Initial plate geometry, shortening variations, and evolution of the Bolivian orocline

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ABSTRACT

Comparisons of newly published cross sections across the Bolivian Andes with existing cross sections through Argentina emphasize significant along-strike changes in crustal shortening. A sharp decrease in the magnitude of crustal shortening from ~530 km to ~150 km (north to south) occurs at ~23°S. A 20–40 m.y. difference in the ages at which deformation was initiated accompanies the abrupt decrease in the magnitude of shortening. Extending the western margin of South America to account for 530 km of shortening in the Bolivian Andes and 150 km of shortening in Argentina produces a central Andean salient that is perpendicular to the Nazca plate shortening direction from 60 to 26 Ma. During this same time interval, the Chilean coast south of 23°S was in an orientation sufficiently oblique to oceanic convergence to allow for predominantly strike-slip offset and backarc extension. Deformation within the Andean mountain chain may be a function of plate convergence where the oblique nature of convergence south of ~23°S inhibited mountain building, whereas north of ~23°S, normal convergence to a central Andean salient facilitated contractional deformation. The magnitude of deformation north of ~23°S is a consequence of both plate-convergence direction, providing a longer period of contractional deformation (from ca. 70 Ma to the present), and a thick Phanerozoic sedimentary package that permitted large magnitudes of thin-skinned deformation. Significant along-strike changes in the shape of the South American margin—allowing for convergence to change from compression to extension along the strike of the orogen—may help explain the dramatic differences in timing, amount, and style of deformation in the Andes.

Keywords: Andes, orocline, mountain building, plate motions, plateaus.

INTRODUCTION

The Andes mountains extend ~8000 km along the western margin of South America (Fig. 1). Although the smooth continuity of the mountain chain and steady subduction of the Nazca plate through time seem to imply a uniformity in deformation from north to south, the Andes display surprisingly significant variations along strike in both structural style and in the width of the deformation zone (Jordan et al., 1983; Isacks, 1988; Allmendinger and Gubbels, 1996; Allmendinger et al., 1997; Kley and Monaldi, 1998; Kley et al., 1999). Along-strike changes in the Andes are attributed to changes in amount and timing of shortening, rock type, legacy of pre-Andean deformation, and climate.

The Central Andes in northern Chile and Argentina, Bolivia, and southern Peru form the widest part of the mountain belt and contain a 4-km-high, 400-km-wide orogenic plateau. Isacks (1988) initially proposed that smooth north to south variations in cross-sectional area of high topography may be used as an indicator for differential shortening, and that this differential shortening produced the Andean Plateau and enhanced the Bolivian orocline. However, as noted by Kley and Monaldi (1998) and Kley et al. (1999), shortening within the Andean Plateau does not vary steadily, but has several abrupt changes in both style and magnitude of deformation not necessarily reflected in the topography. One of the most pronounced changes in geometry, i.e., amount and timing of horizontal shortening, occurs near the center of the Andean Plateau (at ~23°S).

VARIATIONS IN SHORTENING AMOUNTS AND TIMING OF DEFORMATION

Shortening Within the Bolivian Andes (North of 23°S)

The Bolivian Andes form the widest part of the Andean mountain chain. The eastern mountain front is defined by classic fold-and-thrust belt deformation. The fold-and-thrust belt was constructed on a thick (8–15 km) eastward-tapering sedimentary wedge of Paleozoic and Mesozoic rocks that has been telescoped through east- and west-directed thrusting (Roeder, 1988; Baby et al., 1997; McQuarrie, 2002). Shortening estimates are the highest for this part of the Andes and reach 70–140 km of shortening in the frontal, Subandean part of the fold-and-thrust belt (e.g., Kley and Monaldi, 1998) and 300–330 ± 10 km for the entire fold-and-thrust belt (Schmitz, 1994; Kley, 1996; McQuarrie and DeCelles, 2001; McQuarrie, 2002) (Fig. 1). Limits on timing of deformation in the Bolivian Andes are set by integrating sequentially balanced cross sections with thermochronologic data and the foreland-basin migration history. Deformation within the eastern Cordillera began ca. 40 Ma and propagated both to the east and the west (Lamb and Hoke, 1997; McQuarrie and DeCelles, 2001; McQuarrie, 2002). Structures are capped by 20 Ma synorogenic sediments (McFadden et al., 1985; Sempere et al., 1990), providing an upper limit on the age of deformation. Subandean deformation in the frontal parts of the mountain belt propagated eastward from 20 Ma to the present (McQuarrie et al., 2001; McQuarrie, 2002).

