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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 delivers by soil creep and that delivered by landsliding suggests that the frequency and intensity of landslides influences basin scale erosion rates.

Keywords: Physiography; Landslides; Cosmogenic; Denudation

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, in review) 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, 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-Sanchez, 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 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, 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 1,500 to 3,500 mm, and precipitation differs greatly between the dry and wet seasons. On the Caribbean slope, precipitation is more uniform, exceeding 4,000 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 30–100 $m^3 s^{-1}$, whereas rivers draining into the Pacific generally have mean annual discharges from 4 to 30 $m^3 s^{-1}$.

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 assessment for Panama, and produced peak ground acceleration maps. The highest seismic hazard and predicted ground accelerations are on the western side of the country and to the southeast of the country close to the Panama Block-South America plate margin (Camacho et al., 1997) (Fig. 1B). The lowest seismic hazard is in Central Panama, where, considering a return period of 250 years, the average peak ground acceleration (*PGA*) is 50% lower than in the western provinces (Camacho et al., 1997). The Pacific side of the country is characterized by a deep oceanic trench, narrow marine shelf, and active subduction (responsible for volcanic activity and earthquakes). The Atlantic side is a passive, stable margin with a broad marine shelf (Harmon, 2005).

No detailed mapping of Panama’s geology is publicly available; thus, we have little information about the quartz distribution across the country. A significant part of Panama, including eastern Panama and the former Canal Zone, consists mostly of intrusive and extrusive mafic igneous rocks originating in the Paleocene-Oligocene volcanic island arc (Kesler et al., 1977; Grosser, 1989; de Boer et al., 1995; Maury et al., 1995; Harmon, 2005). Only one carbonate marine sequence has been mapped in Panama (Fisher and Pessagno, 1965). It is located on the Pacific side of the country, and is of Cretaceous age. Throughout the country, metamorphic rocks are scarce. Schist has been reported in the eastern province of Darien (Schubert, 1935; Terry, 1956). Small slate outcrops have been reported in several provinces stretching from central Panama to the Costa Rica border. Sedimentary rocks are mostly limited to the eastern region of Panama with only a few located in the west (Schubert, 1935; Terry, 1956).

3. Methods

Samples from active river channels were collected where the channels could be accessed, either at road crossings or by helicopter where clearings in the dense jungle vegetation were sufficient for landing (Fig. 2; Table 1). Unlike most basin-scale cosmogenic studies, for which samples are collected at the outlets of upland basins, we were commonly prevented from sampling in or near the highlands because of access restrictions (heavy jungle and lack of roads; Fig. 2). For six of the rivers we sampled, the only access was far downstream from where the streams exited the highlands and after the channel had crossed many to tens of kilometers of low-relief, alluvial plains characterized by braided, sediment-choked channels. By sampling so far downstream, our samples could include stored material reworked from the lowland floodplains making the assumption of continuous fluvial transport of sampled material less certain.

We collected several spatial (network) and temporal replicates in order to understand the variance of erosion. Three rivers, Rio Nombre de Dios, Rio Cuango, and Rio Pequini, were sampled several times along their length. Rio Pequini was sampled at its headwaters (sample ID: PHW), before its confluence with the Rio San Miguel (sample ID: PSM), and at its outlet (Sample ID: PLA). We collected one sample of the Rio San Miguel before its confluence with Rio Pequini (sample ID: SMP) that is included in the Pequini network analysis. Two rivers were sampled in different years to test for changes in ^{10}Be concentration over time (Fig. 3; Table 2). In 2009, we resampled (sample ID: PLS) the Rio Chagres in a location similar to that reported by Nichols et al. (2005) (sample ID: CTOM, sample year: 2002). The Rio Nombre de Dios was sampled in 2004 (NDD) and 2007 (DIOS) (Fig. 3; Table 2). The replicate samples (both spatial and temporal) are not included in any of our statistical analysis or summary statistics. Data for the replicates can be found in the Data Repository for this article (Supplementary Table 1).

We sampled a landslide scar in 2009, two years after the latest failure. We collected three samples from the landslide scarp (PLSS), channel sediment upstream of the landslide (PLSU), and channel sediment downstream of the landslide (PLSD). These three samples were divided into seven grain-size splits each, making a total of 21 landslide-related samples.

In the laboratory, samples were dried and sieved. Coarse grain size splits were pulverized using a plate grinder. The three landslide-related samples were analyzed for *in situ*-produced ^{10}Be content by size fraction: < 0.25, 0.25–1, 1–2, 2–4, 4–9, 9–12, and > 12 mm. River sediment samples (unrelated to the landslide) were divided into three size fractions: < 0.25, 0.25–0.85, and > 0.85 mm. For all but the landslide-related samples, only the 0.25–0.85 mm split was analyzed. Samples were chemically treated to isolate quartz and remove meteoric ^{10}Be following the method of Kohl and Nishiizumi (1992). *In situ*-produced ^{10}Be was extracted from quartz following the method of Corbett et al. (2011).

