# Consistency of geologic and geodetic displacements during Andean orogenesis

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[1] Present-day displacements within the Central Andes are being measured using high precision GPS geodesy. Until now, comparison of such ground motions within deforming plate boundary zones to those on a geologic time scale has not been possible due to lack of sufficient geological data. In the Central Andes, a comparable dataset for the past 25 Ma of mountain building can be reconstructed. Here, we use new interpretations of shortening rates averaged over 25–10 Ma and 10 Ma–present and find that whilst displacement directions have remained virtually constant and parallel, an acceleration has occurred synchronously with a slowing of convergence between the Nazca and South American plates. Geologic shortening rates in the Andes are initially $\sim$5–8 mm yr$^{-1}$, and increase to $\sim$10–15 mm yr$^{-1}$ whilst convergence slows from $\sim$150 mm yr$^{-1}$ to $\sim$70 mm yr$^{-1}$. Displacement and convergence rates inferred from GPS and marine magnetic data suggest that this trend may be continuing at present. Hence an increasing fraction of convergence is being absorbed by mountain building. This change may reflect increased plate coupling due to decreased sediment supply, younger subducting lithosphere, or increased normal stress at the interface from the effects of uplift. *INDEX TERMS:* 8102 Tectonophysics: Continental contract orogenic belts; 8157 Evolution of the Earth: Plate motions—past (3040); 8158 Evolution of the Earth: Plate motions—present and recent (3040); 8099 Structural Geology: General or miscellaneous

## 1. Introduction

[2] A striking result of the availability of space geodetic data in recent years is that large-scale plate motions on a decadal time scale [*Gordon and Stein*, 1992] are generally quite similar to those predicted by plate motion models developed for the past few million years [*DeMets et al.*, 1994]. Thus it is now possible to identify regions where plate motions have changed over the past few million years. The best example so far is a systematic slowing of convergence between the Nazca and South American plates over the past 25 Ma shown by comparison of GPS and marine magnetic data [*Norabuena et al.*, 1998, 1999; *Angermann et al.*, 1999]. This observation leads to the surprising conclusion that convergence has slowed even though this interval coincides with the estimated initiation of Andean mountain building [*Pardo-Casas and Molnar*, 1987; *Somoza*, 1998], implying a possible negative feedback between convergence rate and mountain building.

[3] To explore this issue, we examine how horizontal shortening within the Andes, the primary mechanism building the mountain belt [*Allmendinger et al.*, 1997], has evolved with time.

## 2. Geological Shortening Estimates in the Andes

[4] It is already clear that estimates of present shortening from geological and geodetic data are comparable [*Norabuena et al.*, 1998; *Lamb*, 2000]. Here, we use new geological data to investigate how both the rate and direction of deformation have varied during Andean mountain building. We do so by extending the traditional geological approach of estimating shortening in mountain belts using two-dimensional cross section balancing. Restored sections show the finite displacement attributed to each fault in the direction the cross-section is drawn, assuming no strain occurred outside of the plane of the cross section. To extend this approach to three-dimensional (actually plan view) displacements, multiple two-dimensional sections along the mountain belts' strike can be integrated, allowing interpolation of the fault displacements between them. Figure 1 illustrates this process for the Central Andes between 10°S and 24°S. Cross sections from various authors were integrated into a block mosaic model for crustal deformation of the region [*Kley*, 1999; *Kley and Monaldi*, 1998]. Large tectonic units (e.g. Altiplano, northern Subandean Zone, Interandean Zone) are considered as semi-rigid blocks with boundary zones including all faults from the cross sections. The block restoration yields a plan view of displacement by drawing vectors between recognisable points (usually block corners) and an estimate of the out-of-plane strain ignored by individual two-dimensional sections. This technique gives a record of ground displacement in the Andean continental margin on a geological time scale comparable to that of the GPS data for the present.

