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**Long-term background denudation rates of southern and southeastern Brazilian
watersheds estimated with cosmogenic ^{10}Be**

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Abstract

In comparison to humid temperate regions of the Northern Hemisphere, less is known about the long-term (millennial scale) background rates of erosion in Southern Hemisphere tropical watersheds. In order to better understand the rate at which watersheds in southern and southeastern Brazil erode, and the relationship of that erosion to climate and landscape characteristics, we made new measurements of *in situ* produced ^{10}Be in river sediments and we compiled all extant measurements from this part of the country.

New data from 14 watersheds in the states of Santa Catarina ($n = 7$) and Rio de Janeiro ($n = 7$) show that erosion rates vary there from 13 to 90 m/My (mean = 32 m/My; median = 23 m/My) and that the difference between erosion rates of basins we sampled in the two states is not significant. Sampled basin area ranges between 3 and 14,987 km², mean basin elevation between 235 and 1606 m, and mean basin slope between 11 and 29°. Basins sampled in Rio de Janeiro, including three that drain the Serra do Mar escarpment, have an average basin slope of 19°, whereas the average slope for the Santa Catarina basins is 14°. Mean basin slope ($R^2 = 0.73$) and annual precipitation ($R^2 = 0.57$) are most strongly correlated with erosion in the basins we studied. At three sites where we sampled river sand and cobbles, the ^{10}Be concentration in river sand was greater than in the cobbles, suggesting that these grain sizes are sourced from different parts of the landscape.

Compiling all cosmogenic ^{10}Be -derived erosion rates previously published for southern and southeastern Brazil watersheds to date ($n = 76$) with our 14 sampled basins, we find that regional erosion rates (though low) are higher than those of watersheds also located on other passive margins including Namibia and the southeastern North America. Brazilian basins erode at a pace similar to escarpments in southeastern North America. Erosion rates in southern and

southeastern Brazil are directly and positively related to mean basin slope ($R^2 = 0.33$) and weakly but significantly to mean annual precipitation ($R^2 = 0.05$). These relationships are weaker when considering all southern and southeastern Brazil samples than they are in our smaller, localized data set. We find that smaller, steeper headwater catchments (many on escarpments) erode faster than the larger, higher-order but lower slope catchments. Erosion in southern and southeastern Brazil appears to be controlled largely by mean basin slope with lesser influence by climate and lithology.

Keywords: escarpment, erosion, isotope, tropical

1. Introduction

Since the mid-1990s, cosmogenic nuclides (most commonly ^{10}Be) have been widely used as a method to measure long-term, background, millennial scale erosion rates (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). Portenga and Bierman (2011) compiled all published ^{10}Be -derived erosion rates and recalculated the erosion rates using the CRONUS online erosion calculator (<http://hess.ess.washington.edu/>) to standardize the measurements and allow for comparison of erosion rates among sites worldwide. Although the method has been applied in all climate regimes, its usage in tropical, subtropical, and arctic landscapes is minimal compared to applications in dry and temperate climates. Out of 1149 samples included in that compilation, only 98 were collected from the tropics.

Studies not included in Portenga and Bierman (2011), with data from tropical areas (such as Puerto Rico, Africa, and Australia), include several from Brazil (Salgado et al., 2006, 2007, 2008, 2013; Cherem et al., 2012; Lal et al., 2012; Barreto et al., 2013, 2014; Hinderer et al., 2013; Rezende et al., 2013, Brocard et al., 2014a,b; Nichols et al., 2014). Of the eight papers that used ^{10}Be to decipher Brazilian landscapes, seven reported samples collected from Minas Gerais State and one reports on samples from Paraná State. Erosion rates in these papers are calculated using a variety of different scaling and production parameters and thus are not directly comparable.

In this paper, we provide new data (from the so-far unsampled Brazilian states of Santa Catarina and Rio de Janeiro), and we compile and reanalyze using a homogeneous approach all extant *in situ* produced ^{10}Be data for southern and southeastern Brazil. The goals of this paper are to (i) understand better the range and central tendency of erosion rates in southern and southeastern Brazil and (ii) determine whether those rates are related to topographic and climatic

variables such as slope and precipitation. Such data are important for land management in rapidly developing, but still agriculturally intensive, nations like Brazil (Martinelli et al., 2010). Long-term background erosion rates, such as those we provide here, are useful as a benchmark against which to compare contemporary rates of erosion and sediment transport driven by human-induced change (Brown et al., 1998; Hewawasam et al., 2003; Vanacker et al., 2007; Reusser et al., 2015).

2. Geologic, tectonic, and climatic setting of Rio de Janeiro and Santa Catarina states

Rio de Janeiro and Santa Catarina states are located close to the Atlantic coast in southeastern and southern Brazil and are mostly underlain by high-grade metamorphic rocks (Domínguez, 2009). Both states have escarpment topography parallel to the coast, associated with the South American plate passive margin, that separates lower coastal plains from higher interior plateaus (Ollier, 2004; Domínguez, 2009). The state of Rio de Janeiro is mostly mountainous and mainly underlain by gneisses and granites (Heilbron et al., 2008; Fernandes et al., 2010; Silva et al., 2015). The eastern part of Santa Catarina State is occupied by Atlantic lowlands and the southern Brazilian highlands (Behling, 1995) (Fig. 1).