Isotopic ratios were measured using Accelerator Mass Spectrometry (AMS) at Lawrence Livermore National Laboratory (Rood et al., 2010, 2013). Blank corrections were made based on the average of all full process blanks ($n = 15$, $^{10}\text{Be}/^{9}\text{Be} = 7.5 \pm 3.6 \times 10^{-16}$), a pair of which was included with each batch of 10 samples. Blank ratios were, for most samples, more than an order of magnitude below measured ratios. Erosion rates based on the isotopic data were obtained using the CRONUS Earth Calculator Version 2.2 (Balco et al., 2008; http://hess.ess.washington.edu/). In order to obtain erosion rates, we calculated the effective elevation of each watershed using the Portenga and Bierman (2011) approach. We used the scaling scheme of Lal (1991) and Stone (2000) and the global production rate calibration. For erosion rates calculations (rock equivalent), we assumed a density of 2.7 g cm^{-3}. We note that if deep saprolitization is occurring in the basins, there will be additional mass loss by solution below the depth of cosmic ray penetration. Our samples were standardized using 07KNSTD3110 with an assumed isotopic ratio of 2850 × 10^{-15} $^{10}Be/^{9}Be$ (Nishiizumi et al., 2007).

Watersheds were delineated using ArcGIS 9.2 and the 90-m resolution Shuttle Radar Topography Mission Digital Elevation Model. For the six watersheds with extensive lowlands between the uplands and the sample point (Anton, Caimito, Chico, Guias, Santa Maria, Pacora), we delineated watersheds twice (Table 1, second delineation in parenthesis). The first delineation used the sample collection point as the downstream limit of the watershed. The second delineation was made by estimating the place along the river where the channel transitioned from an upland landscape, where hillslopes directly input sediment to the channel, to a lowland landscape dominated by braidplains and sediment deposition. To assess the potential for streams to mine stored alluvium away from the range front, we used this transition point as the basin outlet, recalculated the effective elevation of the basin, and recalculated erosion rates using CRONUS.

Erosion rates obtained from CRONUS were not normally distributed so they were logarithmically transformed ($\log_{10}$) in order to perform parametric statistical analysis (Fig. 4). Watersheds were grouped according to their region (Fig. 1): southwestern (three watersheds), northwestern (five watersheds), central (seven watersheds), central-eastern (eight watersheds), and eastern (13 watersheds). For statistical analysis by region, physiographic and climatic parameters for all sampled watersheds within each region were averaged. Regional erosion rates (the average of each region) were normally distributed. ArcGIS was used to quantify landscape variables (physiographic, climatic, seismic, and land-use) and to display the spatial distribution of erosion rates. All spatial information was projected in the North American Datum (NAD) 1927 Zone 17P (previously denominated Canal Zone). Data gaps in the 90-m SRTM DEM were corrected using the USGS Global Topographic Data, of approximately 1-km in resolution, to fill the missing values. This corrected DEM was used to delineate our study watersheds, and quantify slope, area, and mean local relief. We quantified mean local relief using the Neighborhood tool in ArcGIS, using a 5-km moving window. A generalized digital map of Panama’s geology was obtained from the Smithsonian Tropical Research Institute. Peak ground acceleration for each watershed was obtained based on data produced by the Global Seismic Hazard Assessment Program (Giardini, 1999; http://www.seismo.ethz.ch). This dataset includes PGA measurements in a fine-scale grid that covers the world. Using a semivariogram, we determined the parameters to import into the kriging function in ArcGIS to interpolate PGA values for all of Panama. We averaged the PGA for each watershed. Land cover data were extracted from the GlobeLand30 dataset (Chen et al., 2015; http://globallandcover.com), and we quantified land use for each watershed (Supplementary Table 2).

A seismic catalog prepared by the Instituto de Geociencias de Panamá (Camacho, personal communication) was used to identify the epicentral location, depth, and magnitude of each seismic event from 1900–2011. In order to understand the effects of seismicity on erosion at a regional scale, we quantified seismic events by setting a buffer around individual watersheds in each region, summing the seismic events, and averaging the depth and magnitude of events inside the buffer. We set a distance of 10, 25 and 50 km away from the watershed boundary to quantify seismicity (Supplementary Table 3). For regional analysis, we summed the seismic events, within a given buffer, of each watershed. We used the 1-km resolution climatic data from WorldClim (Hijmans et al., 2005; http://www.worldclim.org), and quantified 19 variables for each watershed. For statistical analysis, we averaged, pixel by pixel, the values for each variable in each watershed. Silicate chemical weathering rates for 14 of our sampling sites were calculated by Goldsmith et al. (2015). Data were entered into an SPSS database for simple linear regressions, multiple linear regressions, and analysis of variance (ANOVA) relating erosion rates to landscape metrics (IBM SPSS Statistics 20). From Nichols et al. (2005), we include in our analysis only the outlet sample (CLA) for the Rio Chagres, to avoid analytical complications of nested watersheds, and because the outlet sample integrates the entire upstream watershed containing the other sub-watersheds that were sampled.

4. Results

4.1 Erosion rates in space and time

The concentration of *in situ* ^{10}Be measured in Panamanian river sand varies by almost 20-fold (Table 1). The lowest concentration of ^{10}Be measured as part of this study was in sediment of the Rio Bartolo (BART), in the southwestern region (7.4×10^3 atoms g^{-1}). The highest concentration of ^{10}Be was measured in sediment from the Rio Sajlices in the central-eastern region (138.7×10^3 atoms g^{-1}).

