Using ^{10}Be to determine long-term erosion rates in Panama

Veronica Sosa-Gonzalez[1], Paul R. Bierman[1,2], Kyle K. Nichols[3], Dylan H. Rood[4]

[1]Rubenstein School of the Environment and Natural Resources, University of Vermont [2]Department of Geology, University of Vermont [3]Department of Geosciences, Skidmore College [4]Lawrence Livermore National Laboratory

Abstract

Using measurements of in situ produced 10Be in river sediment we calculated erosion rates for 40 watersheds in Panama. A total of 44 variables (physiographic, climatic, seismic, geology and a land use proxy) were quantified for each watershed and their relationship to erosion rates was assessed using simple linear regressions and Analysis of Variance. Grain size analysis was used to assess the impact of landslides on the concentration of 10be in fluvial sediment and thus on erosion rates.

Cosmogenic 10Be–inferred erosion rates ranged from 26 to 600 /Myr. The strongest and most significant relationship in the dataset was found between erosion rate and silicate weathering rate, the mass of material leaving the basin in solution (R2=0.726, p = 0.004, n=9). None of the physiographic variables showed a significant relationship with erosion at the 95% significance level. Three seismic variables were weakly and negatively related to erosion rates: average magnitude of seismic events in a 75-km buffer (R2=0.550, p < 0.005), average depth of seismic events in a 50-km buffer (R2=0.466, p = 0.002) and average magnitude of seismic events in a 25-km buffer (R2=0.431, p = 0.005). An inverse relationship was found between 10Be concentration and grain size in landslide-related samples. Deep-seated material carries less 10Be than surface material.

Erosion rates in Panama are higher than all other published cosmogenic-derived erosion rates in tropical climates including those from Puerto Rico, Madagascar and Sri Lanka. Many studies have concluded that physiographic controls are related to erosion. The lack of such relationship in Panama suggests a complexity in erosive dynamics.

Keywords: long-term erosion rates, Panama, physiography, seismic controls, landslide input

1. Introduction

Quantification of erosion rates, and knowledge of the factors that determine and impact them, are important to many disciplines including aquatic ecology, geomorphology, economics, and natural resources management. For example, sedimentation of waterways, an effect of accelerated erosion, is associated with deterioration of water quality including increased turbidity and temperature, and changes in dissolved oxygen concentration (Bilotta and Brazier, 2008). The yield of water reservoirs can be affected by erosion because their capacity decreases as they fill with sediment (Harden, 2006).

The effects of physiographic controls on erosion and sediment movement have been long debated. Watershed elevation appears to exert control on erosion at a global (Portenga and Bierman, 2011) and at a site-specific scale (Palumbo et al., 2009). Portenga and Bierman (2011) found that mean basin slope significantly and positively relates to drainage basin erosion rates at both local and global scales, and that relief is important in controlling erosion rates in the tropical climate zones. However, von Blanckenburg (2004) concluded that relief alone does not lead to accelerated erosion.

Cosmogenic isotopes, such as ^{10}Be, are formed when the earth materials are exposed to cosmic rays (Lal and Peters, 1967). These nuclides provide a robust method to quantify erosion rates, because they integrate enough time to average out extreme events on decadal and centennial time scale, integrating erosion rates over 10^3 to 10^5 years. Production of *in situ* cosmogenic isotopes decreases exponentially with depth and is in general inconsequential below 2 meters depth in rocks (Lal and Peters, 1967). Because of this, ^{10}Be is a good indicator of the near-surface residence time of materials and hence, the rate at which Earth's surface is eroding. Such long-term data can help place human influences on the landscape and its processes in context (Bierman and Nichols, 2004; von Blanckenburg, 2005). This research will investigate the importance of sediment delivery to rivers by discrete landslide events by doing grain-size specific ^{10}Be analysis. Fine material located at the surface has been exposed to cosmic radiation longer than coarser material at depth. Coarser material from landslides is expected to have lower isotopic concentrations.

Our research aims to determine long-term, background erosion rates in Panama using ^{10}Be measured in quartz extracted from river sediments (Figure 1). More than 88 studies using ^{10}Be as a proxy for erosion rate; however, just a few studies have been done in tropical environments. Portenga and Bierman (2011) compiled all published data on cosmogenic-derived erosion rates and only 98 of 1599 are from tropical river sediment samples. Of all tropical samples, 17 were obtained in Panama. This research expands the breadth of environments where cosmogenic isotopes have been measured and provides important information for the management of the Panama Canal, in particular, the lifetime of the reservoirs integral to canal operation. Our study presents erosion rate data for 40 Panamanian watersheds and thus the first country-scale determination of background erosion rates in Panama.

Using the ^{10}Be-estimated erosion rates, we place human impact in the context of background erosion rates and gain knowledge about the relationship of erosion rates, in a tropical climate, to physiography, tectonic activity, geology and biologic features. Assessing these relationships demonstrates the lack of physiographic controls on erosion rates in tropical climates.

1.1 Regional Setting

1.1.1 Study area

Panama is the southernmost Central American country. The country comprises 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 (CGRP, 2008).

1.1.2 Geography and Climate

Panama has low-relief coastal plains and a more rugged Central Cordillera extending along most of the isthmus from the border with Costa Rica to the Panama Canal (Palka, 2005). Maximum elevations are located in the southwestern province of Chiriquí: Barú volcano (3,475m) and Cerro Picacho (2,986m) and the northwestern province of Bocas del Toro: Cerro Fábrega (3,335m), Cerro Itamut (3,279m) and Cerro Echandi (3,162m) (CGRP, 2005). Rivers draining into the Caribbean Sea average 56 km in length, and have an average slope of 5.5%. Their discharge volume is greater than those draining to the Pacific, because of their short distance from mountains to sea. Rivers draining to the Pacific Ocean average 106 km in length, and have lower slopes, averaging 2.27% (CGRP-INEC, 2005).

Climate in Panama is tropical maritime with influences from the Caribbean Sea and Pacific Ocean (Contraloría General de la República de Panamá- Instituto Nacional de Estadística y Censo, 2005). The climate is characterized by high year-round temperatures, with low diurnal and annual range, abundant precipitation, and high relative humidity. Temperatures are high year-round. Annual mean temperatures range between 24°C and 28°C. The average diurnal temperature range is approximately 1.9°C on the Caribbean slopes and ranges between 1.5 and 2.9°C on the Pacific side (CGRP-INEC, 2005).

Generally, there are two seasons: wet and dry; the wet season goes from May to December, and the dry one from December to April (CGRP-INEC, 2005). The Pacific's side mean annual precipitation ranges from 1,500 to 3,500mm, and there is a marked difference between the dry and wet seasons. On the Caribbean slope, precipitation is more uniform year round, exceeding 4,000mm annually and with no marked difference between the seasons.

1.1.3 Tectonic setting and geology

Panama is geologically young. The isthmus where Panama is located resulted from collision of the Panama-Choco island arc with South America. This took place in the late Miocene-Pliocene (3.5-7 million years ago). Adamek and others (1988) suggested the existence of a microplate (the Panama-Costa Rica microplate) that includes most of Costa Rica. It shares borders with the Caribbean plate on the north, the Cocos plate on the southwest, the Nazca plate to the south, and the South American plate to the east and southeast (Camacho et al., 1997).

Camacho et al. (1997) conducted a seismic hazard assessment for Panama, and produced peak ground acceleration maps. The highest seismic hazard and ground acceleration is on the western side of the country, close to the Panama Fracture Zone and the western segment of the

North Panama Deformed Belt; and to the southeast of the country close to the Panama Block-South America plate margin. The lowest seismic hazard is in Central Panama. The Pacific side is characterized by its geologic activity, having 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).

Panama is mostly composed of volcanic rocks. The Canal Zone is mostly underlain by volcanic tuffs from the Miocene era. These can also be found in the eastern region of Darien. The geology of eastern Panama consists mostly of volcanic tuffs and ashes, with small areas of limestone. There are regions on the east where limestone is interbedded with dark clay shale formations and sandstone. A region of tuffs, ash and lava blended with marine and terrestrial sediments extends west from the central Canal Zone. To the west, by the province of Bocas del Toro, the sedimentary column includes limestone-volcanic series of Eocene age as well as conglomerates, sandstones, shales and sandy limestones of Miocene age (Schuchert, 1935; Terry, 1956).

Metamorphic rocks are scarce. Schist has been reported on the eastern province of Darien. Small slate outcrops have been reported in several provinces stretching from the center to the west, close to the Costa Rica border. Sedimentary rocks are mostly limited to the eastern region of Panama with a few exceptions on the west.

2. Methods

2.1 Basin selection and sampling

Samples used in this study were collected by Russell S. Harmon and Kyle K. Nichols in three field seasons: 2004, 2007 and 2009. A total of 55 samples river samples were collected, of which 16 could not be analyzed for ^{10}Be, due to their low quartz content.

The 2004 samples were collected in the upper Chagres River, the sediment yield of which was measured between 1981 and 1996 to test for human impact, specifically, deforestation. The Chagres River is essential to the Panama Canal as it fills one of the main reservoirs integral to canal function. Samples on the northern side of the divide, draining to the Caribbean Sea, were collected to test whether average basin slope controlled erosion rates. Three rivers in this region were sampled multiple times along their length. These were Rio Nombre de Dios, Cuango and Pequini. In 2007, samples were collected by Nichols along the Pan-American Highway north of Panama City, where the road was crossed by rivers. Russell Harmon and Steven Goldsmith were conducting research on the chemical weathering in Panama (Harmon, personal communication), and collected sediment samples that were used in our research.

Four samples were collected in 2009, three related to a landslide. One was a temporal replicate for the Rio Chagres, previously sampled in 2002. One sample was collected from landslide material, one sample upstream from the confluence of the river and the landslide, and one from the river channel downstream of the landslide. These last three samples were then divided into 7 grain size splits each, making a total of 21 landslide-related samples.

2.2 Laboratory methods

Samples were dried and sieved. Coarse grain-size splits were pulverized using a plate grinder. The 3 landslide-related samples were all analyzed for ^{10}Be content by size fraction:

<0.25mm, 0.25-1mm, 1-2mm, 2-4mm, 4-9mm, 9-12mm, and >12mm. River sediment samples (unrelated to the landslide) were divided into 3 size fractions: <0.25mm, 0.25-0.85mm, and >0.85mm. Only the 0.25-0.85mm split was chemically treated to isolate quartz and extract ^{10}Be. Samples were chemically treated to isolate the quartz and remove meteoric ^{10}Be following the method of Kohl and Nishiizumi (1992).

