Temporal variation in climate and tectonic coupling in the central Andes

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ABSTRACT

Analog and numerical models predict a coupling between climate and tectonics whereby erosion influences the deformation of orogens. A testable prediction from modeling studies is the decrease in width of mountain ranges as a result of increased precipitation. Here we evaluate the effect of climate on a critically tapered orogen, the central Andes, using sequentially restored, balanced cross sections through wet (15°–16°S) and dry (21°S) regions of the orogen. In these regions, tectonics, basin geometry, and style of deformation are similar, allowing us to use variations in propagation (or changes in percent shortening) to evaluate whether along-strike changes in width and morphology are climate driven in the north. Results indicate similar total percent shortening along the northern (40%) and southern (37%) sections, suggesting that a wetter climate has not limited the width (propagation) in the north. However, comparison of early (45–25 Ma) and recent (ca. 20–0 Ma) shortening indicates that early deformation produced 45% ± 2% shortening of both sections, while recent deformation produced 41% ± 2% (north) versus 32% ± 2% (south) in the actively deforming Subandes. The latter suggests a coupling between climate and tectonics that began between ca. 19 and 8 Ma, and continues to 0 Ma, potentially limiting the width of the northern Subandes by ~40 km.

INTRODUCTION

Analytical and numerical models that couple tectonic and surface processes have led to the hypothesis that climate-modulated erosion can exert a first-order control on orogen deformation. For example, previous studies indicate that climate influences the style, magnitude, and location of deformation, as well as the morphology of mountains (e.g., Roe et al., 2006; Whipple and Meade, 2004; Willett, 1999). However, despite these advances, uncertainties remain regarding the nature and strength of climate-driven erosion in orogen evolution, including whether a diagnostic signature of such can be resolved in the field (Whipple and Meade, 2006). The first-order prediction of climate-tectonic modeling studies is a change in orogen width as a result of increased precipitation-induced erosion (Dahlen and Suppe, 1988; Whipple and Meade, 2004). The effect of erosion on orogen width was first addressed through critical taper theory, which suggests that the erosion rate controls steady-state wedge width and that deformation is influenced by erosion (Dahlen, 1990; Dahlen and Suppe, 1988; Suppe, 1981). The balance between accretionary and erosional fluxes determines whether an orogenic wedge grows, shrinks, or stays constant.

We propose that a robust test of an orogen's response to changes in precipitation is how well precipitation limits the outward propagation of deformation (thus limiting the width of the orogen). Previous explanations for changes in the width of the Andes include erosionally limited growth of a critically tapered wedge (Horton, 1999), significant along-strike changes in the original Paleozoic basin (notably between Bolivia and Argentina; Allmendinger and Gubbels, 1996; and at ~17°S; Sheffels, 1995), and erosional retreat of high topography (Masek et al., 1994; Montgomery et al., 2001). We complement previous studies and suggest that along-strike changes in percent shortening provide a first-order evaluation of erosion-limited propagation of the central Andean fold-thrust belt.

GEOLOGIC AND CLIMATIC SETTING

The Andes Mountains in South America are often cited as an example of how deformation, exhumation, and morphology change due to variations in climate along strike (Fig. 1) (Horton, 1999; Lamb and Davis, 2003; Masek et al., 1994; Montgomery et al., 2001). The high-elevation Andean plateau spans a pronounced switch in hemisphere-scale Hadley precipitation regimes at ~17°–18°S (Fig. 1A). South of ~17°–18°S the mountains are dry (<1 m/yr), wide (550 km from the volcanic arc to the foreland), and exhibit a correlation between thrust belt structure and topography. North of ~17°S the mountains are narrower (410 km). Trade winds bring >2 m/yr of rainfall (Bookhagen and Strecker, 2008; Garreaud et al., 2003) that is orographically focused on the eastern edge of the plateau. As a result, rocks on the northeastern, wet plateau margin show the deepest exposed portions of the Andean fold-thrust belt and the morphological expression of the active Subandes is muted (Fig. 1B).