Basin-average erosion rates of Panamanian river basins based on the concentration of *in situ*-produced ^{10}Be also vary widely, from 26 to 595 m My^{-1} (Table 1); the arithmetic average erosion rate for the 35 rivers we sampled is 201 m My^{-1}, the area-weighted average is 144 m My^{-1}, and the median is 173 m My^{-1}. Slowly eroding basins are generally found in the central and central-eastern region, and rapidly eroding basins are scattered through the country (Fig. 1). When samples were grouped by region, the southwestern region had the highest average erosion rate; however, the central region has the largest variance in erosion rates because it contains the watershed with the highest erosion rate in our dataset (Sample ID: FELIX), 595 m My^{-1}. If that extreme value is not taken into account, the eastern region has the greatest variance (Fig. 5). The average erosion rate for the southwestern region (441 ± 70 m My^{-1}) is significantly different from the average erosion rate of all other regions. All other differences in erosion between regions were not significant. There is no statistical difference between the erosion rate of watersheds draining to the Pacific and those draining to the Caribbean ($F = 0.686$, $p = 0.412$).

Basin-scale erosion rates do not differ dramatically over time or over space in most basins. The Rio Nombre de Dios was sampled in 2004 (Sample NDD), and in 2007 (DIOS). Erosion rates were similar, 402 ± 66 and 440 ± 95 m My^{-1}. The Upper Rio Chagres was sampled in 2002 (CTOM) and 2009 (PLS). Erosion rates were 152 ± 12 and 121 ± 8 m My^{-1}, respectively (Fig. 3; Table 2). Three watersheds were sampled at different locations (Fig. 3; Table 2). The Rio Pequini was sampled at its headwaters (PHW; erosion rate = 377 ± 60 m My^{-1}), before its confluence with the Rio San Miguel (PSM; 318 ± 30 m My^{-1}), and at its outlet downstream from the confluence (PLA; 416 ± 37 m My^{-1}). A sample from the San Miguel before its confluence with the Pequini is also in this basin (SMP; 267 ± 36 m My^{-1}). The upper Rio Chagres was sampled twice in 2009; samples CHAG2009 and PLS had erosion rates of 61 ± 4 and 121 ± 8 m My^{-1} respectively, within the range of erosion rates for this area reported previously (Nichols et al., 2005; data recalculated by Portenga and Bierman, 2011). The Rio Cuango was sampled at different times and in different places (Sample ID: CUAN in 2004; Sample ID CNGO in 2007); the samples had erosion rates of 366 ± 36 and 262 ± 27 m My^{-1}, respectively. Based on the limited network and temporal analysis we have completed, downstream variance in erosion rates mostly appears to exceed temporal changes in ^{10}Be concentration.

4.2 Relationship between landscape-scale variables and erosion rates

In general, linear regression analysis showed few statistically significant bivariate relationships between watershed-scale erosion rates inferred from ^{10}Be measurements and landscape scale variables (Table 3; Fig. 6; Supplementary Table 2). There were no significant relationships ($p < 0.05$) between erosion rates and physiographic metrics (area, slope, and relief; Fig. 7). Using the modified basin area to exclude the extensive alluvial lowlands (Table 1) did not change the results.

Because topographic variables did not relate to erosion rates in Panama, we explored the relationship of erosion rates with seismicity, climate, and forest cover. Several climatic variables showed positive relationships with erosion rates including temperature seasonality ($R^2 = 0.140$, $p = 0.025$), and precipitation during the driest quarter of the year ($R^2 = 0.119$, $p = 0.040$). Temperature did not have a significant relationship with erosion either at the basin ($R^2 = 0.010$, $p = 0.560$) or the regional scale ($R^2 = 0.067$, $p = 0.673$). Forested cover was used as a land use proxy, and it showed no significant relation with erosion rates ($R^2 = 0.048$, $p = 0.197$).

Higher erosion rates were measured in areas of higher seismic activity in western Panama (Fig. 8). Erosion rates decrease as distance to the seismically active zone increases. Peak ground acceleration weakly (and positively) relates to erosion rates ($R^2 = 0.154$, $p = 0.018$). When analyzed at the regional level, the only statistically significant relationship we found is between the number of seismic events within a 10-km distance of the region ($R^2 = 0.837$, $p = 0.029$).

Watershed-scale erosion rates and chemical weathering of silicate rocks (Goldsmith et al., 2015) were well-correlated ($R^2 = 0.409$, $p = 0.014$, $n = 14$). In Panama, silicate weathering accounts for between 3 to 30% of the total denudation (Supplementary Table 2).

