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Climatic imprint on landscape morphology in the western escarpment of the Andes

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ABSTRACT

Because of competing forces and variations through time, the relative importance of geomorphic processes responsible for the long-term topographic evolution of a mountain range is not always obvious. Here we perform a space-for-time substitution with the western escarpment of the Andes between 10 and 20°S to identify the mechanisms of plateau destruction over geological timescales. We use this setting to propose that variations in the precipitation rate play a primary role in setting hillslope relief in uplifted mountainous landscapes. We find that in dry climates local topographic relief grows with increasing precipitation, independent of the underlying lithology and given an overall uniform rock uplift history. We proceed by differentiating Andean landscapes with generally low precipitation rates (80–500 mm a^{-1}, Peruvian Andes 10–20°S) where local relief correlates positively with precipitation, from those with higher precipitation rates (400–1400 mm a^{-1}, Chilean Andes 35–40°S) where increases in precipitation lead to topographic decay. We suggest that these trends result from dominant bottom-up control (channel incision is faster than hillslope response) giving way to an increasing top-down control (hillslope lowering is faster than channel incision). With low precipitation, relief growth is controlled by stream incision and knickzone retreat into a largely undissected plateau. With higher precipitation rates, relief is set by the steepness of graded streams and the rates of sediment production and transport on hillslopes.

Trends of topography can also be interpreted in temporal terms in which the higher precipitation results in shorter response times, such that the Peruvian Andes between 10 and 20°S are still responding to Miocene uplift, while in the Chilean Andes between 35 and 40°S, these knickzones have already propagated through the entire fluvial network. We anticipate that such changes also operate during the formation and destruction of other mountainous plateau landscapes.

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1. Introduction

Empirical and modeling studies suggest that climate variables, especially precipitation, have an important influence on landscape form, particularly in fluvially dominated orogenic settings. A common observation is that relief decreases with increasing rainfall, reflecting either more efficient hillslope erosion or a larger drainage density (e.g., Bonnet and Crave, 2003; Gabet et al., 2004; Rehak et al., 2010). Furthermore, channel metrics like concavity can be strongly affected by orographically induced variations in precipitation (Roe et al., 2002; Schlunegger et al., 2011). Likewise, bedrock strength and rock uplift rates also have a substantial control on hillslope and channel metrics (e.g., Korup and Schlunegger, 2009). In particular, these variables may influence hillslope form via adjustments of stream gradients and threshold angles of hillslopes, which in turn set the basis for magnitudes of elevation differences between summits and valleys (Whipple, 2004). Most studies have focused on landscapes where stream profiles are graded and are characterized by similar steepness and concavity values along the entire length, which is indicative of geomorphic steady state (Flint, 1974; Whipple, 2004; Wobus et al., 2006). Prominent nongraded streams can exist where an uplift pulse forces the drainage network to adjust by headward retreat of a knickzone that separates an upper segment graded to the pre-uplift conditions from a rejuvenated lower reach (Whipple, 2004), indicative of geomorphic transience (Norton and Schlunegger, 2011). These latter landscapes, however, have received much less attention with respect to identifying the driving forces controlling hillslope and channel metrics.

The western flank of the central Andes has been considered a typical transient landscape, where stream longitudinal profiles are adjusting to an uplift pulse that mainly occurred in the late Miocene (Schildgen et al., 2007). Here, we explore the relationships between bedrock lithology, climate, and landscape morphology in the western Andean escarpment of Peru and northern Chile between 10 and 20°S. As we find an overall similar setting regarding the total relief (with rivers originating on the plateau and discharging into the Pacific) and spatially varying lithology and precipitation rates, we perform a space-for-time substitution in order to detect possible controls on landscape evolution.

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2. Regional setting

The western continental margin of northern South America is characterized by the active subduction of the Farallón–Nazca oceanic plate beneath the South American continental plate. Collision and arc magmatism started in the early Jurassic followed by several phases of shortening and thrusting. The last phase of uplift began by ~10–6 Ma and resulted in the formation of the Andean Plateau, which drains westward to the Pacific Ocean along a steep, incised ramp (Isacks, 1988; Hoke et al., 2007; Garzione et al., 2008; Jordan et al., 2010; Schildgen et al., 2010). Based on apatite ^{4}He/^{3}He thermochronometry, Schildgen et al. (2010) showed that this major phase of rapid exhumation, and presumably uplift, ended by ~3–2.2 Ma. Since this time, much of the collisional flux of the Andean orogen has been accommodated by shortening of the eastern and sub-Andes (Norton and Schlunegger, 2011). Upstream of the ramp on the central Andean Plateau, streams have remained graded to the late Miocene base level (Schlunegger et al., 2006; Hoke et al., 2007). Below the ramp, streams have incised more than 1000 m along a series of steep, headward-retreating knickzones that grade to the present-day base level defined by the Pacific Ocean (Schildgen et al., 2007). Additional surface uplift of > 100 m has affected the coastal region since 400 ka (Regard et al., 2010).

The lithology of the ramp primarily comprises Mesozoic sedimentary rocks (sandstones and carbonates) intruded by the Cretaceous Coastal Batholith (granites and granodiorites). On the Plateau, these rocks are unconformably overlain by a thick (100 s m) series of Tertiary volcanic-volcaniclastic rocks (SERNAGEOMIN, 2004; INGEMMET, 2011) (Fig. 1B).