The central Andean plateau is built of rocks deposited in an extensive (~14°–21°S), predominantly marine Paleozoic basin that is ~12 km thick just east of the Eastern Cordillera and tapers eastward to thicknesses of 6–8 km (McQuarrie, 2002; McQuarrie et al., 2008; Sempere, 1995). The basin extends 200–400 km into the undeformed foreland except for a narrow (~150-km-wide) region at ~17°S, where the thrust belt has reached the edge of the Paleozoic basin (Sheffels, 1995; Welsink et al., 1995) (Fig. 1B). The siliciclastic strata that compose the basin, and their respective mechanical stratigraphy, are remarkably similar along strike (e.g., Sempere, 1995; McQuarrie, 2002), and thus we infer that the along-strike strengths are similar (McQuarrie and Davis, 2002). Major décollement horizons are located in shale-rich formations at the base of the Ordovician, base of the Silurian, and in the Devonian (base of the Devonian in the north and Middle Devonian in the south, a change of ~1.5 km) (Baby et al., 1995; Dunn et al., 1995; McQuarrie, 2002; McQuarrie et al., 2008). Tertiary synorogenic sediments are preserved in large-wavelength Subandes piggyback basins (6–7 km thick) and in the foreland (3–5 km), with thicker sections in the north (Baby et al., 1995; Dunn et al., 1995; Horton and DeCelles, 1997).

METHODS: PROPAGATION AND SHORTENING

Orogen growth results from propagation of a fold-thrust belt in the direction of horizontal shortening. Factors influencing thrust belt propagation are (1) the ratio of rock strength to décollement strength, and (2) the magnitude of erosion (Dahlen and Suppe, 1988). Incorporating strong rocks (with respect to décollement strength) into a fold-thrust belt facilitates propagation and allows the fold-thrust belt to maintain or decrease taper. Focused erosion on a critically tapered wedge reduces taper and forces the wedge to deform internally to regain taper before propagating outward. Examination of the central Andes through the lens of critical taper theory suggests that the width of the orogen is controlled by along-strike changes in lithology or variations in erosion, by assuming that erosion is proportional to precipitation magnitude in fluvial-dominated systems (e.g., Whipple and Tucker, 1999). We argue that the largely uniform (in thickness, width, and composition) Paleozoic basin along both transects (Fig. 1B) removes north-south changes in rock strength as a primary control of propagation, enabling us to evaluate the importance of erosion-limited propagation in the final width of a mountain range by quantifying along-strike variations in percent shortening (Fig. 2).

Percent shortening is the shortening amount normalized by the final width of a fold-thrust belt (Fig. 2). For the central Andes, if north-south gradients in precipitation (and, by inference, erosion) have not affected the width of the fold-thrust belt, percent shortening will be equal. If changes in precipitation have influenced orogen width, then the magnitude of that effect should be reflected in percent shortening variations from north (high) to south (low). In the following, we present an analysis of crustal shortening in wet and dry regions of the central Andes. Our approach includes (1) calculation of the total, integrated, percent shortening along each transect, (2) review of temporal variations in percent shortening, and (3) comparison of shortening and exhumation magnitudes.

