NUMERICAL MODELLING OF DEFORMATION PROCESSES IN THE ANDES

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INTRODUCTION

Numerical models taking into account the pressure and temperature dependent rheology of the lithosphere are developed in order to bring insights on the distribution of deformation across the Andean orogeny. A general question concerns the extent of the plate boundary, which is the understanding of deformation that is either directly linked to the subducting plate beneath the South American continent, or deformation that is typical of intra-continental domain. Constraints provided by data such as geological reconstructions, geochronology, geomorphology, or seismicity, allow to propose models or mechanisms of deformation, and numerical models help to validate some of these propositions. At this stage we develop a parametric study, exploring the spatial distribution of strength and thermal heterogeneities within the continental lithosphere, and how the rheological properties are modified by the advancing subducting plate. Proposed subjects of study concern 1) deformation of the fore-arc portion of the continental lithosphere in the Central Andes, 2) the role of inherited structural heterogeneities on the differences in height, crustal thickness and mode of deformation in between the Altiplano and the Puna.

1. NUMERICAL METHOD

We use a finite differences two-dimensional code modified from Parovoz (Poliakov & Podladchikov, 1992). It is based on the Fast Lagrangian Analysis Continuum method (FLAC, Cundall & Board, 1988), which incorporates an explicit time-marching scheme, and allows the use of a wide range of constitutive laws such as brittle-elastic-ductile rheology derived by rock experimentalists (Ranalli, 1995). It handles initiation and propagation of non-predefined faults (shear bands).

As a general approach, the lithosphere and part of the asthenosphere are modelled as a medium of about 100 to 500 km thick and about 10 times longer in width. Each element is 1 to 5 km^2, depending on the specific question that the model addresses. Both lateral borders are free to slip vertically, and a horizontal velocity V_x is applied from the sides. The lithosphere+asthenosphere medium floats on a 'perfect-fluid' asthenosphere within the gravity field; hydrostatic boundary conditions are applied at the bottom of the model.

The equation of motion is resolved for each element and at each time-step, constrained by the boundary conditions. At the stress-free surface, erosion and sedimentation processes are modelled using a diffusion equation. The heat equation is resolved with time, while the initial temperature field is calculated according to an age dependent procedure (e.g. Burov & Diament, 1992), linked to the inherited thermal history.

The modelled lithospheric plate is composed of crustal layers and a lithospheric mantle, which have different densities and rheological properties. Elastic-viscous-brittle behaviour is modelled with pressure-dependent, non-associative, Coulomb criterion for brittle failure and temperature-dependent creep power-law for ductile behaviour. The brittle-ductile transition is self-consistently defined in the modelling, and is empirically referred to as the depth at which the deviatoric shear stress becomes lower than 20 MPa (for a discussion see Ranalli, 1995).

2. LITHOSPHERIC FAULTING IN THE CENTRAL ANDES FOREARC

Numerical models of ongoing subduction incorporate a subducting oceanic lithosphere in contact with the continental lithosphere, and a part of the asthenosphere. Preliminary modelling consists of testing the effects of relative strength contrasts between the different oceanic and continental layers that are in contact: the brittle yield stress and the power-law parameters defined by a dominant composition, together with the geotherm, all contribute to control the localisation of deformation (and the geometry of faults), at the scale of several millions of years convergence.

These models investigate not only the effect of the advancing oceanic lithosphere on surrounding crustal and mantle continental material, but also the far field reaction of the intra-plate domain. A preliminary model (figure 1) containing a relatively high friction between the oceanic plate and the continental plate, displays two main features: 1) shear zones (fault zones) that initiate from the subducting plate, 2) shear zones that develop far into the continental domain, where an initially warmer area has been inserted.

The first set of shear zones result from the compression exerted by the bended slab on the continental lithosphere, and do not require any specific strength contrast within the continental lithosphere. The ‘western most’ shear zone initiates at the base of the ductile continental crust, while the second one to the east initiates above the base of the ‘strong’ continental lithosphere; they both propagate to the surface. At the surface, these shear zones emerge as two bulges, bounding a crustal wedge and a lithospheric wedge. They form the western boundary of a domain subjected to crustal scale folding (oscillations of the topography seen in fig. 1).

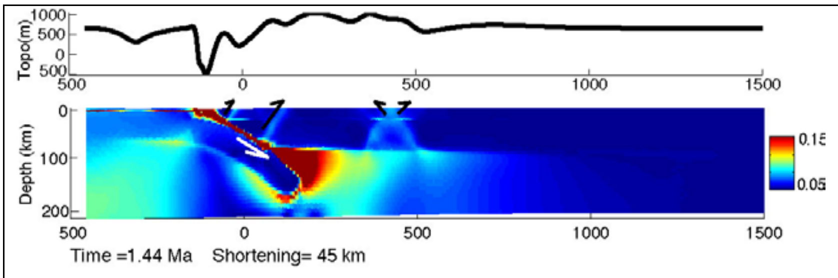

Figure 1 : Preliminary model of continental deformation above a subduction zone : development of shear bands (or fault zones) 1) at the base of the crust and of the lithosphere, 2) strain localisation in an area far away from the subduction zone, where an initial weak rheology has been inserted.

