Long-term evolution of denudational escarpments in southeastern Brazil

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A B S T R A C T

Topographic relief in southeastern Brazil consists of a sequence of stepped surfaces that formed after the fragmentation of Gondwana during the Cretaceous, Tertiary and Quaternary tectonic pulses. This region is drained by four major rivers within four major river basins, with interfluvies that contain denudational escarpments, fault escarpments and mountain ranges. This study presents an analysis of the long-term evolution of two denudational escarpments, the Cristiano Otoni and the São Geraldo steps, which divide the river basins of the São Francisco, Doce and Paraiba do Sul rivers in southeastern Brazil. Denudation rates were obtained through the measurement of mean concentrations of in situ produced cosmogenic 10Be in sand-sized fluvial quartz sediments collected from granitic terrains. The rates were calculated and compared with one another and correlated to the basin-scale mean relief, slope, area, and stream power. The mean denudation rates of the Cristiano Otoni and São Geraldo highlands are 8.77 (±2.78) m My−1 and 15.68 (±4.53) m My−1, respectively. The mean denudation rates of the Cristiano Otoni and São Geraldo escarpments are 17.50 (±2.71) m My−1 and 21.22 (±4.24) m My−1, respectively. The denudation rates of the catchments of highlands that drain toward the escarpments are similar to those of their respective highlands. The results demonstrate that relief and slope have similar positive control on the denudation rates for all of the samples despite their different geomorphic context and history of landscape evolution. The São Francisco River Basin is losing area to the Doce River Basin, which, in turn, is losing area to the Paraiba do Sul River Basin.

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1. Introduction

Escarpments are generally high and steep hillslopes of considerable length that divide highlands from lowlands. Long-term denudation rates of escarpments depend on geological structures, tectonics, climate and time (e.g., Summerfield, 1991; Riebe et al., 2000; Matmon et al., 2003; Goudie, 2004; Huggett, 2007). Several methods are commonly applied to evaluate the rates of the processes controlling the short- and long-term evolution of escarpments, including thermochronology (e.g., Cockburn et al., 2000; Persano et al., 2002; Hacksparser et al., 2004; Balesptier et al., 2005; Gunnell et al., 2007; Hiruma et al., 2010) and measurement of cosmogenic nuclide concentrations (e.g., Fleming et al., 1999; van der Wateren and Dunai, 2001; Heimsath et al., 2006; Humphreys et al., 2006; Burke et al., 2009). Correlation to geomorphic features of escarpments is also used as a method to evaluate escarpment evolution (e.g., Matmon et al., 2002; Moore and Blenkinsop, 2006; Oliveira and Queiroz Neto, 2007; Prince et al., 2011).

Cosmogenic nuclide concentrations are widely applied in studies that focus on the understanding of the denudation of escarpments all over the world by measuring denudation rates from fluvial sediments, soil profiles and rock outcrops. This method is applied to study several escarpments, e.g., the Drakensberg escarpment in southeast Africa (Fleming et al., 1999; Cockburn et al., 2000; van der Beek et al., 2002; Chardon et al., 2006; Moore and Blenkinsop, 2006; Beauvais et al., 2008), the Great Escarpment in southeast Australia (Seidl et al., 1996; Persano et al., 2002; Heimsath et al., 2006; Humphreys et al., 2006; Burke et al., 2009) and the Blue Ridge escarpment in eastern North America (e.g., Hancock and Kirwan, 2007; Sullivan et al., 2007). This sort of research largely focuses on the individual denudation of escarpments as retreat and downwearing and on the geomorphic control on their denudation rates (von Blanckenburg, 2005).

Previous studies demonstrate that some escarpments around the globe have low denudation rates (Table 1) and show that such rates are decoupled from geomorphic parameters (Fleming et al., 1999; Cockburn et al., 2000; Riebe et al., 2000; Matmon et al., 2002; van der Beek et al., 2002; von Blanckenburg, 2005; Heimsath et al., 2006). Other studies have verified that the strong dependence of denudation rates on relief is a consequence of the adjustment of...
landscape to tectonically driven uplift or base-level change, as discussed by von Blanckenburg (2005). In the latter case, morphogenesis is controlled by the difference in the erosive potential headward and the denudation rates of the escarpments are higher than those from the highlands (e.g., Bierman and Caffee, 2001; Persano et al., 2002; Heimsath et al., 2006; Vanacker et al., 2007; Burke et al., 2009).

