Topography growth drives stress rotations in the central Andes: Observations and models

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1Recent numerical models that couple global mantle circulation with lithosphere dynamics show that growth of the central Andes controls the 30% reduction of convergence velocity between the Nazca and South America plates observed over the past 10 Ma. The increase of gravitational potential energy due to topographic growth is also a major control on the stress pattern. Here we use numerical models which reproduce the Nazca/South America convergence history to predict the change of stress pattern in the central Andes for the past 10 Ma. Comparison of the modeled stress orientations at present-day with the observed ones results in ±23.9° mean deviation. Based on this good agreement we attempt to predict paleostress orientations 10 Ma ago. Interestingly, the modeled stress orientations 3.2 Ma ago are very similar to the present-day orientations. From this result we infer that stress rotations occurred between 10 and 3.2 Ma ago, when topography was considerably lower. Citation: Heidbach, O., G. Iaffaldano, and H.-P. Bunge (2008), Topography growth drives stress rotations in the central Andes: Observations and models, Geophys. Res. Lett., 35, L08301, doi:10.1029/2007GL032782.

2. Global Mantle Convection and Lithospheric Plate Model Coupling

4To compute plate motions and crustal stress orientations at present-day, 3.2 Ma and 10 Ma ago, we use the global circulation models from Bunge et al. [1997, 1998] coupled with a global model of the lithosphere [Bird, 1998] as described by Iaffaldano et al. [2006]. The 3D spherical mantle convection model solves the conservation equations of mass, momentum and energy for a highly viscous (Stokes) fluid to compute temperature and velocity throughout the mantle [Bunge et al., 1997]. The model used for the lithosphere, the SHELLS code of Kong and Bird [1995], is based on conservation of mass and momentum (stresses-equilibrium) in the thin-sheet approximation, where the 3D force balance is vertically integrated along depth in order to reduce the 3D problem to 2D [Bird, 1999].

5Asthenosphere velocities derived from our global mantle convection model are used as a velocity boundary condition at the base of plates in SHELLS, such that realistic mantle buoyancy forces are allowed to drive plate motion (Figure 1a). Plate driving tractions are computed in SHELLS through a dislocation olivine creep rheology that depends on temperature, pressure and strain rate, where the strain rate is equal to the vertical gradient of the asthenosphere velocity pattern from our global mantle convection model. Inferences of paleo-topography at 10 Ma and 3.2 Ma as well as the present-day topography are a priori prescribed in the model. In the following we apply the model parameters used by Iaffaldano et al. [2006] which successfully match the convergence between Nazca and South America plates (Figure 1c) over the past 10 Ma. To compare the S11...
Figure 1. (a) Sketch of the global model that combines lithospheric dynamics calculated with the finite element code SHELLS (grey area) from Bird [1998] with a global mantle convection code (colored area) as described by Bunge et al. [1997]. Model rheology is non-linear, temperature and strain-rate controlled power-law rheology. (b) Map view of the change in convergence velocity of the Nazca and South America plate and change in topography. (c) Comparison of the model results (line) for three times steps at 10 Ma, 3.2 Ma and present-day with observed convergence rates (green dots with error bars) of the Nazca plate (NZ) with respect to the South America plate (SA) [Iaffaldano et al., 2006]. Red graph denotes the evolution of topography. Note the inverse correlation between topography growth and decreasing convergence rate.
orientations calculated from this model we use a subset of the WSM database.

3. World Stress Map Data Versus Model Results

[6] The WSM database provides information on the $S_{H}$ orientation and the tectonic regime from a wide range of stress indicators [Heidbach et al., 2007; Zoback, 1992]. In the central Andes between $5°-35°$S and $62°-82°$W the database provides 257 stress data records of A-C quality data. We eliminated three data records from focal mechanism solutions that show normal faulting with N–S orientation of $S_{H}$. This orientation is due to the bending of the subducting Nazca plate in the forebulge, a process that is not represented in our modeling approach.

