Geology

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Geology published online 18 September 2012;
doi: 10.1130/G33229.1

Notes

Geology, published online on 18 September 2012 as doi:10.1130/G33229.1

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ABSTRACT

Quantifying interactions between uplift, climate, deformation, and exhumation remains difficult, in many cases due to a paucity of data relevant to all processes. We synthesize new and existing data to understand the orogen-scale orographic changes across the central Andes, Bolivia. We use a regional climate model and geo-thermochronologic data to identify the correlations between changes in precipitation due to surface uplift and spatiotemporal patterns of deformation and erosional exhumation. Mean orographic rainfall patterns do not reach near present-day gradients and values until the topography grows to >75% modern elevations. New fission-track data near the orocline apex indicate that rapid exhumation moved eastward, beginning in the Eastern Cordillera ca. 50–15 Ma, the Interandean zone ca. 18–6 Ma, and in the Subandes ca. 7–3 Ma. Throughout Bolivia, exhumation is consistent with deformation until ca. 15–11 Ma, after which the pattern corresponds better with the increased rainfall toward modern values. These linked observations suggest that ca. 15–11 Ma, regional elevations reached threshold values (>75% modern) necessary to generate near present-day, enhanced rainfall gradients. These gradients have resulted in variable exhumation implied by the structural level of rocks exposed across the thrust belt and confirmed by fission tracks in apatite. The main insight is that the climate-induced Middle Miocene–recent exhumation varies over scales of a few hundred kilometers across Bolivia and implies that high mean rainfall (>~3 m/yr) and long time scales (~10 m.y.) may be necessary for climate to induce orographically driven exhumation patterns recorded by fission tracks.

INTRODUCTION

Interactions between tectonics, topography, climate, and erosion evolve as mountains grow. Numerical models suggest coupling of tectonics and climate (Willett, 1999) and dramatic climate shifts triggered by increased surface elevations (e.g., Prell and Kutzbach, 1992). However, the significance of these insights is limited by the tenuous connection between the models and data available to critically evaluate them (Whipple, 2009). This failing exists, in part, because data sets that address orogen evolution often represent disparate scales. For example, time spans covered by geologic data can be long (one to tens of millions of years), but modern climate patterns may be short-lived (millennia), even though they are often assumed invariant over geologic time scales (Montgomery et al., 2001; Reiners et al., 2003).

Models show that Andean surface uplift strongly affects regional climate (Lenters and Cook, 1995). Orographic enhancement of precipitation patterns could result in variable orogen erosion recorded by exhumation patterns quantified over million-year time scales using thermochronology. We focus on the central Andes because correlations in topography and climate suggest that erosion has influenced thrust belt development (Horton, 1999) and shortening and exhumation records advocate that tectonics and climate became connected during the Miocene (e.g., Strecker et al., 2007). We hypothesize that this connection developed as elevations reached heights sufficient to induce intense orographic precipitation and erosion gradients across the Bolivian orocline (Masek et al., 1994; Norton and Schlunegger, 2011). We test this idea with new mean rainfall estimates from climate simulations that are forced by rising Andean elevations and link them to the spatiotemporal patterns of exhumation constrained by geothermochronologic data.

GEOLOGIC SETTING

Eocene–present (ca. 45–0 Ma) central Andes mountain building has produced a retroarc plateau and thrust belt (Fig. 1). The thrust belt has migrated eastward through time and varies in width and shortening along strike (McQuarrie et al., 2008a). The plateau and thrust belt is divided into the Altiplano basin (AL) and the higher relief regions of the Eastern Cordillera (EC), Interandean zone (IA), and Subandes (SA). These zones step downward from the EC to the SA in mean elevation and upward in structural depth, exposing Paleozoic to Tertiary rocks (Kley, 1999). In Bolivia, the thrust belt