The age of the onset of mountain building is most readily identified by the age of the oldest strata associated with the growing orogenic wedge. Initiation of mountain building in the Bolivian Andes by the Late Cretaceous is suggested by 70 Ma Altiplano backbulge and forebulge deposits (DeCelles and Giles, 1996) and by the eastward migration of these deposits to the eastern Cordillera by 50 Ma (Horton et al., 2001; DeCelles and Horton, 1999). The eastward migration of the foreland basin indicates 400 km of convergence between the front of the fold-and-thrust belt and a static marker on the Brazilian shield to the east. The structures that would support this narrow, early fold-and-thrust belt have either been eroded or covered by the present, 100–120-km-wide, Western Cordillera volcanic arc. The relationship between foreland-basin migration and shortening and propagation of a fold-and-thrust belt (DeCelles and DeCelles, 2001), however, allows reasonable estimates to be made of both shortening and propagation for this time period, even though the structures to document that shortening are not exposed or preserved. A reasonable shortening estimate for 400 km of foreland-basin migration is 200 ± 50 km of shortening in the early (ca. 60−40 Ma) Andean fold-and-thrust belt (McQuarrie et al., 2001). This value suggests a total shortening estimate as high as 500–530 km.

Shortening Within the Argentine Andes (South of 23°S)

South of 23°S, in the Argentine Andes, the thick Paleozoic and Mesozoic sedimentary wedge that facilitates the classic fold-and-thrust belt in Bolivia thins rapidly, and by 26°S, Precambrian basement is overlain by a

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Geology; October 2002; v. 30; no. 10; p. 867–870; 3 figures.