[7] The 257 data records exhibit a E–W oriented stress pattern that is controlled by the relative plate motion striking approximately N80°W of the Nazca plate with respect to South America. In the Eastern and Western Cordillera of the Altiplano-Puna plateau $S_{H}$ is perpendicular to the strike of the Andes, and thrust faulting is the prevailing tectonic regime. In the central Andes the excess of gravitational potential energy due to the 4000-m-high Altiplano-Puna plateau leads to normal faulting regime with $S_{H}$ oriented parallel to the strike of the Andes (Figure 2a).

[8] Comparison of the contemporary $S_{H}$ orientations from the WSM with our modeling results at present-day yields a mean deviation of ±23.9°. This is within the uncertainties of the A-C quality WSM data that are reliable to within ±25°. Furthermore, the two observed general
trends in $S_H$ orientations and the prevailing tectonic regimes are also well reflected in our model (Figure 2a). The model shows normal faulting in the Altiplano-Puna plateau and thrust faulting in the Western and Eastern Cordillerias. The histogram of the deviation between observed and modeled $S_H$ orientations has a distinct maximum at 0° (Figure 2a).

In our tectonic model corresponding to conditions 3.2 Ma ago results are similar to the ones at present-day. However, in the model representing the scenario at 10 Ma the mean deviation between modeled and today's WSM stress $S_H$ orientations is increased to ±44.8°, i.e. larger than the uncertainties of the WSM A-C quality data. The modeled paleostress field exhibits two first-order stress orientations; a N–S oriented stress field in the South America plate with prevailing thrust faulting and an E–W oriented stress field in the Nazca plate with strike-slip and normal faulting regime (Figure 2b). The histogram of the deviations between observed and modeled $S_H$ orientations at 10 Ma has no clear maximum, but exhibits homogeneous distribution of deviation (Figure 2b).

The model results indicate that the $S_H$ orientations and the tectonic regime changed significantly during the past 10 Ma (Table 1). $S_H$ orientations rotated counter-clockwise north of an axis located in the Arica bend and a clockwise south of it (Figures 2 and 3). This axis coincides with an axis separating rotations of the same sense and similar amount that has been identified from paleomagnetic analysis [Allmendinger et al., 2005, and references therein]. For the northern area of the Altiplano-Puna plateau, our findings are also confirmed by the analysis of paleostress data from Miocene faults [Mercier et al., 1992], which indicate counter-clockwise rotation of 48° and 76° at two locations comparable to the 46° and 59° counter-clockwise rotation predicted from our model (Table 2). However, north of 10°S Mercier et al. [1992] report 33° and 52° counter-clockwise rotation, whereas our model indicates 3° rotation (Table 2).

### 4. Discussion

Qualitatively our model results at present-day are in good agreement with numerical models that use the 2D thin sheet approximation [Coblentz and Richardson, 1996; Meijer and Wortel, 1992; Richardson, 1992; Richardson and Coblentz, 1994; Stefanik and Jurdy, 1992]. These studies state that the major stress sources for the South America plate are topography-induced body forces, basal drag, and the portion of ridge push force from the Nazca plate transferred at the subduction interface. They also argue that the resistive forces at the interface are a key factor in the evolution of the central Andes.

The buoyancy forces per unit length induced by the excess of gravitational potential energy of the Andes have been estimated to be in the order of $5 \times 10^{12} \text{ N m}^{-1}$ [Froidevaux and Isacks, 1984; Husson and Ricard, 2004; Richardson, 1992]. The ridge push force per unit length is in the range of $1.0–7.5 \times 10^{12} \text{ N m}^{-1}$ [Richardson and Coblentz, 1994] and Lamb [2006] estimates the shear forces per unit length along the plate interface in North Chile to be $9.7 \times 10^{12} \text{ N m}^{-1}$. This is in agreement with our modeling results that indicate an increase of resistive forces per unit length at the plate interface due to the Andean growth in the

