^{-1}$. Below the knickpoints, the average erosion rate is less tightly bracketed between 69 ± 3 and $176 \pm 8 \text{ m My}^{-1}$.

Model	$\mathcal{E}$ – UK, all dataset (m/My)		$\mathcal{E}$ – DK, all dataset (m/My)		$\mathcal{E}$ increase, all dataset <i>x upstream</i>		$\mathcal{E}$ increase, IC <i>x upstream</i>		$\mathcal{E}$ increase, SAB <i>x upstream</i>	
	c	f	c	f	c	f	c	f	c	f
NC	116 ± 7	31 ± 1	247 ± 12	53 ± 2	2.1 ± 0.2	1.7 ± 0.1	1.7 ± 0.3	1.4 ± 0.2	2.6 ± 0.6	2.5 ± 0.6
TC	110 ± 7	30 ± 1	235 ± 11	51 ± 2	2.1 ± 0.2	1.7 ± 0.1	1.7 ± 0.3	1.4 ± 0.2	2.7 ± 0.6	2.5 ± 0.6
TC,VC	104 ± 6	29 ± 1	225 ± 11	49 ± 2	2.2 ± 0.2	1.7 ± 0.1	1.7 ± 0.3	1.4 ± 0.2	2.7 ± 0.6	2.5 ± 0.6
TC,VC,DV	81 ± 5	38 ± 1	175 ± 8	64 ± 2	2.2 ± 0.2	1.7 ± 0.1	1.7 ± 0.3	1.4 ± 0.2	2.7 ± 0.6	2.5 ± 0.6
TC,VC,DC,QE	81 ± 5	48 ± 2	175 ± 8	64 ± 2	2.2 ± 0.2	1.3 ± 0.1	1.7 ± 0.3	1.1 ± 0.1	2.7 ± 0.6	2.0 ± 0.5
TC,VC,DC,QE, T	84 ± 6	53 ± 2	176 ± 8	70 ± 3	2.1 ± 0.3	1.3 ± 0.1	1.7 ± 0.4	1.1 ± 0.1	2.6 ± 0.7	1.9 ± 0.5

Table 2. Increase in erosion rate across the knickpoints.

7. Downstream increase in weatherable minerals across the knickpoints

Upstream of the knickpoint, the relict landscape is underlain by a saprolite tens-of-meters-thick (White et al., 1998; Brantley et al., 2011; Buss et al., 2013). It has been shown that the chemical weathering of the quartz diorite takes place chiefly at the base of the saprolite layer. The parent rock, composed of plagioclases, quartz, amphiboles and biotite, is completely converted over a few meters into a highly porous saprolite essentially composed of kaolinite, quartz and iron oxides, with residual amounts of original minerals other than quartz. As a result, the topsoil is completely depleted in easily weatherable minerals (White et al., 1998; Brantley et al., 2011; Ferrier et al. 2010; Buss et al., 2013). Thus far, no similar measurements have been made downstream the knickpoints, but the local abundance of angular blocks in the soils suggests that the saprolite is shallower there. The increase in erosion rate accompanying the passage of the knickpoint diminishes the residence time of the easily weatherable

minerals (plagioclases, amphiboles) into the saprolite. If the residence time becomes short enough, some of these minerals should survive their journey through the saprolite layer and should be present in the topsoil.

Figure 7. Proportion of clays and fresh minerals above versus below the erosion wave demarcated by knickpoints and oversteepened slopes.