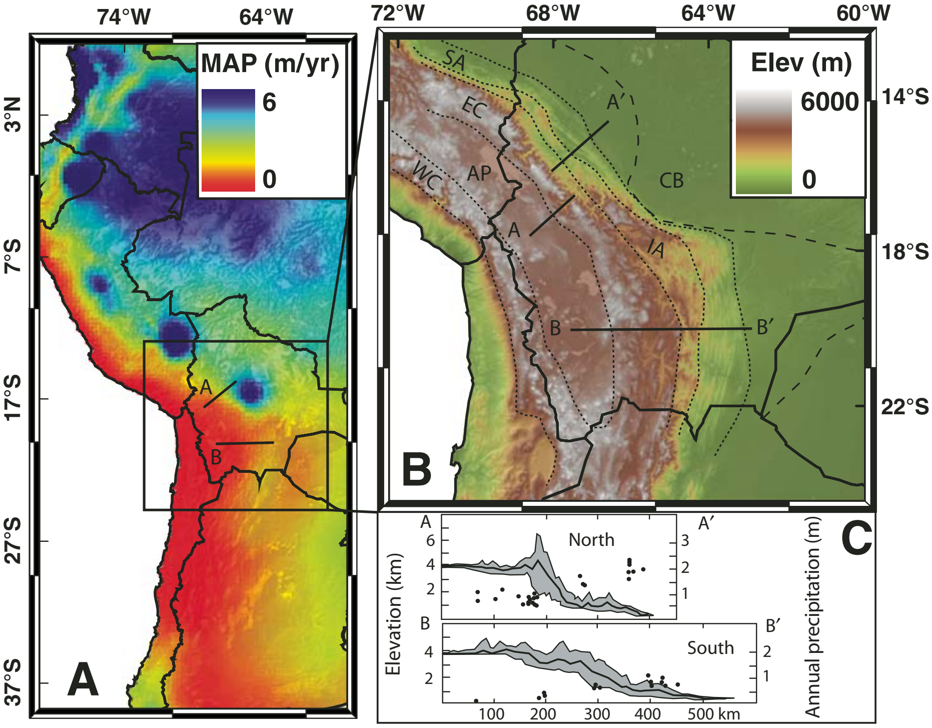

Figure 1. Physiography of central Andes. A: Mean annual precipitation (MAP) overlain on central Andes topography (GTOPO30 1 km data set). Lines A and B show locations of cross sections discussed in text. Black box is location of B. B: Shaded digital relief map centered on Bolivia. Lines A-A′ and B-B′ show locations of cross sections. Dashed line is eastern extent of Paleozoic basin (Sheffels, 1995). Dotted lines are boundaries between morphotectonic zones of the fold-thrust belt (FTB). AP—internally drained Altiplano basin; EC—Eastern Cordillera; IA—Interandean zone; SA—active Subandes; CB—undeformed Chaco-Beni plain; WC—Western Cordillera. C: Topography and precipitation profiles modified from Horton (1999). Mean elevation is black line, maximum-minimum elevation is shaded to highlight latitudinal relief contrast. Black dots are projected MAP measurements.

RESULTS AND DISCUSSION

Balanced cross sections across northern and southern Bolivia (Fig. 3) indicate 276 ± 25 km of shortening in the north and 326 ± 32 km in the south (McQuarrie, 2002; McQuarrie et al., 2008), a 50 km difference (±50 km) in shortening (see the GSA Data Repository[1]). Percent shortening across each section is 40% ± 2% (north) and 37% ± 2% (south) (Table 1), allowing for both (1) identical percent shortening within error, indicating that propagation was not limited by erosion, or (2) a maximum difference in percent shortening of 7%, suggesting that propagation has been limited in the north. We can discriminate between these two possibilities by addressing temporal variations in percent shortening and comparing complementary estimates of shortening and exhumation.

Temporal variations in percent shortening can be used to test if modern climate gradients reflect climate over long (~10^7 yr) time scales (e.g., Horton, 1999). We contend that temporal variations in percent shortening may reflect temporal variations in erosion magnitude, or influence, provided that the timing of deformation is known. Several proxies used to determine the timing of deformation in the Bolivian Andes suggest remarkably similar large-scale deformational histories along strike. Early deformation in the Eastern Cordillera initiated ca. 45–35 Ma and persisted to ca. 25 Ma. Timing of shortening in the Subandes is less certain, but recent mineral cooling ages and basin analysis suggest that deformation initiated at as early as ca. 19 Ma or as late as ca. 8 Ma (Barnes et al., 2006, 2008; Ege et al., 2007; Uba et al., 2006). Taking the combined shortening distance in the Eastern Cordillera and the Interandean zone, there is 171 km of shortening in the north and 218 km of shortening in the south. This 47 km difference indicates that almost all of the 50 km difference in north-south shortening identified previously for the entire fold-thrust belt is located in the Eastern Cordillera and Interandean zone and is a product of early ca. 45–25 Ma deformation. Percent shortening of the Eastern Cordillera and Interandean zone is identical at 45% ± 2% (Table 1), suggesting that north-south variations in erosion had no impact on the development of the fold-thrust belt over this time period. Conversely, shortening amounts in the Subandes are identical, at 66 km in the north and 67 km in the south. Percent shortening is different in the north and south, at 41% ± 2% and 32% ± 2%, respectively. This temporal analysis of percent shortening brings into question the length of time that precipitation in northern Bolivia has been double that to the south, as well as the anticipated impact of the ~2 m/yr north-south precipitation gradient.

A test of the validity of our shortening amounts (see the Data Repository) comes from comparing north and south shortening magnitudes to changes in cross-sectional area and erosion magnitudes. Figure 4 shows two present-day cross-sectional areas. The difference in area between the two sections is 5193 km². The area that has been added solely through propagation is 3024 km². The amount of additional material added through shortening, 2169 km², is the equivalent to 54 km shortening of a 40-km-thick crust, and is consistent with the 50 km difference in shortening amounts determined from cross-section balancing. The 2169 km² also reflects the amount of eroded material from the northern section to account for the narrower width of the orogen if north-south shortening magnitudes were the same. This would essentially double calculated erosion estimates, from 2013 km² to 4182 km², in the north. This magnitude of exhumation determined by cross-section balancing (2013 km²) is consistent with exhumation magnitudes estimated from thermochronometers (Barnes et al., 2006, 2008; Ege et al., 2007; McQuarrie et al., 2008) (Table 2).