4.3 Landslide effects on ^{10}Be concentration in river sediment

^{10}Be concentration in all landslide-related sediment samples (all grain size splits for samples PLSU, PLSS, and PLSD) ranged from 0.74×10^4 to 3.83×10^4 atoms g^{-1} (Table 4), generally lower than the concentrations of river sediments in our dataset. Grain size and isotopic concentrations are well and negatively correlated (Fig. 9; $R^2 = 0.65$, $p = 0.01$; $n = 21$). Mean ^{10}Be concentration in the < 0.25 mm fraction is greater than in all > 2.00 mm fractions at the 0.05 level. For all grain sizes, ^{10}Be concentration of the landslide material is less than that of stream sediment both up- and downstream of the landslide (Fig. 9). The difference in concentration is most pronounced in the small grain sizes (sand) and less in gravel. A simple two-component mixing model, using the ^{10}Be concentration of the sand-size fraction (0.25–1 mm) samples from PLSS and PLSU, shows that ~27% of the sediment in the downstream samples is sourced from the landslide. Landslide material accounts for roughly 11% of the fine-grained (< 0.25 mm) material downstream of where the landslide enters the river. The influence of the landslide is greater in coarser material: 78% of the > 12mm size-fraction comes from the landslide (Table 5; Fig. 10).

5. Discussion

Basin-scale erosion rates across Panama vary over more than an order of magnitude and are in general, quite rapid, with an arithmetic average of 201 ± 146 m My^{-1}, similar to the arithmetic average (158 ± 35 m My^{-1}) reported for Panama's 466 km^2 Rio Chagres by Portenga and Bierman (2011) based on recalculation of data from Nichols et al. (2005). Erosion rates are largely unrelated to topographic metrics, vary in a coherent spatial pattern, and are correlated to various expressions of tectonic activity, and chemical weathering rates. Panama is eroding faster than most tropical field areas where ^{10}Be-derived erosion rates have been measured, with the exception of Bolivia.

5.1. Panamanian and other tropical erosion rates

Erosion rates of Panamanian basins span much of the range previously reported for tropical basins (Portenga and Bierman, 2011). The dataset from Panama (this study and Nichols et al., 2005) is extensive when compared to other tropical studies; the number of samples included in those other studies ranges from 4 to 10, whereas the Panama dataset now includes 35 unique watersheds.

The arithmetic average erosion rate for the Panamanian watersheds considered in this study is significantly different from the average denudation of other tropical regions located in Puerto Rico, Australia, Madagascar, Brazil, and Sri Lanka and lower than areas of Bolivia ($F = 34.25$, $p < 0.001$; Fig. 11). For example, ^{10}Be-derived erosion rates published for southeastern Brazil range between 1 and 90 m My^{-1} ($n = 76$), with an average of 10.5 m My^{-1} (Salgado et al., 2006, 2007, 2008, 2013; Cherem et al., 2012; Rezende et al., 2013; Barreto et al., 2013, 2014; Sosa Gonzalez et al., 2016, in review). These areas of Brazil have, thus far, the lowest cosmogenic-derived erosion rates measured in the tropics. Portions of Madagascar erode at a pace slightly higher than Brazil, 14 m My^{-1} (Cox et al., 2009; $n = 4$). Tropical areas of Sri Lanka (Hewawasam et al., 2003; von Blanckenburg et al., 2004; $n = 16$), and Australia (Heimsath et al., 2009; Nichols et al., 2014; $n = 24$) have relatively low erosion rates averaging 18 and 24 m My^{-1}, respectively. Some eastern basins in Puerto Rico (Brown et al., 1995, 1998; Riebe et al., 2003; $n = 27$) are eroding at an average rate of 62 m My^{-1}; faster than other tropical basins but slower than the Panamanian basins. Tropical areas of Bolivia (Wittmann et al., 2009; Insel et al., 2010; $n = 12$) are eroding at an average of 327 m My^{-1}, more rapidly than Panama.

The Panamanian basins that we sampled share some similar characteristics with other tropical sites where basin-scale erosion rates have been determined. For example, the Panamanian basins have a similar mean annual temperature compared to the other tropical basins in which erosion rates have been measured (Panama watersheds, 24.4°C; Sri Lanka watersheds, 19.2°C; Madagascar watersheds, 20.2°C; Puerto Rico watersheds, 21.6°C). Mean annual precipitation for all tropical watersheds is similar, 2500 to 2800 mm yr^{-1}, except for Madagascar where the sampled watersheds, located in the highlands and subject to seasonal precipitation, record an average precipitation of 1134 mm yr^{-1}.

Significant differences between the Panamanian sites and the other tropical sites also exist. The average slope of all the watersheds studied in each country differs; the mean slope for Panamanian basins we sampled is 10.8º. Using the data published by Portenga and Bierman (2011), slopes are higher for sampled Puerto Rican (13.3º; Brown et al., 1995, 1998; Riebe et al., 2003) and Sri Lankan basins (13.5º and 21.4º for Hewawasam et al., 2003 and von Blanckenburg et al., 2004, respectively), but lower for basins in Madagascar (7.6º; Cox et al., 2009). Yet, Panama with its relatively low slope basins and low mean local relief has some of the highest average erosion rates of all tropical areas sampled so far suggesting that slope is not the dominant control on erosion rate in these areas, consistent with the bivariate regression results showing no correlation between slope and erosion rate in Panama.