The Brazilian southeastern passive-margin escarpments are quite different from the other escarpments around the globe. Here, a single escarpment separates the coastal plains (lowland) from the inlands (highland). In southeastern Brazil, a sequence of three stepped surfaces drained by three different major rivers (São Francisco, Doce and Paraíba do Sul) is separated by two escarpments (Fig. 1). The stepped relief of eastern Brazil is a long-term consequence of three distensive tectonic episodes: (1) The first episode commenced with the development of the passive continental margin after the breakup of Gondwana. (2) Next, the Cenozoic Rift System of Southeastern Brazil (Almeida et al., 1981; Riccomini, 1989) developed from distensive tectonics in the Tertiary period (Fig. 2). (3) Finally, Quaternary distensive tectonics occurred in the middle of the Doce River Basin (Fig. 2; Mello et al., 1999; Riccomini and Assumpção, 1999; Saadi et al., 2005). Moreover, this

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Sample</th>
<th>Authors</th>
<th>Mean denudation rate (m My(^{-1}))</th>
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<tbody>
<tr>
<td>Drakenberg escarpment</td>
<td>Southeastern Africa</td>
<td>Sediment</td>
<td>Fleming et al. (1999)(^{a})</td>
<td>50–95, 6</td>
</tr>
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<td>Namibia escarpment</td>
<td>Southwestern Africa</td>
<td>Sediment</td>
<td>Bierman and Caffee (2001)</td>
<td>16, 5</td>
</tr>
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<td>Great Escarpment</td>
<td>Southeastern Australia</td>
<td>Sediment; Outcrop</td>
<td>Heimsath et al. (2001; 2006)</td>
<td>5–35, 15</td>
</tr>
<tr>
<td>Blue Ridge escarpment</td>
<td>Eastern North America</td>
<td>Sediment</td>
<td>Sullivan et al. (2007)</td>
<td>20, 12</td>
</tr>
<tr>
<td>Sri Lankan escarpment</td>
<td>Oceania</td>
<td>Sediment</td>
<td>Vanacker et al. (2007)</td>
<td>26–71, 4</td>
</tr>
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\(^{a}\) Denudation rates calculated from in situ produced \(^{36}\)Cl.

**Table 1**: Denudation rates of escarpments in granitic bedrock derived from in situ produced \(^{10}\)Be.

*Fig. 1.* (A) The location of the studied area in southeastern Brazil; (B) an SRTM image depicting the relief of southeastern Brazil, including the major morphological features and river basins: (1) Paraná River, (2) São Francisco River, (3) Jequitinhonha River, (4) São Matheus River, (5) Doce River, (6) Paraíba do Sul River, (7) coastal rivers; (C) location of the denudational escarpments studied; (D) a geological map. Panel D was modified from COMIG and CPRM, 2003.

region has experienced regional non-orogenic uplift since the early Tertiary period, reactivating Tertiary and Quaternary faults (Riccomini and Assumpção, 1999; Saadi et al., 2005).

The Paraiba do Sul River Basin drains the lower level, the Doce River Basin drains the intermediate level and the headwaters of the basins of Paraná and São Francisco rivers drain the higher level. The latter two river basins and the structural provinces of São Francisco and Paraná are divided by the High Paranaiba Arc (Brito Neves, 2003). Despite being in the same morphoclimatic region (i.e., humid tropical; Büdel, 1982; Thomas, 1994), these escarpments are of differing heights, lengths and mean slopes as a consequence of a major tectonic control (Fig. 1C).

Our study investigates the long-term denudation of the two escarpments that separate the three major river basins by measuring the mean long-term denudation rates obtained from the measurement of in situ produced cosmogenic $^{10}$Be (Lal, 1991) in alluvial sand-size quartz sediments from small catchments between 3.0 and 12.0 km (Brown et al., 1995; Granger et al., 1996; Binnie et al., 2006; Vanacker et al., 2007; Salgado et al., 2008) that drain the highlands and escarpments (Fig. 1). Our study aims to enrich our understanding of the factors that control the long-term development of relief of the escarpments that serve to separate the stepped surfaces. We evaluate the question as to whether the river basins draining the escarpments gain areas from the basins draining the highlands and, consequently, how the major river basins are responsible for the evolution of the stepped eastern Brazilian landscape.