Samples of purified quartz were spiked with Be and Al carrier, to reach desirable total element loads (2500 µg Al and 250 µg Be), and dissolved in hydrofluoric acid. Digestion of the samples took place with increasing heat over the course of two days until the quartz dissolved completely. Samples were treated with perchloric and hydrofluoric acid dry downs to prepare them for anion chromatography, where they were stripped of iron. A solution of weak sulfuric acid and hydrogen peroxide prepared the samples for cation chromatography which divided the sample into aluminum and beryllium fractions. Titrations with ammonium hydroxide, using methyl red as an indicator, neutralized the acid in the sample and precipitated the Be fractions into hydroxide jells. Jells were dried, the BeOH oxidized over a flame to BeO, and the oxide packed into metal targets after being mixed in a 1:1 molar ratio with niobium (Hunt et al., 2006).

2.3 ^{10}Be measurement and erosion rates calculations

Isotopic ratios were measured using Accelerator Mass Spectrometry (AMS) at Lawrence Livermore National Laboratory (LLNL). Blank corrections were made based on fully processed blanks. Erosion rates based on the isotopic data were obtained using the CRONUS Earth Calculator Version 2.2 (http://hess.ess.washington.edu/). Watersheds were delineated in ArcGIS 9.2, based on a 30-DEM and their effective elevation was obtained (Portenga and Bierman, 2011).

Erosion rates obtained from CRONUS were highly skewed so they were logarithmically transformed (log_{10}) in order to be able to perform parametric statistical analysis (Figure 2). Because no spatial pattern of erosion rates was evident across Panama, watersheds were grouped according to their region. Five regions resulted from this clustering: southwestern region (3 watersheds), northwestern (5 watersheds), central (7 watersheds), central-eastern (8 watersheds), and eastern (17 watersheds). For statistical analysis of the regions, physiographic and climatic parameters for all the watersheds were averaged, except for the number of seismic events, for which the sum of the events in all watersheds was used for parametric analysis.

2.4 Data Analysis

A Geographical Information System (GIS) was used to quantify landscape (physiographic, climatic, seismic and land use) variables and study the spatial distribution of erosion rates. All spatial information was projected in NAD 1927 Zone 17N (previously denominated Canal Zone). Gaps in the 90-meter resolution SRTM Digital Elevation Model (DEM) used for watershed delineation were corrected using the USGS GTOPO30. The corrected DEM was used to quantify slope, area, and relief. A digitized map of Panama's geology was obtained from Smithsonian Tropical Research Institute. Peak Ground Acceleration (PGA) for each watershed was obtained based on data produced by the Global Seismic Hazard Assessment Program and downloaded from their website (http://www.seismo.ethz.ch) The amount of seismic events from 1900-2011, as well as average depth and magnitude of seismic events in each watershed, were extracted from a seismic catalog from the Instituto de Geociencias de Panamá (Dr. Eduardo Camacho, personal communication). Climatic data (19 variables) was developed by WorldClim and obtained from their website (http://www.wordclim.org). Isothermality, included in the climatic data, is a measure of the annual temperature range experienced on a daily basis (Varela, 2009).

Data were entered into an SPSS database for simple linear regressions and analysis of variance relating erosion rates to landscape metrics. IBM SPSS Statistics 20 was used for these analyses.

3. Results

3.1 River sediment samples

The concentration of *in situ* ^{10}Be measured in Panamanian river sand varies widely from 7.4 ± 1.6 to $139 \pm 3 \times 10^3$ atoms/g (Table 1, 1 standard deviation (SD)here and elsewhere in the paper). When samples were grouped by region, quartz extracted from rivers in the southwestern region had the lowest ^{10}Be concentration ($8.37 \pm 1.27 \times 10^3$ atoms/g). The lowest concentration of ^{10}Be measured as part of this study was in the river sediment of the Rio Bartolo (BART), in the southwestern region (Table 2). Samples from the central-eastern region had an average ^{10}Be concentration of $64.0 \pm 46.6 \times 10^3$ atoms/g. The variance in the central-eastern region was the largest of all regions (72% SD). The mean ^{10}Be concentration was significantly different between the eastern and central-eastern region ($p = 0.007$) but no significant differences were found in mean ^{10}Be concentrations for stream sediment between other regions as shown by ANOVA.

Erosion rates, inferred from the concentration of *in situ* produced ^{10}Be, range from 26.1 ± 0.6 m/Myr to 597 ± 62 m/Myr (Table 1); the average rate for the 35 rivers we sampled is 218 m/Myr ± 151 m/Myr, the area-weighted average is 150 m/Myr. The most slowly eroding basins are generally found in the central-eastern region, and rapidly eroding basins are scattered through the country (Figure 3). When samples were grouped by region, the southwestern region had the highest average erosion rates; however, the central region has the biggest variance in erosion rates because of the outlier (FELIX); if that extreme value is not taken into account, the eastern region has the greatest variance (Figure 4). Average erosion rate for the southwestern region is significantly different from the average erosion rate of the central ($p = 0.020$) and central-eastern regions ($p = 0.003$). All other differences were not significant.

Two rivers, the Pequini and Chagres were sampled multiple times along their length to assess spatial variations in erosion (Figure 5). A sample from the Pequini headwaters (PHW) was 7.40km away from the sample extracted before the confluence of the Pequini with the Rio San Miguel (PSM), and 13.3km away from a sample taken at the outlet of the watershed (PLA). Erosion rates calculated for the three nested watersheds showed a 13 percent standard deviation. The upper Rio Chagres was sampled in 2009 (CHAG2009), and a landslide on the Chagres watershed. Amalgamated samples from upstream of the landslide were combined to represent a sediment sample (PLS) that included the watershed for CHAG2009. Erosion rates calculated for both segments of the upper Rio Chagres (PLS and CHAG2009) differed by a percent standard deviation of 71 (Table 3).

Two rivers were sampled in similar locations but at different times. The Rio Nombre de Dios was sampled in 2004 (NDD) and 2007 (DIOS), and so was the Rio Cuango (CUAN, 2004; CNGO, 2007). A smaller variation between samples was found in the Rio Nombre de Dios, (6%) than the Rio Cuango, 23%. Erosion rates were calculated for the area between subcatchments (Table 4). In general, inferrred ^{10}Be content and erosion rates of the subwatersheds were similar.

In general, bivariate linear regression analysis showed few statistically significant relationships between watershed scale erosion rates inferred from ^{10}Be measurements and landscape scale variables (i.e., physiographic, climatic, geology, seismic and land use; Table 5). There were no significant relationships between erosion rates and physiographic metrics (area, slope, and relief). Several bioclimatic variables showed weak but positive relationships with erosion rates including temperature seasonality (R^2= 0.445, p= 0.004), and precipitation during both the driest month (R^2= 0.319, p= 0.045) and the driest quarter (R^2= 0.376, p= 0.017). Two bioclimatic variables showed a weak negative relation to erosion rates: isothermality (R^2= 0.381, p= 0.015) and precipitation seasonality (R^2= 0.394, p= 0.012). Tree cover was used a land use proxy, and it showed a negative relation with erosion rates (R^2= 0.351, p= 0.026).

The relationship between erosion and seismicity was tested using six arbitrarily chosen buffer distances (100m, 10km, 25km, 50km, 75km and 100km) to examine changes, if any, in seismic control of erosion rates as a function of distance from the watershed. These buffers were applied to each delineated watershed and seismic variables were quantified within each buffer. The strongest relationships with seismicity are negative (Table 6). The average magnitude of seismic events showed a relationship at a 75km buffer from the watersheds (R^2= 0.550, $p<0.005$) and at the 25km buffer (R^2= 0.431, p= 0.005). Within a 50km buffer, the strongest relation was found between erosion rates and the average depth of the events (R^2= 0.466, p= 0.002). Other weak relationships were found with the 25km, 50km, 75km and 100km buffers. No significant relationships were found at the 100m and only one at the 10km distance.

The strongest relationship was found between physical erosion rates and chemical weathering of silicate rocks ($R^2 = 0.558$, p= 0.021, n = 9). In Panama, silicate weathering accounts for roughly 2-18% of the total denudation (Table 7). Stepwise regression results in a model that includes both chemical weathering and precipitation of the driest month as explanatory variables (R^2=0.915, p= 0.001).

Although erosion rates and landscape scale parameters are not well correlated at the basin scale, they are better correlated if considered at a regional scale. Clustering samples into regions and assessing their relationship to parameters, shows an increase in correlation coefficients, except for mean annual precipitation, which decreases. However, when only five samples (geographical regions) are considered for analysis, the test has low power. As a result of this, p-values increase and the relationships are no longer statistically significant.

3.2 Landslide samples

^{10}Be concentration in the grain size fractions of all landslide-related sediment samples ranged from 7.33 ± 0.40 to $39.1 \pm 1.71 \times 10^3$ atoms/g, on the low end of concentrations measured as part of this study. Grain size and *in situ* ^{10}Be concentration are inversely related (Figure 6). Individual linear regressions showed that they are well correlated (R^2= 0.600; $p < 0.005$). The isotopic concentration of the landslide material is less than that for the upstream and downstream material, in almost all size fractions, except for >12mm.

Sediment upstream of the landslide contains more ^{10}Be than sediment downstream. Analysis of variance showed that the relationship between ^{10}Be content and grain size is statistically significant (F = 4.175; p = 0.013). Based on visual examination of the trend observed in the graph of ^{10}Be concentration as a function of grain size, size fractions were grouped into 4 categories to test for differences in isotopic concentrations: <0.25mm-1mm, 1-2mm, 2-9mm, and >9mm. Using these categories, an ANOVA was run, and a stronger relationship between isotopic concentration and grain size was found (F=9.536, p = 0.001). Mean isotopic concentration of the <0.25mm fraction is statistically different from all the fractions greater than 2.00mm at the 0.05 level. No relationship holds between ^{10}Be concentration and sediment source (F= 2.193; p = 0.141), but there is an evident difference in their average ^{10}Be concentration. Using a two-component mixing model suggests that the landslide accounts for 50% of the sediment just downstream of the slide.

4. Discussion

Basin-scale erosion rates in Panama vary over more than an order of magnitude and are in general, quite rapid, averaging several hundred meters per million years. Erosion rates are largely unrelated to topographic metrics, vary in a coherent spatial pattern, and are correlated to various expressions of tectonic activity. Physical erosion rates and chemical weathering of silicate rocks are well correlated.