In order to link modelled shear zones with observational data, these models require further investigations such as their sensitivity to rheological variations within the lithospheric plates but also at their contact. However the first set of shear zones initiating from the subducting plane finds some support in seismic and geological records. David et al. (ISAG, 2002) studied the crustal seismicity recorded in the northern most part of the Chilean forearc from about 18°S to 19°S. Below the Precordillera and the Central Depression, seismic events define a zone under compression dipping about 45° towards the trench, connecting nearly perpendicular to the subducting plane. Focal mechanisms and stress tensors show a consistent compressive stress regime for earthquakes occurring down to 59 km depth. David et al (ISAG, 2002) suggest that this quasi-planar zone of seismicity probably results from the difference in rheology of the forearc and of the Altiplano and Western Cordillera. However, our preliminary models indicate that such a rheological boundary is not necessary to the formation of such a shear zone.

3. LATERAL FLOW FROM THE PUNA TOWARDS THE ALTIPLANO?

The subduction styles are quite similar in the Central Andes in the Puna and in the Altiplano (no significant internal deformation or rotations in Neogene times neither in the fore-arc nor in the Brazilian Craton), but geological and geophysical studies indicate different features:

1) On a general east-west direction, the amount of crustal shortening across the Altiplano is twice as large as that across the Puna (about 100 km difference). Crustal shortening in the Altiplano would contribute for 20% less than the present day crustal volume (Kley et Monaldi, 1998; Rochat et al. 1999).
2) Paleomagnetism measurements show clockwise rotation of crustal blocks in the southern part of the Altiplano (Roperch et al. 2000).
3) Seismic velocities attenuation at depths ~50 to ~150 km is stronger under the Altiplano than under the Puna. Amongst several different interpretations, Whitman et al. (1992) suggested this could be due to the absence of continental mantle lithosphere below the Puna (the crust is directly in contact with the asthenosphere).
4) Best fitting models of interseismic crustal velocities in the central Andes (Bevis et al. 2001) are inclined about 30° to much towards the west with respect to measured GPS velocities.

Although aware that other data may contradict these features, we propose to explain them by an active lateral flow of the lower crust, from the Puna towards the Altiplano. Preliminary 2D numerical models show that for a higher average elevation of the Puna, upper crustal material flows towards the Altiplano, which is however compensated by a strong counter flow at the base of the crust. However, if in addition the continental mantle lithosphere under the Puna is lighter or thinner than under the Altiplano, crustal-scale flow from the Puna towards the Altiplano develops on a large time-scale, at a rate of about 2 mm/yr (Fig. 2). This velocity cannot be precisely constrained, since its value is highly dependent on the poorly known lower crust viscosity. The value obtained in this example shows, however, that this phenomenon may occur at non-negligible geological rates.

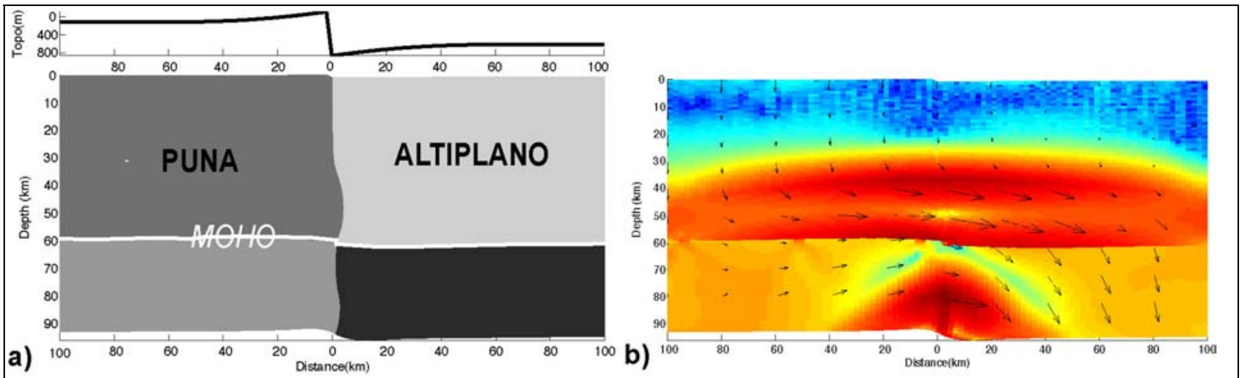

Figure 2: 2D north-south model in which the Puna crust to the left is initially higher and thinner than the Altiplano crust to the right. **a)** Surface topography after 2 Ma, with the Puna and Altiplano crusts respectively in blue and green, and the Puna and Altiplano mantle, respectively in orange and brown. **b)** Shear strain rate and velocity vectors, showing lower crustal flow in red, at rate of about 2mm/yr. The Puna crust is initially higher by 1 km than the Altiplano crust. When a density difference exists between the mantle lithospheres of the Puna and Altiplano, then a sustained flow from the Puna towards the Altiplano develops.

This mechanism of lateral flow is one amongst other ways to explain, by initial mechanical heterogeneities, the origin of observed different styles of deformation between the Puna and the Altiplano. This study is still in very preliminary stage and requires a deeper investigation of geological and geophysical information.

CONCLUSIONS

Preliminary modeling can reproduce the development of crustal and lithospheric scale shear zones as a result of the advancing subducting plane into the continent, and without introducing pre-existing rheological heterogeneities. However, rheological or thermal heterogeneities could explain the localization of deformation in an intraplate domain, such as for example where a Proterozoic basin would exist. Crustal thickness or densities variations may also explain large-scale south-to-north crustal flow.

These preliminary results are promising but still require improvement of specific initial and boundary conditions, which can only be provided by adequate and precise geological and geophysical information. The numerical method is still under development, for its application to the large scale of the Andes, requiring to take into account phase transitions and other temperature dependent deformation processes, for the implementation of surface processes, capable of reproducing geomorphologic markers, and finally for the development of a 3D approach, necessary to reproduce fundamental features in the Andes.

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