2. Regional settings

The Cristiano Otoni Step is a 30 km long denudational escarpment with a mean height of ~250 m and a maximum height of 350 m (Figs. 3A and 4B). The escarpment front and the highland are almost entirely covered by highly weathered soils (Ferralsol), which overlap several meters of weathered rock (UFV et al., 2010). The Cristiano Otoni Step divides the southeastern São Francisco River Basin (altitudes ranging between 850 and 1000 m) from the southwest Doce River Basin (altitudes ranging between 650 and 850 m). The highest crest of the escarpment reaches 1050 m. The substrate is composed predominantly of granitoid rocks from the Alto Maranhão Suite (2.1 Ga); no major structures are present (COMIG and CPRM, 2003).

The São Geraldo Step is a 65 km long escarpment with a mean height of 450 m and a maximum height of 550 m in the southwestern part (Figs. 3B and 4C). The soils profiles of the São Geraldo Step are different from those of the Cristiano Otoni Step in that the soils are highly weathered at the highlands and overlie several meters of weathered rock (up to 60 m as reported in Sarcinelli et al., 2009) and are weathered to a low degree at the escarpment front where bare rock outcrops locally (UFV et al., 2010). This segment divides the southeastern Doce River Basin from the northeastern Paraiba do Sul River Basin, with altitudes ranging between 650 and 850 m and 300 and 450 m, respectively. The substrate is dominated by metamorphosed granitoid rocks of the Piedade Complex (2.3 Ga), and no major structures are present (COMIG and CPRM, 2003).

Fig. 3. Three-dimensional view of the studied escarpments obtained from the ASTER database: (A) Cristiano Otoni Step and (B) São Geraldo Step (vertical exaggeration: 3.5 times).

Fig. 4. (A) Regional features on ASTER; sampled basins along the (B) Cristiano Otoni Step and the (C) São Geraldo Step. Major river basins numbered according to Fig. 1.
The studied region is in the tropical morphoclimatic zone, where the temperature and the precipitation decrease toward the high altitude inland area of the continent interior. The climate of the low stepped surface (400 m altitude, near the city of Ubat; Fig. 1) is classified as dry-winter tropical (Amw), with a mean annual temperature of ~25 °C and a mean annual precipitation of ~1300 mm. The middle (800 m altitude, near the cities of Viçosa and Alto Rio Doce; Fig. 1) and high (1100 m altitude, near the city of Barbacena; Fig. 1) surfaces are both classified as tropical highland (Cwa), where mean annual precipitation is ~1200 mm. The higher stepped surface has relatively colder annual temperatures than the lower and middle stepped surfaces, showing a mean annual temperature of ~20 °C (Kottek et al., 2006; Peel et al., 2007).

3. Material and methods

3.1. Sampling strategy

We sampled fluvial sediment from selected pairs and trios of small catchments that drain the highlands and escarpment fronts (10³–10⁴ km²) at locations along each escarpment crest (Fig. 4). The criteria used to select the pairs and trios of catchments were as follows: (1) the pairs must share part of their interfluves along the escarpment crest and be of similar surface area; (2) all catchments must develop on the same type of bedrock; and (3) for segments in which the highlends drain toward the escarpment, a third catchment must also be sampled within this area. The denudation rates obtained from the highlends and escarpment fronts were compared with one another and correlated to the mean slope, mean relief, stream power and area of each catchment.

According to these criteria, one pair and two trios were selected along the Cristiano Otoni Step. The sampled catchments AD1 to AD5 are located along the escarpment front, and the samples SF1 to SF3 are located within the adjacent highland (Fig. 4B). Similarly, four pairs and one trio of catchments were selected along the São Geraldo Step. The sampled catchments P1 to P6 are located along the escarpment front, while the catchments D1 to D6 are located within the adjacent highland (Fig. 4C). The sampled catchments AD3, AD5 and P6 are located in the highlands and drain toward the escarpment.