4.1 Comparison to other cosmogenic studies

Erosion rates of Panamanian basins span much of the range previously reported for tropical basins. Forty watersheds in Panama, some of which are nested and vary in area from 13.6 km^2 to 2,410 km^2, had erosion rates that range from 26.1 ± 0.6 m/Myr to 597 ± 62 m/Myr. The average erosion rate for the Panamanian watersheds considered in this study is significantly higher than that for other tropical regions including Puerto Rico, Madagascar, and Sri Lanka (F=19.767, p< 0.005; Figure 7) (Brown et al., 1995; Brown et al., 1998; Cox et al., 2009, Hewawasam et al., 2003; von Blanckenburg et al., 2004). Watersheds included in those tropical studies, ranged in area from 0.02 to 134.6 km^2 with most less than 50 km^2. Panama's dataset is extensive when compared to other tropical studies; the number of samples included in those studies ranges from 4 to 10, whereas the Panama dataset has 40 watershed samples.

Erosion rates have been determined in Puerto Rican watershed, in two separate studies. Brown et al. (1995) determined an average erosion rate of 61.7 ± 41.3 m/Myr for the Rio Icacos. In 1998, Brown et al. determined the erosion rates for the Quebrada Guabá (50.8 ± 27.7 m/Myr) and Rio Cayaguás (70.1 ± 19.9m/Myr). Average erosion rates in tropical Madagascar (n = 4) are 13.9 ± 5.7 m/Myr (Cox et al., 2009). Two separate studies have quantified cosmogenically-derived erosion rates in Sri Lanka. In 2003, Hewawasam et al. found that the average erosion rate of six tropical subwatersheds of the Upper Mahaweli catchment was 21.1 ± 4.2 m/Myr. Von Blanckenburg et al. (2004) reported an average erosion rate of 16.2 ± 7.0 m/Myr on the same region in Sri Lanka (n=16).

When compared to these study sites, Panama is eroding faster than all of them. Seismicity and tectonic setting differ between Panama, Madagascar, and Sri Lanka; the latter two are located in a region with little tectonic activity. In contrast, Panama is located in an active tectonic zone. 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 studied watersheds Sri Lanka, and 0.36 for Madagascar (Portenga and Bierman, 2011). For Panama, mean peak ground acceleration in the 40 studied watersheds, is more than an order of magnitude higher, ranging between 1.77 and 4.37 g (average: 2.29). In Puerto Rico, peak ground acceleration averaged 1.88.

Using the data published by Portenga and Bierman (2011) and the data from this study, mean temperature and precipitation were compared for tropical cosmogenic studies. Mean temperature in the sampled Panamanian watersheds averaged 24.4 °C; in Sri Lanka, it averaged 19.2°C, in Madagascar, 20.2°C and 21.6°C in Puerto Rico. Mean annual precipitation for the watersheds is relatively similar in Panama, Puerto Rico and Sri Lanka, averaging 2796 mm, 2599 mm and 2480 mm respectively. They differ from Madagascar, where precipitation averages only 1134mm. Higher erosion rates are associated with elevated annual precipitation.

4.2 Relation to silicate weathering

The strongest and most significant relationship in our dataset was found between erosion rates and chemical weathering of silicate rocks (R^2= 0.726, p= 0.004, n= 9). A positive relationship between chemical and physical erosion has been found before by Riebe et al. (2003; 2004) and von Blanckenburg (2005).

In their study of the controls on chemical weathering in a variety of climate regimes, Riebe et al. (2004) argued that there is a potential positive feedback between physical and chemical erosion. Physical erosion depends, in part, on the chemical breakdown and weakening of rocks as minerals alter, and chemical weathering depends on the availability of fresh mineral surfaces created by physical erosion. In a study of physical erosion and chemical weathering in Rio Icacos (Puerto Rico), Riebe et al. (2003) concluded that there is a tightly coupled relationship between physical erosion and chemical weathering. Von Blanckenburg (2005) also found that physical erosion and chemical denudation are related. That study compiled previously published isotopic data and related it to physiographic metrics and chemical weathering data. He found that the slope of the best fit line on the plot of chemical versus physical erosion rates was 0.2, supporting that there is a relationship between physical erosion and chemical weathering. For Panama, we compared chemical and physical denudation and we find that the relationship is strong ($R^2 = 0.726$, $p = 0.004$). Our data agrees with von Blanckenburg's findings, in that the relationship between physical and chemical weathering is strong.

Von Blanckenburg et al. (2004) observed that while erosion rates in Sri Lanka are low, so are silicate weathering rates. 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 denudation rates ranged between 5 and 30 t km^{-2} yr^{-1}, and silicate weathering ranged between 5 and 20 t km^{-2} yr^{-1}. In Panama, silicate weathering accounts for roughly 2-18% of the total denudation. The remaining percentage can be attributed to material being washed out of the basin.

West (2005) compiled previously published data on chemical weathering and physical denudation for study sites across the world. Chemical weathering rates had been determined via surface water chemistry and physical erosion using sediment fluxes or cosmogenic nuclides.

After comparing both datasets, he found that in a transport-limited environment (that is, when the physical erosion is slow and limits the movement of chemically weathered material) total denudation rate – chemical and physical- explains 94% of the variability in silicate denudation rate.

A transport-limited environment is not likely to be found in Panama, where the physical erosion rates are among the highest cosmogenic-derived ones ever published (Portenga and Bierman, 2011). Because of this, silicate weathering is not expected to account for much of the variability in the physical erosion rates.

4.3 Spatial scale of analysis

Both alone and together, none of the 45 landscape-scale metrics explained well the spatial variation in Panamanian basin-scale erosion rates. Although some relationships were statistically significant, there was large scatter (low R^2). When data were lumped at a regional scale, the strength of the relationships (R^2) increased, but the statistical significance decreased (small *n*). A similar trend of weakening relationship as the analysis scale increased was found globally by Portenga and Bierman (2011). As the scale of analysis increases, so does the number of factors that influence a certain phenomenon; also, factors are likely to interact with each other. This can reduce the explanatory power of a single variable.

Because the cosmogenic nuclide method measures the concentration of ^{10}Be, one can test effective sediment mixing within the watershed. A t-test comparing watersheds smaller than $100km^2$ with those greater than $100km^2$ in our dataset showed that there is no significant difference in their average erosion rate ($t=-1.308$; $p = 0.306$). This lack of difference confirms that sediment mixing is effective and that the erosion rate of small watersheds is on average no different than that of large watersheds. Portenga and Bierman (2011) also found no relationship between erosion rates and basin area with a much larger dataset.

4.4 Tectonics and seismicity

Of the seismicity proxies analyzed, several showed a significant relationship to erosion rates. Average magnitude of the seismic events is inversely related to erosion at a variety of buffer distances, suggesting that it is the most important seismic variable of the ones we analyzed. Quantity of seismic events at the 10-km buffer was positively related to erosion rates. When analyzing at the regional scale, the only significant relationship (of all metrics) is between the number of seismic events in the 10-km buffer and erosion (R^2= 0.813, p = 0.036). This relationship is positive.

At the medium (25km) and large (75km and 100km) scale, the energy released during seismic events is the important factor, at the medium scale (50km), it is the depth of the events and at a shorter scale (10km), it is the number of seismic events, regardless of magnitude or depth. In the immediate scale (100m buffer) none of the seismic variables is significantly related to erosion rates. Western Panama has the greatest density (Figure 8). However, the events of greatest magnitude occur outside of this region. This may explain the negative relation of erosion with average magnitude of seismic events. Peak Ground Acceleration, another seismicity proxy, showed a weak positive relationship with erosion rates (R^2= 0.096, p = 0.054).

The density of seismic events is highest where some of the most rapidly eroding watersheds are located (southwestern region). For example, the watershed for the Rio Felix (FELIX), which has the highest erosion rate (598 m/Myr), located east of the region with a high frequency of seismic events.

There is a spatial gap (where no erosion rates were determined) between the southwestern region and the central region. A total of 10 samples were taken from this area, but due to their low quartz content, no ^{10}Be analysis was done. Covering this spatial gap would be helpful in identifying trends in erosion rates in that region. Because of this, it is difficult to reach any specific conclusions from our data regarding the high erosion rate of Rio Felix and its relationship to seismic activity.

One of the mechanisms by which erosion may be triggered due to seismicity is by increasing landslide events. Recently, Ouimet (2008) studied the effect of M 7.9 earthquake on erosion in China. As a result of the ground shaking associated with the earthquake, slope stability was decreased. He concluded that the frequency of landslides increased erosion rates after the earthquake.

In a study examining weathering and denudation in Sri Lanka, von Blanckenburg et al. (2004) concluded that weathering and erosion were sensitive to base-level change resulting from tectonic forcing but were not accelerated by increased precipitation and temperature.

Kong et al. (2007) observed the effect of climate and tectonics on long-term erosion rates in Tibet. They compared the erosion rates for the Tibet to those in different climate regimes and found them to be similar, suggesting that there is no climatic control on erosion. Their work found a positive relationship between erosion and tectonics. They concluded that rock uplift, as a result of tectonic activity in the Tibet region, is related to erosion. In a study of the coupling of tectonics and erosion in the Western Alps, Malusá and Vezzoli (2006) concluded that regardless of the lithology of the source area, most of the sediments produced in the region are due to tectonically-related uplift.

Erosion may also be related to tectonic uplift in Panama. Davidson (2010) measured uplift rates in the Burica Peninsula, on the border of Panama and Costa Rica, using GPS measurements. He concluded that the Burica Peninsula is uplifting at a rate of ~55mm/yr. The southwestern region we demarcated has the highest erosion rates in Panama and is located in the Burica Peninsula. Although average erosion rates are 100 times less than uplift rates, rapid uplift in this area suggests that increased denudation may be related to tectonic uplift.

It is important to point out that the response to seismic events may be tied to lithological differences. This is hard to assess in Panama, where knowledge of the geology, hidden as it is under deep jungle cover, is scarce, and the available digital information on surface geology and bedrock is not detailed.

4.5 Topographic controls

Topographic variables (i.e., basin area, relief, slope, elevation) have been related to erosion rates in many studies (see Summerfield and Huton, 1994; Milliman and Syvitski, 1992). Erosion rates of Panamanian watersheds does not appear to be related to elevation (R^2= 0.002, p = 0.804), relief (R^2= 0.038, p = 0.232) or average basin slope (R^2= 0.000, p = 0.951). Stepwise regressions showed no relation between erosion rates and topographic variables. This means that no combination of topographic variables or combination of a topographic and climatic (or other type of) variable is significantly related to erosion.

These findings contrast with previously published work that concluded such relationships exist. Summerfield and Huton (1994) found a strong relationship between relief and mechanical denudation rate. Local relief and runoff were the dominant controls on erosion in the large basins they analyzed. Milliman and Syvitski (1992) concluded from their data that basin size and topography are important controls of the export of sediment (sediment yield).

