Bending the Bolivian orocline in real time

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ABSTRACT

Global positioning system (GPS) data from the central Andes record vertical axis rotations that are consistently counterclockwise in Peru and Bolivia north of the bend in the mountain belt, and clockwise to the south in southern Bolivia, Argentina, and Chile. These geologically instantaneous rotations have the same sense as rotations that have accrued over millions of years and are recorded by paleomagnetic and geologic indicators. The change in sign of the rotation at both decadal and million-year time scales occurs across the axis of topographic symmetry that defines the Bolivian orocline. When extrapolated to a common time interval, the magnitudes of rotation from geologic features and from GPS are surprisingly similar, given that a significant part of the instantaneous deformation field is probably elastic and due to interseismic locking of the plate boundary. Some of the interseismic deformation field must reflect permanent deformation, and/or some of the current elastic deformation will be converted to upper-plate permanent deformation over time rather than be recovered by elastic rebound during interplate earthquakes. We suggest that the spatial patterns of the elastic and the permanent modes of bending are similar because they are driven by the same stress field.

Keywords: central Andes, orocline, rotation, global positioning system, paleomagnetism.

INTRODUCTION

The central Andes are a prime example of oroclinal bending (Isacks, 1988)—the idea that mountain ranges form initially in a linear geometry and then are bent into their more highly curved configuration (Carey, 1955). The kinematics by which this process occurs are not well understood, but in the upper crust must be achieved by horizontal components of displacement on suites of faults (Beck, 1987; Lamb, 2000, 2001a). In the central Andes, most workers follow the lead of Isacks (1988), who ascribed the Bolivian orocline to north-south gradients in horizontal shortening, primarily along foreland thrust faults.

Because the bending is associated with a rotation about a vertical axis (Marshak, 2004), oroclines have traditionally been studied with paleomagnetic data, where the declination of the local pole in the rocks sampled is compared to that of similar-aged rocks in stable South America (e.g., Arriagada et al., 2003; Beck, 1987; Coutand et al., 1999; Lamb, 2001b; MacFadden, 1990; Roperch and Carlier, 1992; Scanlan and Turner, 1992). Although paleomagnetic data can measure vertical axis rotation, it cannot distinguish between deformation and rigid body rotation, nor can it show whether the rotation is purely local or regional. Nonetheless, paleomagnetic data (see GSA Data Repository[1]) document a clear pattern of clockwise rotations south of the Arica bend and counterclockwise rotations to the north (Fig. 1).

Recent interpretations of paleomagnetic data suggest that most of the rotation in the forearc predates the late Miocene (e.g., Roperch et al., 2000; Somoza et al., 1999), even as younger vertical axis rotations are documented in the backarc of the orogen. This result poses a conundrum: because it is difficult to conceive of the orogen-scale kinematics by which this would occur, one is seemingly forced to conclude that oroclinal bending is no longer continuing and that the backarc rotations are the result solely of local block rotations.

Global positioning system (GPS) data provide a real-time look at regional kinematics, because they are geologically instantaneous. In this paper we use GPS data from the central Andes between 12°S and 35°S latitude to show that the orocline is currently undergoing bending at rates that are comparable to geological rates over the past 10 m.y.

[1]GSA Data Repository item 2005176, reference list of papers used to compile Figure 1, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

METHODS

Strain rate is the local gradient of the velocity field and thus can be calculated for any region covered by a GPS network. The relations between position, velocity, and deformation are given by:

$$u_i = t_i + \frac{\partial u_i}{\partial X_j} X_j = t_i + D_{ij} X_j, \quad (1)$$