The Serra do Mar escarpment is mostly composed of gneisses, granites, and migmatites (Heilbron and Machado, 2003; Silva et al., 2015) intruded by Mesozoic diabase dikes (Guedes et al., 2005; Almeida et al., 2013). Normal faults of Mesozoic-Cenozoic age raised and lowered tectonic blocks, topographically partitioning the area (Fernandes et al., 2010). One of these raised blocks, the Serra do Mar escarpment, may represent a Cretaceous South Atlantic rift border (Gallagher et al., 1995; Almeida and Carneiro, 1998) or the retreat of a dissected Cenozoic fault scarp (Asmus and Ferrari, 1978). The dissection increased during Paleogene and Neogene tectonic and thermal reactivations, causing subsidence or uplift of earlier erosional

surfaces (Hackspacher et al., 2004; Zalán and Oliveira, 2005). The topography is the result of differential chemical and physical denudation of the gneisses and granites, which are intersected by subvertical faults and fractures that accelerate channel incision, as well as landslides and rock falls along the fractured walls (Fernandes et al., 2010).

Rio de Janeiro and Santa Catarina experience high average humidity and temperatures along the coast and more stable and lower temperatures in the highlands (Williams, 1962; Nunes et al., 2009). Based on the Köppen-Geiger climate classification, Rio de Janeiro has a tropical climate, with a dry season in the winter (Aw) along the coast and warm temperatures along with dry winters (Cw) toward the interior (Alvares et al., 2013). Temperatures reach their maximum between January and February (29°C) and minimum in June and July (21°C) (Brickus et al., 1998), with mean annual temperature around 23°C (Nunes et al., 2009). Rio de Janeiro State receives between 1200 and 2000 mm rainfall annually (Nunes et al., 2009; de Sherbinin and Hogan, 2011; Alvares et al., 2013). Santa Catarina State has a steady warm and moist climate with precipitation in all months (Cfa) and a temperature over 22°C during its warmest month based on the Köppen-Geiger system (Behling, 1995; Alvares et al., 2013). Mean temperatures range from 14°C in the winter to 23°C in the summer (annual mean of 19°C), the relative humidity remains around 85% year round, and precipitation varies between 1250 and 1400 mm annually (Alvares et al., 2013).

3. Previous work measuring denudation rates in Brazil

Eight studies of erosion rates in southeastern Brazil have been published, some of which report subsets of the same data using different nomenclature. Salgado et al. (2006) used ^{10}Be to compare chemical weathering and long-term denudation rates in Minas Gerais, Brazil (see Fig.

DR1 for watershed locations). They found that chemical weathering and denudation were the highest in marbles; intermediate in schists, phyllites, granites, gneisses, and migmatites; and lowest in quartzites. A later study by Salgado et al. (2008) in the same region provided more evidence consistent with differential erosion: watersheds underlain by quartzites and itabirites (banded iron formations) eroded more slowly than those underlain by other lithologies.

Barreto et al. (2013) measured denudation in watersheds draining three different escarpments in Minas Gerais, Brazil, and found that they all eroded slowly, from 2 to 6 m/My (Fig. DR2). In another study, Salgado et al. (2007) measured erosion rates in subbasins underlain by schist, phyllite, granite, and gneiss (a subset of the lithologies included in their 2008 publication) and found no difference in erosion because of lithology, but rather that slope dissection controlled the rate of denudation in Minas Gerais (Fig. DR1). Rezende et al. (2013) also found differences in denudation based on lithology; their work measured background erosion rates of nine subbasins along the drainage divide between the Grande and Paraíba do Sul rivers in Minas Gerais (Fig. DR3). They measured erosion rates between 7 and 28 m/My, with the slowest rates in watersheds underlain by granite (Rezende et al., 2013).

Two studies compared denudation rates of watersheds draining the Serra do Mar (in Paraná State) and the Serra da Mantiqueira (in Minas Gerais State close to the border with Rio de Janeiro) escarpments to watersheds draining the highlands (Cherem et al, 2012; Salgado et al., 2013; FigsDR1, DR4). Both studies found that escarpment-draining watersheds eroded at a significantly faster pace than the watersheds draining the highlands. Rezende et al. (2013), also working in Serra da Mantiqueira, compared denudation rates at the divide between the Grande (a tributary of the Paraná River) and the Paraíba do Sul river basins at the southern border of Minas Gerais State. Their work found that basins draining the escarpment erode faster than those

draining the highlands. Barreto et al. (2014) examined the effects of diamond extraction denudation rates. They found that drainages overloaded with material resulting from mining saprolite upstream had higher apparent denudation rates than unaffected streams, likely because mining introduced material from well beneath the surface into the streams.

4. Methods

We collected 14 active channel sediment samples in two different field seasons. Rio de Janeiro watersheds ($n = 7$) were sampled in 2011 and Santa Catarina watersheds ($n = 7$) in 2012 (Fig. 2). We also sampled river cobbles at three Rio de Janeiro sites where we sampled active channel sediments (BRA01, 02, 03). We sample sand from several locations in and adjacent to the active channel and mixed them. Cobbles were sampled in a similar fashion and amalgamated before analysis.