Riebe et al. (2001) used cosmogenic nuclides to measure erosion rates in seven topographically different watersheds in Sierra Nevada, California. They argued that a lack of relationship between topography and erosion rates may be indicative of equilibrium. If the base-level lowering rates are uniform, hence the system is at equilibrium, hillslopes exerts no control on erosion, and it is rather due to bedrock erodibility. On the other hand, when local base-level lowering rates are variable (not in equilibrium), erosion rates are related to average basin slope. This is a potential explanation for the lack of such relationships in Panama.

4.6 Climatic control

It has been thought that both the average precipitation and exceptional hydrologic events are positively related to erosion rates (Milliman and Syvitski, 1992). However, for this research, 19 bioclimatic variables were considered, including maximum and minimum precipitation for each watershed, and none had a statistically significant relation to erosion. Mean annual precipitation exerts only a weak control in erosion at the basin scale. (R^2= 0.095, p = 0.057). When regional analysis was performed, this relationship got weaker. Temperature did not have significant relationship with erosion either at the basin (R^2= 0.002, p = 0.807) or the regional scale (R^2= 0.016, p = 0.841).

Riebe et al. (2001) concluded that climate exerted a minimal control on erosion in 7 watersheds in Sierra Nevada, California. These watersheds varied in average temperature and precipitation regime; none of these seemed to relate to erosion rates. From their research in Sri Lanka, von Blanckenburg et al. (2004) suggested that increasing temperature alone does not accelerate erosion rates. Findings of this research agree with the conclusions reached in both works.

4.7 Lithology

Analysis of Variance found no significant difference between the three geology classifications considered (igneous intrusive, volcanic, and sedimentary rocks) and erosion rates at the 0.05 significance level (F=2.469; p= 0.099). The watersheds in the southwestern region, the fastest eroding, coincide with sedimentary lithologies cropping out at the surface, similar to the finding made in the world-wide dataset by Portenga and Bierman (2011). This is also the area where the seismic activity is greater; this may imply a relationship between seismicity and the existence of sedimentary basins. However, the relationship between sedimentary lithology and higher erosion rates is significant only at the $p < 0.1$.

4.8 Grain size and isotopic concentration

My data suggest that sediment introduced to Panamanian rivers by landslides has lower ^{10}Be concentrations than sediment entering the rivers by other means such as bank collapse and creep down slopes. Furthermore, the ^{10}Be concentration of the landslide material is related to grain size with large grains having 3.5 times less ^{10}Be than small grains.

The difference in isotopic concentration among grain sizes is useful to infer material sourcing. Samples with the greatest diameter result from deep-seated landslides, and carry less ^{10}Be than surface materials. Bedrock landslides can carve deeper than the attenuation length of secondary cosmic rays, bringing to the surface material that has considerably less ^{10}Be content (Niemi et al., 2005). On the other hand, fine-grained material is preferentially sourced from near the land surface, and thus its isotopic concentration is greater.

This relationship was also found in Puerto Rico by Brown et al. (1998). In a study of chemical and physical erosion in Puerto Rico, Riebe et al. (2003) observed that ^{10}Be concentrations decrease with increasing fractions of coarse material for stream sediments. They attributed this to material sourcing, and suggested that coarse fractions in stream sediments are derived from deep landslides. Given that Puerto Rico and Panama are similar in climate, it is possible that this inverse relationship between ^{10}Be concentration and grain size will be only seen in such steep, wet environments (Bierman et al., unpublished data).

5. Conclusions

This work presented the first determination of long-term erosion rates in Panama, at the country scale, using cosmogenic nuclides. Erosion rates range from 26.1 ± 0.6 m/Myr to 597 ± 62 m/Myr. The great variability in erosion and its lack of relationship to topography suggests a complexity in erosive dynamics that is not possible to explain with the metrics we considered.

Based on their sediment yield calculations, Nichols et al. (2004) estimated that the main reservoir supplying water to the Panama Canal would decrease its capacity by 69% in 600 years. Our data were not compared to theirs, because some of differences in watershed delineation. If this is not addressed correctly, comparisons are invalid. Future work should include correcting this discrepancy in watershed delineation, in order to compare our results to Nichols et al. (2004). This will allow us to explore any changes in reservoir storage capacity based on our erosion rates.

Panama has erosion rates that are high when compared to other tropical regions where cosmogenic nuclides studies have taken place. The lack of relationships between physiographic variables and erosion rates found in this study suggests that there are other factors at play in controlling erosion at Panama. Seismicity seems to be an important control of erosion, as shown by the relationships found between seismic events and events magnitude at various distances off the watersheds.

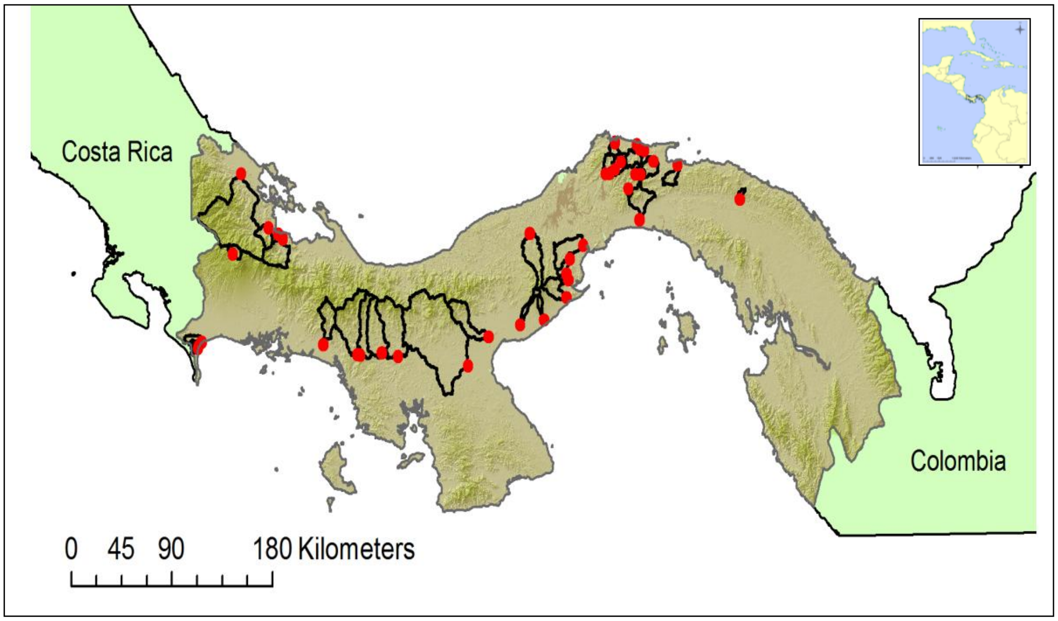

Figure 1: Location of samples and delineated watersheds across Panama. Sampling locations (n=40) are indicated with red dots, and the watersheds draining to them have been delineated and are outlined. Map data from CGIAR-CSI.

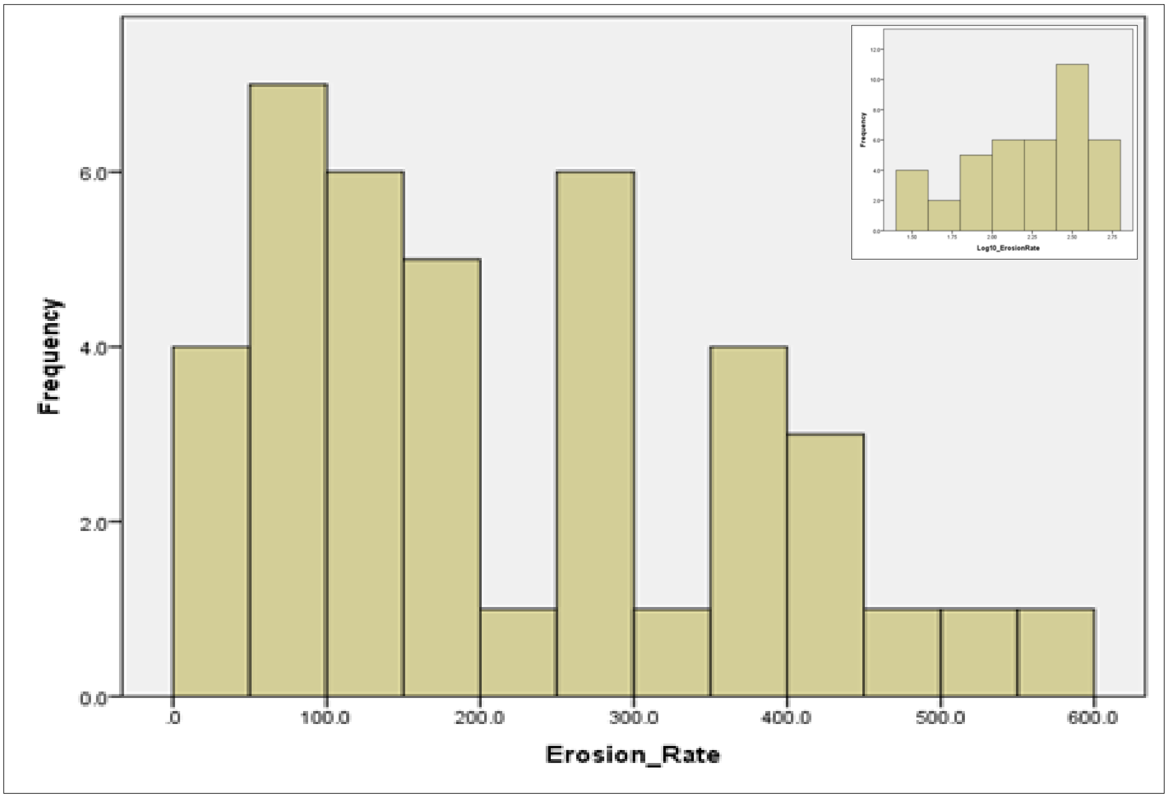

Figure 2: Erosion rate distribution. Erosion rates are highly skewed and do not follow a normal distribution. Skewness in the distribution is reduced after erosion rates are logarithmically (base 10) transformed, and the distribution approaches normality. Transformed erosion rates were used for parametric analysis.