To determine the long-term denudation rates at both steps, the mean concentration of in situ produced cosmogenic ¹⁰Be (Lal, 1991; Bierman, 1994; Cockburn and Summerfield, 2004; Duni, 2010) in the bed load sediments from the streams of the selected catchments was measured (Granger et al., 1996; Seidt et al., 1997; Brown et al., 1998; Binnie et al., 2006; Heimsath et al., 2006; Hancock and Kirwan, 2007; Salgado et al., 2008).

3.2. Sample preparation and data analysis

We collected ~3 kg of bed load sediments from the streams of the selected catchments by sampling across the main channels. We collected the samples at the end of the dry season to avoid contamination that is contributed by episodic landslide events (Binnie et al., 2006). We isolated the quartz fraction from the sieved sediment samples (250–1000 μm) by dissolving other minerals with a mixture of HCl and H₂SO₄. Then, we isolated the quartz by dissolving ~60 g of each sample in HF. The resulting solution was spiked with 100 μg of a synthetic carrier with a ²³⁰Th concentration of 3.025 ± 0.009 ppm (Merchel et al., 2008). Beryllium was separated from the spiked solution after its dissolution in HF by successive anionic and cationic resin extraction (DOWEX X8 followed by 50WX8; Merchel and Herpers, 1999) and precipitation. We dried and heated the final precipitate at 800 °C to obtain BeO and finally, we mixed it with Nb powder prior to analysis at the Accelerator Mass Spectrometry (AMS) National Facility at CEREGE in Aix-en-Provence, France.

The data were calibrated against the National Institute of Standards and Technology (NIST) standard reference material 4325 with an assigned value of 2.79 (±0.03) × 10⁻¹¹ and a ¹⁰Be half-life (T1/2) of 1.387 (±0.012) × 10⁶ years, i.e., a radioactive decay (λ) of 4.997 (±0.043) × 10⁻⁷. Analytical uncertainties (reported at 1σ) include those associated with AMS counting statistics, AMS internal error (0.5%) and chemical blank measurements. Long-term measurements of a chemically processed blank yielded ratios on the order of 3.0 (±1.5) × 10⁻¹⁵ for ¹⁰Be (Arnold et al., 2010). We determined the denudation rates (Table 2) considering steady erosion (Brown et al., 1995; Granger et al., 1996) by applying Eq. (1) for each sample:

$$ C = \frac{P_0 \times P_n}{\pi + \lambda} \times e^{-\frac{\lambda}{\pi}} + \frac{P_0 \times \mu_P}{\pi + \lambda} \times e^{-\frac{\lambda}{\pi}} + \frac{P_0 \times \mu_B}{\pi + \lambda} \times e^{-\frac{\lambda}{\pi}} $$

where C is the concentration of in situ produced cosmogenic ¹⁰Be (atom g⁻¹); x is the depth (g cm⁻²); P₀ is the mean basin spallation production rate (atom g⁻¹ s⁻¹); P₀ and P₀ are the slow and fast muon (µ) contributions (Braucher et al., 2011); A₀, Aₐ₀ and Aₐ₀ are the attenuation lengths (g cm⁻²), with values of 160, 1500, and 4320, respectively (Granger and Smith, 2000); λ is the radioactive decay constant (s⁻¹), with a value equal to 4.997 (±0.043) × 10⁻⁷; e is the denudation rate (g cm⁻² y⁻¹); and t is time (y). For measuring catchment-wide denudation rates, we assumed time to be infinite (Brown et al., 1995; Granger et al., 1996) and muonic contributions were only scaled for altitude (Braucher et al., 2011). The sea-level altitude spallation production rate of 4.49 at g⁻¹ s⁻¹ was scaled by using the Stone polynomial (Stone, 2000) and by calculating the mean altitude across the catchment.

To account for possible local variation in atmospheric pressure, we used the NCEP/AM MATLAB routine (Balco et al., 2008) from the online CRONUS calculator. This routine provides a default atmosphere approximation that uses the basic formula of the standard atmosphere but incorporates the geographically variable mean sea level pressure and the 1000 mbar temperature fields as a means of capturing regional variations in the height–pressure relationship. We incorporated the NCEP/NCAR reanalysis dataset (www.cdc.noaa.gov/ncep_reanalysis/) on the mean sea level pressure and the 1000 mbar temperature fields used in this routine. The density used for the granite bedrock in the region is 2.60 g cm⁻³. The mean topographic shielding across the catchment was calculated by applying the shielding equation on the DEM (Codel, 2006).