All watersheds sampled in Rio de Janeiro State are subbasins of the Paraíba do Sul basin (Fig. 1), with the exceptions of three samples (BRA01, 02, 03) that were collected in coastal watersheds that drain the escarpment of the Serra dos Órgãos (a local name for the Serra do Mar). Four samples (BRA19, 20, 21, 22) came from watersheds where most of the catchment area is located in Minas Gerais State, which drains the Serra da Mantiqueira. Basin areas range from 3 to 9,169 km². The watersheds are mostly underlain by deformed and metamorphosed gneiss and granitic rocks. Mean elevation for the Rio de Janeiro basins is between 235 and 1606 m, average basin slope ranges between 12 and 29°, and mean annual precipitation is between 1215 and 1824 mm.

The Santa Catarina watersheds we sampled, all located within the Itajaí-Açu basin, drain the Serra Geral, which extends to the southern part of Santa Catarina State (Fig. 1). Sampled

watersheds have areas between 5 and 14,987 km², with mean basin elevations ranging from 293 to 695 m and mean basin slopes between 11 and 17°. The watersheds receive between 1484 and 1649 mm of precipitation annually. Three of the watersheds are underlain by granite-gneiss-migmatite-granulite complexes, and four are underlain by sedimentary sequences.

Sediments were field-sieved to 250-850 µm, and river cobbles were crushed and sieved to the 250-850 µm fraction at the University of Vermont. Quartz from the samples was isolated and purified through a series of hydrochloric, hydrofluoric, and nitric acid etches, a modification of the method of Kohl and Nishiizumi (1992). Clean quartz was dissolved in hydrofluoric acid after the addition of a ⁹Be carrier extracted from beryl in the University of Vermont cosmogenic nuclide laboratory. Beryllium was isolated through successive anion and cation exchange extractions and precipitated as Be hydroxide (Corbett et al., 2016). The hydroxide was dried, burned, and packed into copper cathodes after being mixed with niobium. Samples were analyzed by Accelerator Mass Spectrometry (AMS) at the Scottish Universities Environmental Research Centre (SUERC) in East Kilbride, Scotland (Xu et al., 2010) and normalized to the NIST standard with an assumed ¹⁰Be/⁹Be ratio of 2.79×10^{-11} (Nishiizumi et al., 2007). Background correction was done using full process blanks run with each batch of 10 samples; the final uncertainty of the ratio is the uncertainty of the isotopic measurement and the blank propagated in quadrature.

All erosion rates (for our new data and for data from the literature) were calculated using the CRONUS online calculator version 2.2 (<http://hess.ess.washington.edu/>), the global production rate, and the time invariant Lal (1991)/Stone (2000) scaling scheme (see Table DR1 for CRONUS input). We chose that scaling scheme to allow for comparisons with the global dataset of Portenga and Bierman (2011). Changes in calculated erosion rates due to different

scaling schemes are negligible. The calculator requires an elevation and latitude representative of the basin from which the sediment is sourced. We typically generate these values following the approach of Portenga and Bierman (2011). However, in some cases, despite extensive communication with the authors of other published Brazilian studies, it was not possible to determine precisely their sampling locations; because of this uncertainty, we used the average elevation of each watershed and its centroid latitude and longitude to calculate the erosion rates we report here. As a sensitivity test, we compared CRONUS-calculated erosion rates for the 14 basins we sampled using effective elevation (c.f., Portenga and Bierman, 2011) and mean elevation. We find, on average, less than a 10% difference (Fig. 3). Because of this similarity, we used centroid location and mean basin elevation to calculate the erosion rate of all watersheds considered in this paper.

Climatic variables were extracted from the WorldClim data set (Hijmans et al., 2005) available at <http://www.worldclim.org/>. To calculate area, elevation, and slope for the watersheds, we used the Topodata 30-m DEM data set created and published by the Instituto Nacional de Pesquisas Espaciais, (available at <http://www.webmapit.com.br/inpe/topodata/>). The lithology data set we used was published by the Serviço Geológico do Brasil (available at <http://geobank.cprm.gov.br/>). The lithology data set is not detailed; hence, the description of lithology in our watersheds is generalized. We analyzed the relationship between erosion rates and a wide array of topographic, climatic, and geologic variables (elevation, slope, area, precipitation, lithology).

In order to compare our results to those previously published for Brazil, we used published locations of sampling points ($n = 76$) to delineate the watersheds and extract the information necessary to obtain erosion rates from CRONUS. We also quantified topographic

and climatic variables (mean annual precipitation, basin slope, area, and elevation) following the same procedure we used for our sites (see Table DR2).

All of the explanatory (topographic and climatic) variables for each watershed were quantified using ArcGIS 10.3 and entered into JMP 11, a statistical package, for parametric analysis. We performed all statistical analyses assessing significance at the 95% confidence level; therefore, we concluded that tests with p -values > 0.05 are not statistically significant.