SAMPLE ID	River	Region	Northing	Easting	^{10}Be content (x 10^3 atoms/g)	Erosion rate (m/Myr)
ANT	Anton	Central-East	928349	581595	22.7 ± 0.8	175 ± 7
BART	Bartolo	Southwest	916325	296212	7.4 ± 1.7	505 ± 120
BLA	Boquerón- Outlet	Eastern	1035402	657862	15.1 ± 1.3	258 ± 22
C_NATA	Chico near Nata	Central	919929	553005	137.0 ± 2.6	27.4 ± 0.5
CAIM	Caimito	Central-East	984975	637879	95.4 ± 1.8	34.1 ± 0.7
CAPI	Capira	Central-East	964402	622520	34.8 ± 0.7	115 ± 2
CHAG2009	Chagres Headwaters	Eastern	1034979	689087	68.1 ± 1.7	60.6 ± 1.6
CHAME	Chame	Central-East	947518	622722	23.7 ± 2.0	168.2 ± 14.2
CHAN	Changuinola	Northwest	1035839	331670	39.4 ± 1.2	160 ± 5
CHVIE_H	Chiriqui Viejo Headwaters	Northwest	978626	324237	36.1 ± 1.3	284 ± 10
CNGO	Cuango	Eastern	1056452	685595	14.3 ± 1.2	262 ± 22
COBRE	Cobre	Central	908408	457641	51.7 ± 2.2	75.8 ± 3.4
CORO	Corotu	Southwest	913112	293805	7.9 ± 0.6	459 ± 33
CUAN	Cuango	Eastern	1053293	688405	10.5 ± 0.8	366 ± 29
CUL	Culebra	Eastern	1052186	692279	13.1 ± 1.0	291 ± 23
DIOS	Nombre de Dios	Eastern	1057813	666135	8.3 ± 1.7	441 ± 92
FELIX	Felix	Central	914518	405028	8.0 ± 0.8	597 ± 62
GLOR	La Gloria	Northwest	993157	364491	35.4 ± 1.5	124 ± 5
GRUMO	Guarumo	Northwest	989538	369257	17.6 ± 1.0	283 ± 16
GUAN	Guanabano	Southwest	911892	293354	9.8 ± 1.2	367 ± 46
GUI	Guias	Central-East	931896	602809	18.1 ± 0.6	221 ± 8
IND	Indio	Central-East	993439	590052	66.4 ± 1.8	54.1 ± 1.5
MAND	Mandinga	Eastern	1044547	700401	19.6 ± 0.7	192 ± 7
MARIA	Santa Maria	Central	899354	534672	55.6 ± 1.3	68.0 ± 1.6
NDD	Nombre de Dios	Eastern	1058344	666294	9.0 ± 1.4	403 ± 62
PACORA	Pacora	Eastern	1003367	688077	10.9 ± 0.5	366 ± 18
PAN02	Carti Grande	Eastern	1041964	722329	31.7 ± 0.9	116 ± 3
PAN06	Brazos de Diablo	Eastern	1017356	777490	36.1 ± 0.9	107 ± 3
PERE	Perequete	Central-East	975402	625864	112.4 ± 2.1	29.1 ± .6
PHW	Pequini Headwaters	Eastern	1043899	671363	10.5 ± 1.5	378 ± 56
PLA	Pequini- Outlet	Eastern	1035529	660978	9.4 ± 0.6	417 ± 28
PLS	Upper Chagres	Eastern	684394	1035285	34.6 ± 0.7	121 ± 3
PSM	Pequini	Eastern	1038574	666242	12.4 ± 0.9	319 ± 24
ROBO	Robalo	Northwest	997213	356281	30.5 ± 0.9	148 ± 5
SAJ	Sajlices	Central-East	960284	624479	138.7 ± 3.1	26.1 ± 0.6
SAN_T	San Cristobal	Eastern	1025128	678293	57.6 ± 1.4	76.2 ± 1.9
SANPAB	San Pablo	Central	906069	472211	31.8 ± 0.7	134 ± 3
SMP	San Miguel	Eastern	1038660	666261	14.5 ± 1.7	268 ± 33
TABA	Tabasara	Central	907203	435575	61.9 ± 2.5	78.2 ± 3.2
VIGUI	Vigui	Central	906818	438230	50.1 ± 1.5	88.2 ± 2.6

Table 1: Sample locations are based in NAD 27-Canal Zone. Measured ^{10}Be in the samples is expressed in 1,000 atoms/g. CRONUS Earth Calculator was used to calculate erosion rates. The internal uncertainty calculated by CRONUS is expressed as the uncertainty of each erosion rate. Isotopic data standardized to KNSTD2007 with assumed ratio at 2850×10^{-15}

Region	**Average ^{10}Be (x 10^3 atoms/g)**	**Average erosion rate (m/Myr)**	**Average basin area (km^2)**
Southwestern (n= 3)	8.37 ± 1.27	444 ± 70	34 ± 28
Northwestern (n= 5)	31.8 ± 8.55	200 ± 77	476 ± 752
Central (n= 7)	56.6 ± 39.8	153 ± 199	783 ± 815
Central-east (n= 8)	64.0 ± 46.6	103 ± 77	142 ± 141
Eastern (n= 17)	18.7 ± 15.0	264 ± 151	84 ± 64

Table 2: Regional clustering data. Isotopic content, erosion rates and area for each region were averaged, and the standard deviation was calculated and is expressed as the standard deviation of the measurements. The number of watersheds in each region is indicated on the first column.

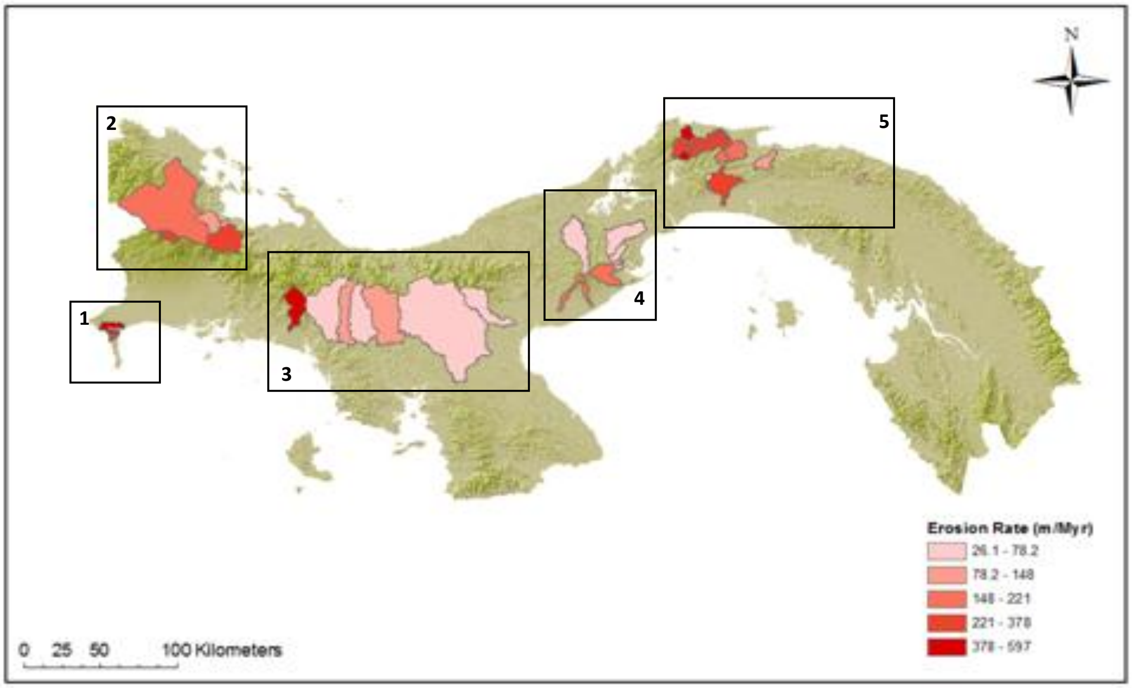

Figure 3: Spatial distribution of erosion rates. There is no spatial pattern of the erosion rates across Panama. Rapidly eroding watersheds are scattered through the country. For regional analysis, samples were divided into 5 groups: Southwestern (box 1), Northwestern (2), Central (3), Central-East (4), and Eastern (5). In order to perform ANOVA at the regional scale, watersheds were classified using the number assigned to each geographical region in this figure.

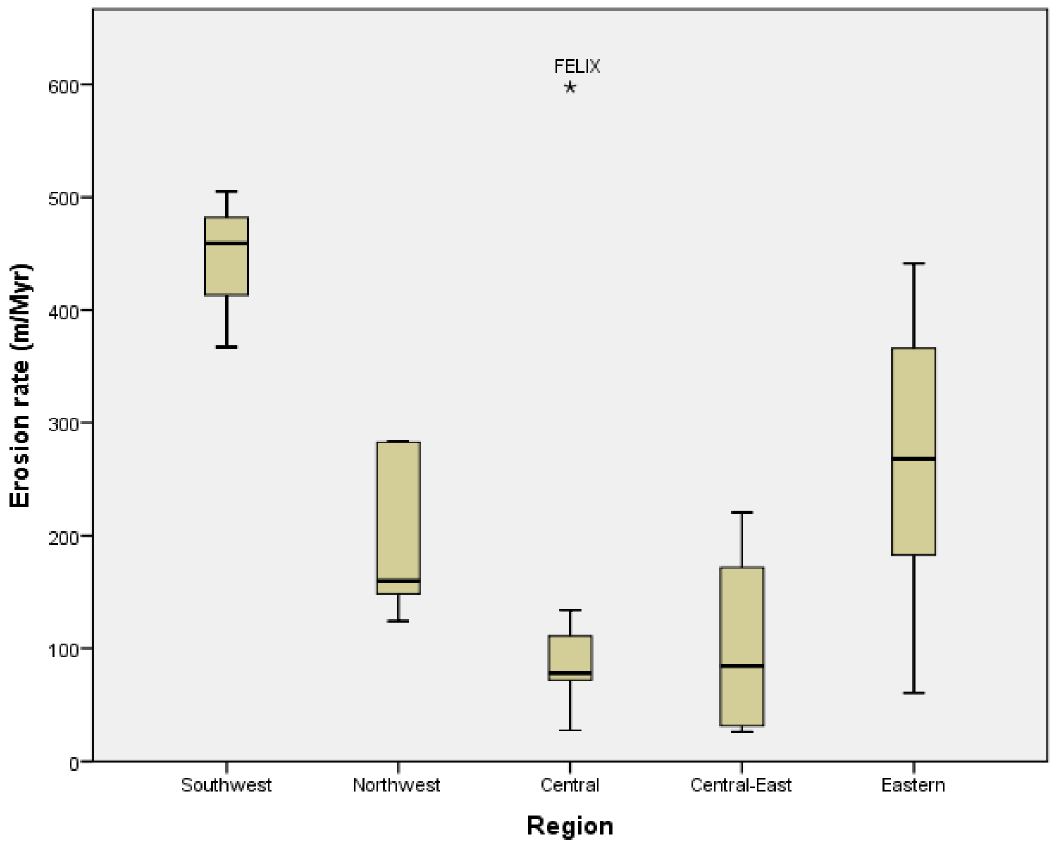

Figure 4: Average erosion by region. The lines inside the boxes represent the median of each region. Horizontal lines in the bars represent the minimum and maximum values for each region. The southwestern region hast the highest average erosion rate, and the central region has the highest variability. Rio Felix, represented by an asterisk, is an extreme outlier in our dataset.