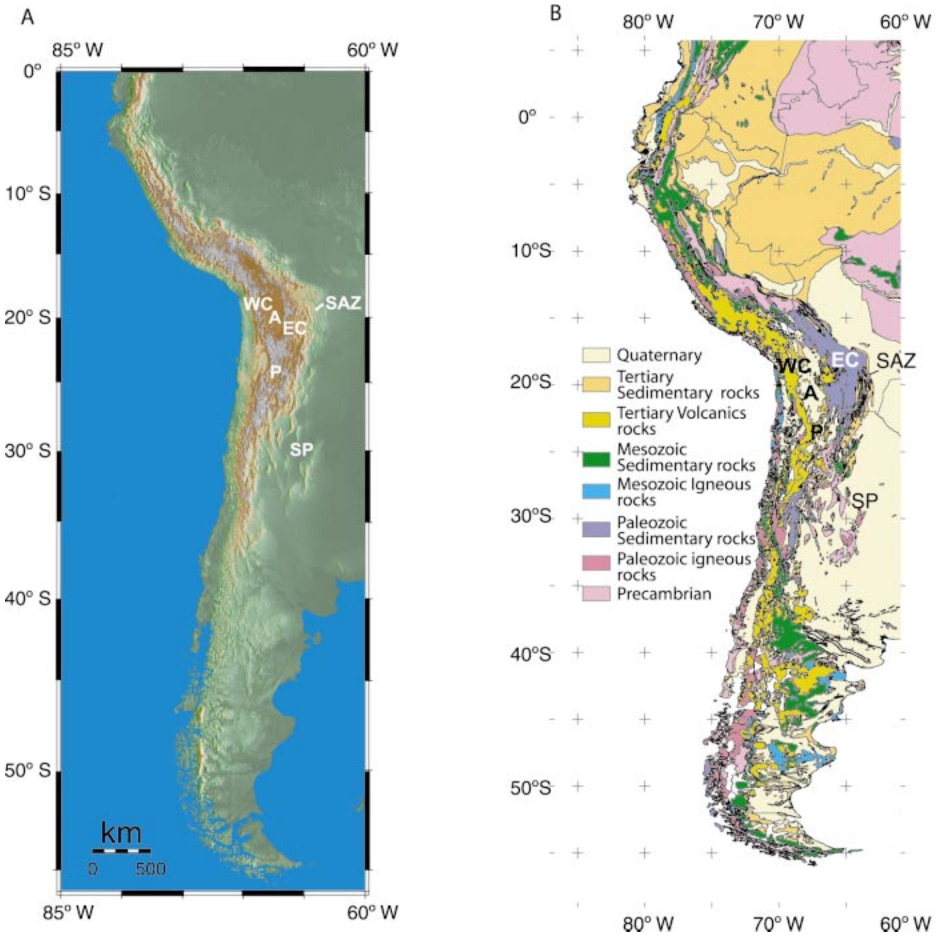

Figure 1. Topography and simplified geology of western part of South America. A—Altiplano, P—Puna, WC—Western Cordillera, EC—Eastern Cordillera, SAZ—Subandean fold-and-thrust belt, SP—Sierras Pampeanas basement uplifts.

thin layer of Cretaceous through Tertiary clastic sedimentary rocks (Jordan et al., 1983; Allmendinger and Gubbels, 1996; Allmendinger et al., 1997) (Figs. 1 and 2). Correlative with the loss of the Paleozoic to Mesozoic sedimentary wedge is a change in foreland structures from thin-skinned folds and thrusts that deform sedimentary cover rocks to thick-skinned deformation characterized by faults that carry wide zones (10–30 km) of broadly folded basement in their hanging walls. Fault geometries as shown by seismic lines, broad basement folds, and preservation of Cretaceous through Tertiary basin sedimentary rocks argue against significant transportation of material along décollement horizons (Allmendinger et al., 1990; Grier et al., 1991; Jordan et al., 1993, 1997, 2001; Coutand et al., 2001). Estimates of shortening obtained through composite cross sections south of 23°S support significantly less shortening (90–170 km) compared to the north (Kley and Monaldi, 1998, and references therein).

Foreland-basin sedimentation and initiation of mountain building started significantly later in the Argentine Andes than in the Bolivian Andes (Jordan et al., 1993, 1997, 2001; Allmendinger et al., 1997). In the transition zone, ~23°S, Eocene red beds (conglomeratic to the west and sandy to the east) are laterally extensive and stretch across the Puna uninterrupted by faults or local basins (Vandervoort et al., 1995; Jordan et al., 1997; Coutand et al., 2001). Although the Eocene sedimentary sequence can be attributed to a growing orogenic high in the west (Coutand et al., 2001), sedimentation associated with local structures and accompanying basins throughout the Puna and Eastern Cordillera are much younger (15 Ma), suggesting that structural shortening may have started as late as middle Miocene time (Vandervoort et al., 1995; Jordan et al., 1997). Chronology on basins east of the Puna plateau suggests that deformation began at 15.1 Ma and migrated from west to east with time (Reynolds et al., 2000). In the latitudes between 29°S and 34°S, thrust initiation in the westernmost Precordillera is bracketed between 21 and 19 Ma. This age is inferred from clastic red-bed sedimentation, capping synorogenic conglomeratic rocks, and K-Ar cooling ages (Jordan et al., 1993, 1997). Farther south, early Miocene time was a period of extension in the arc and backarc at the latitudes of 33°–45°S. These extensional basins were subsequently inverted when the basins were subjected to a compressional environment starting between 20 and 18 Ma (Jordan et al., 2001).

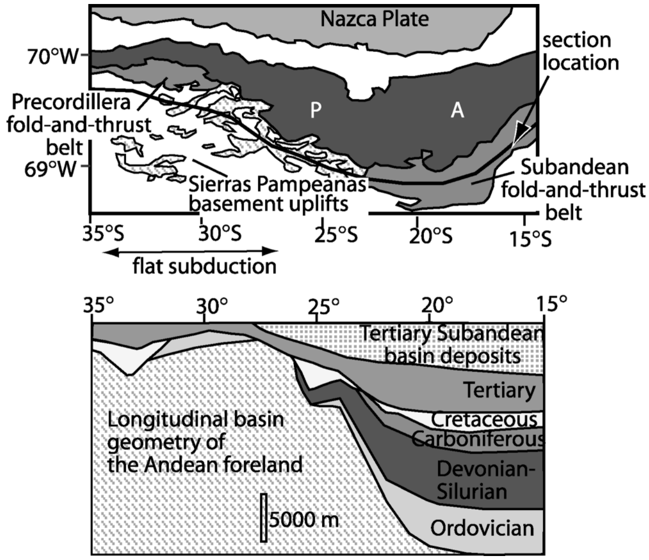

Figure 2. Simplified longitudinal stratigraphic section modified from Allmendinger and Gubbels (1996). Dark gray shading—topography above 3 km, light gray shading—Subandean fold-and-thrust belt and location of Paleozoic and Mesozoic basins, diagonal dashes—basement rock, and dot pattern—Precordillera fold-and-thrust belt.