where X_j is the position, u_i is the velocity at that position, t_i is a constant of integration that represents the velocity at the origin, and D_{ij} is the displacement rate gradient tensor. In two dimensions, there are six unknowns, so a minimum of three GPS velocities is needed (each station provides two equations). For more than three stations, a least-squares best fit can be obtained using standard methods or by singular value decomposition where more information about the fit is desired. The only assumption in this procedure is that strain is homogeneous within the region of the stations used in the analysis. Once the displacement gradient rate tensor is obtained, it can be additively decomposed into a symmetric infinitesimal strain rate tensor and an antisymmetric rotation rate tensor. These tensors are fixed to the material coordinates and thus differ slightly from the deformation rate and spin tensors, which are fixed to the spatial coordinates. With small gradients typical of GPS velocities, the two reference frames and sets of tensors are equivalent. In infinitesimal strain, the rotation, even that associated with simple shear, can be treated as a rigid body rotation (e.g., Malvern, 1969). The rotation rate tensor is particularly germane to the question of oroclinal bending but is not necessarily directly equivalent to the vertical axis rotation measured by paleomagnetic data (see discussion in Lamb, 2001a).

Our basic approach is similar to that employed by Lamb (2000) and Hindle et al.

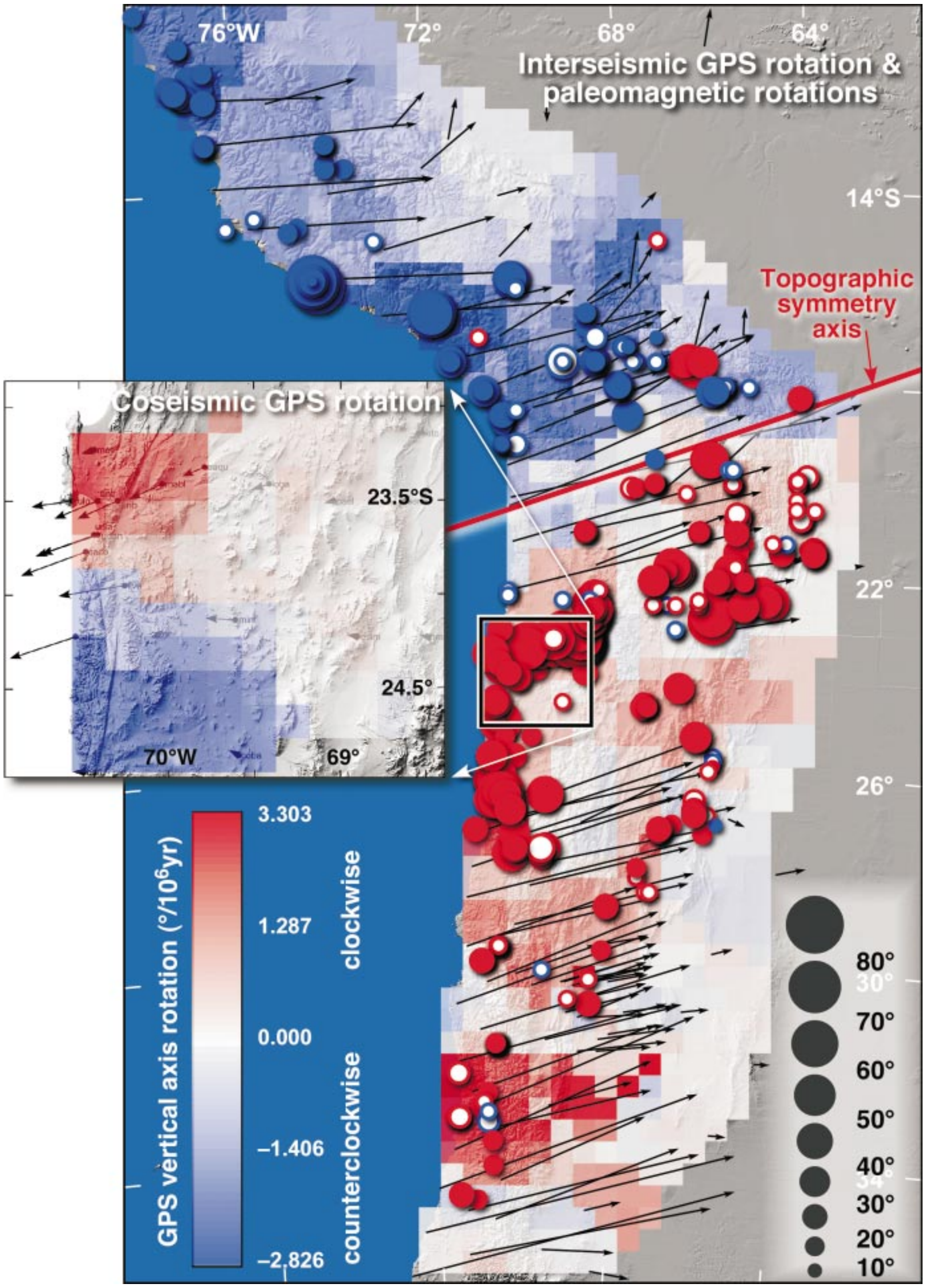

Figure 1. Map of central Andes, showing oroclinal axis and contoured vertical axis rotations from analysis of interseismic global positioning system (GPS) data (clockwise rotations are positive and colored red, counterclockwise rotations are negative and blue). Vertical axis rotations from 477 paleomagnetic analysis of rocks of all ages are shown as red dots (clockwise rotations) and blue dots (counterclockwise); size of dot is proportional to magnitude (scale in lower right corner). For hollow dots, uncertainty is greater than absolute value of magnitude. Inset shows coseismic rotation for 1995 M8.1 Antofagasta earthquake; colors represent sense of rotation, as in main figure, but amount of rotation is two orders of magnitude larger. Black arrows are original GPS vectors on which analysis is based (error ellipses not shown for clarity of presentation). Coseismic GPS data are from Klotz et al. (1999); interseismic data are from Brooks et al. (2003) and Kendrick et al. (2001); latter are partly reanalyized data of Norabuena et al. (1998).