### Table 1. Mean Deviation Between $S_H$ Orientation From the WSM Data Set and the Model Results and Fit of the Tectonic Regime

<table>
<thead>
<tr>
<th>Time</th>
<th>Mean Deviation*</th>
<th>Tectonic Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Ma</td>
<td>±23.9°</td>
<td>68%</td>
</tr>
<tr>
<td>3.2 Ma</td>
<td>±23.2°</td>
<td>65%</td>
</tr>
<tr>
<td>10 Ma</td>
<td>±44.8°</td>
<td>42%</td>
</tr>
</tbody>
</table>

*Distance weighted mean of the three nearest model values.

Figure 3. Comparison of observed and modeled $S_H$ orientations in the northern section. Thin lines on the continent (ocean) are the 4000 m (~3500 m) topography (bathymetry) contour lines. SW–NE striking black line at the Arica bend separates areas with prevailing counter-clockwise rotations from areas with clockwise rotations. Black dotted line separates counter-clockwise rotations from clockwise rotations from the analysis of paleomagnetic data [Allmendinger et al., 2005, and references therein]. (a) Comparison of model results at 10 Ma and present-day. Note the small rotations north of 10°S where topography is less than 4000 m. (b) Comparison of observed paleostress and present-day stress data.
order of 10^{13} \text{ N m}^{-1}. Thus, large topographic features do indeed contribute to lithosphere dynamics by as much as the far-field stresses due to mantle convection. We also infer that the increase of resistive forces at the plates interface due to the variation in paleo-topography controlled most of the stress rotations in the South America plate.

[13] Using the analytical approach of Sonder [1990] for the amount of $S_{H}$ rotation $\theta'$ for extensional and compressional tectonic stress regime

$$\theta' = \frac{1}{2} \tan^{-1} \left( \frac{\sin 2\theta}{-\tau / \tau' - \cos 2\theta} \right)$$

we can also estimate the relative stress increase that is needed for the observed stress rotation of $\theta' = 59^\circ$ at 75.2°W and 15.4°S (Table 2). Inserting in expression (1) $\theta = 2^\circ$ as the angle between the orientation of the far-field stress at 10 Ma (N137°) and the regional stress anomaly, i.e. the strike of the Andes (N135°) we receive for the stress ratio $\tau'/\tau = -0.96$, $\tau$ is the magnitude of the far-field stress and $\tau'$ the magnitude of the regional stress anomaly. Thus, the stress anomaly needed to rotate $S_{H}$ by $\theta' = 59^\circ$ is of similar magnitude as the far-field stress magnitude at 10 Ma.

[14] Whereas south of 10°S our modeled stress rotations match the observed ones, north of 10°S the model does not predict rotations backwards in time as indicated by paleostress data (Figure 3). Here the increase of topography in the model did not rotate $S_{H}$, but only changed the tectonic regime from prevailing thrust faulting at 10 Ma to normal faulting and strike-slip at present-day in agreement with the WSM stress data (Figure 2).

[15] This misfit in $S_{H}$ rotation can result from the spatial resolution of our model. As our model is global, local to regional effects are not represented. E.g. one parameter not represented in our approach is the change of trench sediment thickness. Lamb [2006] concludes from his analytical modeling that trench sediment fills can act as lubricants in subduction zones and that they are probably the key control of shear force magnitudes at the plates interface. North of 10°S the sediment fill in the Nazca plate trench increases from less then 0.1 km to 0.5 –2.5 km [Lamb and Davis, 2003]. At the same time the subduction dip angle decreases from >30° to 10–15°. Thus, the resistive forces at the plates interface probably vary significantly along strike of the Andes.

[16] In general local to regional effects can be of great importance when the stress state is close to isotropic [Heidbach et al., 2007]. Therefore, when the far-field stress has a small magnitude, even small changes in topography can induce large stress rotations. Likewise the change of other regional stress sources such as lateral tear-off of a slab after continental collision (e.g. southern Apennines, SE-Carpathians) or the far-field stresses due to re-organization of plate motion (e.g. Pacific plate at c. 5 Ma) can become a major control of the $S_{H}$ orientation.