Since the range of climatic and topographic variables are grossly similar for all tropical sites, yet erosion rates differ significantly, erosion must be influenced by another variable, such as tectonic setting and thus seismicity. Madagascar, Brazil, Australia, and Sri Lanka are located in regions with little tectonic activity. Peak ground acceleration, defined as the magnitude of ground motion with a 10% chance of being exceeded within 50 years, and expressed as a fraction of the acceleration due to gravity (*g*) is 0.06*g* for the 16 watersheds studied in Sri Lanka, and 0.36*g* for Madagascar (data from Giardini, 1999, as quantified and published by Portenga and Bierman, 2011). Australia and Brazil are located in passive margins, with average peak ground accelerations of 0.64*g* and 0.01*g* respectively in the sampled watersheds. For Panama, mean peak ground acceleration in the 41 studied watersheds, is more than an order of magnitude higher, ranging between 1.77*g* and 4.37*g* (average: 2.29*g*; data from Giardini, 1999). For Puerto Rican sites, peak ground acceleration averaged 1.88*g*. Panama and Puerto Rico are located in active tectonic zones, where seismic shaking likely weakens and fractures rocks, making them easier to erode as evidenced by high cosmogenically-determined erosion rates. Seismicity can also trigger mass movements (Keefer, 1984; Wang et al., 2003), adding lesser-dosed sediment from landslides to rivers and thus increasing erosion rates calculated from ^{10}Be concentration in sediment. Even in tectonically stable Madagascar, there is a correlation between erosion by gullies and seismicity. The highest density of gullies was found in or near areas where earthquakes of magnitude up to 5.6 occur (Cox et al., 2010).

5.2. Controls on Panamanian erosion

The relationship between slope and erosion rate is not significant for Panama as a whole although Nichols et al. (2005) found a relationship between erosion rate and average basin slope in the much smaller 466 km^2 Rio Chagres basin. We suspect that as the studied area increases, seismicity, climate, lithologic variables, and other landscape characteristics more strongly influence erosion rate and the relationship with slope becomes subordinate (Fig. 12). Such a decrease in the bivariate relationship between slope and erosion coincides with similar findings from watershed-scale to regional- and even the global-scale. (Portenga and Bierman, 2011).

The reason for the lack of bivariate correlation between erosion rate and topographic variables is not clear, though a similar lack of correlation has arisen in other studies. For example, Scharf et al. (2013) found no relationship between basin average slope and denudation rate in far southern Africa, an area underlain by extremely strong and uniform quartzite bedrock. Perhaps the Panamanian landscape overall is in an erosional steady state, as per Riebe et al. (2001); in that case, the lack of relationship between topography and erosion rates would then be indicative of dynamic equilibrium where hillslope gradients reflect rock strength, not erosion rate. It is possible that relationships between topographic variables and erosion are masked by spatial differences in quartz content; many of the samples contained only a few percent quartz but the lack of detailed geologic mapping makes it impossible to determine quartz distribution on the landscape and thus to test this hypothesis.

The relationships between precipitation variables and erosion rate in our dataset are weak. Erosion rate is only weakly correlated to mean annual precipitation and there is no significant difference between erosion rates of watersheds draining to the Caribbean Sea and those draining to the Pacific Ocean despite the difference in the annual distribution of precipitation. Precipitation during the driest quarter of the year has a stronger (and positive) relationship with erosion rate than mean annual precipitation has with erosion. Evidence of soil water repellency, and thus lower infiltration rates, during the dry season has been found in Panama (Hendrickx et al., 2005). This would increase runoff and potentially erosion in the dry season and early in the wet season.

The weak relationship between erosion rates and climate that we observe in Panama is consistent with other studies such as Riebe et al. (2001), which concluded that climate exerted minimal control on erosion in seven watersheds in Sierra Nevada, California. Similarly, von Blanckenburg et al. (2004) suggested that increasing temperature alone did not accelerate erosion rates in Sri Lanka. The lack of relationship between temperature and erosion rates in Sri Lanka suggests that temperature alone does not drive chemical weathering, which could in turn increase denudation rates. Likely the apparent disconnect between erosion rates and climate is due to regional and localized variables (e.g. rock type, topography, and tectonics) exerting a greater control on denudation than precipitation and temperature.

The control of lithology on long-term erosion rates is poorly constrained (Portenga and Bierman, 2011; Duxbury et al., 2015). The lack of understanding is in part due to the minimal lithologic variation in the studied catchments, since most studies, by necessity, sample areas underlain in large part by quartz-bearing rocks. In our dataset, an ANOVA did not show a significant difference in erosion rates between three broad lithologic classifications (igneous intrusive, volcanic, and sedimentary rocks) at the 0.05 significance level ($F = 2.469$; $p = 0.099$). However, the watersheds in the southwestern region are underlain by sedimentary lithologies and are eroding quickly, similar to those basins composed of sedimentary rocks in the global compilation of ^{10}Be-determined erosion rates (Portenga and Bierman, 2011).