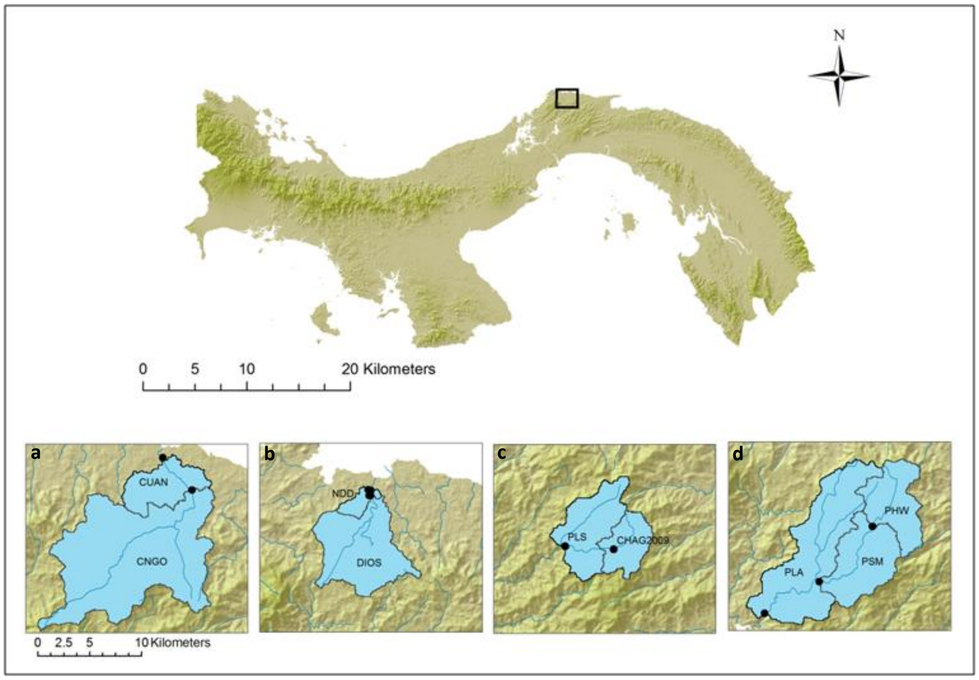

Figure 5: Spatial replicate samples. Nested watersheds for rivers that were sampled more than once along their length: Rio Cuango (a), Rio Nombre de Dios (b), Rio Chagres (c), and Rio Pequini (d). Black dots represent the sample locations. Black box outlines the area where all nested watersheds are located.

River	Sample name	Distance between samples (km)	Sample collection year	^{10}Be concentration (× 10^3 atoms/g)	Erosion Rate (m/Myr)	% SD erosion rates within each river	Subwatershed area (km^2)
Nombre de Dios	NDD	0.55	2004	9.0 ± 1.4	403 ± 62	6	62.46
	DIOS		2007	8.3 ± 1.7	441 ± 92		56.6
Cuango	CNGO		2007	14.3 ± 1.2	262 ± 22		27.49
	CUAN	4.20	2004	10.5 ± 0.8	366 ± 29	23	142.04
Pequini	PHW		2004	10.5 ± 1.5	378 ± 56		34.21
	PLA	13.3 (PHW-PLA)	2004	9.4 ± 0.6	417 ± 28		35.14
	PSM	7.40 (PHW-PSM)	2004	12.4 ± 0.9	319 ± 24	13	76.06
Upper Chagres	CHAG2009	4.7 (CHAG2009-PLS)	2009	68.1 ± 1.7	60.6 ± 14.2		21.27
	PLS		2009	23.2 ± 0.7	183 ± 68	71	56.57

Table 3: Nested watersheds summarized data. Distances were measured in ArcGIS. Percent standard deviation was calculated for each river. Area for each subwatershed was calculated based on a 90-m SRTM DEM using Matlab.

River	Sample Name	Erosion Rate (m/Myr)	Subwatershed Area (km^2)	Erosion between Watersheds (m/Myr)
Nombre de Dios	NDD	403 ± 62	58.60	215
	DIOS	441 ± 92	53.05	
Cuango	CNGO	262 ± 22	158.05	269
	CUAN	366 ± 29	132.18	
Upper Chagres	CHAG2009	60.6 ± 14.2	20.11	250
	PLS	183 ± 68	56.57	
Pequini (A)	PHW	378 ± 56	32.06	270
	PSM	319 ± 24	70.76	
Pequini (B)	PSM	319 ± 24	70.76	509
	PLA	417 ± 28	146.18	
Pequini (C)	PHW	378 ± 56	32.06	428
	PLA	417 ± 28	146.18	

Table 4: Erosion rates for the area between subwatersheds were calculated using the equation presented by Granger et al. (1996): $E_{2-1} = E_2A_2 - E_1A_1 / A_2 - A_1$, where A is the Area and E the erosion rate of the subcatchments, obtained from Matlab and CRONUS, respectively. These data was used to calculate the erosion rate of the area between two samples. A_1 and E_1 represent the area and erosion of the watershed delineated from the upstream sampling point. Similarly A_2 and E_2 represent the sample taken downstream, with reference to A_1 and E_2.

Variable	R^2 (n=40)	R^2 (n=5)
Slope	*0.009 (p=0.955)*	*0.192 (p=0.460)*
Area	*0.223 (p= 0.166)*	*0.267 (p=0.372)*
Relief	*0.196 (p= 0.226)*	*0.353 (p=0.290)*
Elevation	*0.040 (p= 0.805)*	*0.186 (p=0.468)*
Average Temperature	*0.041 (p= 0.800)*	*0.071 (p=0.666)*
Isothermality	0.381 (p= 0.015)	*0.164 (p=0.499)*
Temperature Seasonality	0.445 (p= 0.004)	*0.419 (p=0.237)*
Max Temp Warm Month	*0.066 (p= 0.686)*	*0.160 (p=0.504)*
Min Temp Cold Month	*0.005 (p= 0.676)*	*0.004 (p=0.921)*
Temperature Range	*0.019 (p= 0.907)*	*0.270 (p=0.369)*
Temperature Wet Quart	*0.074 (p= 0.648)*	*0.074 (p=0.658)*
Temperature Dry Quart	*0.037 (p= 0.823)*	*0.060 (p=0.692)*
Temperature Warm Quart	*0.026 (p= 0.876)*	*0.076 (p=0.654)*
Temperature Cold Quart	*0.084 (p= 0.605)*	*0.046 (p=0.728)*
Annual Precipitation	*0.307 (p= 0.054)*	*0.000 (p=0.973)*
Mean Diurnal Range	*0.055 (p= 0.737)*	*0.156 (p=0.511)*
Precipitation Wet Month	*0.048 (p= 0.771)*	*0.450 (p=0.215)*
Precipitation Dry Month	0.319 (p= 0.045)	*0.000 (p=0.981)*
Precipitation Seasonality	0.394 (p= 0.012)	*0.003 (p=0.936)*
Precipitation Wet Quart	*0.045 (p= 0.784)*	*0.083 (p=0.638)*
Precipitation Dry Quart	0.376 (p= 0.017)	*0.003 (p=0.928)*
Precipitation Warm Quart	*0.292 (p= 0.068)*	*0.005 (p=0.913)*
Precipitation Cold Quart	*0.023 (p= 0.889)*	*0.027 (p=0.792)*
Tree Cover	0.351 (p= 0.026)	*0.417 (p=0.239)*
Chemical Weathering	0.726 (p= 0.004)	-
Peak Ground Acceleration	0.307 (p= 0.054)	*0.589 (p=0.130)*
Surface Geology	*F = 2.427 (p= 0.102)*	-
Seismic Events 100m	*0.184 (p= 0.256)*	*0.392 (p=0.258)*
Average Depth 100m	*0.128 (p= 0.430)*	*0.028 (p=0.786)*
Average Magnitude 100m	*0.155 (p= 0.340)*	*0.074 (p=0.658)*
Seismic Events 10km	0.338 (p= 0.033)	0.813 (p=0.036)
Average Depth 10km	*0.140 (p= 0.389)*	*0.302 (p=0.338)*
Average Magnitude 10km	*0.220 (p= 0.172)*	*0.196 (p=0.456)*
Seismic Events 25km	0.350 (p = 0.027)	*0.474 (p=0.199)*
Average Depth 25km	0.334 (p = 0.035)	*0.477 (p=0.196)*
Average Magnitude 25km	0.431 (p = 0.005)	*0.679 (p=0.086)*
Seismic Events 50km	0.363 (p = 0.021)	*0.706 (p=0.075)*
Average Depth 50km	0.466 (p = 0.002)	*0.450 (p=0.215)*
Average Magnitude 50km	0.368 (p = 0.019)	*0.173 (p=0.486)*
Seismic Events 75km	0.348 (p = 0.028)	*0.389 (p=0.157)*
Average Depth 75km	0.420 (p = 0.007)	*0.390 (p=0.260)*
Average Magnitude 75km	0.550 (p = 0.000)	*0.407 (p=0.247)*
Average Depth 100km	0.*198 (p= 0.221)*	*0.286 (p=0.354)*
Average Magnitude 100km	0.352 (p = 0.026)	*0.407 (p=0.247)*
Seismic Events 100km	0.316 (p= 0.047)	*0.179 (p=0.478)*

Table 5: Regression coefficients for erosion and analyzed variables. Column two presents the results for the global analysis, including all watersheds individually. Results for regional analysis, when samples were grouped and the sample number is reduced to five, are presented in column three. All parametric analyses were performed with $\log_{10}$ transformed erosion data. Fields in italics represent relationships that are not statistically significant at the 0.05 significance level. For regional analysis, the number of seismic

events is the sum of the events in all watersheds. For all other parameters, values were averaged. No analysis was done for surface geology at the regional scale, because only two categories were present when samples were grouped. Sedimentary rocks are not represented. No chemical weathering analysis was done at the regional scale. The 9 watersheds that have silicate weathering data are not representative of all regions.