We analyzed the correlation between the catchment-wide denudation rates and the following catchment-wide parameters: mean relief, mean slope, stream power and area. Both the mean slope and relief of each sampled catchment were calculated from the digital elevation model (DEM) generated from the Advanced Spaceborne Thermal Emission and Reflection (ASTER) dataset. The relief of each catchment was calculated by subtracting the minimum elevation from the mean catchment elevation (von Blankenburg, 2005). The stream power ω (W m⁻²) was calculated by applying Eq. (2) (Goudie, 2004):

$$ \omega = \frac{\rho Q v s}{w} $$

where, Q is the discharge (m³ s⁻¹), ρ is the fluid density (kg m⁻³), g is gravity (m s⁻²), s is the slope (m m⁻¹) and w is the width (m). Simplifying Eq. (2) by applying Q, we have Eq. (3):

$$ \omega = \rho g d v s $$

where d is the depth (m) and v is the velocity (m s⁻¹). Fluid density equals 1 kg dm⁻³ and gravity equals 10 m s⁻². We obtained the other variables from the field measurements at each stream during the dry season (winter).
4. Results

4.1. Cosmogenic nuclide-derived denudation rates and morphometric parameters

The Cristiano Otoni highland catchment-wide mean denudation rate derived from \(^{10}\text{Be}\) in situ produced cosmogenic \(^{10}\text{Be}\) is 7.41 (±1.55) mm\(^{-1}\) and ranges from 5.21 (±0.01) to 9.73 (±0.03) mm\(^{-1}\), while the escarpment mean denudation rate is 14.68 (±1.55) mm\(^{-1}\) and ranges from 12.64 (±0.09) to 17.01 (±0.10) mm\(^{-1}\) (Table 2 and Fig. 5). The São Geraldo highland mean denudation rate is 12.55 (±3.18) mm\(^{-1}\) and ranges from 9.09 (±0.03) to 19.30 (±0.13) mm\(^{-1}\), while the escarpment mean denudation rate is 18.12 (±2.77) mm\(^{-1}\) and ranges from 14.44 (±0.19) to 23.07 (±0.26) mm\(^{-1}\) (Table 2; Fig. 5). The catchments of the highlands that drain toward the escarpment have denudation rates of 12.82 (±0.12) mm\(^{-1}\) for the São Geraldo Step, and 6.04 (±0.01) mm\(^{-1}\) and 8.30 (±0.02) mm\(^{-1}\) for the Cristiano Otoni Step (Table 2; Fig. 5). A more heterogeneous pattern is observed for the highlands, where the pattern deviations of the denudation rates are 20.94% and 25.4% for Cristiano Otoni and São Geraldo, respectively. In contrast, the escarpment fronts show relatively lower pattern deviations of 10.6% and 15.3%.

The Cristiano Otoni highland has the lower level relief ranging from 47 to 82 m with a mean value of 58.6 (±18.4) m, whereas the escarpment relief ranges from 120 to 146 m with a mean of 135.3 (±13.6) m. The catchment relief of the São Geraldo highland ranged from 56 to 69 m with a mean relief of 62.0 (±5.9) m. The escarpment front has the highest relief ranging from 204 to 291 m with a mean value of 251.2 (±39.5) m (Table 2; Fig. 5).

The Cristiano Otoni highland is the flattest domain with catchment relief ranging from 0.153 to 0.229 m\(^{-1}\) and a mean slope of 0.185 (±0.030) m\(^{-1}\); the catchment slope of the escarpment front ranges from 0.249 to 0.288 m\(^{-1}\) with a mean of 0.269 (±0.020) m\(^{-1}\). The São Geraldo highland slope ranges from 0.189 to 0.244 m\(^{-1}\) with a mean slope of 0.216 (±0.017) m\(^{-1}\). The escarpment front of the São Geraldo Step is the steepest domain with a slope that ranges from 0.283 to 0.328 m\(^{-1}\) with a mean slope of 0.301 (±0.019) m\(^{-1}\) (Table 2; Fig. 5).

