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Tectonic and lithological controls on denudation rates in the central Bolivian Andes

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ABSTRACT

The topographic signature of a mountain belt depends on the interplay of tectonic, climatic and erosional processes, whose relative importance changes over times, while quantifying these processes and their rates at specific times remains a challenge. The eastern Andes of central Bolivia offer a natural laboratory in which such interplay has been debated. Here, we investigate the Rio Grande catchment which crosses orthogonally the eastern Andes orogen from the Eastern Cordillera into the Subandean Zone, exhibiting a catchment relief of up to 5000 m. Despite an enhanced tectonic activity in the Subandes, local relief, mean and modal slopes and channel steepness indices are largely similar compared to the Eastern Cordillera and the intervening Interandean Zone. Nevertheless, a dataset of 57 new cosmogenic ^{10}Be and ^{26}Al catchment wide denudation rates from the Rio Grande catchment reveals up to one order of magnitude higher denudation rates in the Subandean Zone (mean 0.8 mm/yr) compared to the upstream physiographic regions. We infer that tectonic activity in the thrusting dominated Subandean belt causes higher denudation rates based on cumulative rock uplift investigations and due to the absence of a pronounced climate gradient. Furthermore, the lower rock strength of the Subandean sedimentary units correlates with mean slopes similar to the ones of the Eastern Cordillera and Interandean Zone, highlighting the fact, that lithology and rock strength can control high denudation rates at low slopes.

Low denudation rates measured at the outlet of the Rio Grande catchment (Abapo) are interpreted to be a result of a biased cosmogenic nuclide mixing that is dominated by headwater signals from the Eastern Cordillera and the Interandean zone and limited catchment sediment connectivity in the lower river reaches. Therefore, comparisons of short- (i.e., sediment yield) and millennial denudation rates require caution when postulating tectonic and/or climatic forcing without detailed studies.

1. Introduction

Mountain ranges stand out because of their relief. In general, relief is formed due to (plate) tectonic forcing shifting a landscape into a constructional topographic state. When critical elevations and slope values are approached, erosion begins to significantly contribute to landscape development. Topography then modulates air circulation and precipitation patterns (orographic rainfall) which in turn may enhance the effects on erosion (Roe et al., 2002). Eventually, tectonic influx and erosional outflux are balanced, shifting a mountain range into a topographic steady state (Montgomery, 2001). With ceasing tectonic forcing, persistent erosional processes outpace tectonic processes and set the mountain range into a destructional topographic state with decreasing relief. Studying such relief - erosion relationships and finding causal links between tectonics, climate and erosion can be performed by analysing topographic metrics (Champagnac et al., 2012) and quantifying exhumation and denudation rates (Burbank, 2002). However, it has been challenging to quantify the conditions and magnitudes of a tectonic, erosional, topographic transient or steady state and the timescales associated with them – a crucial prerequisite in the understanding and modelling of landscape evolution. Numerous parameters have to be considered because the construction of topography is

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spatially and temporarily variable and multiple evolutionary states may simultaneously exist or have variable response times. Furthermore, measuring uplift or erosion rates depends on various methods that are sensitive to spatial and temporal scales or have variable responses to transient processes (Schumm and Lichty, 1965). Moreover, common tectonic (e.g., seismicity, strain rates) and climatic (e.g., temperature, rainfall) parameters potentially preserved in a landscape are gathered over modern or historical timescales and may not be representative over longer timescales.

In order to illustrate the debate, common characteristics of tectonically active landscape studies are a steep relief, threshold slopes and mass-wasting processes (Korup et al., 2010; Montgomery and Brandon, 2002; Schmidt and Montgomery, 1995). Threshold slopes are referred to as being on the order of 25° or higher (DiBiase et al., 2010; Ouimet et al., 2009) with erosion rates increasing nonlinearly above this threshold value. However, it has also been shown that younger sedimentary sequences, lower grade exhumed structural depth levels or dip-slip/anti-dip-slip conditions can also yield threshold slopes with values <25° but under high denudation rates (Dadson et al., 2003; Duvall et al., 2004; Korup and Weidinger, 2011; Schmidt and Montgomery, 1995).

For the central Andes, it has been suggested that, on a regional scale, the geodynamic evolution and climate play a significant role in landscape evolution (Hilley and Coutand, 2009; Montgomery et al., 2001; Strecker et al., 2007). Studies on various spatial and temporal scales of uplift or denudation rates in the central Andes, however, identified different driving forces, amongst them regional tectonics and rock properties (Aalto et al., 2006; Insel et al., 2010; Safran et al., 2005; Whipple and Gasparini, 2014). In general, relief, slopes, orographic precipitation and denudation rates have higher values in the north of the Bolivian orocline (18°S), while south of it, these parameters reflect lower values (Masek et al., 1994; Montgomery et al., 2001). Here, we study the eastern Andes south of 18°S in detail by highlighting the complex interactions in mountain belt evolution with a compilation of various topographic metrics for the Rio Grande catchment in combination with a cosmogenic nuclide (^{10}Be and ^{26}Al) derived denudation rate dataset. The data are supplemented by previously acquired decadal denudation rates from sediment yield data (Guyot et al., 1994), and geo-thermochronologic estimates on million year timescales (Barnes et al., 2008). We assess the tectonic imprint, its reflection in cumulative seismic uplift and its potential effects on denudation rates in the Subandean Zone of the central Bolivian Andes, where a migrating tectonic front and the current shallow seismic activity constantly rejuvenates the landscape (Barnes et al., 2012; Horton, 1999; Montgomery et al., 2001). Consequently, denudation rates should be highest there. We will show that for the entire dataset common topographic metrics typical for a tectonic forcing reveal no distinct correlations with denudation rates in the eastern central Andes, as observed elsewhere in active tectonic regions. This is despite the fact that the denudation rates vary by an order of magnitude, similar to tectonic activity. Moreover, we will discuss the possible occurrence of threshold hillslope angles in the Subandes relating to the limited rock strength of young sedimentary sequences.