[5] Comparison of the block restoration to the GPS data requires assumptions about the timing of deformation within the Andes. There is general agreement that the major phase of horizontal shortening leading to the formation of the modern Andes began around 30 – 25 Ma [*Sempere*, 1990]. with small amounts of deformation and uplift possibly in thethe preceding 10 Myr [*Benjamin et al.*, 1987]. There is also a consensus that most deformation in the Eastern Cordillera took place prior to 12 – 7 Ma [*Reynolds et al.*, 2000; *Isacks*, 1988; *Gubbels et al.*, 1993; *Gregory-Wodzicki*, 2000], and that the locus of shortening subsequently jumped eastward to the Subandean Zone [*Isacks*, 1988; *Gubbels et al.*, 1993].

[6] Using the deformation and uplift ages, we decompose the displacement history into two phases (25–10 Ma and 10 Ma–present) incorporating the eastward migration of the locus of deformation. In each, we convert finite displacement vectors to average velocity vectors by assuming that displacement rates were constant. These geological estimates have uncertainties due to the interpetation of field measurements, the dating of phases of displacement, and the averaging technique. In our view, the

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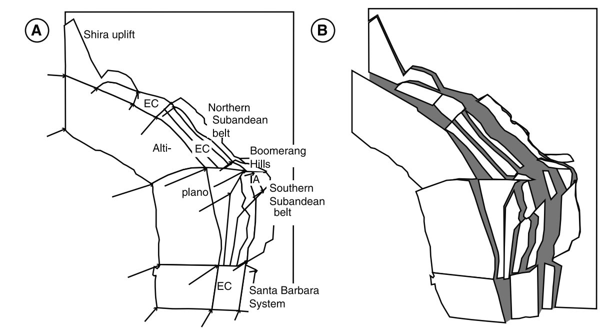


**Figure 1.** (a) Present day position and names of the blocks used in the Andean geological displacement model. EC - Eastern Cordillera, IA - Interandean Zone. Arrows show geologic, finite displacements at block edges. (b) Retro deformed state of the block model at 25 Ma. Grey zones are block boundary zones representing fold and fault displacements internal to each block.

velocity estimates shown in Figure 2 represent the most plausible results combing all timing and shortening data.

## 3. GPS and Geological Velocity Comparison

[7] Figure 2 shows a comparison of geological velocity estimates to those derived from GPS. It is important to note that GPS velocities near the coast are not directly comparable to the geologic data, because they probably have a large component of rapid, transient, elastic deformation due to strain that builds up between large earthquakes and is then released [*Norabuena et al.*, 1998; *Liu et al.*, 2000]. However, GPS motions within the foreland thrust belt

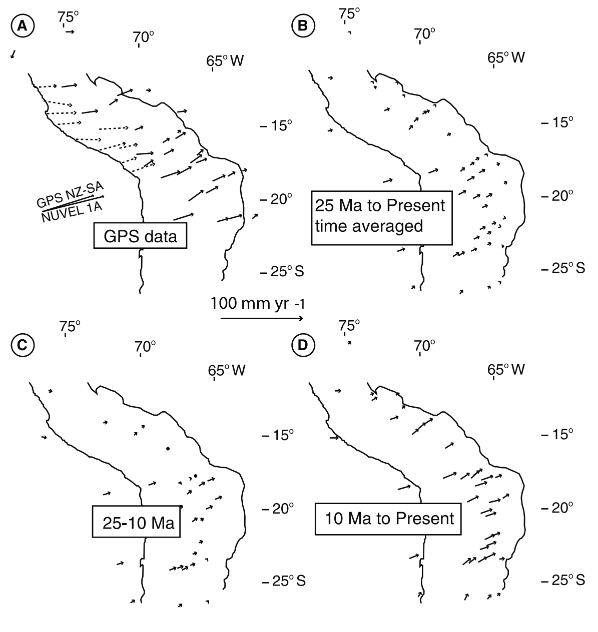


**Figure 2.** Comparison of geodetic and geologic velocities within the the Central Andes. (a) shows the GPS velocities with respect to the stable interior of South America[1] and the convergence vector for the Nazca plate with respect to South America derived from the GPS data and predicted by the NUVEL-1A global plate motion model[4]. Dashed vectors are transiently elastically loaded and not directly comparable in magnitude to the geologic data (b) shows the average geologic velocities over the past 25 Ma. (c) and (d) show average velocities for a two step displacement field, 25–10 Ma and 10 Ma–Present.

