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Transient river response, captured by channel steepness and its concavity

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ABSTRACT

Mountain rivers draining tropical regions are known to be great conveyor belts carrying efficiently more than half of the global sediment flux to the oceans. Many tropical mountain areas are located in tectonically active belts where the hillslope and stream channel morphology are rapidly evolving in response to changes in base level. Here, we report basin-wide denudation rates for an east–west transect through the tropical Andes. Hillslope and channel morphology vary systematically from east to west, reflecting the transition from high relief, strongly dissected topography in the escarpment zones into relatively low relief topography in the inter-Andean valley. The spatial pattern of differential denudation rates reflects the transient adjustment of the landscape to rapid river incision following tectonic uplift and river diversion. In the inter-Andean valley, upstream of the wave of incision, slopes and river channels display a relatively smooth, concave-up morphology and denudation rates (time scale of 10^4–10^5 a) are consistently low (3 to 200 mm/ka). In contrast, slopes and river channels of rejuvenated basins draining the eastern cordillera are steep to very steep; and the studied drainage basins show a wide range of denudation rate values (60 to 400 mm/ka) that increase systematically with increasing basin mean slope gradient, channel steepness, and channel convexity. Drainage basins that are characterised by strong convexities in their river longitudinal profiles systematically have higher denudation rates. As such, this is one of the first studies that provides field-based evidence of a correlation between channel concavity and basin mean denudation rates, consistent with process-based fluvial incision models.

1. Introduction

Topographic variables have long been used as surrogates for inferring erosion and/or uplift rates. First analyses on topographic control of landscape-scale denudation rates already date from the late 1960s and early 1970s and mainly focused on the relationships between elevation, relief, local slope, and denudation rates. Among previous studies of the spatial variation in sediment transport by rivers, Schumm (1963) and Ahnert (1970) paid special attention to the effect of relief on sediment loads and denudation rates. The functional relationship between denudation and relief that is discussed in the seminal paper of Ahnert (1970) for mid-latitude basins set the tone for later work on the topographic control of denudation rates. Based on global compilations of river load data, various authors have reported on the strong linear relationship between continental denudation rates and river basin topography (e.g., Milliman and Meade, 1983; Summerfield and Hulton, 1994; Hinderer et al., 2013).

Only since the availability of cosmogenic nuclide-derived denudation rates, averaging over 10^3 to 10^6 years, have detailed correlations between topographic metrics and denudation become available. Various authors have observed correlation between basin-wide cosmogenic nuclide-derived denudation rates and basin relief (Schaller et al., 2001; von Blanckenburg, 2005), basin mean local relief (Safran et al., 2005), basin mean slope gradient (Riebe et al., 2000; Matmon et al., 2003; Abbühl et al., 2011), or basin mean elevation (Kober et al., 2007). In landscapes with low to moderate relief, such as middle Europe, the Appalachians, or the Sri Lankan highlands, basin-wide denudation rates are reported to be a linear function of basin relief or basin mean slope gradient (Schaller et al., 2001; Matmon et al., 2003). However, the most recent studies of denudation rates in high relief landscapes provide evidence of highly nonlinear slope gradient–denudation relationships. Data from the Olympic Mountains (Washington), the central Swiss Alps, and the San Bernandino Mountains (Southern California) indicate that the relationship between denudation rates and basin mean hillslope gradient breaks down once slope gradient reaches a threshold value (Montgomery and Brandon, 2002; Binnie et al., 2007; Wittmann et al., 2007; DiBiase et al., 2010).

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Even before these nonlinear relationships were quantified, observations of planar hillslopes in steep, high relief mountainous terrain had already led to the proposal of nonlinear hillslope erosion models that predicted sediment transport as a nonlinear function of slope gradient (Anderson, 1994; Roering et al., 1999). In tectonically active belts, rock mass strength ultimately limits further increases of slope or topographic relief (Schmidt and Montgomery, 1995). When slopes approach their mechanically limited steepness, they adjust to rapid uplift or river incision by increasing the rate of mass wasting rather than slope steepening (Burbank et al., 1996). Various authors have stated that commonly used morphometric indices such as slope steepness and topographic relief are, therefore, poor indicators of erosion rates in steep, landslide-prone topography; as a wide range of erosion rates can be found for a relatively narrow range of slope gradients (Montgomery and Brandon, 2002; Binnie et al., 2007; Korup et al., 2007; Kirby and Whipple, 2012).

The fluvial network is, in contrast to hillslopes, directly coupled to the basin outlet. Whipple et al. (1999) have suggested that the longitudinal profiles of river channels are more sensitive indicators of denudation rates than any other morphological properties, such as basin mean slope steepness or relief. Safran et al. (2005) first analysed spatial patterns in river channel gradient in relation to cosmogenic nuclide-derived denudation rates for the Bolivian Andes. They showed that the normalized channel steepness, k_{sn}, a measure of the relative channel gradient corrected for the drainage area, correlated with basin-wide denudation rates. Based on ^{10}Be-derived denudation rates from 65 basins draining the eastern margin of the Tibetan Plateau, Ouimet et al. (2009) showed that the relationship between channel steepness and erosion rate is nonlinear, a finding similar to that of DiBiase et al. (2010) in the San Gabriel Mountains of California. Numerous studies from the Siwalik hills (Kirby and Whipple, 2001), eastern Tibet (Kirby and Ouimet, 2011), coastal California, San Gabriel Mountains (DiBiase et al., 2010), and the central Andes (Abbühl et al., 2011; Norton and Schlunegger, 2011) now suggest that the channel steepness is set by the tectonic uplift rate. However, such a relationship implicitly assumes that the landscape is in topographic steady state, whereby the rates of tectonic uplift are balanced by the rates of erosion (Howard, 1994). Under such conditions, river profile steepness will be controlled by the balance between erosion and uplift rates.