5. Results

Erosion rates in the Brazilian drainage basins we sampled vary by a factor of 7, from 13 to 90 m/My ($n=14$, Table 1, Figs. DR5, DR6), with an average of 32 m/My and a median of 23 m/My. Erosion averaged 36 ± 19 m/My for the watersheds in Rio de Janeiro and 27 ± 13 m/My for the Santa Catarina watersheds (uncertainties here and elsewhere are one standard deviation). We found no statistically significant difference between the erosion rate of samples collected from Rio de Janeiro and those from Santa Catarina ($t = -0.77$, $p = 0.46$). The highest and lowest erosion rates in our study are in Rio de Janeiro watersheds. The highest erosion rate we measured was for a watershed draining the Serra do Mar escarpment (BRA3S). The erosion rates we measure, tens of meters per million years, integrate over tens of thousands of years and thus over late Pleistocene climate oscillations.

Based on lithology, our sampled watersheds can be divided into granitoid ($n = 5$), granite and gneiss ($n = 5$), and consolidated sedimentary lithologies ($n = 4$). There is no statistically significant difference in erosion rates as a function of these three lithologies ($F = 1.29$, $p = 0.31$). Basins underlain by consolidated sedimentary rocks in our study erode at an average rate of $20 \pm$

2 m/My, whereas the basins underlain by granite and gneiss are eroding at an average rate of 29 ± 15 m/My; watersheds underlain by granitoids erode at 43 ± 32 m/My on average.

Erosion rates in our data set are proportional to mean basin slope ($R^2 = 0.73$, $p < 0.001$; Fig. 4). The highest average basin slopes in our study (24 to 29°) are in watersheds that drain the Serra do Mar escarpment, where three of the four highest erosion rates are found. The relationship between erosion and mean annual precipitation (MAP) was also significant ($R^2 = 0.57$, $p = 0.002$; Fig. 5). If precipitation and slope are combined as predictive variables, the relationship with erosion improves slightly ($R^2 = 0.78$, $p = 0.0002$). While there is no significant bivariate relationship between erosion and watershed area ($R^2 = 0.13$, $p = 0.20$), smaller watersheds in general erode faster than larger ones (Fig. 6A, inset). Based on the area distribution of our watersheds, we can divide the samples by quartiles into the following groups: 2-9, 9-150, 150-7,010, and 7,010-15,000 km². Comparing the means (Fig. 6B), we find that the smaller watersheds (2-9 km²) erode significantly faster than the larger basins ($t = 2.23$, $p = 0.05$; Fig. 6A), most likely because small headwater watersheds on average have steeper hillslopes (21°) than larger watersheds (12°).

Comparing the isotopic concentration of cobbles and sand transported as bedload in three Rio de Janeiro channels (BRA01, 02, 03), the concentration of ¹⁰Be in cobbles is lower than in sand for all three sites (see Table 1). At one of the sites (BRA02), the isotopic concentration differs by over an order of magnitude between river sand (1.22×10^5 atoms/g) and cobbles (2.26×10^4 atoms/g).

6. Discussion

New erosion rate data, many of which are from samples collected from the steep continental margin of southern and southeastern Brazil, are broadly consistent with, although

generally higher than, erosion rates measured elsewhere in Brazil. Combining our new data for 14 watersheds with those for which data have already been published, we find that erosion rates in southern Brazil range between 1 and 90 m/My, with an average of 14 m/My (Fig. 7).

Considering all southern Brazil samples, we identify topographic and climatologic correlations with erosion rate. We find in Brazil, as others (e.g., Brown et al., 1998) have found in steep, tropical regions, that coarser fluvial sediment has less ^{10}Be than sand-sized sediment, either the result of landslides delivering coarser material once at depth to the stream (Brown et al., 1998) or because of the sourcing of coarser sediment from lower elevations (Matmon et al., 2003).

The relationship between mean basin slope and erosion is the strongest one in the compiled data set of Brazilian erosion rates ($R^2 = 0.33$, $p < 0.001$). However, the relationship is weaker than it is when we consider only our spatially limited data set (Fig. 4). Portenga and Bierman (2011) noted that as the scale of analysis grows (from local to regional to global), the strength of the relationship between topographic variables and erosion rate decreases, presumably as other factors such as lithology, tectonics, and climate influence erosion rates. Similarly, we found a relationship between precipitation and erosion at the regional scale in Brazil ($R^2 = 0.05$, $p = 0.03$), but it is much weaker than the relationship shown by our 14 samples collected in a smaller area ($R^2 = 0.57$; Fig. 4). Considering all Brazilian data, basin area is not related to erosion ($R^2 = 0.01$, $p = 0.30$) although regional studies (including ours) find that erosion is more rapid in smaller, steeper headwater subbasins in Brazil than in larger, lower-slope basins (Salgado et al., 2006, 2007).

Considering all Brazilian studies, we find a significant difference in erosion rate as a function of lithology ($F = 10.9$, $p < 0.01$). Basins underlain by granite, granitoid, and

consolidated sedimentary material erode significantly faster than those underlain by quartzite, schist, and phyllite (Fig. 8). Lithologic effects on erosion rate have been noted in other, smaller-scale Brazilian studies. Similar to our findings at the large scale, Barreto et al. (2013) found that basins underlain by schist and phyllite erode more slowly than watersheds underlain by granite and quartzite; and Salgado et al. (2008) measured the fastest erosion rates in watersheds underlain by granite and the slowest in those underlain by quartzite. In another study, Salgado et al. (2013) showed that watersheds in Paraná State underlain by granite eroded more slowly than watersheds underlain by migmatites and gneisses. In Brazil, only Rezende et al. (2013) reported that granite-bearing watersheds eroded more slowly than watersheds underlain by other lithologies.

