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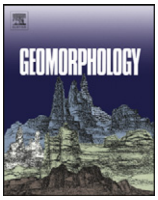

Long-term erosion rates of Panamanian drainage basins determined using in situ ^{10}Be

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ABSTRACT

Erosion rates of tropical landscapes are poorly known. Using measurements of in situ-produced ^{10}Be in quartz extracted from river and landslide sediment samples, we calculate long-term erosion rates for many physiographic regions of Panama. We collected river sediment samples from a wide variety of watersheds ($n = 35$), and then quantified 24 landscape-scale variables (physiographic, climatic, seismic, geologic, and land-use proxies) for each watershed before determining the relationship between these variables and long-term erosion rates using linear regression, multiple regression, and analysis of variance (ANOVA). We also used grain-size-specific ^{10}Be analysis to infer the effect of landslides on the concentration of ^{10}Be in fluvial sediment and thus on erosion rates.

Cosmogenic ^{10}Be-inferred, background erosion rates in Panama range from 26 to 595 m My^{-1}, with an arithmetic average of 201 m My^{-1}, and an area-weighted average of 144 m My^{-1}. The strongest and most significant relationship in the dataset was between erosion rate and silicate weathering rate, the mass of material leaving the basin in solution. None of the topographic variables showed a significant relationship with erosion rate at the 95% significance level; we observed weak but significant correlation between erosion rates and several climatic variables related to precipitation and temperature. On average, erosion rates in Panama are higher than other cosmogenically-derived erosion rates in tropical climates including those from Puerto Rico, Madagascar, Australia and Sri Lanka, likely the result of Panama's active tectonic setting and thus high rates of seismicity and uplift. Contemporary sediment yield and cosmogenically-derived erosion rates for three of the rivers we studied are similar, suggesting that human activities are not increasing sediment yield above long-term erosion rate averages in Panama.

^{10}Be concentration is inversely proportional to grain size in landslide and fluvial samples from Panama; finer grain sizes from landslide material have lower ^{10}Be concentration than fine-grained fluvial sediment. Large grains from both landslide and stream sediments have similarly low ^{10}Be concentrations. These data suggest that fluvial gravel is delivered to the channel by landslides whereas sand is preferentially delivered by soil creep and bank collapse. Furthermore, the difference in ^{10}Be concentration in sand-sized material delivered by soil creep and that delivered by landsliding suggests that the frequency and intensity of landslides influence basin scale erosion rates.

1. Introduction

Over 100 studies have used in situ-produced ^{10}Be measured in river sediment to estimate erosion rates at the basin scale. Portenga and Bierman (2011) compiled two decades of such data, normalized them to currently accepted standard values, and re-calculated erosion rates using the CRONUS calculator (Balco et al., 2008; http://hess.ess.washington.edu/). In their compilation, only 98 of 1149 river sediment samples were collected in tropical climates including samples from Australia, Bolivia, Puerto Rico, Madagascar, and Sri Lanka. Some studies not included in Portenga and Bierman's, 2011 compilation constrain denudation for tropical watersheds in Brazil (Salgado et al., 2006, 2007, 2008, 2013; Cherem et al., 2012; Barreto et al., 2013, 2014; Rezende et al., 2013; Sosa Gonzalez et al., 2016) and the tropical regions of Africa (Hinderer et al., 2013) and Australia (Nichols et al., 2014). Still, the tropics remain underrepresented in studies of erosion rates at the basin scale.

Cosmogenic isotopes, such as ^{10}Be, are formed by spallation when earth materials are exposed to secondary cosmic rays (Lal and Peters, 1967). Measurement of isotope concentration, typically made in quartz mineral separates, allows calculation of background erosion rates,

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integrated over 10^3 to 10^5 years; this long integration time averages out extreme erosion events, such as deep-seated landslides or low-frequency floods, that occur at the decadal and centennial time scales (Gosse and Phillips, 2001; Kirchner et al., 2001; Bierman and Nichols, 2004). Integration time of cosmogenically-derived erosion rates varies with erosion rate; high erosion rates integrate less time (e.g. 10^2 m My^{-1} integrates 10^4 y) while low erosion rates integrate longer time spans (e.g. 10^1 m My^{-1} integrates 10^5 y).

In the near surface, the production rate of in situ cosmogenic isotopes decreases exponentially with depth with an attenuation length of 160 g cm^{-2} (Gosse and Phillips, 2001), and is low (only a few percent of surface production) below 2 m depth in rock (Lal and Peters, 1967). Because of this, ^{10}Be is a good indicator of the near-surface residence time of material in the uppermost several meters and hence the rate, both chemical and physical, at which Earth's surface is eroding. In areas of deep weathering, additional mass can be lost by solution below the penetration depth of cosmic ray neutrons (Riebe and Granger, 2012).

Sediment can be delivered to the channel in different ways. In mountainous humid tropical regions, mass movements, triggered by heavy rainfall and seismic activity, can deliver large amounts of sediment to river channels and thus impact the distribution of ^{10}Be (Larsen and Simon, 1993; Larsen and Torres-Sánchez, 1998; Dai and Lee, 2001). Erosion rate calculations based on measured cosmogenic isotope concentrations assume steady denudation of rock or regolith to produce sediment over the integration time; an assumption violated if deep-seated landslides episodically (millennial time-scale) deliver large amounts of material to the channel at time-scales that approach the effective integration time of ^{10}Be (Bierman and Steig, 1996; Niemi et al., 2005). However, if the recurrence interval of landslides is much longer than the ^{10}Be integration time, and the spatial-distribution is wide, the effect of landslides will decrease. Similarly, as basin area increases, the effect of episodic landsliding on ^{10}Be concentrations in river sediment diminishes (Niemi et al., 2005; Yanites et al., 2009).