The mean stream power of the Cristiano Otoni highland is 0.17 (±0.06) W m\(^{-2}\), ranging from 0.11 to 0.23 W m\(^{-2}\); the escarpment mean power is 0.21 (±0.06) W m\(^{-2}\), ranging from 0.12 to 0.28 W m\(^{-2}\). The mean stream power of São Geraldo highland is 0.20 (±0.12) W m\(^{-2}\), ranging from 0.05 to 0.38 W m\(^{-2}\). The escarpment mean power is 0.29 (±0.26) W m\(^{-2}\), ranging from 0.02 to 0.65 W m\(^{-2}\) (Table 2; Fig. 5). The São Geraldo escarpment has the highest stream power and the most heterogeneous pattern, with a deviation pattern that is ~90% of the mean value. The Cristiano Otoni escarpment has a mean stream power similar to that of the São Geraldo highland, but the values of the São Geraldo highland are more heterogeneous than those of the Cristiano Otoni escarpment.

5. Discussion

5.1. The denudational escarpments in global perspective

Both studied escarpments showed low denudation rates that are similar to those measured at other escarpments worldwide. Comparisons include the Namib escarpment, where catchment-wide values of granitic environment denudation rates vary from 5.3 to 16.2 mm\(^{-1}\) (Bierman and Caffee, 2001); the Blue Ridge escarpment, where the high plateau average denudation rate is 12.5 mm\(^{-1}\) and the escarpment itself erodes at 17.1 mm\(^{-1}\) (Sullivan et al., 2007); the Sri Lankan escarpment, where the average apparent denudation rate of both plateau and escarpment are 3.93 and 46.33 mm\(^{-1}\), respectively (Vanacker et al., 2007); and the Great Escarpment in SE Australia, with
where rates vary between 25.0 and 30.0 mm My$^{-1}$. Denudation rates were measured at the Great Smoky Mountains, highland and the escarpment (Fig. 6A and B; Table 2). The positive correlation has been assumed to be dominant only in escarpments, where local base level readjustment controls river incision (von Blanckenburg, 2005), as observed in the Blue Ridge escarpment (Sullivan et al., 2007) and in the Sri Lanka escarpment (Vanacker et al., 2007). In the denudational escarpments that separate the stepped surfaces of southeastern Brazil, the correlation of denudation rates with relief and slope is also observed for the highlands, confirming the general relation between relief and denudation rates at low gradients (Arnhert, 1970; Montgomery and Brandon, 2002). At both of the study areas, the positive correlations of relief and slope to denudation rates are represented by the same trend line (Fig. 6A and B).

For escarpments, many authors assert that the general positive correlation between mean denudation rates and mean slope and relief might be linked to tectonic forcing, as observed in other escarpments (e.g., Schaller et al., 2001; Matmon et al., 2003; von Blanckenburg, 2005; Sullivan et al., 2007; Vanacker et al., 2007). Moreover, for many other authors, low values of the regional long-term denudation rates observed in other escarpments were interpreted as a dynamic equilibrium condition (e.g., Biermann and Caffee, 2001; van der Wateren and Dunai, 2001; Cockburn et al., 2000; van der Beek et al., 2002; Hancock and Kirby, 2007; Sullivan et al., 2007). On the other hand, Matmon et al. (2003) concluded, from their observations of the southern Appalachians Plateau, that when no correlation exists between denudation rates and catchment relief, the independence of slope and denudation rates is the result of the absence of landscape rejuvenation despite the slow evolution of the steps.

von Blanckenburg (2005) states that rejuvenation of denudation is caused by the uplift or by the lowering of the base level, as is revealed by the positive correlation between relief and low denudation rates (10$^{-4}$ m My$^{-1}$), such as in Middle Europe (Schaller et al., 2001). The correlation between the denudation rates and mean relief of the denudational escarpments of southeastern Brazil is similar to what Schaller et al. (2001) verified for Middle Europe, where the non-orogenic Neogene uplift is the likely dominant control over denudation, as stated by von Blanckenburg (2005). Plotting the denudation rates against dry season stream power reveals no clear general correlation (Fig. 6C), as observed in the Sri Lanka escarpment (Vanacker et al., 2007). However, individually, the highland samples show a positive correlation between the stream power and the denudation rate (Fig. 6C).