When seismic data are analyzed at the regional scale, the most significant relationship is between the number of seismic events within 10 km of the watersheds and erosion rate; this relationship is positive. Peak ground acceleration is also weakly and positively related to denudation rates. These findings suggest that the frequency of seismic events exerts a greater control in rates of erosion than the magnitude of the events as determined by the 111 years of record (Camacho, personal communication). Perhaps this reflects the proximity of seismic zones and the pervasive brittle deformation and weakening of rock near such zones. It is possible that erosion rates in Panama may be related to tectonic uplift rates but sufficient data are lacking to test this hypothesis. It is suggestive that the southwestern region of Panama, the Burica Peninsula, has the highest long-term, cosmogenically determined erosion rates and is also the site of several studies that document relatively fast, short-term (years) rates of uplift ranging between 2 and 19 mm yr^{-1} (Morell et al., 2008, 2011; Davidson, 2010). The more than 100-fold difference between long-term erosion rates (0.03 to 0.6 mm yr^{-1}) and short-term uplift rates (2 to 19 mm yr^{-1}) suggests that uplift rates, when averaged over longer time frames, are likely much lower than those determined by GPS-based geodesy.

5.3. Landslide effect on measured ^{10}Be concentration

In the mountainous regions of Panama, landslides deliver material of diverse grain sizes to stream channels. This material has ^{10}Be concentrations significantly lower than sediment transported by streams that is presumably delivered by shallower, slower, and more diffusive-like hillslope processes. The contrast in ^{10}Be concentration likely reflects the depth of erosion because landslides, if deep enough, source much of the material they deposit into streams and rivers from below the penetration depth of cosmic-ray neutrons (Bierman and Steig, 1996; Niemi et al. 2005). Samples collected from the landslide scarp in the Rio Chagres Basin suggest that much of the landslide sediment is in fact deeply sourced because this material that has considerably lower concentrations of ^{10}Be than sediment in the adjacent stream, consistent with the findings from Niemi et al. (2005).

Our data show that sand-sized sediment introduced into the Rio Chagres by the landslide we sampled has approximately half the concentration of ^{10}Be as sediment already in the river. Conversely, larger grains in the channel have ^{10}Be concentrations similar to those delivered by the landslide. Our data are consistent with other data showing that the concentration of both stream sediment and landslide material is inversely related to grain size. For example, similar relationships were also found in landslide material from Puerto Rico (Brown et al., 1998; Riebe et al., 2003), Chile (Aguilar et al., 2013), and the Himalayas (Puchol et al., 2014).

Our grain size-specific ^{10}Be data help us to understand the delivery mechanisms of sediment to channels. A simple mixing model suggests that for small grain sizes much of the sediment (~74 to 89% of the sediment up to 1 mm, similar to the grain size we analyzed in the Panamanian drainage basins) is delivered by near-surface slope processes. By adjusting the inferred basin-scale erosion rates by −26% (the maximum amount of fine-grained sediment delivered by the landslide) the arithmetic mean erosion rate for all of our samples lowers to 159 m My^{-1}, still well within the range of the erosion rates that we measured for all basins. Considering only sand-sized material, landslides seem to have a minimal influence on measured erosion rates.

In contrast, the cosmogenic data suggest that 78% of sediment in the > 12 mm split could be derived from landslide debris. Rengers and Wohl (2007) measured the D_{50} value of point bar sediment down the Rio Chagres. At the location of the landslide we sampled and for which we have ^{10}Be data, their liner regression model suggests that point bar sediment has a D_{50} value of ~70 mm, much larger than our largest landslide grain-size split which contributes 78% of channel sediment. Thus, the ^{10}Be data for cobbles are consistent with landslides supplying the majority of coarse sediment to the Rio Chagres with the caveat that this sediment input is episodic and spatially restricted to the sites of landslides.

The landslide data clearly suggest different delivery mechanisms of sediment to the channel for different grain sizes. The grain size that we measured for ^{10}Be-derived erosion rates (0.25–1.0 mm) appears to represent primarily the rate of diffusive slope processes. On the other hand, large grain sizes, those that constitute the sediment on point bars and bedload, are more likely to be derived from landslides. If we assume that the fine-grained sediment is removed as suspended load (Stallard, 1999) and that most sediment is removed from Panama as suspended load, then on the basis of studying this one landslide, our cosmogenically-based erosion rates are representative of rates of sediment generation on Panamanian hillslopes.

The landslide data show a discrepancy in every grain size between ^{10}Be concentration in landslide material (lower) and channel sediment (higher). This gran-size dependent difference implies that the depth and spatial/temporal frequency of landslides in part set the ^{10}Be concentration in channel sediment; thus, cosmogenically-determined rates of erosion are to some degree, irrespective of the grain size analyzed, are in part controlled by landsliding. If controls on landslide initiation and the depth of landslides are different for different basins, then the traditional landscape and climatic metrics described above would not necessarily correlate to the ^{10}Be derived erosion rates, as we find in this study. Instead, the long-term landslide frequency, modeled at ~1 landslide km^{-2} y^{-1} for the Panama Canal watershed (Stallard and Kinner, 2005), would in part set both the overall landscape erosion rate and the concentration of ^{10}Be in fluvial sediment.