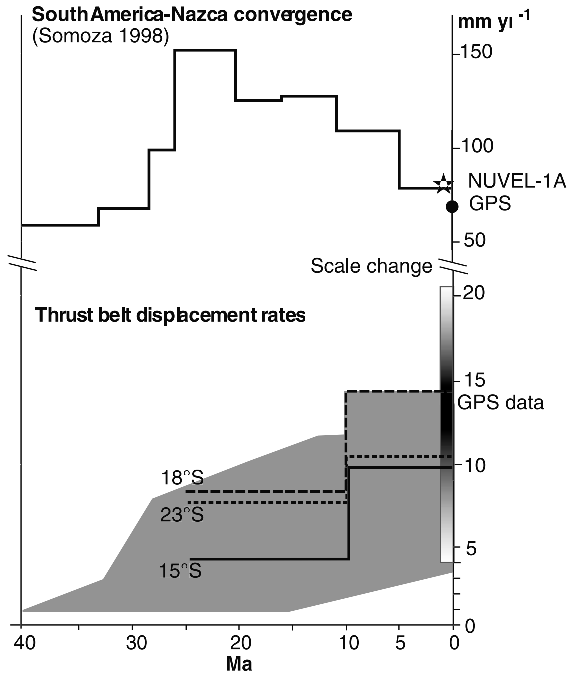


**Figure 3.** Graphic representation of velocity transects (most likely values) across the Andes at 23°S, 18°S and 15°S, showing the time evolution of velocities according to the geologic model presented in Figures 2c and 2d compared to the present range of GPS velocities across the foreland. Grey area around curves represents qualitative uncertainties. Upper segment of graph shows the evolution of plate convergence rates over the same time period. GPS shortening estimate and uncertainties are an average of north and south profiles in [*Norabuena et al.*, 1998].

(e.g., Subandean and Interandean zones) appear to largely reflect permanent shortening and so should be comparable to the geological data. The utility of the comparison depends on the uncertainites in the two velocity fields.

[8] Assessing uncertainties associated with velocity estimates derived from positions inferred from GPS data is a complex issue depending on a variety of assumptions about both random and systematic error sources [*Mao et al.*, 1999]. It is generally accepted that accuracy and precision of velocity estimates will improve with longer time series of measurements [e.g. *Bevis et al.*, 1999]. However, we believe that in spite of uncertainties of both the geological and GPS datasets, the inferred velocities are adequate for useful comparison, especially because the techniques are independent without common sources of uncertainties.

[9] The most direct comparison (spanning 6 orders of magnitude in time) is between GPS and the velocities for the past 10 Ma. Both the rates and directions are similar. This agreement is surprising given the independence of the techniques and the large difference in time scales. The 25 –10 Ma vectors are similar to the GPS in direction, but of smaller magnitude. This model is less directly comparable to the GPS field, because much of the present day "active" Andes (Subandes) was stable throughout this period. The net 25 Ma–present vectors have similar orientation and somewhat smaller magnitude than the GPS vectors. Thus the displacement directions have remained constant, whereas the rate has accelerated. As shown in Figure 3, with uncertainties, the 25–10 Ma period shows maximum velocities of $\sim$8 mm yr$^{-1}$, approximately half of present values, whereas the 10 Ma–present velocities are comparable to the average present shortening rate we can estimate from a two-parameter fit to GPS data [*Norabuena et al.*, 1998] ($\sim$14 ± 7 mm yr$^{-1}$, 1 sigma) for the two profiles. This

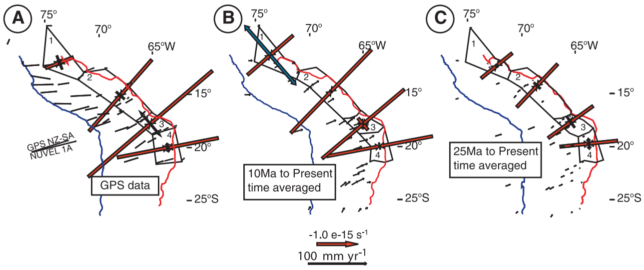


**Figure 4.** Bulk strain rate tensors for long term geologic rates and present day GPS values, averaged over approximately similar regions of the foreland. (a) shows GPS data, (b) shows geologic data averaged over 10 Ma (c) over 25Ma. Red arrows indicate contractional strain, blue, extensional. The values plotted are in Table 1.

acceleration is consistent with clustering of fission track ages since 15–10 Ma [*Benjamin et al.*, 1987].