The positive correlation between denudation rates and mean relief and between denudation rates and slope (Fig. 6A and B) provides evidence that similar controls over denudation rates extend to all of the sampled catchments, independent of site (São Geraldo and Cristiano Otoni) or domain (escarpment and highland). The general positive correlation between denudation rates, mean slopes and mean relief is similar to what was observed in other escarpment fronts (Riebe et al., 2000; Sullivan et al., 2007; Vanacker et al., 2007).

The results show that the escarpment denudation rates are higher than their respective highlands. Consequently, the escarpment headwaters are propagating headward, implying a long-term scenario in which the major river basins of the highlands lose area to the basins of their respective lowlands and escarpment fronts. Therefore, in southeastern Brazil, the Paraíba do Sul River Basin is invading areas that originally belonged to the Doce River Basin and concurrently the Doce River Basin is invading areas that originally belonged to the São Francisco River Basin. The catchments of highlands that drain toward the escarpments erode at the same rates as their corresponding highland river basins even though they are part of a different major river basin. Thus, for long-term landscape evolution, these catchments behave just as any other catchment from their original highlands.

5.2. Controls on denudation rates

The individual denudation rates of both steps differ slightly from each other in that the Cristiano Otoni Step rates are smaller than those from the São Geraldo Step (Fig. 5). This difference can be explained by the positive correlation between denudation rates and both relief and slope, and in light of the fact that the São Geraldo Step has a higher mean slope and a higher mean relief for both the highland and the escarpment (Fig. 6A and B; Table 2). The positive correlation is also observed for the stream power (Fig. 6C) and catchment area of highland samples (Fig. 6D), but not for escarpment samples.

The positive correlation between denudation rates and mean relief and between denudation rates and slope (Fig. 6A and B) provides evidence that similar controls over denudation rates extend to all of the sampled catchments, independent of site (São Geraldo and Cristiano Otoni) or domain (escarpment and highland). The general positive correlation between denudation rates, mean slopes and mean relief is similar to what was observed in other escarpment fronts (Riebe et al., 2000; Sullivan et al., 2007; Vanacker et al., 2007).
In this study, a positive correlation between the denudation rates and the areas for the escarpment catchments is not observed for the largest catchments (Fig. 6D). This lack of a correlation might be because part of the lower basins drains the lowland (not only the escarpment), reducing the mean slope and mean relief, resulting in an implied relative reduction of the final denudation rates. For catchments in the highlands, the catchment area and mean slope are positively correlated (Fig. 6E), this might be evidence of relief dissection in the highlands, and would explain the relative higher denudation rates for the larger sampled catchments (D4 and D3). By ignoring samples D3 and D4, the mean denudation rate of the São Geraldo highland is 9.90 (±0.86) m y$^{-1}$, which is quite similar to the Cristiano Otoni highland mean rate of 7.41 (±1.55) m My$^{-1}$. This similarity might be because both highlands correspond to segments of plateaus, where denudation rates are generally low. These relatively lower rates are also observed in other escarpments around the globe (Fleming et al., 1999; Bierman and Caffee, 2001; Heimsath et al., 2001; Sullivan et al., 2007; Vanacker et al., 2007).

Plotting denudation rates against the dry season total dissolved solids (TDS)—measured by Cherem et al. (in press)—demonstrates a generally positive correlation (Fig. 7A). Similar to the TDS, the annual chemical denudation rates (Cherem et al., in press) increase with long-term denudation rates (Fig. 7B). The coupling of chemical denudation rates and long-term denudation rates reveals their intense interdependence in tropical environments (Fig. 7A and B; Thomas, 1994). Furthermore, the correlation between chemical denudation rates and long-term denudation rates is similar to what is observed for other granitic environments (Oliva et al., 2003; Riebe et al., 2004; Salgado et al., 2006).

This general homogenous control suggests that after initial faulting, the regional slow and continuous uplift of southeastern Brazil (Riccomini and Assumpção, 1999; Saadi et al., 2005) might be a regional factor controlling long-term denudation rates along the studied denudational escarpments. Moreover, this general homogenous control could explain why the denudational escarpments are evolving slowly, commensurate with the low long-term and chemical denudation rates of the Quaternary.

Our results show that the escarpment front is eroding faster than the highlands and, consequently, that the headwaters are propagating headward, implying a long-term scenario in which the major
Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2012.06.002.

References