Some previously published ^{10}Be data show that where landslides are frequent, fine-grained river sediment contains more in situ-produced ^{10}Be than coarse material (Brown et al., 1995; Clapp et al., 2002; Matmon et al., 2003; Aguilar et al., 2013; Puchol et al., 2014). Brown et al. (1995) suggest that this relationship indicates that fine-grained material is sourced closer to the surface and thus has been exposed to more cosmic radiation than coarser material which is preferentially sourced from greater depth. Conversely, Matmon et al. (2003) offer an alternative explanation; they suggest that coarse material could be sourced from lower on the landscape, at lower elevations and thus has less ^{10}Be because nuclide production rates diminish with elevation.

Geomorphologists have extensively considered both topographic and climatic controls on erosion and sediment generation. Anhert (1970) concluded that relief was positively correlated with denudation rates. Montgomery and Brandon (2002) found that long-term erosion rates are non-linearly related to mean basin slope in the Olympic Mountains. Similarly, DiBiase et al. (2010) concluded that channel steepness is related to erosion in the San Gabriel Mountains. Watershed elevation appears to exert some control on erosion rates at a global (Portenga and Bierman, 2011) and at a site-specific scale (Palumbo et al., 2009). In their compilation of ^{10}Be data, Portenga and Bierman (2011) found that mean basin slope was significantly and positively related to drainage basin erosion rates at both local and global scales and that relief is important in controlling erosion rates in tropical climate zones.

The rates of chemical weathering and physical erosion are often positively correlated (West et al., 2005). In a global compilation, von Blanckenburg (2005) found that chemical weathering accounted for ~20% of total denudation. Examining weathering and denudation in Sri Lanka, von Blanckenburg et al. (2004) concluded that both chemical weathering and erosion were sensitive to base-level change resulting from tectonic forcing but were not accelerated by increased precipitation and temperature.

Yet, another metric to classify erosion of landscape features is erosional efficiency. Erosional efficiency determines the rate of erosion for a given topography, and depends on rock type, debris size, tectonics, and climate (Whipple and Meade, 2004; Whipple, 2009). Coupling of climate and topography dictates the efficiency of sediment removal from the terrain. For example, a dry landscape in an active uplift zone is characterized by steep slopes in order to increase erosional efficiency and balance uplift.

This paper reports long-term, natural erosion rates in Panama inferred using the concentration of in situ-produced ^{10}Be measured in quartz extracted from river sediments (Fig. 1). We present erosion rate data for 35 distinct Panamanian watersheds and thus provide basin-scale determination of background erosion rates across many physiographic regions of Panama. Using the ^{10}Be-inferred erosion rates, we determine the relationship of erosion rates to physiography, tectonic activity, geology, silicate weathering, and climatic characteristics in a tropical region. This research expands the breadth of environments where cosmogenic isotopes have been measured and builds upon the ^{10}Be measurements ($n = 17$) reported by Nichols et al. (2005) for Panama's Rio Chagres Basin.

2. Geographic and geologic setting

Panama is the southernmost Central American country with an area of 75,517 km^2 (Contraloría General de la República de Panamá, 2008). It is bounded on the north by the Caribbean Sea, on the south by the Pacific Ocean; on the east it shares borders with Colombia and on the west with Costa Rica (Fig. 1).

The climate in Panama is tropical maritime with influences from the Caribbean Sea and Pacific Ocean (Contraloría General de la República de Panamá, 2005). It is characterized by high year-round temperatures with low diurnal and annual range, abundant precipitation, and high relative humidity. Annual mean temperatures range between 24 °C and 28 °C. The average diurnal temperature range is low, about 1.9 °C on the Caribbean slopes and between 1.5 °C and 2.9 °C on the Pacific side (Contraloría General de la República de Panamá, 2005). In the mountains, the daily variation in temperature may be greater. Generally, there are two seasons: wet and dry; the wet season extends from May to December, and the dry season from December to April (Contraloría General de la República de Panamá, 2005). The mean annual precipitation on the southern Pacific side ranges from 1500 to 3500 mm, and precipitation differs greatly between the dry and wet seasons. On the Caribbean slope, precipitation is more uniform, exceeding 4000 mm annually with no marked difference between the seasons.

Panama has low-relief coastal plains and a more rugged Central Cordillera extending almost the length of the isthmus from the Costa Rican border to the Panama Canal (Palka, 2005). Data from the Contraloría General de República de Panamá show that rivers draining into the Caribbean Sea average 56 km in length and have an average slope of 5.5%; rivers draining to the Pacific Ocean average 106 km in length, and have lower slopes, averaging 2.3% (Contraloría General de la República de Panamá, 2005). The discharge of rivers draining to the Caribbean Sea is greater than those draining to the Pacific Ocean. Historic data from Empresa de Transmisión Eléctrica (http://www.hidromet.com.pa/hidro_historicos.php) show that rivers draining into the Caribbean have mean annual discharges ranging from 30 to 100 $\mathrm{m}^3\ \mathrm{s}^{-1}$, whereas rivers draining into the Pacific generally have mean annual discharges from 4 to 30 $\mathrm{m}^3\ \mathrm{s}^{-1}$.

Panama is geologically young and tectonically active. The Panamanian isthmus resulted from collision of the Panama–Choco island arc with South America in the late Miocene–Pliocene (3.5–7 million years ago) and it is still tectonically active today (Camacho et al., 1997; Harmon, 2005; Fig. 1B). Kellogg and Vega (1995) conducted a seismic hazard