Comparing our data to other cosmogenic ^{10}Be -derived erosion rates for watersheds in southern and southeastern in Brazil, we find that some of our 14 watersheds are among the most rapidly eroding (Table 2, Table DR3). For example, the coastal portions of Rio de Janeiro and Paraná states have similar geologic settings, with the Serra do Mar escarpment crossing both states. Previously published denudation rates for watersheds draining the escarpment in Paraná State (Salgado et al., 2013) range between 8 and 62 m/My, with an average of 20 m/My. This is considerably slower than the average erosion rate of the escarpment-draining watersheds in our small data set ($n = 4$), 63 m/My. In all Brazilian studies, steep escarpment-draining watersheds have the highest erosion rates.

At a global scale, in comparison with erosion rates derived from cosmogenic ^{10}Be measured in river sand collected from other passive margin locations, Brazilian erosion rates have a wider range than those in Africa (Namibia) and eastern North America (Table 2, DR3; Fig. 9). A one-way ANOVA comparing the erosion rate of basins in these three passive margins

shows a statistically significant difference in at least two of the groups ($F = 4.81$, $p < 0.01$). Basins sampled in Brazil and eastern North America are eroding at a similar pace. In contrast, the escarpment-draining watersheds sampled in Namibia are eroding at a slower pace, significantly different to Brazil and North America, perhaps because Namibia is far drier than Brazil and eastern North America. The average erosion rate for passive margin watersheds in Namibia is 9 ± 3 m/My ($n = 46$; Bierman and Caffee, 2001; Bierman et al., 2007). Several studies have measured erosion rates for watersheds draining the southeastern USA passive margin. Published cosmogenic-derived erosion rates for Virginia watersheds average 11 ± 8 m/My ($n = 69$; Duxbury et al., 2015; Reusser et al., 2015). Samples from other sites in southeastern USA (North Carolina, South Carolina, Georgia, and Alabama) also suggest an average erosion rate of 11 ± 5 m/My ($n = 19$; Reusser et al., 2015). The Blue Ridge escarpment in North Carolina and Virginia is eroding more rapidly, 17 ± 9 m/My (Sullivan, 2007).

Comparing the erosion rates of our sampled watersheds with other tropical regions where cosmogenic ^{10}Be has been measured in river sediments, we found that areas of Brazil sampled so far are eroding considerably slower than areas sampled in Puerto Rico, Panama, Sri Lanka, and Bolivia but faster than tropical regions of Madagascar and at a similar pace to Australian basins (Tables 2, DR3; Fig. 9). Madagascar is the most slowly eroding with an average erosion rate of 13 ± 5 m/My ($n = 7$; Cox et al., 2009). The tropical regions in Australia erode on average at 18 ± 12 m/My ($n = 14$; Heimsath et al., 2009; Nichols et al., 2014). Tropical watersheds in Sri Lanka erode at an average pace of 22 ± 11 m/My ($n = 16$; Hewawasam et al., 2003; von Blanckenburg et al., 2004). The average erosion rate for watersheds in Puerto Rico is 61 ± 34 m/My ($n = 27$; Brown et al., 1995, 1998; Riebe et al., 2003). Panama is eroding significantly faster than Brazil at an average erosion rate of 158 ± 35 m/My ($n = 17$; Nichols et al., 2005). Cosmogenically

derived erosion rates measured in the tropical region of Bolivia average 360 ± 296 m/My ($n = 12$; Wittmann et al., 2009; Insel et al., 2010). Erosion rates in Brazil are significantly different only from those in Bolivia, Panama, and Puerto Rico ($F = 38.7$, $p < 0.01$).

Some of the basins sampled in Bolivia, Panama, and Puerto Rico record a greater mean annual rainfall than the Brazilian ones we studied, which may explain in part the higher erosion rates. However, tectonic activity appears to be the major controlling factor for rates of erosion at a basin scale in tropical region studies. Bolivian erosion rate samples were collected in a tectonically active region of the Andes; Puerto Rico and Panama are also tectonically active, which contrasts with the passive margin setting of southern and southeastern Brazil.

The influence of tectonic setting can be quantified using expected Peak Ground Acceleration (PGA) from earthquake activity where PGA is 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) in soil (Giardini, 1999). The PGA maps, a proxy for tectonic activity, from the Global Seismic Hazard Assessment Program (Giardini, 1999; <http://www.seismo.ethz.ch/static/GSHAP/>) show that Brazilian sample sites have PGA values well below $1g$. Watersheds in Puerto Rico average $1.88g$, whereas Bolivia and Panama record a lower average PGA of 1.55 and $1.43g$, respectively. Tectonic activity has been linked to accelerated rates of erosion (Dedkov and Moszherin, 1992), perhaps because repeated shaking fractures and weakens the rocks (Young et al., 2000). Furthermore, Milliman and Syvitski (1992) suggested that a complex relationship between fractured rocks, steep slopes, and seismic and volcanic activity, rather than relief alone, controls erosion in active orogenic belts. This may be the case for Puerto Rico, Bolivia, and Panama.