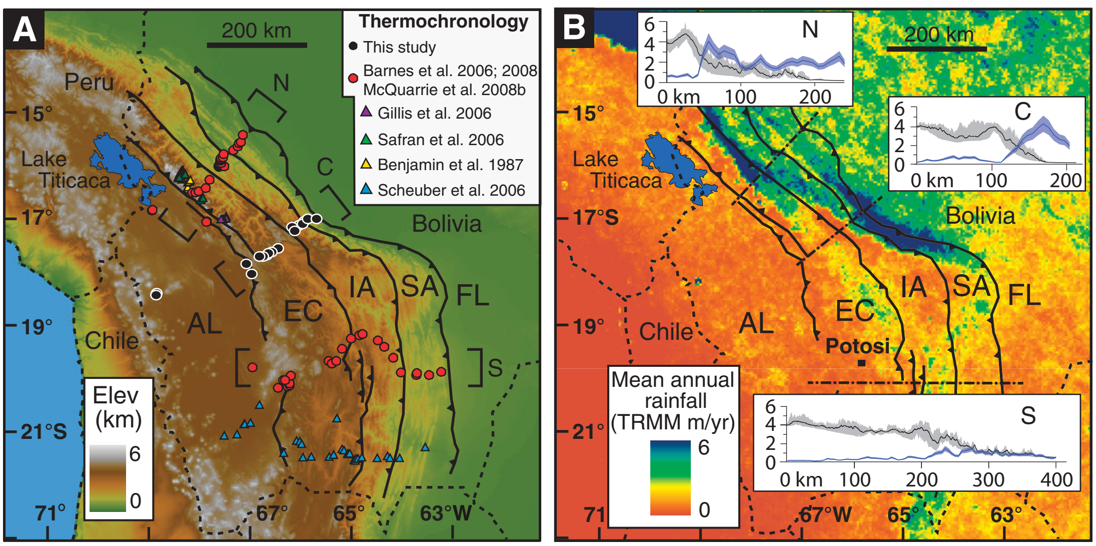

Figure 1. Central Andes topography, tectonics, and climate. Transects: N—north, C—center, S—south. A: Thrust belt region bounding faults and zones: AL—Altiplano, EC—Eastern Cordillera, IA—Interandean zone, SA—Subandes, FL—foreland. B: Tropical Rainfall Measuring Mission (TRMM) estimated rainfall (1998–2006; Bookhagen and Strecker, 2008). Insets are 50 km swath mean elevation (km; black line, gray is range; 90 m digital elevation model) and rainfall (m/yr; blue line ± 20%) profiles.

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straddles a sharp change in precipitation, from subtropical dry conditions south of ~18°S to subequatorial wet conditions to the north. Orography alters the rainfall distribution, producing small mean rainfall gradients (~2 to <1 m/yr) in the south compared to the center and north (~4 to <1 m/yr; Fig. 1B).

METHODS: CLIMATE MODEL AND THERMOCHRONOLOGY

$REMO_{iso}$ is a limited-domain general circulation model (~55 km resolution) that replicates modern South American climate patterns well (Sturm et al., 2007). Topography is the most important factor forcing Andean flank climate gradients on geologic time scales (Jeffery et al., 2011). We extracted mean rainfall values from simulations with 50%, 75%, and 100% mean modern Andean elevations to examine the first-order response of rainfall patterns to surface uplift along three thrust belt transects (Fig. 2A) (Insel et al., 2012; see the GSA Data Repository[1]).

Low-temperature thermochronology can resolve the ~50–350 °C cooling history of rocks to quantify regional patterns of orogen erosion (e.g., Gillis et al., 2006). We combine 17 new fission-track samples (see the Data Repository) that traverse the thrust belt apex with other transects of published data (~125 samples; Fig. 1). We interpret the data with standard methods of (1) thermal modeling to constrain cooling histories and identify the onset of most recent, rapid exhumation and (2) estimating depths to closure temperatures using geothermal data to constrain the exhumation magnitude (cf. Barnes et al., 2006, 2008). For brevity, we summarize the constraints from good-fit thermal models associated with the robust apatite fission-track data (samples with >10 measured grains, >20 measured tracks; see the Data Repository) combined with published $^{40}Ar/^{39}Ar$, fission-track, and (U-Th)/He data (Fig. 2B).