2. Geology & Tectonics

The Rio Grande catchment upstream of Abapo (Fig. 1) covers an area of 58939 km^2 over an altitude ranging from 400 to 5150 m asl. From west to east, five physiographic provinces can be distinguished (Fig. 1): the low relief Altiplano plateau, the Eastern Cordillera (EC), the Interandean Zone (IAZ) and the Subandean zone (SA), grading into the low-relief - flat Chaco plain (Amazon basin) (Soruco, 2000). The formation of these large-scale physiographic regions has been controlled by duplexing and stacking of two thrust sheets (McQuarrie, 2002). The development of the fold and thrust belt occurred by Cenozoic crustal shortening and thickening forced by the subduction of the Nazca plate below the South American plate (Isacks, 1988). The EC, composed of marine metasedimentary siliciclastic rocks of Palaeozoic age, experienced a period of intense shortening and exhumation between the Late Oligocene and Miocene (Echavarria et al., 2003; Horton and DeCelles, 1997). The IAZ and SA form an east-vergent thin-skinned fold and thrust belt in a retroarc position and comprise Palaeozoic and Mesozoic units (McQuarrie, 2002). Farther east, the structures of the Subandean zone progressively include Neogene continental strata of the low relief Chaco foreland basin. The deformation stepped from the SA into the Chaco foreland basin at c. 8 Myr by forming wider and gentler anticlines on top of a critical taper (Barnes et al., 2012; Echavarria et al., 2003; Uba et al., 2006). Present-day deformation and earthquake activity is located in a few frontal thrusts (Oncken et al., 2012) with aseismic shortening within the remaining parts of the SA (Brooks et al., 2011). Current GPS-shortening rates are 6.5 – 13 mm/yr (Barnes et al., 2008, 2012; Brooks et al., 2011; McQuarrie, 2002; Oncken et al., 2012).

Uplift rates based on geodetic, paleomagnetic and structural data are on the order of 10–100 mm/ky for the EC and IAZ and 500 – 2000 mm/ky for the SA (Lamb, 2000), implying a 10-fold increase between the EC/IAZ and SA. The SA are characterized by recent seismicity associated with dip-slip (thrust) events whereas the Cochabamba province (EC) is dominated by slightly oblique strike-slip events (Brooks et al., 2011; Echavarria et al., 2003; Rhea et al., 2010; Vega and Buforn, 1991), acknowledging the regional influence of the bending of the eastern Andes at ~18°S (Isacks, 1988).

South of 18°S, long-term denudation rates based on apatite fission track data yield rates of ~ 200 ± 70 mm/ky for the EC, ~150 ± 60 mm/ky for the IAZ and ~ 310 ± 110 mm/ky for the SA (Insel et al., 2010). For the EC and the IAZ they broadly match with the estimates on uplift, while they are significantly lower for the SA. Denudation rates increase from 10^6 to 10^3 yr timescales with no concomitant systematic correlations with morphometric parameters or precipitation changes (Insel et al., 2010). The temporal variability in these denudation rates was attributed to Holocene climate changes, while an observed spatial variability was proposed to reflect local tectonic variations (Insel et al., 2010). Sediment gauging data revealed high sediment load rates in the Rio Grande upstream of Abapo with seasonal and inter-annual variability on sediment transport processes (Guyot et al., 1994; Guyot et al., 1996). According to Aalto et al. (2006), lithology and rock erodibility control some variance on decadal denudation rates, but do not control millennial denudation rates (Insel et al., 2010; Safran et al., 2005). Bookhagen and Strecker (2012) point out the importance of climatic parameters on the efficiency of surface processes through time. By coupling the specific stream power concept with their cosmogenic denudation rates their data are best explained. Today, hillslopes in the EC and IAZ are thinly soil covered, mainly characterized by regolith, whereas in the SA soils up to 1 m thick are common (Coppus, 2002).

3. Climate

The Eastern Andes act as a barrier for moisture from the Amazon basin and impose an orographic rainfall pattern. However, south of the Bolivian Bend, at ~ 18°S where the fold and thrust belt widens, the precipitation pattern is characterized only by a gentle modern E-W gradient (Bookhagen and Strecker, 2008; Díaz et al., 2010; Masek et al., 1994). Since the main moisture transport across the southern Amazon basin is WSW oriented, the Bolivian Bend shields the area just S of it from strong precipitation. Mean annual precipitation ranges from 200–1200 mm/yr (Fig. 1, Bookhagen and Strecker, 2008). With altitude, the amount of rainfall decreases gently and vegetation cover declines rapidly.

4. Methods

4.1. Sampling strategy, cosmogenic nuclide analysis, denudation and sediment flux estimations

Sediment sampling for establishing cosmogenic nuclide concentrations took place in sub-catchments of each physiographic region along