Variable	R^2	p	Slope of line
Events 100m	*0.184*	*0.256*	*0.006*
Depth 100m	*0.128*	*0.760*	*-0.002*
Magnitude 100m	*0.155*	*0.340*	*-0.026*
Events 10km	0.338	0.033	0.001
Depth 10km	*0.140*	*0.389*	*-0.001*
Magnitude 10km	*0.220*	*0.172*	*0.050*
Events 25km	0.350	0.027	0.001
Depth 25km	0.334	0.035	-0.005
Magnitude 25km	0.431	0.005	-0.165
Events 50km	0.363	0.021	0.000
Depth 50km	0.466	0.002	-0.008
Magnitude 50km	0.368	0.019	-0.361
Events 75km	0.348	0.028	0.0000
Depth 75km	0.420	0.007	-0.012
Magnitude 75km	0.550	0.000	-1.359
Events 100km	0.316	0.047	0.000
Depth 100km	*0.198*	*0.221*	*-0.006*
Magnitude 100km	0.352	0.026	-1.080

Table 6: Seismic variables and their relation to erosion. Regional analyses of the relationship between seismic variables and erosion is included in table 5. Seismicity variables (number of events, average depth and average magnitude) were quantified in the six arbitrarily selected buffers shown in column one. The strength of the relationship between any given variable and erosion is presented in column two and p-value in column three. The slope of the line is presented in the last column four. Fields in italics represent relationships that are not statistically significant at the 0.05 significance level.

River (sample ID)	Silicate weathering[1] (t km^{-2} yr^{-1})	Sediment yield (t km^{-2} yr^{-1})	Percent of Silicate in sediment yield
Anton (ANT)	38.6	474	8.2
Chagres (CHAG2009)	20.8	164	12.7
Chiriqui Viejo (CHVIEH)	42.7	766	5.6
Chico (C-NATA)	13.8	73.9	18.7
Cobre (COBRE)	26.2	205	12.8
Felix (FELIX)	34.2	1613	2.1
San Pablo (SANPAB)	26.9	362	7.4
Tabasara (TABA)	23.7	211	11.2
Vigui (VIGUI)	26.5	239	11.1

Table 7: Comparison of sediment yield and silicate weathering rates in Panama. Silicate weathering was measured by Steven Goldsmith and Russell Harmon (unpublished data)

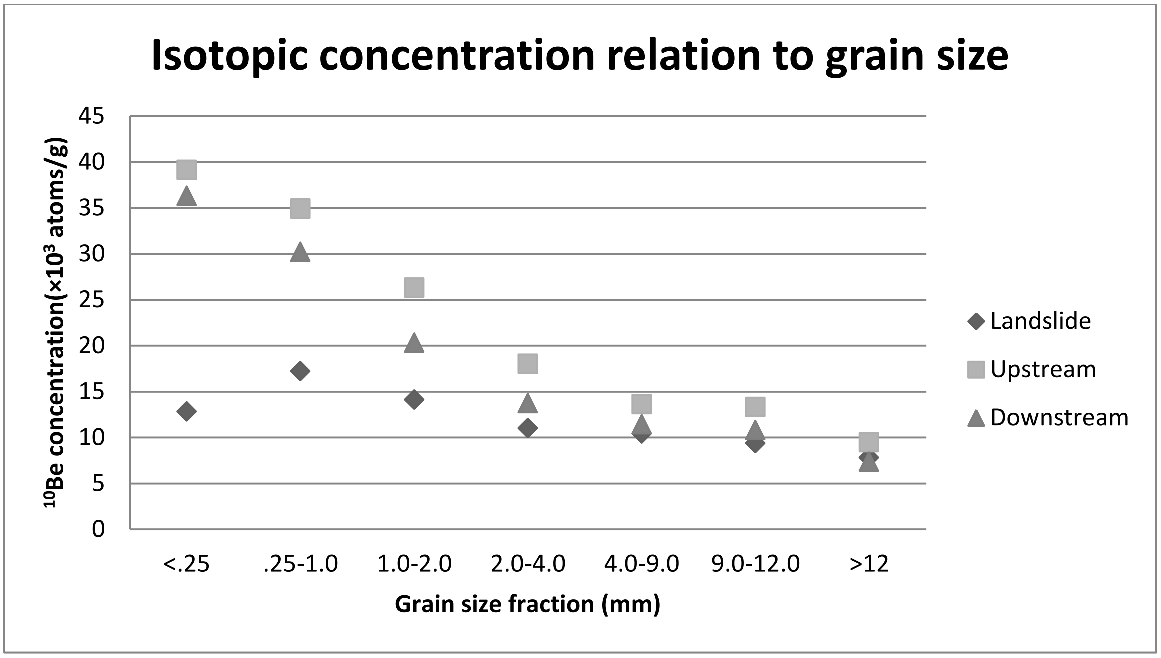

Figure 6: Isotopic concentration variation with grain size. Two general trends can be identified from the grain size fractions of our data. First, ^{10}Be concentration decreases as grain size increases, except for the coarser size fraction (>12mm). Also, material from the landslide (PLSS) almost always has the lowest isotopic concentration of each grain size fraction.

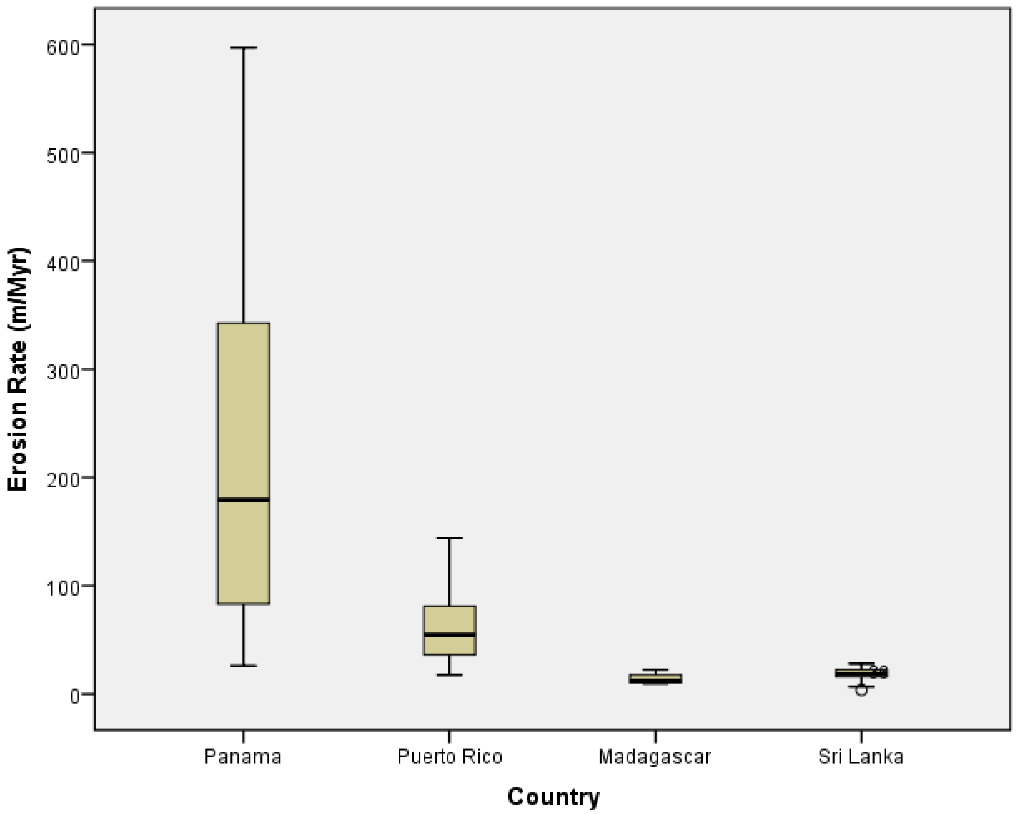

Figure 7: Comparison of cosmogenic-determined erosion rates in tropical climates. Bottom and top of the boxes represent the lower and upper quartile, respectively. Lines inside the boxes represent the median erosion rate of published data for each country. The minimum and maximum erosion rates are represented by the horizontal lines in the bars. In Panama, erosion rates averaged 218 m/Myr (n=40), in Puerto Rico averaged 60.9 m/Myr (n=24). Erosion rate averaged 18.1 m/Myr in the 4 watersheds studied in Madagascar, and 13.9 m/Myr in Sri Lanka (n=16). Panama data previously published by Nichols et al. (2005) is not included in this figure.

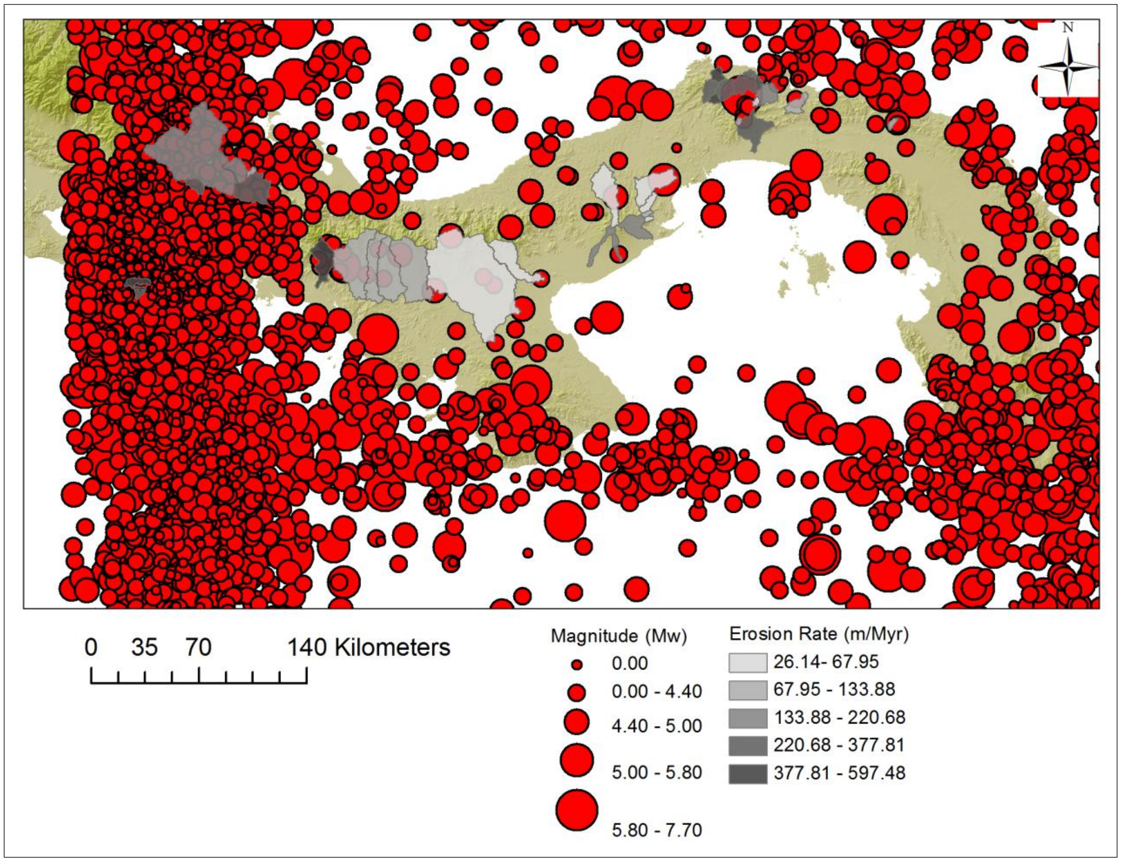

Figure 8: Seismic activity in Panama. Circles represent individual seismic events (1900-2011). Circle size is representative of the event magnitude. Watershed color is representative of erosion rate. Location of Rio Felix, with the highest erosion rate in our dataset, is marked with the black box. Seismic data provided by the Instituto de Geociencias (Eduardo Camacho, personal communication).