[1]GSA Data Repository item 2008247, Appendix A (evaluation of the magnitude of error in the balanced cross sections used in this study) and Appendix B (comparison of measured changes in orogen width [from this study] to changes predicted by analytical models), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

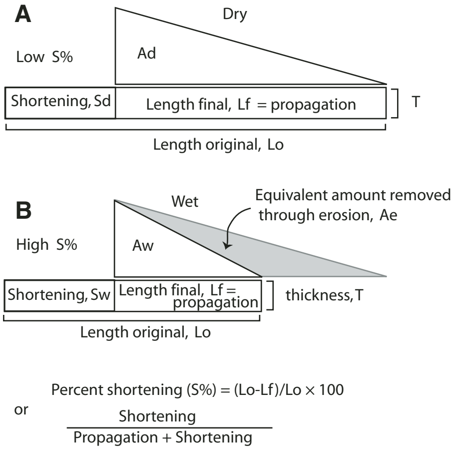

Figure 2. Idealized critically tapered wedges for dry (A) and wet (B) orogen. Area of the wedge, Ad (dry) Aw (wet), is function of thickness of undeformed strata (T), amount of shortening (S), and amount of propagation (length final). Ae is the amount of material that has been removed from the wet wedge.

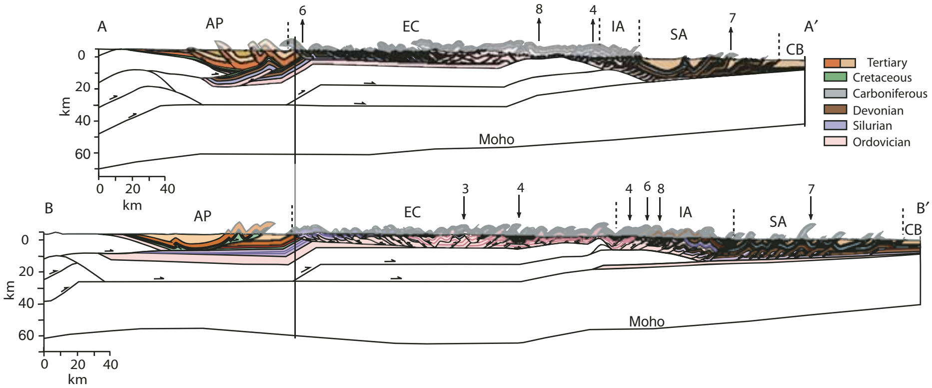

Figure 3. Balanced cross sections through Andean fold-thrust belt (FTB) of Bolivia. Section locations are shown in Figure 1. Arrows represent magnitude of shortening (km) that could feasibly be added (up arrows) or removed (down arrows) within constraints of "minimum" shortening estimates (Data Repository [see footnote 1]). Cross sections are aligned at eastern edge of Altiplano (solid line) to show differences in propagation of similar aspects of FTB. Lightly shaded area above modern topography represents material removed via erosion. Dashed lines are boundaries between morphotectonic zones of the FTB. Abbreviations as in Figure 1. Modified from McQuarrie (2002) and McQuarrie et al. (2008).

Our combination of area balancing, which supports a 50 km north-south shortening difference, with temporal constraints that indicate the shortening differential developed between ca. 45 and 25 Ma, suggests that from ca. 45 to 25 Ma a north-south precipitation gradient was not sufficient to limit propagation (45% shortening in the north and the south). During the development of the Subandes (between ca. 19–8 Ma and 0 Ma) the magnitude of shortening is the same north and south, but the difference in percent shortening is significant enough that percent shortening does not overlap within a 10% error in shortening amounts. The 43 km difference in Subandes width is purely a function of additional propagation of the fold-thrust belt in the south. This difference reflects a change in width that can be directly compared to a north-south change in precipitation (a decrease from >2 to <1 m/yr). Our calculations suggest that the two-fold increase in precipitation in the north limited Subandes growth (propagation) by ~30%, a value near the lower bounds of analytical models (30%–80%) (see the Data Repository).

TABLE 1. PERCENT SHORTENING ESTIMATES

	Lo (km)	Lf (km)	Shortening (km)	Shortening (%)
North				
Entire fold-thrust belt	690	414	276 ± 25	40 ± 2
EC and IA	375	204	171 ± 18	45 ± 2
Subandes	162	96	66 ± 7	41 ± 2
Altiplano	153	114	39	25
South				
Entire fold-thrust belt	882	556	326 ± 32	37 ± 2
EC and IA	482	264	218 ± 25	45 ± 2
Subandes	264	139	67 ± 7	32 ± 2
Altiplano	194	153	41	21

Note: Lo—Length original, Lf—length final; EC—Eastern Cordillera; IA—Interandean zone.