RESULTS AND INTERPRETATIONS

Climate simulations predict the response of rainfall to Andean surface uplift (Fig. 2A). At 50% modern elevations, mean rainfall rates decrease from ≤2 m/yr with increasing elevation across the northern and central transects and have no gradient across the southern transect. At 75% modern elevations, rates increase to 2.8 m/yr, but remain far below the observed peak values (Figs. 2A and 1B); only above 75% modern elevations are near modern rainfall maxima and orographic gradients established. Specifically, rainfall maxima (~3.8 m/yr or more) become focused in the northern EC and in the eastern IA to SA along the central transect. The control case (100% modern elevations) simulates the across-strike rainfall patterns well, but broadens the distribution of orographic precipitation and overpredicts the rainfall in places (e.g., the AL; Fig. 2A), common biases in most climate models (Codron and Sadourny, 2002). Regardless, the precipitation sensitivity to uplift and the >75% modern elevation threshold inducing peak rainfall is consistent with many models of various resolutions and elevation gain increments, and is related to enhanced latent heat transport, convergence, and convection (Insel et al., 2009; Poulsen et al., 2010).

The Cenozoic history of central Andean growth shows that deformation and initial rapid exhumation are synchronous and that this initial exhumation front tracks the eastward propagation of the thrust belt from the EC since the Eocene (ca. 45 Ma; Fig. 2B) (Barnes and Ehlers, 2009). In the south, exhumation began in the central EC ca. 36–32 Ma, moved into the IA ca. 22–19 Ma, and into the SA ca. 20–8 Ma (Barnes et al., 2008). Results from further south at ~21°S are similar (Fig. 1A; Scheuber et al., 2006). In the center, exhumation began in the EC ca. 50–45 Ma, in the IA ca. 18–6 Ma, and in the SA ca. 7–3 Ma. In the north, exhumation began ca. 50–30 Ma in the EC, ca. 25 Ma or earlier in the IA, and ca. 20–8 in the SA (McQuarrie et al., 2008b). Collectively, deformation and initial exhumation migrated eastward across the EC ca. 50–30 Ma, the IA ca. 25–18 Ma, and the SA ca. 20–3 Ma.

The eastward propagation of linked deformation and exhumation breaks down along the northern transect, marking a vital change in the exhumation history ca. 15–11 Ma (Fig. 2B).