The difference in ^{10}Be activity in landslide material compared channel sediment in the sand-size fraction is only 2-fold. Such a difference is similar to the ~2.5-fold variability of ^{10}Be concentration within the 17 sub-watersheds of the Rio Chagres (Nichols et al., 2005). Thus, the Chagres data are consistent with different amounts of landslide-derived material in different rivers, perhaps just a snapshot in time, with ^{10}Be concentration reflecting the proximity in time and space of the nearest landslide. However, ^{10}Be concentrations in the entire Panama data set reported here vary by almost 20-fold. This variation is much larger than the several-fold variability in ^{10}Be concentration between landslide-derived and channel sediment in the Rio Chagres. While not the focus of this paper, we speculate that landslide frequency and magnitude (specifically the average depth of landslides) for the basins along the Panamanian Isthmus, may in part dictate ^{10}Be concentrations in fluvial sediment and thus ^{10}Be-derived erosion rates. This hypothesis could be tested if more landslide data were available. Specifically, if the magnitude and frequency of landslides in specific drainage basins was inversely correlated to ^{10}Be concentrations in those same basins, then landsliding would have a significant control on rates of erosion determined with ^{10}Be.

5.4. Relation to silicate weathering

Recently, Goldsmith et al. (2015) reported dissolved loads for many of the same Panamanian Rivers we sampled, and just as we did, they found significant relationships with watershed lithology, topography, and precipitation. Our data sets are complimentary, with theirs revealing the rate and distribution of chemical weathering and ours indicating the rate at which sediment is generated and the landscape erodes.

Using the data of Goldsmith et al. (2015), we too find a positive relationship between chemical weathering (their data) and total erosion rates (our ^{10}Be data) in Panama. The strongest and most significant relationship in our dataset is between cosmogenically-derived erosion rates and chemical weathering of silicate rocks in the same watersheds (Goldsmith et al., 2015, $R^2 = 0.41$, $p = 0.014$, $n = 14$). Similarly, a positive relationship between chemical and physical erosion measured using ^{10}Be has been reported by Riebe et al. (2003, 2004) and Riebe and Granger (2012) and von Blanckenburg (2005). von Blanckenburg et al. (2004) observed that both erosion rates and silicate weathering rates in Sri Lanka are low. They attributed the low rate of silicate weathering to slow rates of physical erosion, thereby limiting the supply of readily weathered material. However, they concluded that silicate weathering represents a significant fraction of the total denudation. They found that total denudation rates ranged between 5 and 30 tons km^{-2} yr^{-1}, and silicate weathering ranged between 5 and 24 tons km^{-2} yr^{-1}, suggesting that much of the total denudation was accomplished chemically. In Panama, where erosion is much more rapid, silicate weathering range between 29 and 60 tons km^{-2} yr^{-1}, up to an order of magnitude greater than in Sri Lanka, perhaps because physical weathering is so rapid.

5.5. Comparison to contemporary sediment yields

Three of the sampled rivers (Chagres, Boqueron, and Pequini) have contemporary sediment yield data collected over a period of 16 years (Stallard, 1999). The ^{10}Be-derived sediment yield for the Rio Chagres (Nichols et al., 2005; recalculated by Portenga and Bierman, 2011) is 479 ± 46 tons km^{-2} yr^{-1}, higher than the sediment yield estimated from 16 years of suspended sediment data, 289 ± 56 tons km^{-2} yr^{-1}. The ^{10}Be derived sediment yields for the Rio Pequini range from 721 to 1,123 tons km^{-2} yr^{-1} (this paper) while the contemporary sediment yield was 658 tons km^{-2} yr^{-1} (averaged yield). The sediment yield derived from ^{10}Be data for the Rio Boqueron is 697 ± 73 tons km^{-2} yr^{-1} whereas the 16 year-average is 887 ± 236 tons km^{-2} yr^{-1}. Comparing sediment yields over two timescales (decades vs millennia) shows gross similarity. Differences between short-term sediment yields and long-term erosion rates likely reflect the episodic nature of sediment delivery that is captured by contemporary measurements, but averaged in long-term measurements

(Kirchner et al., 2001). In no case are the current day sediment yields significantly higher than the long-term rates of sediment generation. While sediment may be stored in the basin, our data imply that contemporary land use practices are not causing sediment to be removed from the landscape faster than it is being generated.

6. Conclusions

Erosion rates in Panama, at a basin scale, appear to vary by more than a factor of 20, ranging from 26 to 595 m My^{-1}; yet, the lack of well-defined relationships between topographic metrics or lithology and the rate of erosion suggests complex erosion dynamics not directly tied to the topography. This lack of correlation between denudation and topography is seldom found in the literature and in Panama could be due to landslide frequency and magnitude.

It appears that climate is weakly related to basin-scale rates of erosion. Seismicity (a metric for tectonic activity) is related to erosion rates, perhaps through its effect on rock strength (Young et al., 2000). Likely because it is tectonically active, Panama is eroding more rapidly than other tropical regions where cosmogenic nuclides have been measured in river sediments, including Puerto Rico, Brazil, Sri Lanka, Madagascar and Australia. The Panamanian landscape exhibits a high erosional efficiency, a function of its tectonic activity, lithology, climate, and topography. By contrast, Panama is eroding slower than the tectonically active Andean region of Bolivia.