[10] We also compare the associated strain rate fields in various portions of the study area (Figure 4). The geodetic strain rate tensor is easily estimated by inverting the GPS velocities for the best-fitting velocity gradient tensor [*Feigl et al.*, 1990]. To estimate geological strain rate tensors, we grouped data in comparable regions (GPS sites and locations of geological data differ) and made estimates for both the 10 Ma -present and the 25 Ma–present velocity fields.

[11] The strain rate tensors show a "rotation" of principal axes (Figures 4a, 4b, and 4c, Table 1). The axes are oblique to the regional velocity field that trends ~070°. This pattern reflects the N-S gradient in the velocity fields [*Hindle et al.*, 2000] (maximum at around 18°S, decreasing to the north and south). For regions 2, 3, and 4 the consistency of principal axes orientations is apparent between geologic and geodetic data (see Table 1, Figure 4). The angular differences are as small as ~1° (region 3) and are generally smaller for the 10 Ma–present field. Region 1 has a larger difference in axis orientations (~18°). With the exception of region 1, present day principal strain rates (shortening) are over one order of magnitude higher than the long-term (25 Ma) average. The rates for the last 10 Ma are by contrast as high as those at the present day in regions 1,3 and 4. The highest present (and of any) rate is in region 3 ($-2 \times 10{-}15$ $s^{-1}$), in accordance with the proposal [*Horton*, 1999] that faster erosion in this region is causing more rapid shortening in order to attain a critical taper. The geological shortening estimates for regions 2, 3, and 4 are similar.

## 4. Discussion

[12] These results indicate, despite their uncertainties, geologic and geodetic estimates of shortening rates and directions in mountain belts can be usefully compared. Velocity and strain analyses yield several primary results. We see an apparent acceleration of displacement in the foreland which is synchronous with the slowing of convergence between Nazca and South America [*Norabuena et al.*, 1999]. This long-term acceleration is shown by the geological data, which indicate shortening over 10 Ma–present consistent within uncertainties to the overall shortening inferred from GPS data. We can think of these changes in terms of the partitioning of the plate convergence. An Euler vector derived from the GPS data predicts about 61–64 mm $yr^{-1}$ of convergence at the trench in the study area. From the variation in GPS site velocities from the trench to stable South America, it appears that about 30–38 mm $yr^{-1}$ (~50%) of the convergence is locked at the plate interface, causing elastic deformation that will be released in future large earthquakes. About 12–15 mm $yr^{-1}$ (~20%) of the convergence causes permanent deformation in the foreland, and the remaining motion (~30%) is presumed to occur as stable sliding (aseismic slip) at the trench, causing no permanent or elastic deformation. In contrast, the geological data indicate that an early stage of foreland shortening (25–10 Ma) occurred at rates of 5–8 mm $yr^{-1}$, and a second stage (10 Ma–present) at 10–15 mm $yr^{-1}$. This slower shortening occurred while convergence was much faster, perhaps double the present rate (~150 mm $yr^{-1}$ at 25 Ma). Hence a significantly lower portion of the total convergence went into crustal shortening at that time.

[13] If the earthquake cycle has been similar through time (an assumption difficult to test), then the observation that in the past, foreland shortening occurred at less than 50% of present rates suggests that the fraction of locked slip was much lower (<20 mm $yr^{-1}$), and most movement on the subduction interface (~85% of convergence) occurred by stable sliding. Conditions at the plate interface would have changed substantially, to a situation close to present conditions, around 10 Ma, when the foreland displacements accelerated as the locus of deformation moved eastward to the Subandean zone. By then, ~60% of the observed slowing of convergence had already taken place, so at 10 Ma, the percentages of locked slip and stable sliding would still be different from today's even if the absolute value of locked slip were very similar.