EVOLUTION OF THE WESTERN MARGIN OF SOUTH AMERICA

Four balanced cross sections with shortening estimates ranging from 300 to 330 km (Schmitz, 1994; Kley, 1996; McQuarrie and DeCelles, 2001; McQuarrie, 2002) were used to restore the western Andean margin in Bolivia from the volcanic arc to the foreland. An additional 200 km was added to these estimates to account for the early (60–40 Ma) propagation of the fold-and-thrust belt as suggested by the foreland-basin history. Shortening estimates for the Andean fold-and-thrust belt south of 23°S range between 90 and 170 km (Kley and Monaldi, 1998, and references therein). An upper average of 150 km of margin shortening was used for the area between 23°S and 40°S to account for undocumented

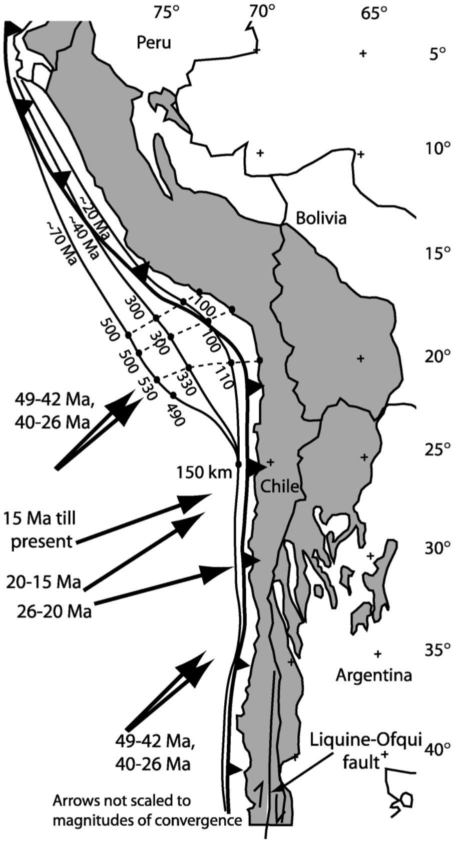

Figure 3. Evolution of Bolivian orocline. Thin black lines represent edge of continent ca. 70, ca. 40, and ca. 20 Ma. Numbers next to black dots indicate amount of shortening restored for each time interval. Arrows indicate convergence direction of subducting Nazca plate at different time intervals, from Pardo-Casas and Molnar (1987) and Somoza (1998).

shortening within the fold-and-thrust belt and to average second-order variations in shortening along strike. Figure 3 shows the migration of the South American coastline with time in accordance with the evolution of the fold-and-thrust belt.

Although second-order variations in shortening magnitudes exist north and south of 23°S, significant amounts of shortening (500+ km) in the north and moderate amounts of shortening to the south produce a central Andean salient in the plate margin (Fig. 3). The rapid decrease in shortening to the south argues for an embayment centered on ~25°S (Figs. 1 and 3). Between 60 and 20 Ma, the central Andean salient shortened, while south of 23°S, the Chilean arc and Argentine backarc were the sites of strike-slip deformation and associated extension (Hervé, 1976; García et al., 1988; Suarez and Emparan, 1995; Jordan et al., 2001). By 20 Ma the central Andean salient had shortened sufficiently to mimic its present geometry. The more uniform nature of the South American coast in conjunction with marked decrease in the amount of subduction obliquity (see subsequent discussion) created a favorable geometry for active compression along the entire South American plate margin from 20 Ma to the present.