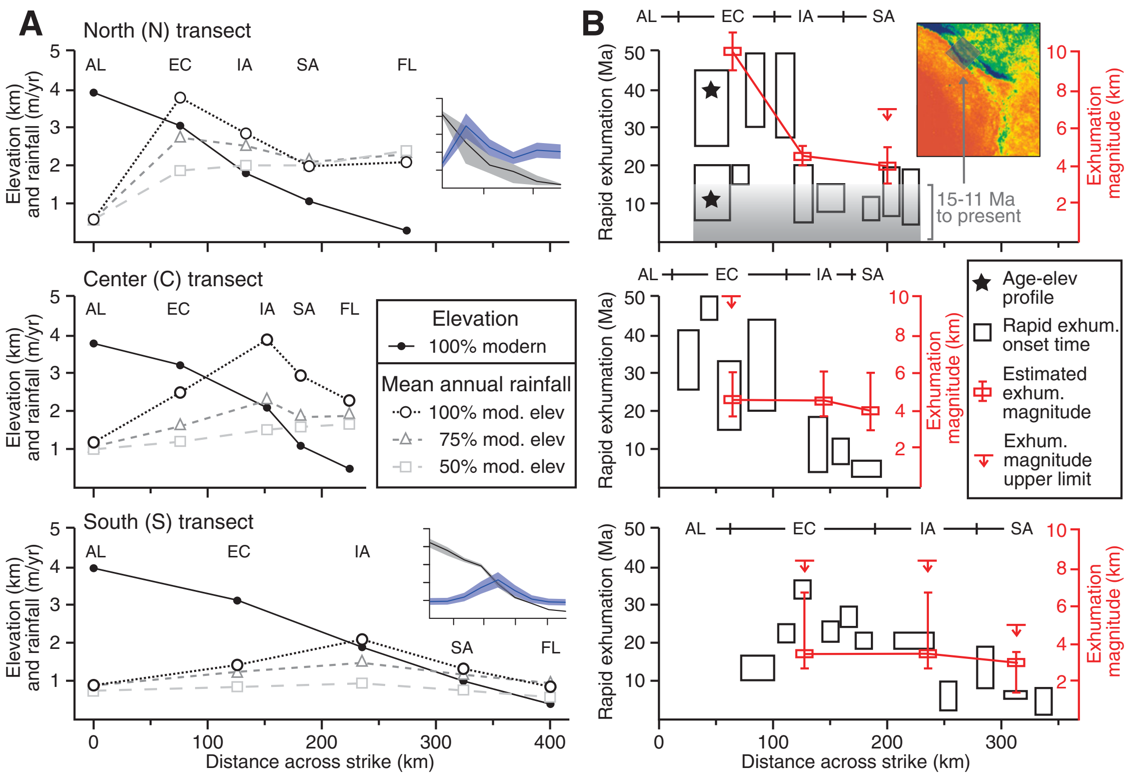

Figure 2. Climate and exhumation along transects in Figure 1. A: Regional circulation model $REMO_{iso}$ rainfall estimates for 50%, 75%, and 100% modern (mod) elevations (elev) compared to 100% model elevations. Insets are ~150 km swath profiles for 100% mod elevation run for comparison to Figure 1B profiles. AL—Altiplano, EC—Eastern Cordillera, IA—Interandean zone, SA—Subandes, FL—foreland. B: Cordilleran exhumation patterns (Fig. 1A data). Gray is rapid exhumation (exhum.) since ca. 15–11 Ma that correlates with climate in north. Inset is spatial extent overlying Tropical Rainfall Measuring Mission (TRMM) rainfall (Fig. 1B). Stars are best age constraints (age-elevation profiles) for both exhumation phases in the northern EC (Gillis et al., 2006).

[1]GSA Data Repository item 2012328, climate model and fission-track data, methods, and results, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Here, EC exhumation began at 40 Ma, best constrained by age-elevation profiles of biotite $^{40}Ar/^{39}Ar$ and zircon fission-track data (Benjamin et al., 1987; Gillis et al., 2006). A second rapid exhumation phase began ca. 15–11 Ma, spanning the entire EC to SA (Barnes et al., 2006). The best constraint (an apatite fission-track age-elevation profile) for this phase is 11 Ma, which postdates EC upper crustal deformation by ~14 m.y. (Gillis et al., 2006).

Thermochronology data also estimate exhumation magnitudes across the orogen (Fig. 2B). Precambrian–Mesozoic (ca. 600–150 Ma) zircon fission-track and (U-Th)/He ages limit Andean exhumation to <10–8 km in the southern and central EC–IA regions and to <7 km in the northern SA. In the south, Cenozoic apatite fission-track data suggest ~4 km of exhumation from the EC and IA and ~3 km from the SA. Results from ~21°S suggest ~6–2 km of exhumation across the EC and IA (Ege et al., 2007). In the center, we estimate ~4.4 km of exhumation from the EC and IA, and ~4 km from the SA. The north is different where Eocene–Oligocene $^{40}Ar/^{39}Ar$ ages imply ~10 km of total exhumation in the EC compared to ~4 km in the IA and SA (Gillis et al., 2006). These results show that exhumation has barely decreased eastward across the orogen, with the exception of the northern EC.