However, in many environments this steady state is not yet reached. Transient (non-equilibrium) river profiles are now increasingly used to infer spatial and temporal variations in tectonic uplift and/or denudation rates (Demoulin, 1998; Hoke et al., 2007; Johnson et al., 2009; Abbühl et al., 2010; Kirby and Whipple, 2012; Walcek and Hoke, 2012). As a response to tectonic perturbations, knickpoints or longitudinal profile convexities migrate through a transient river network. This generates important deviations from an equilibrium concave-up longitudinal profile (Goldrick and Bishop, 2007; Whittaker et al., 2008) and questions the direct association of channel steepness (k_{sn}) values with uplift and/or denudation rates. The implication of non-equilibrium topography for the interpretation of topographic metrics gained considerably less attention, with only a few recent studies addressing this problem quantitatively (Zaprowski et al., 2005; Whittaker et al., 2010; Schlunegger et al., 2011; Kirby and Whipple, 2012).

In this study, we test the robustness of topographic metrics of hillslope and river channel morphology as indicators of denudation rates in transient (non-equilibrium) topography for the Ecuadorian Andes. We quantified spatial patterns of denudation based on cosmogenic nuclide-derived erosion rates for 31 small drainage basins. Topographic metrics derived from a 30-m digital elevation model (DEM) are used to test the association between basin-wide denudation rates and (i) basin mean hillslope gradient, (ii) river channel steepness, and (iii) river channel longitudinal form. We then analyse the spatial variability in denudation rates across this transect in the Ecuadorian Andes to discuss the major topographic and climatic controls on denudation rates in transient topography.

2. Regional setting

The development of the inter-Andean Cuenca basin is associated with the late Miocene uplift of the Andean western cordillera. This uplift also caused a major drainage reversal of the Paute River that shifted from its Miocene westward course to its present course toward the Amazon basin (Steinmann, 1997). As a response to this uplift, the Paute River incised a deep gorge where it traverses the eastern cordillera (Fig. 1). The longitudinal profile of the Paute River clearly shows a knickzone where the wave of incision has propagated upstream through the fluvial network (Fig. 2B). This is setting the local base level for hillslope and fluvial processes. The location of this knickpoint zone is not lithologically controlled, as its location is clearly east of the transition zone between the weak volcanoclastic and sedimentary rocks of the inter-Andean basin and the hard metasedimentary and metavolcanic rocks of the eastern cordillera (Fig. 2A; Basabe et al., 1998).

The resulting landscape displays strong east–west contrasts in hillslope and river channel morphology (Fig. 1). The central part of the inter-Andean basin can be characterised as the predisturbance morphology with a moderate relief landscape with 90% of the slopes having slope gradients of < 0.30 m/m (Vanacker et al., 2007a), while the downstream part has a rejuvenated morphology that is currently adapting to local base level change (Fig. 1). Slopes are typically steep to very steep with slope gradients mostly above 0.40 m/m and local relief is generally higher than 150 m over a length scale of 450 m (Guns and Vanacker, 2013).

Long-term exhumation rates for the southern Ecuadorian Andes have been derived from stratigraphy and fission track analysis of ash layers within the basin fill series of two sedimentary basins (Cuenca and Quingeo) located in the Paute inter-Andean basin. The chronostratigraphy of marine and continental sedimentary facies of middle to late Miocene age was first established by zircon fission-track dating on tephra beds in the basin series (Steinmann et al., 1999). Assuming a geothermal gradient of 35 °C/km, Steinmann et al. (1999) estimated for the Paute inter-Andean basin a mean rock uplift rate of 700 mm/ka and a surface uplift of 300 mm/ka for the last 9 Ma years. For the last 3 Ma years, a mean erosion rate of 560 mm/ka was calculated using the information from the formational thicknesses of the basin series and the maximum burial of the basin fills from palaeotemperatures derived from apatite fission-track analysis. These values give a first indication of overall long-term exhumation and erosion rates of the central part of the Paute basin.

On the other hand, short-term (10 to 50 years) erosion rates derived from reservoir sedimentation measurements range from 50 to more than 2000 mm/ka (Vanacker et al., 2007a). Contemporary erosion rates in the Paute basin have been shown to be very sensitive to human activities (Molina et al., 2008) and are therefore not representative of longer term geomorphic process rates. High erosion rates are measured wherever the ground surface is bare of vegetation and where the soil has completely been stripped by water erosion leaving weakly resistant rocks at the surface (Vanacker et al., 2014). In contrast, in situ produced cosmogenic nuclides integrate erosion rates over time scales of 10^3 to 10^4 years in the Ecuadorian Andes, thereby damping short-term anthropogenic or climatic fluctuations in denudation rates (von Blanckenburg, 2005; Vanacker et al., 2007a). Denudation rates measured at these time scales may therefore be used to study the factors controlling erosion in transient landscapes that have not yet fully adjusted to the disturbance caused by rapid uplift, which is the main objective of this paper.

3. Sampling and methods

The approach used here is to quantify basin-wide ^{10}Be-derived denudation rates for catchments with strongly contrasting hillslope and stream channel morphology in the Tropical Andes. Cosmogenic