To test this possibility, we analyzed the mineralogical composition of soils at sampling sites located upstream and downstream the knickpoints (Fig.7; Table 3), 11 samples representing the relict landscape and 9 samples representing the downstream, adjusting landscape. At some sites measurements were conducted on the end-members of the soil catena (ridge and valley positions). As expected, the topsoil above the knickpoint is mostly made of quartz and kaolinite. Quartz concentration is greater in the soils than in the saprolite due to faster removal of the clays in the soil (Ferrier et al., 2010). Feldspars and mafic minerals are still present, but in residual amounts, with more complete disappearance on the ridges (Table 3). Downstream of the knickpoints the concentration of weatherable minerals increases at all measured sites but two locations on top of broad flat ridges that may be eroding more slowly (sites Codys 8 and Palmdys 23). While the proportion of mafic minerals marginally increases on average by 15%, the proportion of feldspars increases by more than 400%. The mineralogical analysis thus shows that the

increase in erosion rate that results from the passage of the knickpoints, although modest according to the detrital ^{10}Be signature, is large enough to generate a substantial increase in the amount of weatherable minerals in the forest soil.

<i>Sample</i>	<i>Position</i>	<i>Longitude</i>	<i>Latitude</i>	<i>Quartz</i>	<i>Clays</i>	<i>Feldspars</i>	<i>Gibbsite</i>	<i>Goethite</i>	<i>Mafics</i>	<i>Phosphate</i>
		°	°	%	%	%	%	%	%	%
CODYS 5*	R	65.785	18.294	74.4	14.8	1.0	4.1	0.6	2.6	1.2
COLDYS 5 ⁺	R	65.785	18.294	59.4	27.3	4.0	3.1	2.1	<1	2.1
COLDYS 5 ⁺	V	65.786	18.294	68.7	8.0	13.7	2.5	1.7	<1	3.2
CODYS 6*	R	65.795	18.291	82.3	14.5	<1	0.7	0.7	<1	1.0
COLDYS 6 ⁺	R	65.795	18.291	68.5	17.8	6.8	1.5	1.5	<1	2.2
CODYS 6*	V	65.796	18.290	81.7	3.7	5.3	1.9	<1	2.5	3.6
COLDYS 6 ⁺	V	65.796	18.290	77.8	6.7	8.4	2.9	1.4	<1	<1
CODYS 7*	R	65.785	18.270	70.4	18.0	<1	2.5	1.2	<1	3.0
PALMDYS 21*	R	65.795	18.292	73.0	16.1	2.1	1.9	0.8	1.7	0.8
PALMDYS 21 ⁺	R	65.795	18.292	57.4	28.5	3.9	2.4	2.5	<1	4.6
PALMDYS 21 ⁺	V	65.793	18.292	62.9	18.7	10.1	<1	2.5	<1	4.0
PALMDYS 22*	R	65.791	18.289	75.9	14.4	4.4	0.8	0.7	1.6	0.7
CODYS 8*	R	65.794	18.269	81.5	15.0	<1	<1	<1	<1	1.8
TABDYS 14*	R	65.795	18.266	52.6	10.1	30.0	<1	0.7	<1	3.8
TABDYS14 ⁺	R	65.795	18.266	34.4	12.1	44.0	0.5	0.7	3.4	2.6
TABDYS 14 ⁺	V	65.795	18.267	42.0	10.3	40.6	<1	0	1.2	5.0
TABDYS 15*	R	65.803	18.261	55.5	9.0	28.1	<1	0.6	2.1	3.6
TABDYS 16*	R	65.793	18.261	64.8	16.0	11.8	<1	1.2	1.1	0.5
PALMDYS 23*	R	65.794	18.270	73.0	21.9	1.3	<1	2.1	<1	0.2
PALMDYS 24*	R	65.786	18.2861	31.0	5.5	46.1	0.8	<1	<1	7.0

Table 3. Summary of the soil mineralogy. The clay fraction is dominated by kaolinite, the feldspars fraction by plagioclases; mafics are dominantly hornblende and biotite, and ancillary clinopyroxenes. Positions: R : ridges, V: valleys