The SA apatite fission-track data record a south to north gradient in exhumation magnitude from low to high to intermediate, coincident with modern rainfall. This is evident from Paleozoic–Mesozoic cooling ages exhumed from partial annealing zone temperatures at ≤3.5 km in the south, reset Miocene–Pliocene cooling ages exhumed from below closure temperature at ≥4 km in the center, and mostly early Cenozoic mixed and/or partially reset cooling ages exhumed from partial annealing zone temperatures at ~4 km depth in the north (this study; Barnes et al., 2008).

In summary, climate simulations indicate that near modern rainfall gradients become established after >75% modern elevations are attained. The exhumation patterns emphasize a Middle Miocene (ca. 15–11 Ma) shift to distributed exhumation in the northern transect, unassociated with EC upper crustal deformation, yet ~4 km in magnitude since ca. 11 Ma (Gillis et al., 2006). The patterns also feature Middle Miocene–Pliocene (ca. 13–3 Ma) exhumation in the eastern IA–SA in the central transect and imply that SA exhumation magnitude varies along strike. These collective exhumation patterns coincide better with the modern rainfall patterns than they do with the eastward propagation of Miocene–recent deformation (e.g., gray; Fig. 2B).

Erosion is the main exhumation mechanism in active thrust belts, often facilitated by deformation creating topographic relief. However, exhumation can continue after deformation ceases and can vary in response to climate change (e.g., Fig. 2A). We propose that near modern rainfall gradients have persisted enough to affect the regional exhumation patterns, best exemplified by the northern transect with distributed exhumation since ca. 15–11 Ma and a high magnitude in the EC. Apatite fission-track data record the erosion of several kilometers of rock (sensitive to ~110 °C; geothermal gradients are ~35–20 °C/km; see the Data Repository). We propose that near-modern rainfall gradients were established at >75% modern elevations ca. 15–11 Ma and have mainly driven the Middle Miocene to present exhumation patterns north of 18°S.

DISCUSSION

Existing geologic and isotopic records in Bolivia suggest changes in climate and topography consistent with increasing rainfall and altitudes ca. 15–11 Ma (Fig. 3). SA stratigraphy records a tenfold increase in sedimentation rate with Yecua Formation deposition at 12.4 Ma (Uba et al., 2009). A decrease in δ^{18}O of pedogenic carbonate from these strata starting ca. 12 Ma is interpreted to indicate low δ^{18}O rainfall due to enhanced rainout caused by growing topography (Mulch et al., 2010). By ca. 9–6 Ma, increased climate seasonality and a sediment source change via headward catchment growth caused a further increase in sedimentation and an increase in multiple soil carbonate isotope ratios (Mulch et al., 2010; Uba et al., 2009). The northern EC exhumation ca. 11 Ma is recorded by ongoing Cangalli Formation deposition ca. 10 Ma in an adjacent wedge-top basin, followed by its incision beginning ca. 7 Ma (Mosolf et al., 2010).

Critical taper theory for thrust belt growth offers a mechanical basis for erosion restricting orogen width (e.g., Suppe, 1981). The SA are a good test case because deformation began ca. 16 Ma or later, coincident with or after the establishment of the near modern rainfall gradients (Fig. 3) (Espurt et al., 2011). North to south variations in SA shortening (41%, 55%, 32%), width (96, 56, 139 km), and modern rainfall are consistent with erosion limiting thrust belt propagation along the northern and central transects relative to the south (Figs. 1 and 3) (McQuarrie, 2002; McQuarrie et al., 2008a). This suggests a tectonics-climate correlation at a scale of a few hundred kilometers. However, the shortening estimates may overlap within uncertainty and inherited tectonostratigraphic differences may also affect propagation (Judge and Allmendinger, 2011).