Cosmogenic ^{10}Be has been used as an erosion proxy in tropical regions with escarpment topography in Sri Lanka and Australia (see Table 2 and Fig. 9). Considering all published data, Brazilian escarpments are eroding at an average rate of 13 ± 16 m/My ($n = 60$; Salgado et al., 2006, 2007, 2008, 2013; Cherem et al. 2012; Barreto et al., 2013, 2014; Rezende et al., 2013; this study; Table DR2). This rate is considerably slower than the average rate for Sri Lanka, where published data suggest that escarpment watersheds erode at an average of 23 ± 23 m/My ($n = 19$; Vanacker et al., 2007). Australian escarpment basins erode even more quickly, at an average rate of 43 ± 30 m/My ($n = 17$; Heimsath et al., 2006; Nichols et al., 2014). A one-way ANOVA comparing the erosion rates of escarpment watersheds in Australia, Sri Lanka, and Brazil shows differences between at least two of the countries ($F = 16.4$, $p < 0.01$). The Australian escarpment is eroding significantly faster than the Brazilian and Sri Lankan escarpments. The main lithology of the sampled watersheds in the Australian escarpment is sedimentary, in contrast with those watersheds sampled on the Brazilian escarpment, which are mostly underlain by crystalline rock. If the relationship between lithology and erosion rate in Brazilian watersheds is similar in Australia, this might explain why the Australian escarpment erodes more quickly than escarpments in Brazil and Sri Lanka. Precipitation could also be driving the increased rates of erosion on the Australian escarpment. Mean annual precipitation in the sampled Australian watersheds is up to 2500 mm/y, greater than rainfall in the Brazilian watersheds we sampled.

7. Conclusions

The first ^{10}Be -based, drainage-basin-scale erosion rate estimates from Rio de Janeiro and Santa Catarina States in Brazil are broadly consistent with other cosmogenic erosion rate data from southern and southeastern Brazil and indicate that erosion rates in this tectonically inactive

environment are mostly a few tens of meters per million years. Drainage basins in southern and southeastern regions of the country are eroding between 1 and 90 m/My with an average rate of 14 m/My. Erosion rates are greater in basins draining escarpments than in basins draining lower-relief highlands. Similar to other cosmogenic studies in Brazil, we found that the smaller, steeper headwater catchments erode faster than the larger, higher-order but lower slope catchments. Erosion in Brazil is mostly controlled by mean basin slope with lesser influence of climate and lithology.

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Table and Figure captions:

Fig. 1. Topographic and geographic features of southern and southeastern Brazil. The states of Minas Gerais (MG), Goiás (GO), Espírito Santo (ES), Rio de Janeiro (RJ), São Paulo (SP), Paraná (PR), and Santa Catarina (SC) are shown. (A) Sample locations for this study and previously published cosmogenic studies in Brazil. The escarpment topography can be distinguished along the Atlantic coast by the change in elevation. (B) Approximate location of major geographic and political features of southern and southeastern Brazil.

Fig. 2. Sampling sites. Field photographs of two fluvial sediment sampling sites: (A) BRA02 in Rio de Janeiro State, draining the Serra do Mar escarpment. (B) BRA43 in Santa Catarina State. All samples were field sieved.

Fig. 3. Erosion rates calculated using different parameter values. Regression of erosion rates calculated using the basin effective elevation and centroid location (x-axis) and calculated using mean basin elevation and centroid location (y-axis) are very similar. Shaded zone represents the 95% confidence interval.

Table 1. Erosion rates and topography variables for river sediment samples from Brazilian states of Rio de Janeiro and Santa Catarina^a

Fig. 4. Regression plot of the relationship between erosion rate and mean basin slope. The strongest relationship in our data set (open circles) was found between erosion and basin slope. The relationship is still significant but weaker in the entire southern and southeastern Brazilian data set (filled black circles). Portenga and Bierman (2011) found slope to be the strongest predictor of erosion in their global data set (filled grey circles).

Fig. 5. Regression plot of the relationship between erosion rate and mean annual precipitation. The shaded zone represents the confidence interval of the linear fit at the 95% level.

Fig. 6. (A) Erosion rates sorted by basin area. Although erosion rates are not linearly related to basin area (inset), there is a statistically significant difference in erosion rates by basin area category. Categories not connected by the same letter are significantly different. (B) Erosion rate by mean basin slope subgroup. The positive relationship between erosion and slope in our data set (inset) can be further explained by the correlation between area and slope. Steep headwater basins have a higher mean slope than larger basins with extensive lowlands. Categories not connected by the same letter are significantly different. Categories for area and slope were selected based on the quartiles of the values distribution. In both insets, the shaded zone represents the 95% confidence interval. The bottom and top limits of boxplots represent the first and third quartile of the data, respectively. The line across the boxes is the median of each category. The whiskers represent the minimum and maximum value of each category.

Fig. 7. Histogram of all cosmogenic ^{10}Be -derived erosion rates published for southern Brazil. Erosion rates range from 1 to 90 m/My, with an average erosion rate of 14 m/My. Most watersheds are eroding at < 30 m/My.