8. Discussion

Despite relying on different values of physical and environmental parameters, our estimate for denudation rate upstream of the knickpoints is only marginally different from Brown et al.'s (1995) denudation estimate of 43 m My^{-1} in the Río Icacos catchment. It is also similar to the soil denudation values of 58 m My^{-1} obtained by White et al. (1998) and of 87 m My^{-1} by Stallard (2012) who measured solute exports and calculated denudation rates by assuming equilibrium at the scale of the watershed between the rate of saprolite deepening (determined by solute exports) and the rate of soil denudation. As pointed out by Turner et al. (2003) and Stallard (2012), denudation rate estimates based on suspended sediment exports in the last few decades are much higher (McDowell and Asbury, 1994; Larsen and Stallard, 2000; Stallard and Murphy, 2012; Stallard, 2012). Differences between measured sediment exports and cosmogenic rates are generally ascribed to the different timescales over which the rates are averaged (typically a few 10s of thousands of years for the cosmogenic isotopes). The cosmogenic signal dampens higher frequency fluctuations in erosion rates due to climate oscillations (Schaller and Ehlers, 2006) as well as anthropogenic disturbances (e.g. Brown et al., 1998; Hewawasam et al., 2003). The Icacos catchment is covered by dense old-growth primary forest subjected to little anthropogenic disturbance, so the cause of elevated suspended exports remain unclear. The denudation rates obtained here and in previous studies (Brown, 1995; Riebe et al., 2003) place denudation rates of the relict landscape at the lower end of the erosion spectrum encountered for catchments with similar average slopes of $22\text{-}25^\circ$ (Portenga and Bierman, 2011; Willenbring et al., 2013).

Below the knickpoints rates are higher (69 ± 3 - $176\pm8 \text{ m My}^{-1}$) but still lower than some other rates measured at other sites in the Luquillo Mountains. In the Mameyes catchment, Dosseto et al (2012) found a denudation rate of $334 \pm 46 \text{ m My}^{-1}$ using U-series isotopes compositions in the volcanoclastic saprolite, assuming equilibrium between saprolite deepening a surface denudation. The concave profile of Río Mameyes suggests that all its catchment is entirely coupled to the modern base level. Our rates suggest that the quartz diorite, where submitted to the new base level, does not erode as fast as the volcanoclastics.

The magnitude of the wave of erosion documented by the detrital ^{10}Be varies according to the sediment grain size (Table 2). The gravel fraction yields a larger downstream increase ($\times 2.1\pm0.2$) than the fine sand ($\times 1.7\pm0.1$), assuming no correction for the environmental parameters (topography, vegetation, soil density and quartz enrichment). Environmental corrections reduce the spread to $1.3\text{-}2.1\pm0.1$.

Soils upstream of the knickpoints are more thoroughly depleted in fresh minerals, forcing plant communities above the KPs to retrieve their nutrients from the atmosphere (McDowell et al., 1990; Zarin

and Johnson, 1995; Pett-Ridge, 2009). Downstream of the KP lips, incompletely weathered minerals make their way through the saprolite up into the soils, potentially providing an alternative source of nutrients to the plants. A multi- regression analysis of environmental parameters, geochemical and Sr isotopes tracing of nutrient sources suggests that these minerals effectively represent a major source of plant-available nutrients downstream of the knickpoints (Porder et al., 2015). This implies that the knickpoints have a profound effect on the ecology of the Luquillo Mountains primary forests. They represent a major boundary between an upstream forest that retrieves most of its nutrient from the atmosphere from a downstream forest that retrieves a significant fraction of its nutrients from the bedrock. They illustrate the first-order importance of long-term geomorphological processes on the structure of an old-growth tropical forest.

9. Conclusion

Streams draining the southern flank Luquillo Mountains have developed prominent knickzones over a stock of quartz diorite. The lips of these knickzones cluster about the 600 m elevation of a long-known dissected low-relief surface that surrounds the Luquillo Mountains. We interpret this surface as a former shore platform that has been uplifted since the Early Pliocene (5 My ago). These dramatic knickpoints represent the front of an upstream-propagating erosion wave that adjusts river profiles to the resulting 600 m lower coastal base level. They illustrate how a tectonic disturbance that occurred millions of years ago still significantly impacts the stream morphology to these days.