The gross similarity between long-term erosion rates determined cosmogenically and sediment yields determined over decadal time scales suggests that current land use practices does not significantly affect the amount of sediment moving through Panamanian rivers. Well correlated physical and chemical erosion rates are consistent with rapid physical erosion exposing fresh mineral surfaces, which can then be rapidly weathered in the wet, warm tropical climate.

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Figure captions:

Fig. 1. Panama topography and tectonic setting. (A) Sampled watersheds in Panama (*n* = 35). Black circles indicate the Pacific and Caribbean access points to the Panama Canal. Boxes indicate the breakdown used for regional analysis. Location of Panama within Central America (inset). (B) Generalized map of tectonic features in Panama. Faults are common in Panama, which is located at the junction of the Cocos and Caribbean tectonic plates. Solid gray lines show faults, barbs indicate thrust faults, and half arrows along a fault indicate strike-slip faults. Dashed lines represent the boundary of tectonic plates. Map data from the US Geological Survey.

Fig. 2. Photographs of field area. (A) Aerial view of the Panamanian jungle. (B) Narrow, highland Panamanian river. (C) Sampling site for Rio San Felix (sample ID: Felix). (D) Sampled landside site (sample ID: PLSS).

Fig. 3. Sampling locations for spatial and temporal variation analyses (Table 2). Each frame includes samples taken within the same watershed. Samples analyzed for temporal analysis were

collected in close proximity to each other; network analysis samples were collected at different distances downstream. All the watersheds sampled for these analyses are located east of the Panama Canal (see inset).

Fig. 4. Erosion rates measured in this study (dark gray shaded areas). They are not normally distributed. Skewness in the distribution is reduced after erosion rates are logarithmically (base 10) transformed (inset). Transformed erosion rates were used for parametric analysis. Data for tropical studies (hollow bars with dashed lines) includes all cosmogenic-derived erosion rates from Portenga and Bierman (2011) that were classified as tropical.

Fig. 5. Arithmetic average erosion rate by region. Lines inside the boxes represent the median. The uppermost and lowermost horizontal bars represent the minimum and maximum of each group. The bottom and top of the boxes represent the lower and upper quartile of the data, respectively. The southwestern region has the highest average erosion rate, and the central region has the highest variability. The Rio Felix, represented by the black dot, is an extreme outlier in our dataset and not included in summary statistics. Average basin area and standard deviation are shown above boxes.

Fig. 6. Summarized bi-variate linear regressions. R^2 values of variables positively correlated to erosion are marked with a cross; negative correlations are marked with a bar. The dashed horizontal line represents the level of significance of the regressions; variables under the line are not significantly related to erosion, variables above are significantly related.

Fig. 7. Regression plots of erosion rate and a variety of parameters. (A) Chemical weathering strongly related to erosion rate. (B to D) No significant relationship between erosion rate and mean annual temperatures (B), mean basin slope (C), or mean annual precipitation (D). Samples are coded by region.

Fig. 8. Seismic activity in Panama. Circles represent individual seismic events (1900–2011), map data provided by the Instituto de Geociencias de Panamá (personal communication). Circle size represent event magnitude. Watershed tone represents the erosion rate. Rivers where contemporary sediment yield has been measured are identified in the map.

Fig. 9. Concentration of ^{10}Be according to grain size for samples upstream of, within, and downstream of the landslide. ^{10}Be decreases as grain size increases. Material from the landslide (PLSS) usually has the lowest isotopic concentration for each grain size fraction.

Fig. 10. Landslide influence on downstream material. We quantified what percentage of the downstream material was delivered by the landslide. Our results show that the influence of the landslide increases systematically with grain size.

Fig. 11. Boxplot comparing erosion rates measured at tropical sites. Black dots represent outliers within each dataset. Countries not connected by the same letter have significantly different erosion rates. Bolivia (Wittmann et al., 2009; Insel et al., 2010) is eroding faster than all other tropical sites and has the widest range in data. Basins in our dataset are eroding faster than those previously published for Panama (Nichols et al., 2005), as well as tropical sites in Australia (Heimsath et al., 2009; Nichols et al., 2014), Brazil (Salgado et al., 2006, 2007, 2008, 2013; Cherem et al., 2012; Barreto et al., 2013, 2014; Rezende et al., 2013), Madagascar (Cox et al.,

2009), Puerto Rico (Brown et al. 1995, 1998; Riebe et al., 2003), and Sri Lanka (Hewawasam et al., 2003; von Blanckenburg et al., 2004).

Fig. 12. Bivariate linear regression between slope and erosion rate. Data from this study data are coded by region. Global dataset, represented in gray circles, are from Portenga and Bierman (2011). Previously published Panamanian data (Nichols et al., 2005) are represented by hollow circles. The relationship between erosion rate and slope is significant at the regional scale, but decreases in strength for broader scales.

Table captions:

Table 1. Watershed parameters and isotopic concentrations

Table 2. Summarized data for temporal variation and network analysis

Table 3. Correlation coefficient of topographic variables and variables significantly related to erosion.

Table 4. Isotopic concentration of landslide-related samples.

Table 5. Landslide influence on downstream sediment

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