Fig. 8. Brazilian erosion rates by predominant basin lithology. The compiled Brazilian data set shows differences in average erosion rates as a function of dominant lithology in each samples basin. Basins underlain by granite and granitoids erode significantly faster than those underlain by quartzite, schist, and phyllites consistent with findings from smaller-scale studies in Brazil. The bottom and top limits of boxplots represent the first and third quartile of the data, respectively. The line across the boxes is the median of each category. The whiskers represent the minimum and maximum value of each category. Categories not connected by the same letter are significantly different. Dots represent the data points in each category; to avoid overlap of data points, they are jittered.

Table 2. Summarized published cosmogenic ^{10}Be -derived erosion rates for tropical climates and passive margin topography sites

Fig. 9. Summary of previously published cosmogenic ^{10}Be -derived erosion rates in (A) tropical climates (note the y-axis scale), (B) passive margin, (C) Brazil, and (D) tropical escarpments. Hollow circles represent escarpment draining watersheds. In all the boxplots the compiled Brazil data is included for reference. For this comparisons we used the CRONUS calculated erosion rates published by Portenga and Bierman (2011), except when otherwise noted (see Table 2). For the previous Brazil studies, we calculated the erosion rates using CRONUS and used that for comparisons. Table DR1 includes the CRONUS input table for these studies. Categories not connected by the same letter are significantly different. Dots represent the data points in each category; to avoid overlap of data points, they are jittered.

Fig. DR1. Watersheds sampled for Salgado et al. 2006, 2007, 2008 and 2013 publications. Watersheds are shown imposed over a Digital Elevation Model (DEM) background. DEM data from Instituto Nacional de Pesquisas Espaciais. Published sampling location and watershed delineation were confirmed with the corresponding author.

Fig. DR2. Watersheds sampled for Barreto et al. 2013, 2014 publications, imposed over a DEM. DEM data from Instituto Nacional de Pesquisas Espaciais. Sampling location was confirmed by one of the authors.

Fig. DR3. Watersheds sampled for Rezende et al 2013 publication. Watersheds are shown imposed over a DEM background. DEM data from Instituto Nacional de Pesquisas Espaciais. Published sampling location and watershed delineation were confirmed with the corresponding author.

Fig. DR4. Watersheds sampled for Cherem et al. 2012 publication. Watersheds are shown imposed over a DEM background. DEM data from Instituto Nacional de Pesquisas Espaciais. Published sampling location does not align perfectly with the delineated watersheds provided by the corresponding author. We adopted the author's delineation for our analysis

Table DR 1: CRONUS input data for all Brazilian cosmogenic studies

Table DR 2: Topographic variables for all cosmogenic studies in Brazil

Table DR 3: Data used for global comparisons

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Table 1

Erosion rates and topography variables for river sediment samples from Brazilian states of Rio de Janeiro and Santa Catarina^a

Sample ID	State	Sample type	Drainage	Latitude	Longitude	Quartz mass (g)	SUERC ID	⁹ Be carrier (μ g)	¹⁰ Be/ ⁹ Be ratio ($\times 10^{-14}$ atoms)	¹⁰ Be concentration ($\times 10^4$ atoms/g)	Erosion rate (m/My)	Elevation (m)	Slope (degrees)	Area (km ²)	Precipitation (mm)	Lithology
BRA01S	RJ	River sand	E	-22.52	-43.00	20.1	b7653	247.4	9.9 $\pm$ 0.4	8.4 $\pm$ 0.3	53 $\pm$ 4	708	24.0	8	1744	Granitoid
BRA01	RJ	River cobbles	-	-22.52	-43.00	13.2	b8122	221.4	2.9 $\pm$ 0.3	3.5 $\pm$ 0.3	-	-	-	-	-	-
BRA02S	RJ	River sand	E	-22.49	-43.00	20.0	b7654	246.8	14.5 $\pm$ 0.4	12.2 $\pm$ 0.3	46 $\pm$ 3	1351	26.1	18	1824	Granitoid
BRA02	RJ	River cobbles	-	-22.49	-43.00	14.8	b8123	222.0	2.0 $\pm$ 0.2	2.3 $\pm$ 0.3	-	-	-	-	-	-
BRA03S	RJ	River sand	E	-22.47	-43.00	16.0	b7656	248.2	8.1 $\pm$ 0.4	8.7 $\pm$ 0.4	90 $\pm$ 7	1606	29.2	3	1808	Granitoid
BRA03	RJ	River cobbles	-	-22.47	-43.00	20.1	b8124	221.4	8.1 $\pm$ 0.3	6.2 $\pm$ 0.3	-	-	-	-	-	-
BRA19	RJ	River sand	M	-21.51	-42.20	20.0	b8125	249.8	21.9 $\pm$ 0.6	18.5 $\pm$ 0.5	23 $\pm$ 2	483	12.3	9169	1376	Granite, gneiss
BRA20	RJ	River sand	M	-21.25	-41.78	20.1	b8126	249.8	29.7 $\pm$ 0.8	24.9 $\pm$ 0.6	16 $\pm$ 1	531	13.8	7243	1292	Granite, gneiss
BRA21	RJ	River sand	M	-21.33	-41.88	20.4	b8489	235.4	31.1 $\pm$ 0.6	24.1 $\pm$ 0.5	13 $\pm$ 1	235	13.5	247	1223	Granitoid
BRA22	RJ	River sand	M	-21.38	-41.92	20.2	b8128	247.7	29.3 $\pm$ 0.7	24.2 $\pm$ 0.6	13 $\pm$ 1	244	14.9	15	1215	Granitoid
BRA40	SC	River sand	M	-26.81	-48.91	20.0	b8130	249.1	8.9 $\pm$ 0.3	7.6 $\pm$ 0.3	55 $\pm$ 4	293	16.2	5	1649	Granite, gneiss
BRA41	SC	River sand	M	-26.78	-48.99	20.3	b8131	244.0	17.6 $\pm$ 0.6	14.4 $\pm$ 0.5	27 $\pm$ 2	369	16.8	9	1646	Granite, gneiss
BRA43	SC	River sand	M	-26.78	-48.99	20.0	b8135	248.3	17.4 $\pm$ 0.5	14.6 $\pm$ 0.4	27 $\pm$ 2	377	16.5	8	1644	Granite, gneiss
BRA44	SC	River sand	M	-26.88	-49.10	20.0	b8136	248.7	23.4 $\pm$ 0.6	19.6 $\pm$ 0.5	24 $\pm$ 2	596	11.7	14987	1533	Consolidated sedimentary
BRA45	SC	River sand	M	-27.06	-49.53	20.4	b8137	249.1	27.5 $\pm$ 0.8	22.6 $\pm$ 0.6	20 $\pm$ 1	612	12.1	4167	1484	Consolidated sedimentary
BRA46	SC	River sand	M	-27.08	-49.50	20.0	b8139	248.6	25.6 $\pm$ 0.6	21.4 $\pm$ 0.5	20 $\pm$ 1	628	11.0	6931	1543	Consolidated sedimentary
BRA47	SC	River sand	M	-27.33	-49.62	21.2	b8490	234.8	31.9 $\pm$ 0.6	23.8 $\pm$ 0.5	19 $\pm$ 1	695	11.6	2335	1578	Consolidated sedimentary