[14] The physical processes causing the partitioning between locked slip, earthquakes, and stable sliding are unclear. These ideas were first posed in terms of seismic coupling, the fraction of plate motion that occurs by trench earthquakes, via two end members: coupled Chilean-type zones with large earthquakes and uncoupled Mariana-style zones with largely aseismic subduction [*Kanamori*, 1977]. It has been suggested that this fraction should depend on the rate and age of subducting lithosphere (highest when young lithosphere subducts rapidly), trench sediments (least when sediment flux is high), and the normal stress on the plate interface (lowest when stress is low). Although these ideas seem plausible, efforts to correlate the seismic slip fraction with convergence rate or plate age find no clear pattern [*Pacheco et al.*, 1993], and the sediment and normal stress arguments have yet to be rigorously tested. Moreover, inferring seismic slip faces problems including the variability of earthquakes on a boundary, whether the time sampled is long enough, and estimating source parameters for earthquakes that predate instrumental seismology. These difficulties can be avoided using GPS to estimate plate coupling from the deflection of the overriding plate [*Norabuena et al.*, 1998], but this approach samples the present earthquake cycle, which may not be representative of long-term behavior, and the relation between seismic and geodetic locking may be complicated. Thus although seismic coupling can be defined from the seismic slip fraction, its relation to the mechanics of convergence has yet to be resolved.

**Table 1.** Principal Strain Rates and Azimuths of Short Axes (P-Short Axis, T-Long Axis) from the 4 Regions Shown in Figure 4

| Region/Dataset | P($s^{-1}$) | T($s^{-1}$) | azimuth(°) |
|---|---|---|---|
| 1. geodetic | −3.5e-16 | −1.7e-16 | 073° |
| 10 Ma geologic | −7.2e-16 | 9.2e-16 | 053° |
| 25 Ma geologic | −4.7e-16 | −3.7e-17 | 055° |
| 2. geodetic | −1.1e-15 | −1.2e-16 | 045° |
| 10 Ma geologic | −1.4e-15 | −3.7e-17 | 048° |
| 25 Ma geologic | −7.4e-16 | −9.1e-17 | 047° |
| 3. geodetic | −2.0e-15 | 3.8e-16 | 053° |
| 10 Ma geologic | −1.3e-15 | −1.8e-16 | 053° |
| 25 Ma geologic | −6.6e-16 | −1.6e-16 | 058° |
| 4. geodetic | −1.2e-15 | 1.0e-16 | 083° |
| 10 Ma geologic | −1.3e-15 | −7.2e-17 | 083° |
| 25 Ma geologic | −7.0e-16 | 1.3e-16 | 088° |

[15] Even so, it is natural to ask whether the factors proposed as controlling plate coupling might have given rise to the apparent increase with time. The trench sediment supply may have decreased, due to aridification of the area west of the Eastern Cordillera post 15 Ma [*Vandervoort et al.*, 1995] which would be interpreted as increasing seismic coupling [*Scholz*, 1990]. The age of the subducting Nazca plate is decreasing, which has been proposed as favoring increased coupling, although this effect seems likely to be small [*Norabuena et al.*, 1999]. The growth of the Andes would presumably have increased plate coupling [*Norabuena et al.*, 1999]. Hence all three of the proposed controlling factors would favor plate coupling increasing toward the present. Thus although the mechanics of the negative feedback between convergence and mountain building are unclear, there are several tantalizing possibilities. A second striking result is the consistency of the displacement direction in the deforming foreland region over time. The geologically estimated displacements are approximately parallel, trending close to the present day plate convergence vectors given by either the NUVEL-1A model or the GPS data, and slightly convergent at the northern and southern extremes. Moreover, the orientations of the strain rate tensor's principal axes have remained similar. This stability may reflect both the stability of the convergence direction and topographic effects, because the topography of both the present day mountain chain (which contributes gravitational body forces) and the subducting plate [*Gephart*, 1994] are roughly symmetric about the convergence direction. Hence the curved form of the mountain belt can be attributed to differential displacement along its strike [*Hindle et al.*, 2000], with a maximum velocity near 18°S and diminishing to the north and south of this point. The resulting strain pattern is "arcuate" along strike. Beyond these specific results for the Andes, we find it exciting that space - based geodesy and structural geology can be integrated to study plate boundary zone evolution through time. This combination and comparison of kinematic tools provides new opportunities to study plate boundary dynamics.

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