To quantify the impact of this wave of erosion on soil denudation we have used in situ-produced cosmogenic ^{10}Be in quartz transported by these rivers to compared catchment-wide erosion rates in watersheds located upstream of the front of the erosion rate with erosion rates in catchments completely within the erosion wave. The detrital ^{10}Be documents a twofold increase in denudation rate, compatible with the limited amount of propagation of the knickpoints over the past millions of years.

Despite this limited increase in erosion, the mineralogy of the soils located within the area impacted by the erosion wave differs markedly from the soils located farther upstream. Soils located upstream develop at the expense of a thick saprolite where weathering of nutrient-bearing minerals is complete. As a result, soils are almost devoid of primary minerals, and vegetation there is known to retrieve its nutrients mostly from atmospheric inputs such as sea aerosols and Saharan dust (McDowell et al, 1990; Zarin and Johnson, 1995). Within the erosion wave, we find that soils retain some of the primary weatherable minerals such as feldspars and mafic minerals. This in turn increases the availability of

extractable cations in the soil (Porder et al., 2015), profoundly changing the mode of nutrient delivery to the forest between the upstream and downstream portions of the forest.

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Appendix. Scaling factors for the cosmogenic ^{10}Be – derived erosion rates

One fundamental assumption of cosmic-ray exposure techniques for both dating surfaces and measuring erosion rates is that the annual production of the cosmogenic isotopes is almost steady over timescales of 10^3 - 10^5 years. This assumption is reasonable here considering the geographic location of the study area. Production rate is affected by variations in the atmospheric pressure and by fluctuations of the Earth's magnetic field. Soil denudation rates are averaged over the time required to erode 160 g.cm^{-2} of soil, which spans 5-50 ky in most cases, so the assumption is that climate oscillations and variations of the magnetic field average out over this timescale. An earlier study at our location (Brown et al, 1955) has shown that quartz grains in the soils reside in the cosmogenic zone of the soil for several 10s of thousands of years, such that the production rate could be affected by the last glacial-interglacial climatic transition. Sea-level lowering by as much as 125 m during the last glaciation had little effect on the atmospheric pressure and cosmic-ray attenuation (Omatson, 2006). Another effect was the redistribution of atmospheric pressure around ice sheets, but its induced and change in production rate of less than 2% in Puerto Rico during the last glacial maximum (Staiger et al., 2007). Over this time range, variations in the Earth's magnetic field strength resulted in a time-integrated increase of 0% to 8% of the ^{10}Be production rate with respect to its modern value (Masarik *et al.*, 2001). Such an effect is taken into account by the CHRONUS online calculator used to compute our production rates (Balco et al., 2008, version 2.2, 2009, with standardizations values of 2011), and its effect on erosion rates is tested in our sensitivity analysis (Tables A1-1 and Table 2).

Catchment-wide erosion rates are based on a series of assumptions that are commonly violated due to the natural complexity of the natural environment. The study area favorably meets many of the expected requirements and has been one of the first sites where the method was used (Brown et al., 1995). One requirement is that quartz distribution is even so that quartz comes equally from all parts of the landscape. The studied rivers drain the Río Blanco quartz diorite, its hornfels aureole, and volcanoclastic rocks. The volcanoclastic rocks and hornfels locally contain microcrystalline metamorphic quartz (Buss et al., 2013), but the volcanic rocks are basalts and basaltic andesites poor in quartz phenocrysts in our analyzed range of grain size (Seiders, 1971; Briggs and Aguilar-Cortés, 1980). Because the quartz diorite is very quartz-rich, we can safely consider that the contribution of the volcanoclastics to our quartz pool is negligible. To further increase the purity, volcanoclastics and hornfels were hand-picked from the analyzed gravel fractions. We also tested our extraction procedure on various hornfels and volcanoclastics and did not retrieve any quartz larger than 50 microns. In the Caribbean, Saharan dust is abundant and quartz-rich, but its grain-size prevents it from