The strong correlation between the location of the central Andean salient and an abrupt change in rock type can be seen by comparing Figures 2 and 3. This correlation may imply a genetic link between the location of the salient and the thick Paleozoic-Mesozoic basin strata. Loss of a thick sedimentary wedge may also be the strongest controlling factor on the location and existence of basement-cored uplifts in a compressional orogen, as suggested by Allmendinger and Gubbels (1996) and Kley et al. (1999).

VARIATIONS IN PLATE-MARGIN ORIENTATION AND PALEOMAGNETIC RESULTS

The proposed evolution of the South American plate margin is testable through paleomagnetic data. Paleomagnetic data have consistently shown uniform (15°–20°) counterclockwise rotations in the Peruvian forearc and variable (10°–60°) clockwise rotations in the Chilean forearc (Kono et al., 1985; May and Butler, 1985; Beck et al., 1986, 1994; Roperch et al., 2000). The paleomagnetic data have been used to argue both for (Kono et al., 1985; Isacks, 1988) and against (Kley, 1999; Roperch et al., 2000) the Cenozoic bending of the Bolivian orocline. The evolution of the South American margin presented here supports uniform, coherent rigid rotations of the Peruvian forearc, as suggested by paleomagnetic studies (Kono et al., 1985; May and Butler, 1985; Rousse et al., 2002), and more local shear-induced rotations of the Chilean coast in response to oblique subduction since ca. 50 Ma (Beck et al., 1986, 1994; Somoza et al., 1999). It also predicts deformation and rotation of the Chilean arc and forearc to accommodate the pronounced increase in shortening north of ~23°S. This predicted deformation is supported by early shortening (60–30 Ma) within the Chilean Precordillera between 25° and 21°S (Hartley et al., 1992; Maksaev and Zentilli, 1999) and significant rotations (40°–60°) within the arc and forearc (Randall et al., 1996; Roperch et al., 2000; Arriagada et al., 2000).

CHANGES IN OBLIQUITY OF THE NAZCA PLATE WITH TIME

The convergence history of the Nazca (Farallon) and South American plates since 60 Ma is well documented through several studies (Pilger, 1984; Pardo-Casas and Molnar, 1987; Somoza, 1998; Norabuena et al., 1999). Before 59 Ma (between 68.5 and 49.5 Ma), the inferred motion of the Nazca plate was strongly oblique to the north-trending southern half of the South American continent, but significantly less oblique to the northwest-trending part of the continent (Pardo-Casas and Molnar, 1987). Although the uncertainties are large, the strong obliquity suggests slower convergence and a significant component of right-lateral strike-slip deformation along the southern part of the continent (Pardo-Casas and Molnar, 1987). Between 50 and 26 Ma, a northeastward direction (49°–59°) of plate convergence was maintained (Pardo-Casas and Molnar, 1987; Somoza, 1998). This northeastward convergence direction was perpendicular to the reconstructed Bolivian salient (Fig. 3) over the time period (ca. 60–26 Ma) of early deformation in the Bolivian Andes. Between 26 and 16 Ma, the Nazca plate underwent two large shifts in obliquity and convergence rate to establish its present rate and direction of convergence ca. 16 Ma (Pardo-Casas and Molnar, 1987; Somoza, 1998). By ca. 16 Ma, the central Andean salient had shortened sufficiently to mimic its present geometry (Fig. 3).

IMPLICATIONS FOR THE ANDEAN PLATEAU

The 500–530 km of shortening (north of 23°S) is more than enough to account for the high elevation and thick crust of the Andean Plateau, whereas 150–200 km of shortening (south of 23°S) cannot account for the crustal thickness (~50 km) (Yuan et al., 2000) of the Puna Plateau. Perhaps the increased shortening in the north created a gradient sufficient to drive extra crustal material from the Altiplano region to the Puna Plateau, thickening the crust and smoothing elevation gradients. Lower-crustal flow as a mechanism to maintain elevation and crustal thickness has been proposed to explain areas of shortening deficit by Kley and Monaldi (1998) for the Andean Plateau and by Clark and Royden (2000) for eastern Tibet. Thus, the uniform nature of the Andean Plateau as it crosses profound changes in amount, style, and timing of deformation reflects the compensating nature of ductile crust, emphasizing the importance of a weak lower crust in the creation of orogenic plateaus (e.g., Royden, 1996).

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