TABLE 1. ROTATION RATES IN DIFFERENT SEGMENTS OF THE CENTRAL ANDES

	North of oroclinal axis		South of oroclinal axis	
	No. of stations	Rotation rate (°/yr)	No. of stations	Rotation rate (°/yr)
Forearc and arc	28	$-1.6 \times 10^{-6} \pm 5.9 \times 10^{-8}$	38	$6.3 \times 10^{-7} \pm 3.2 \times 10^{-8}$
Backarc	22	$-4.4 \times 10^{-7} \pm 1.1 \times 10^{-7}$	41	$8.1 \times 10^{-7} \pm 1.6 \times 10^{-8}$

(2002), but with some important differences. First, we are not trying to develop a smoothed velocity distribution that is best fit to a variety of different types of data. Instead, we only calculate the infinitesimal strain and rotation for groups of three or more GPS stations. Second, our GPS database is much larger than that used by Lamb, including stations to the west in the forearc as well as considerably farther north and south. Finally, we use GPS velocities that have been carefully fit to a stable South American reference frame (Bevis et al., 2001; Brooks et al., 2003; Kendrick et al., 1999, 2001); these velocities were not available at the time of the studies of Lamb (2000, 2001a, 2000b) and Hindle et al. (2002), who relied on data reported in Norabuena et al. (1998).

RESULTS

We calculated an evenly spaced (50 km) grid using an over-constrained least-squares solution to average and smooth the strain and rotation (Fig. 1). Errors accrue both from the uncertainties in the individual input GPS vectors and from the least-squares fit, using twice the minimum number of stations required for a solution. The results of our method compare well, both in magnitude and orientation, with the principal strain axes calculated in the global strain rate model (Kreemer et al., 2003). Statistically significant rotations were calculated at ~80% of the grid nodes. The pattern of clockwise and counterclockwise rotation rates is clear (Fig. 1): the vast majority of counterclockwise rotation rates occur north of the topographic symmetry plane that defines the axis of the orocline (Gephart, 1994), whereas the vast majority of the clockwise rotations occur to the south.