The northern EC and eastern IA to SA in the central transect are sites of high (~4 km) and young (Miocene–Pliocene) exhumation (Fig. 2B; Gillis et al., 2006). This is also implied by the (1) peak rainfall today (~4 m/yr; Fig. 1B), (2) deepest stratigraphic exposures,

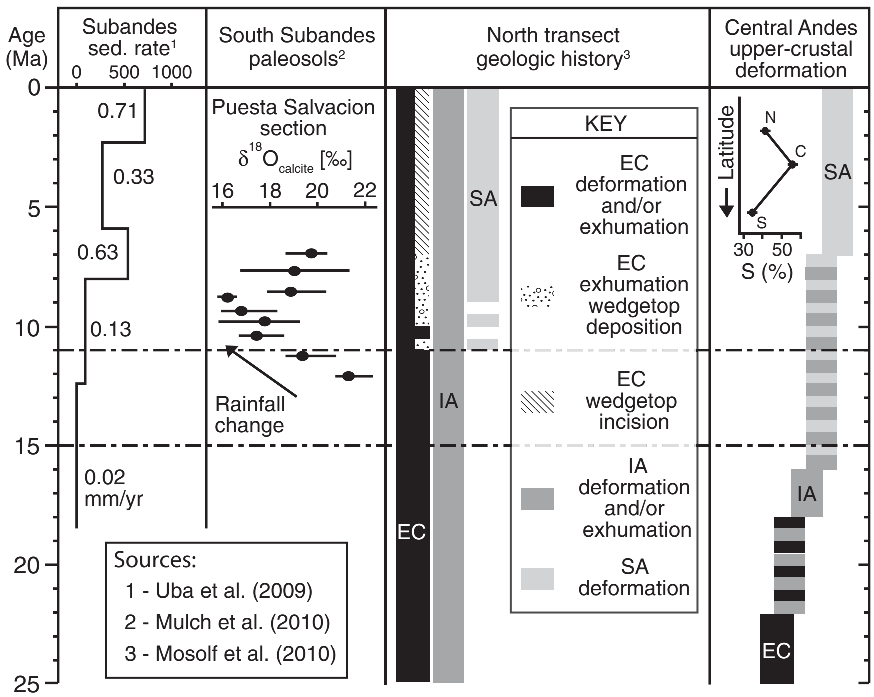

Figure 3. Geologic data consistent with enhanced rainfall starting 15–11 Ma (dashed lines); sed—sedimentation, S—shortening. Transects: N—north, C—center, S—south; AL—Altiplano, EC—Eastern Cordillera, IA—Interandean zone, SA—Subandes. See text for discussion. Central Andes deformation history is integrated over all transects plus data from Peru and Argentina (Espurt et al., 2011). Inset is latitudinal variations in SA shortening with 5% error (McQuarrie, 2002; McQuarrie et al., 2008a).

i.e., Cambrian in the central SA only at ~17°S (McQuarrie, 2002) and lowermost Ordovician in the northern EC at ~16.5°S (McQuarrie et al., 2008b), and (3) high channel concavities signifying climatic forcing in the northern EC (Schlunegger et al., 2011). These results broadly suggest that high (~3 m/yr or more) mean orographic rainfall and ~10 m.y. time scales (~15–11 m.y. here) may be required to link fission-track–recorded exhumation and climate patterns in other active orogens.

ACKNOWLEDGMENTS

We thank Sohrab Tawackoli and Jaime Tito for logistical support and the National Science Foundation for financial support (grants EAR-0409289, EAR-0738822, and EAR-0907817 to Ehlers and Poulsen). We thank F. Schlunegger, J.-D. Champagnac, and an anonymous reviewer for their constructive reviews.

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Manuscript received 23 January 2012
Revised manuscript received 25 May 2012
Manuscript accepted 14 June 2012

Printed in USA