^aNotes: Sampling locations are based in WGS1984. CRONUS Earth Calculator Version 2.2 was used to calculate erosion rates, we used the scaling of Lal (1991) and Stone (2000). The external uncertainty calculated by CRONUS is expressed as the uncertainty of each erosion rate. Isotopic data standardized to NIST_27900 with assumed ratio of 2.79×10^{-11} . Data have been blank corrected. Carrier blank concentration averaged $2.44 \pm 1.67 \times 10^{-15}$ (1SD, n = 3). Mean basin elevation is reported as the elevation of each basin. Slope and area were calculated using the slope and calculate area ArcGIS 10.3 tools, respectively. We used the Topodata30m DEM from the Instituto Nacional de Pesquisas Espaciais. Precipitation data extracted from the WorldClim dataset (Hijmans et al., 2005). Drainage refers to the terrain each basin drains: escarpment (E), or a mixed terrain of escarpment and highlands (M).

Table 2

Summarized published cosmogenic ^{10}Be -derived erosion rates for tropical climates and passive margin topography sites

Country	Publications	Samples	Erosion rates (m/My)			Comparison type
			Range	Average	Median	
Australia	Heimsath et al., 2009 ^a	14	8.3 - 51.9	18	20.8	Tropical
	Nichols et al., 2014 ^b					
Bolivia	Insel et al., 2010 ^a	12	33.6 - 907	360	260	
	Wittmann et al., 2009 ^a					
Madagascar	Cox et al., 2009 ^a	7	5.8 - 22.3	13	11.8	
Panama	Nichols et al., 2005 ^a	17	88.3 - 218	158	160.5	
Puerto Rico	Brown et al., 1995 ^a	27	17.6 - 144	61	51.5	
	Brown et al., 1998 ^a					
	Riebe et al., 2003 ^a					
Sri Lanka	Hewawasam et al., 2003 ^a	16	3.81 - 28.2	22	18.5	
	von Blanckenburg et al., 2004 ^a					
Namibia	Bierman and Caffee, 2001 ^a	46	1.51 - 14.6	9	8.7	Passive margin
	Bierman et al., 2007 ^a					
Southeastern USA	Duxbury et al., 2015 ^b	136	3.02 - 48.7	13	10.6	
	Sullivan, 2007 ^a					
	Reusser et al., 2015 ^b					
Australia	Heimsath et al., 2006 ^a	17	6.49 - 119.4	43	45.7	Tropical passive margin
	Nichols et al., 2014 ^b					
Sri Lanka	Vanacker et al., 2007 ^a	19	1.92 - 69.4	23	12.2	
Brazil - escarpment	Barreto et al., 2013, 2014 ^c	57	1.49 - 61.5	10	5.3	Brazil studies ^d
	Cherem et al., 2012 ^c					
	Rezende et al., 2013 ^c					
	Salgado et al., 2013 ^c					
Brazil - highland	Cherem et al., 2012 ^c	19	1.07 - 21.9	11	11	
	Salgado et al., 2006, 2007, 2008 ^e					

^a Erosion rates recalculated using CRONUS and published by Portenga and Bierman (2011).^b Erosion rates from the original publication, calculated using CRONUS.^c Erosion rates recalculated using CRONUS.^d Data from this study is not included in this table, see Table 1.^e Samples in Salgado et al. (2006, 2007, 2008) are from the same locations but were processed using different AMS standards. We used the most complete data set of all three, the 2008 publication, for our comparison.