[17] Another source for the deviation between the modeled $S_{H}$ orientation and the observed one is the uncertainty of the stress data itself. Most of the WSM stress data in South America have C-quality. This implies that the $S_{H}$ orientation is reliable to within ±25°. Furthermore, the exact timing of the paleostress data is difficult and can deviate from the chosen model time of 10 Ma.

### Table 2. Observed and Modeled $S_{H}$ Orientations at 10 Ma and Present-Day

<table>
<thead>
<tr>
<th>Location</th>
<th>10 Ma Observed</th>
<th>10 Ma Modeled</th>
<th>0 Ma Observed</th>
<th>0 Ma Modeled</th>
<th>Rotation Observed</th>
<th>Rotation Modeled</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.1°W 7.3°S</td>
<td>$157^\circ \pm 23^\circ$ (n = 12)</td>
<td>$83^\circ$</td>
<td>$105^\circ \pm 9^\circ$ (n = 11)</td>
<td>$80^\circ$</td>
<td>$52^\circ$</td>
<td>$3^\circ$</td>
</tr>
<tr>
<td>77.5°W 9.4°S</td>
<td>$157^\circ \pm 25^\circ$ (n = 4)</td>
<td>$93^\circ$</td>
<td>$124^\circ \pm 29^\circ$ (n = 4)</td>
<td>$90^\circ$</td>
<td>$33^\circ$</td>
<td>$3^\circ$</td>
</tr>
<tr>
<td>72.5°W 13.4°S</td>
<td>$173^\circ \pm 3^\circ$ (n = 5)</td>
<td>$157^\circ$</td>
<td>$97^\circ \pm 7^\circ$ (n = 13)</td>
<td>$111^\circ$</td>
<td>$76^\circ$</td>
<td>$46^\circ$</td>
</tr>
<tr>
<td>75.2°W 15.4°S</td>
<td>$137^\circ$ (n = 1)</td>
<td>$123^\circ$</td>
<td>$89^\circ \pm 5^\circ$ (n = 2)</td>
<td>$64^\circ$</td>
<td>$48^\circ$</td>
<td>$59^\circ$</td>
</tr>
</tbody>
</table>

*Locations are taken from sites where Mercier et al. [1992] provide paleostress data.

*Mean $S_{H}$ orientation with standard deviation at 10 Ma from Mercier et al. [1992] and at present-day from the WSM [Reinecker et al., 2005]. Numbers in brackets indicate the number of data records used for the mean value and its standard deviation.

*Positive values denote counter-clockwise rotation.

### 5. Conclusions

[18] Our modeling results are in good agreement with the observations and show that growth of the central Andes controls the overall slow down of the Nazca/South America plate convergence, the change of the tectonic regime, and the rotation of $S_{H}$ orientation. Furthermore, modeling results indicate that 3.2 Ma ago the stress field orientation was very similar to the present-day one. This provides independent support for the suggestion that a large part (75%) of the current topography was already in place at that time. As the fit of the $S_{H}$ orientations is satisfactory for different time stages, we argue that our models reveal the relative importance of the participating stresses responsible for the evolution of the kinematics and the stress field pattern. We conclude that the degree of coupling at the plate interface and its time variability are key controls also for the evolution of the stress pattern in the central Andes.

[19] Acknowledgments. We thank Gwendolyn Peters, Karl Fuchs, Birgit Müller, and Zvi Ben-Avraham for constructive comments on an earlier version of this paper. We also acknowledge the reviews from Sjerd Cloetingh and the editor Fabio Florindo that improved the paper. Oliver Heidbach acknowledges the financial support from the Heidelberg Academy of Sciences and Humanities and the Task Force VII of the International Lithosphere Program. Giampiero Iaffaldano acknowledges the support by the Elitenetwork of Bavaria.

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