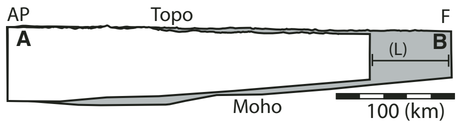

Figure 4. Area of northern (A) and southern (B) cross sections. "Topo" is modern-day erosion surface; lower boundary is geophysical Moho (Beck and Zandt, 2002; Dorbath and Granet, 1996; Watts et al., 1995); AP is eastern edge of Altiplano (shown as black vertical line in Fig. 3); and F is easternmost edge of Subandean zone. Area difference between A and B is shaded gray. Extra area added through shortening is total area shaded in B minus length (L) times a 40-km-thick crust.

TABLE 2. CENTRAL ANDES EXHUMATION ESTIMATES

	Extra area (see Fig. 4) (km^2)	Exhumation cross sectional area (km^2)	Cross section* / Thermochronometry† estimate (km)§			
			All	EC	IA	SA
North		2013	7 km / 4–9	5–9 / 5.5–11.0	6–7.5 / 4–5	4–5.5 / 4.0–6.0
South		2357	6 km / 3–6	4–8 / 2.6–6.5	5–7 / 2.6–6.5	4–5 / <3.8–7.0
North-south difference	2169	344	1 km / 0–3	1 / 0–3.5	0–1 / 0–1.5	1–2 / 0.5–3.0

Note: EC—Eastern Cordillera; IA—Interandean zone; SA—active Subandes.
*Vertical point estimates from balanced cross section
†Vertical estimate in range based on nominal closure temperatures
§From Barnes et al. (2006, 2008); McQuarrie et al. (2008); and Ege et al. (2007).

SUMMARY

The previous analysis suggests equivalent propagation of the fold-thrust belt in both the north and south from ca. 45 to 25 Ma. From ca. 19 or ca. 8 Ma to present, propagation of the northern Subandean zone has been limited. Implications of these results for the evolution of the Andes are as follows.

First, as previously stated, both rock strength and erosion can alter the efficacy of propagation. North-south changes in the original sedimentary basin include a slightly thinner (by 2 km) Paleozoic basin, a slightly thicker (by 2 km) Subandes basin, and subtle changes in décollement horizons that could potentially limit propagation in the north. We argue that these lithologic variations existed from ca. 45 Ma to present and had no impact on the early propagation history of the fold-thrust belt, suggesting that lithology is not limiting Subandes propagation in the north.

Second, early (ca. 45–25 Ma) variations in shortening amount are due to factors other than lithology or precipitation. Higher (~50 km) amounts of shortening in the south could be the result of greater tectonic forces there. Causes for this could include a stronger coupling between the Nazca and South America plates (e.g., Lamb and Davis, 2003) that allows for greater deformation south of ~17°S.

Third, north-south differences in the width of the Subandes (~40 km) and north-south differences in the width of high topography (~50 km) both suggest an influence of erosion on orogen width. Although erosion magnitudes are similar between the northern and southern parts of the Andean plateau (Table 2), most northern plateau erosion has been focused along its eastern edge while exhumation of the southern plateau has been more uniform across the entire plateau width (Figs. 1 and 3). In northern Bolivia, the eastern edge of the physiographic plateau is 50 km west of the eastern limit of exposed Ordovician rocks (which indicate the eastern limit of the plateau to the south), suggesting that the plateau edge has retreated (Fig. 3) (Masek et al., 1994). Additional support for the erosional retreat of the plateau edge is found in thermochronometer cooling ages that indicate two periods of exhumation: ~7.5 km of material was removed ca. 45–25 Ma in conjunction with early Andean shortening, and ~3.5 km was removed from ca. 11 Ma to present (Gillis et al., 2006). This later exhumation correlates in time with limited propagation of the northern Subandes. Because the strong north-south gradients in precipitation are connected to hemisphere-scale Hadley cells, whose positions are largely invariant with time (e.g., Takahashi and Battisti, 2007), we suggest that temporal changes in north-south precipitation magnitudes could be associated with the rise of the Andean plateau above a threshold level needed to intensify orographic and monsoonal precipitation (e.g., Bookhagen and Strecker, 2008; Lenters, and Cook, 1995; Walsh, 1994).

Thus, our analysis suggests a coupling between climate and tectonics since ca. 19 or 8 Ma to 0 Ma in response to an intensification of orographic precipitation in northern Bolivia. The enhanced role of climate and erosion in the evolution of the orogen over this time interval may have limited the width of the northern Subandes by ~40 km.

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