contaminating sediment coarser than 20 microns (Prospero and Carlson 1971), and has therefore no influence on our measurements. The geochemical composition of the quartz diorite is remarkably homogenous (Smith et al., 1998; Riebe *et al.*, 2003, Stallard, 2012): its quartz content is typically 21-25 % and show little variation except near the batholith border (Smith et al., 1998; Ferrier *et al.*, 2010). The areas underlain by the quartz diorite represent 52-100 % of the sampled catchments. GIS-based catchment-wide calculations are restricted to the quartz diorite area.

The method of Codilean (2006) was used on the LiDAR DEM to calculate topographic shielding throughout the catchments. Due to extreme cloudiness, thick undercanopy and rough uneven ground, the 1-m-DEM fails to accurately reproduce meter-scale details of the topography, especially along corestone-strewn corridors. As a result, though the 1-m-DEM is the best suited for calculating topographic shielding (Norton and Vanacker, 2009), we resampled it at 5 meters to remove such artifacts. Where the LiDAR coverage is missing data were extracted from the NED 10-m-DEM. Catchment-averaged topographic shielding reaches 5-9% over the 5-m-LiDAR but less than 2 % over the 10-m-DEM areas. To correct for the smoothing over the 10-m-DEM, 6% shielding value was applied to the areas not covered by the LiDAR using the correction technique of Norton and Vanacker (2009). Two methods were then used to obtain catchment-integrated production rates. In one method, CRONUS was used to calculate the production rate dependence with elevation across the study area, and a grid of production rate was produced. The shielding and elevation grids were combined to calculate the catchment-integrated production rate. CRONUS does not allow for the introduction of production rate as an input. We adjusted input values of elevation iteratively to make CRONUS calculate a production rate equal to our basin-integrated rate. In a second method, basin-averaged elevation and shielding values were entered in CRONUS to calculate erosion rates. Both methods are equivalent and their results diverge by less than 2%, owing to the modest amount of topographic shielding and limited elevation range of the contributing area.

Brown et al. (1995) estimated shielding by vegetation to 3% for an above-ground biomass of 3g.cm^{-2} . Vegetation in the Icacos catchment upstream of the stream gage is made of 75% Palo Colorado, 24% Sierra Palm. Here we ascribed a shielding of 3.5 % to the palm forest based on their biomass of 2.3 g.cm^{-2} (Frangi and Lugo, 1985), corrected for a water content of 60-70% for palm trunks and 50% water for leaves. For the Palo Colorado forest we use the dry biomass values of Zarin and Johnson (1995), adding 20 % water to the trunks and 50 % water to the leaves, resulting in 5 % shielding on topographic positions where they are thinned by 50% on average by hurricanes every 50 to 80 years (Scatena and Larsen, 1991), and 8% on lower topographic positions. The resulting average value (7%) is equal to the value obtained by Plug et al (2007) in an old-grown temperate rainforest.