Because there is little systematic variation in rotation rate along strike with distance from the oroclinal axis, we calculate the magnitudes of the rotation rates for just four different segments: the forearc and arc north and south of the oroclinal axis, and the two backarc regions, north and south of the axis (Table 1). The forearc rotation rate north of the oroclinal axis is almost three times greater than the rotation rates to the south of the axis. The most obvious explanation is that the Nazca–South America plate convergence angle is significantly more oblique to the plate boundary on the north limb of the monocline.

The region between 22.5°S and 25°S must be treated separately because this area was perturbed by the 1995 M8.1 Antofagasta earthquake. This event, well recognized for its record of elastic rebound (Klotz et al., 1999, 2001), provides a convenient look at the coseismic strain field, in contrast to the interseismic strain recorded elsewhere along the margin. A similar analysis of the coseismic deformation (Fig. 1, inset) shows that GPS stations overlying the northern termination of the rupture zone recorded right-lateral simple shear, whereas at the southern end of the rupture zone there is left-lateral simple shear. The best-fit deformation gradient tensor for the eight stations at the south end of region yields a counterclockwise rotation of $-1.8 \times 10^{-4} \pm 8.2 \times 10^{-7}$ degrees. Similarly the coseismic rotation at the northern end of the rupture zone, calculated from 10 GPS stations, yields a clockwise rotation of $3.5 \times 10^{-4} \pm 2.1 \times 10^{-6}$ degrees. The coseismic rotation due to the Antofagasta earthquake is substantially larger than that observed elsewhere but is also much more limited geographically, essentially characterizing half the north-south length of the rupture zone (100–150 km). Presumably, the rotation at a margin of the rupture zone is canceled out when an adjacent segment of the plate boundary is ruptured.

DISCUSSION

To compare GPS results to geological data on shortening and rotation, it is convenient to cite these instantaneous rates as though they were extrapolated to geological time scales. Were the rotation rates to continue for 10 m.y., the forearc and backarc north of the oroclinal axis would have rotated 16 degrees and 4 degrees counterclockwise, respectively; to the south of the axis, the forearc and backarc would have rotated 6 degrees and 8 degrees, respectively. This extrapolation is approximate, as infinitesimal strains and rotations cannot actually be added together 10 million times to yield the correct finite strains and rotations. However, the errors are still considerably less than the uncertainties in the geological rates. These projected values are within the range of values observed from paleomagnetic vertical axis rotations in rocks 25 Ma and younger (Fig. 2). They also compare well with the results of Lamb's (2000) inversion of all late Cenozoic deformation indicators for just the center of the region discussed here, as well as Hindle and Kley's (2002) block restoration of late Cenozoic deformation in the central Andes. The similarity of the extrapolated GPS deformation-related rotation with the geological measures of rotation raises several important paradoxes.

It is widely accepted that much of the deformation documented by GPS data is due to interseismic locking of the plate boundary and is therefore elastic (i.e., nonpermanent), particularly in the forearc (Bevis et al., 2001; Brooks et al., 2003; Klotz et al., 1999, 2001; Norabuena et al., 1998). As the Antofagasta earthquake clearly showed, coseismic elastic rebound recovers much of the strain, at least back to the magmatic arc. However, the scale of the region characterized by either clockwise or counterclockwise GPS-measured rotation on either side of the oroclinal axis dwarfs the regions of individual seismic segments of the interplate boundary (Comte and Pardo, 1991; Tichelaar and Ruff, 1991). No one plate-boundary earthquake will relieve all of the accumulated elastic strain responsible for the rotation. Thus, the sense of interseismic rotation, though perhaps not the magnitudes, should represent normal, long-term, time-averaged behavior.