Paper references→NEED JOURNAL FORMATTING!(Also, check order specially for multiple works from same author)

Adamek, S., C. Frolich, and W. Pennington. "Seismicity of Te Carubbean-Nazca Boundary: Constraints on Microplate Tectonics of the Panama Region." *Journal of Geophysical Research* 93 (1988): 2053-75.

Bierman, P.R., and Kyle Keedy Nichols. "Rock to Sediment—Slope to Sea With ^{10}Be—Rates of Landscape Change." *Annual Review of Earth and Planetary Sciences* 32, no. 1 (2004): 215-55.

Bilotta, G. S., and R. E. Brazier. "Understanding the Influence of Suspended Solids on Water Quality and Aquatic Biota." [In eng]. *Water Res* 42, no. 12 (Jun 2008): 2849-61.

Brown, Erik T., Robert F. Stallard, Matthew C. Larsen, Didier Bourles, L., Grant M. Raisbeck, and Francoise Yiou. "Determinarion of Predevelopment Denudation Rates of an Agricultural Watershed (Cayaguás River, Puerto Rico) Using in-Situ Produced ^{10}Be in River-Borne Quartz." *Earth and Planetary Science Letters* 160 (1998): 723-28.

Brown, Erik T., Robert F. Stallard, Matthew C. Larsen, Grant M. Raisbeck, and Francoise Yiou. "Denudation Rates Determined from the Accumulation of in-Situ Produced ^{10}Be in the Luquillo Experimental Forest, Puerto Rico." *Earth and Planetary Science Letters* 129 (1995): 193-202.

Camacho, E., C. Lindholm, A. Dahle, and H. Bungum. "Seismic Hazard Assessment in Panama." *Engineering Geology* 48 (1997): 1-6.

Cox, Rónadh, Paul Bierman, Matthew C Jungers, and A. F Michel Rakotondrazafy. "Erosion Rates and Sediment Sources in Madagascar Inferred From ^{10}Be Analysis of Lavaka, Slope, and River Sediment." *The Journal of Geology* 117, no. 4 (2009): 363-76.

Davidson, D. "Recent Uplift of the Burica Peninsula, Panama and Costa Rica, Recorded by Marine Terraces." Honors Thesis, Trinity University 2010.

Gosse, John C., and Fred M. Phillips. "Terrestrial in Situ Cosmogenic Nuclides: Theory and Application." *Quaternary Science Reviews* 20 (2001): 1475-560.

Harden, Carol P. "Human Impacts on Headwater Fluvial Systems in the Northern and Central Andes." *Geomorphology* 79, no. 3-4 (2006): 249-63.

Harmon, R. S. "Geological Development of Panama." In *The Río Chagres, Panama: A Multidisciplinary Profile of a Tropical Watershed*, edited by R. S. Harmon. 354. Netherlands: Springer, 2005.

Hewawasam, Tilak, Friedhelm von Blanckenburg, M. Schaller, and Peter Kubik. "Increase of Human over Natural Erosion Rates in Tropical Highlands Constrained by Cosmogenic Nuclides." *Geology* 31, no. 7 (2003): 597-600.

Hunt, A. L., G. A. Petrucci, P. R. Bierman, and R. C. Finkel. "Metal Matrices to Optimize Ion Beam Currents for Accelerator Mass Spectrometry." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 243, no. 1 (2006): 216-22.

Kohl, C. P., and K. Nishiizumi. "Chemical Isolation of Quartz for Measurement of in-Situ Produced Cosmogenic Nuclides." *Geochimica et Cosmochimica Acta* 56 (1992): 3583-87.

Lal, D., and B Peters. "Cosmic-Ray Produced Radioactivity on the Earth." In *Handuch Der Physik*, edited by K. Sitte. 551-612. New York: Springer-Verlag, 1967.

Malusà, Marco G., and Giovanni Vezzoli. "Interplay between Erosion and Tectonics in the Western Alps." *Terra Nova* 18, no. 2 (2006): 104-08.

Milliman, J. D., and J. P. Syvitski. "Geomorphic/Tectonic Control of Sediment Discharge to the Ocean: The Importance of Small Mountainous Rivers." *The Journal of Geology* 100 (1992): 525-44.

Nichols, Kyle K., Paul R. Bierman, Robert Finkel, and Jennifer Larsen. "Long-Term (10 to 20 Kyr) Sediment Generation Rates for the Upper Rio Chagres Basin Based on Cosmogenic ^{10}Be." In *The Rio Chagres, Panama: A Multidisciplinary Profile of a Tropical Watershed*, edited by Russell S. Harmon. 354. The Netherlands: Springer, 2004.

Niemi, Nathan A., Michael Oskin, Douglas W. Burbank, Arjun M. Heimsath, and Emmanuel J. Gabet. "Effects of Bedrock Landslides on Cosmogenically Determined Erosion Rates." *Earth and Planetary Science Letters* 237, no. 3-4 (2005): 480-98.

Ouimet, William B. "Landslides Associated with the May 12, 2008 Wenchuan Earthquake: Implications for the Erosion and Tectonic Evolution of the Longmen Shan." *Tectonophysics* 491, no. 1-4 (2010): 244-52.

Palka, E. J. "A Geographic Overview of Panama." In *The Rio Chagres, Panama. A Multidisciplinary Profile to a Tropical Watershed*, edited by Russell S. Harmon. 3-18. Netherlands: Springer, 2005.

Palumbo, L., R. Hetzel, M. Tao, and X. Li. "Topographic and Lithologic Control on Catchment-Wide Denudation Rates Derived from Cosmogenic ^{10}Be in Two Mountain Ranges at the Margin of Ne Tibet." *Geomorphology* 117, no. 1-2 (2010): 130-42.

Panamá, Contraloría General de la República de. "Estadísticas Ambientales: Años 2000-04." edited by Instituto Nacional de Estadística y Censo. Panamá, República de Panamá: Contraloría General de la República de Panamá, 2005.

Panamá, Contraloría General de la República de. "Panamá en cifras: Años 2000-04." edited by Instituto Nacional de Estadística y Censo. Panamá, República de Panamá: Contraloría General de la República de Panamá, 2005.

Panamá, Contraloría General de la República de. "Estadísticas Ambientales: Años 2000-2004." Instituto Nacional de Estadística y Censo, 2008.

Panamá, Contraloría General de la República de. "Plan Nacional de Desarrollo Forestal: Modelo Forestal Sostenible." edited by Autoridad Nacional del Ambiente- ANAM, 2008

Portenga, Eric W., and Paul R. Bierman. "Understanding Earth's Eroding Surface with ^{10}Be." *GSA Today* 21, no. 8 (2011): 4-10.

Riebe, Clifford S., James W. Kirchner, and Darryl E. Granger. "Quantifying Quartz Enrichment and Its Consequences for Cosmogenic Measurements of Erosion Rates from Alluvial Sediment and Regolith." *Geomorphology* 40 (2001): 15-19.

Riebe, Clifford S., James W. Kirchner, Darryl E. Granger, and R. C. Finkel. "Minimal Climatic Control on Erosion Rates in the Sierra Nevada, California." *Geology* 29, no. 5 (2001): 447-50.

Riebe, Clifford S., James W. Kirchner, and Robert C. Finkel. "Long-Term Rates of Chemical Weathering and Physical Erosion from Cosmogenic Nuclides and Geochemical Mass Balance." *Geochimica et Cosmochimica Acta* 67, no. 22 (2003): 4411-27.

Riebe, Clifford S., James W. Kirchner, and Robert C. Finkel. "Erosional and Climatic Effects on Long-Term Chemical Weathering Rates in Granitic Landscapes Spanning Diverse Climate Regimes." *Earth and Planetary Science Letters* 224, no. 3-4 (2004): 547-62

Schuchert, C. "Panama." Chap. 37 In *Historical Geology of the Antillean-Caribbean Region or the Lands Bordering the Gulf of Mexico and the Caribbean Sea*. 810. New York: John Wiley & Sons, 1995von Blanckenburg, Friedhelm. "The Control Mechanisms of Erosion and Weathering at Basin Scale from Cosmogenic Nuclides in River Sediment." *Earth and Planetary Science Letters* 237 (2005): 462-79.

Summerfield, M. A., and N. J. Hulton. "Natural Controls of Fluvial Denudation Rates in Major World Drainage Basins." *Journal of Geophysical Research* 99, no. B7 (1994): 13871-83.

Terry, R. A. *A Geological Reconnaissance of Panama*. San Francisco, CA: California Academy of Sciences, 1956.

Trimble, S.W.. "The Fallacy of Stream Equilibrium in Contemporary Denudation Studies." *American Journal of Science* 277 (1977): 876-87.

Varela, Sara, Jesús Rodríguez, and Jorge M. Lobo. "Is Current Climatic Equilibrium a Guarantee for the Transferability of Distribution Model Predictions? A Case Study of the Spotted Hyena." *Journal of Biogeography* 36, no. 9 (2009): 1645-55.

von Blanckenburg, F., T. Hewawasam, and P.W. Kubik. "Cosmogenic Nuclide Evidence for Low Weathering and Denudation in the Wet, Tropical Highlands of Sri Lanka." *Journal of Geophysical Research* 109, no. F3 (2004).

von Blanckenburg, Friedhelm. "The Control Mechanisms of Erosion and Weathering at Basin Scale from Cosmogenic Nuclides in River Sediment." *Earth and Planetary Science Letters* 237 (2005): 462-79.

West, A., A. Galy, and M. Bickle. "Tectonic and Climatic Controls on Silicate Weathering." *Earth and Planetary Science Letters* 235, no. 1-2 (2005): 211-28.