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Stream	Grain size	NC	TC	TC+VC	TC+VC+DV	TC+VC+DV	TC+VC+DV
		ϵ_o	ϵ_o	ϵ_o	ϵ_o	+QE ϵ_o	+QE+T ϵ_o
		(m/My)	(m/My)	(m/My)	(m/My)	(m/My)	(m/My)
ES-UK	C	103.8 ± 8.2	98.4 ± 7.7	93.6 ± 7.3	72.7 ± 5.7	72.7 ± 5.7	75.6 ± 7.4
	F	24.8 ± 1.9	5.93 ± 0.29	5.93 ± 0.29	5.93 ± 0.29	± 2.9	43.4 ± 2.5
IC-UK	C	138 ± 17	131 ± 16.2	125 ± 15	97 ± 12	97 ± 12	100 ± 16
	F	32.1 ± 2.4	31.5 ± 2.3	29.8 ± 2.2	39.2 ± 2.9	49.7 ± 3.6	55.0 ± 4.0
	F	33.9 ± 2.5	33.2 ± 2.4	31.5 ± 2.3	41.4 ± 3.0	52.4 ± 3.8	57.9 ± 3.2
SAB-UK	C	99 ± 16	94 ± 16	89 ± 15	70 ± 12	70 ± 12	72 ± 15
	F	24.6 ± 2.4	24.1 ± 2.3	22.8 ± 2.2	29.9 ± 2.9	37.9 ± 3.6	42.7 ± 3.2
CUY-UK	C	401 ± 64	382 ± 61	365 ± 58	283 ± 45	283 ± 45	281 ± 56
	F	49.5 ± 4.7	48.2 ± 4.6	46.1 ± 4.4	60.6 ± 5.7	76.8 ± 7.3	83.0 ± 7.8
	F	15.4 ± 1.2	14.9 ± 1.2	14.2 ± 1.1	18.7 ± 1.4	23.7 ± 1.8	27.3 ± 1.6
PRI-UK	C	122 ± 13	116 ± 12	111 ± 12	85.8 ± 9.0	85.8 ± 9.0	87 ± 12
	F	36.1 ± 3.4	35.6 ± 3.3	33.8± 3.2	44.4 ± 4.2	56.3 ± 5.3	61.9 ± 4.5
SAB-TDK1	C	237 ± 28	225 ± 27	215 ± 25	167 ± 20	167 ± 20	169 ± 20
	F	57.4 ± 7.7	55.8 ± 7.5	53.1 ± 7.1	69.8 ± 9.4	70 ± 9.4	75 ± 10
SAB-TDK2	C	255 ± 27	243 ± 25	232 ± 24	180 ± 19	180 ± 19	181± 19
	F	72.4 ± 8.1	69.5 ± 7.7	66.2± 7.4	86.9 ± 9.7	86.9 ± 9.7	92 ± 10
SAB-TDK3	C	290 ± 35	276 ± 33	264 ± 32	205 ± 25	205 ± 25	206± 24
	F	55.9 ± 5.9	53.3 ± 5.6	50.7 ± 5.3	66.6 ± 7.0	66.6 ± 7.0	71.3 ± 7.4
IC-TDK1	C	178 ± 15	169 ± 14	161± 13	125 ± 10	125 ± 10	127 ± 10
	F	40.3 ± 2.9	38.7 ± 2.7	37 ± 2.6	48.6 ± 3.4	48.6 ± 3.4	53.1 ± 3.7
IC-TDK2	C	278 ± 39	265 ± 37	253 ± 35	197 ± 27	197 ± 27	197 ± 27
	F	50.5 ± 3.6	49.2 ± 3.5	46.8 ± 3.3	61.4 ± 4.3	61.4 ± 4.3	66.2 ± 4.6
IC-TDK3	C	245 ± 25	233 ± 24	222 ± 22	173 ± 17	173 ± 17	174 ± 17
	F	45.7 ± 3.1	44.7 ± 3.1	42.5 ± 2.9	55.9 ± 3.8	55.9 ± 3.8	60.6 ± 4.1
CUY-TDK	F	49.8 ± 3.9	47.8 ± 3.7	45.8 ± 3.6	60.1 ± 4.7	60.1 ± 4.7	64.9 ± 5.0

Table A1-1. ^{10}Be -derived denudation rate for various correction parameters, using the coarse (c) and fine (f) sediment fractions as defined in Table 1. ϵ_o (NC): erosion rate in case of no shielding, for a vertically homogeneous soil density of 2.1 g cm⁻³. TC: with topographic shielding, VC: vegetation shielding, SD: spatially-variable soil density (6) in Table 1, QE: spatially-variable soil quartz enrichment (5) in Table 1, and T: effect of time-dependent production rate estimated by the CHRONUS calculator.