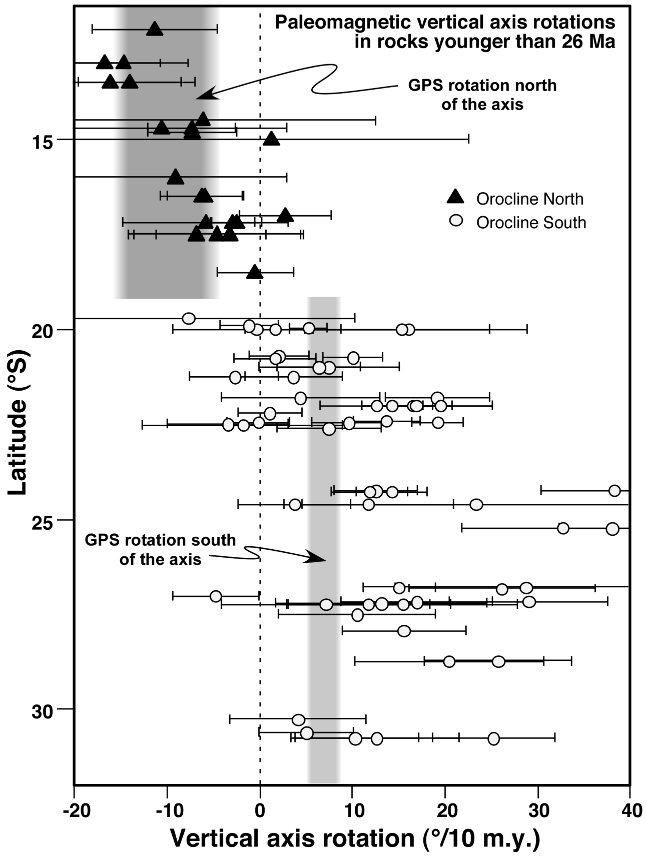

Figure 2. Variation and uncertainty of paleomagnetic vertical axis rotation in rocks 25 Ma and younger with latitude in central Andes, averaged over 10 m.y. Gray bars show range of global positioning system (GPS) rotations if extrapolated over 10 m.y.

The current GPS data contain no intrinsic information about how much of the signal is permanent versus ephemeral elastic deformation. Were South America entirely elastic, of course, there would be no permanent deformation due to subduction and no mountains would form; this is clearly not the case. Over geologic time, ~10% of the plate convergence is accommodated by upper-plate deformation and the rest by subduction (Echavarría et al., 2003; Jordan et al., 1993). Thus, at a minimum, ~10% of the GPS-measured velocity is or will be converted into permanent deformation. Modeling using the Savage (1983) backslip formalism shows that, in the backarc, as much as 50%–90% of the instantaneous velocity field is probably related to permanent crustal deformation (Bevis et al., 2001; Brooks et al., 2003; Norabuena et al., 1998). One could predict that rotation rates calculated from GPS stations located in the backarc would approach those of geological indicators, whereas those in the forearc should be an order of magnitude smaller.

However, during that last 15 m.y., the plate convergence rate has dropped by a factor of 2 (Kendrick et al., 2003; Somoza, 1998). If the degree of locking of the plate boundary were the same as today, which is not necessarily the case (Lamb and Davis, 2003), then higher magnitudes of rotation should have characterized the 10–15 Ma interval. The majority of paleomagnetic sites sample rocks from this interval or older (though the rotation could have happened at any time after the rocks were deposited). In contrast, much of the foreland deformation that is thought to be responsible for a significant part of Andean mountain building has occurred since 10 Ma.

CONCLUSIONS

The order of magnitude of rotation at geodetic and geologic time scales is apparently equivalent within the broad error afforded by the geologic data and the large uncertainties associated with the extrapolation across six orders of magnitude of time scale. Whether they should be, or if this equivalence is a misleading coincidence, must remain unresolved for the present. The key point is that permanent deformation will be driven by the same stresses that are producing the (truly ephemeral) elastic deformation due to interseismic interplate locking. Accordingly, the direction fabric of the permanent intraplate deformation should mimic to some degree that associated with the entire interseismic velocity field. To preserve the consistent sense of rotation that matches the orocline, we need only preserve the lateral (north-south) gradients in the GPS velocity field over geologic time. Given the shape of the plate boundary and the consistent direction of convergence during the past 40 m.y. (Gephart, 1994; Pardo-Casas and Molnar, 1987), the nature of these gradients is unlikely to change over geologic time. Thus, the GPS networks in the central Andes have captured the bending of the orocline in real time.

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