The western Andean margin is characterized by generally low precipitation rates, which result from large-scale mid-tropospheric subsidence over the SE Pacific acting in concert with regional factors (Rutllant et al., 2003). Rainfall is largely concentrated in the austral summer month, caused by a seasonal expansion of the equatorial easterlies, which carry moisture from the Atlantic to the Plateau (Garreaud et al., 2003). The resulting precipitation pattern is characterized by precipitation rates decreasing from ~1000 mm a^{-1} near the Equator to <100 mm a^{-1} in northern Chile, and likewise from the Plateau to the Pacific coast (Huffman et al., 2007; Bookhagen and Strecker, 2008) (Fig. 1A). The magnitude of precipitation has varied on orbital timescales as inferred from lake level highstands (Baker et al., 2001; Fritz et al., 2004) and Quaternary cut-and-fill terraces (Steffen et al., 2009). The strong N–S and E–W gradients in precipitation have likely been in place since the Plateau reached one-half to three-quarters of its present-day elevation (e.g., Lenters and Cook, 1995, 1997; Ehlers and Poulsen, 2009).

3. Methods

We analyzed a total of 27 watersheds of transverse rivers between 10 and 20°S with sources on the Plateau and outlets to the Pacific Ocean for relationships between hillslope metrics, climate, bedrock lithologies, and neotectonics. We excluded rivers north of 10°S latitude

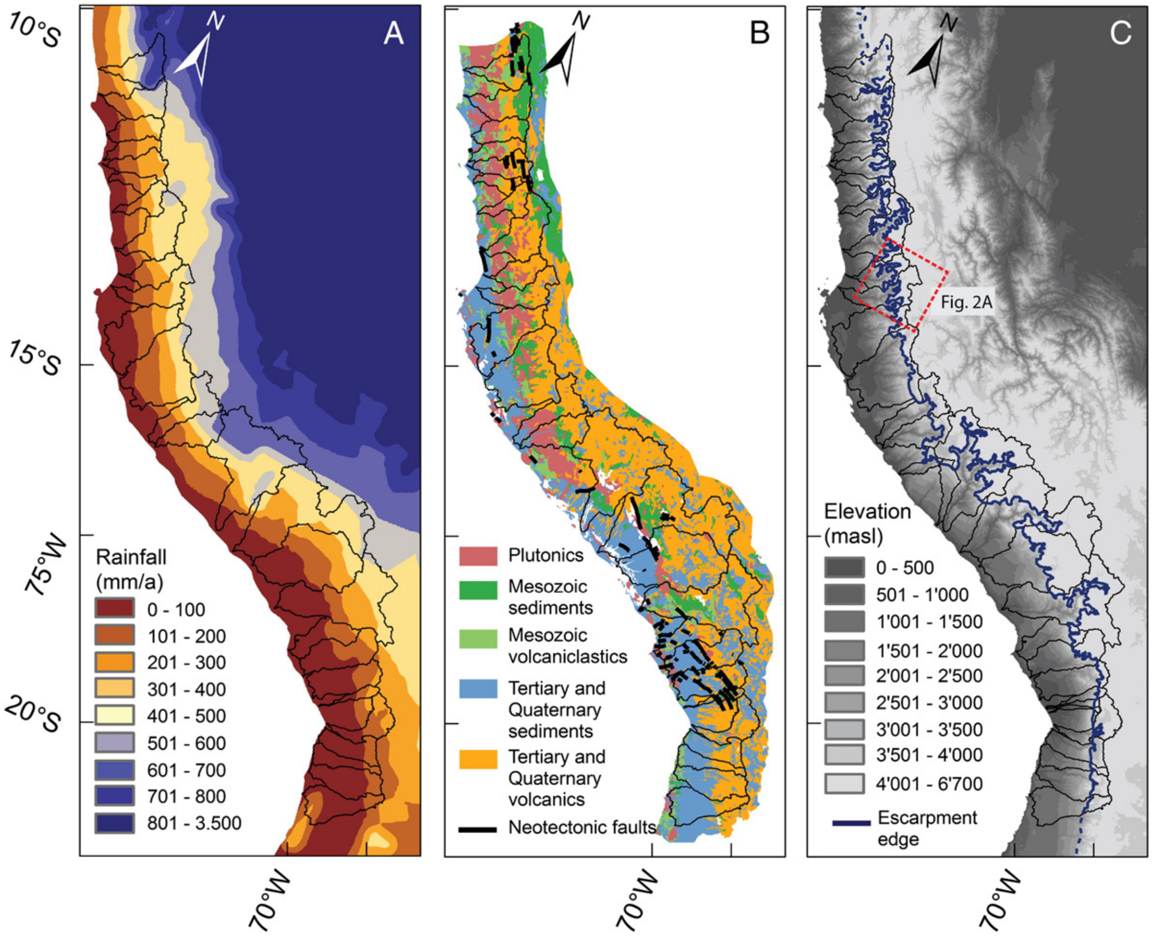

Fig. 1. Study area showing basins. (A) Precipitation data taken from medium-resolution (ca. 25 × 25 km) rainfall data set TRMM V6.3B43.2 averaged over 12 years from 1998 to 2010 (Huffman et al., 2007); (B) broadly generalized geological map of the study area based on the geological map 1:1,000,000 of Peru and Chile (SERNAGEOMIN, 2004; INGEMMET, 2011) and neotectonic faults based on the neotectonic map of Peru 1:2,000,000 (Macharé et al., 2009). Note that the map of Quaternary faults in Chile 1:4,000,000 does not indicate any neotectonic structures for the Chilean part of the study area (Lavenu et al., 2000); (C) elevation data (90-m-resolution SRTMV3) and escarpment edge.

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