ALTIPLANO UPLIFT FROM GRAVITY DRIVEN CHANNEL FLOW

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INTRODUCTION

The discrepancies between several observations and a homogeneous crustal deformation in convergence zones led numerous authors in the last decade to propose alternative models. Bird (1991) showed from an analytical approach that a temperature dependent rheology implied that a low resistance zone prevails at the base of thickened crusts. The lateral variations in crustal thickness induce stress gradients on this low viscosity zone, which in turn can easily be driven from thickened, high stress zones towards lowlands where gravity stresses are lower.

In the Central Andes, the measured shortening of the upper crust does not show much correlation with crustal thickness (e.g. Kley & Monaldi, 1998; Rochat et al., 1999). The very thick crust is however globally related to its elevated thermal regime (e.g. Springer, 1999). As a consequence, the crust matches the conditions required for a low viscosity and a mid-lower crustal flow.

In this paper, we adapt a gravity driven channel flow model to explain the uplift of the Altiplano and explain the mismatch between upper crust deformation and crustal thickness.

GEODYNAMIC EVOLUTION OF THE CENTRAL ANDES

Although the Central Andes beneficiated from numerous studies in the last decades, the Altiplano area remains widely misunderstood. The uplift history is however now fairly well constrained (Kennan, 2000; Gregory-Wodzicki, 2000) and provides useful data in the comprehension of the Andean history. The Western Cordillera initiated its surrection 60 Ma ago and was followed by the more gentle uplift of the Eastern Cordillera. This former stage lasted until 30-40 Ma BP as the Western and Eastern Cordilleras reached elevations of about 1000 m and 2000 m respectively. Eventually, the rapid uplift of both Cordilleras increased from 20 Ma BP until now, leading to very high elevations (more than 4000 m on average). The Altiplano *sensu stricto*, in between these two Cordilleras, mainly uplifted during the last 20-10 Ma.

The formation of the Eastern Cordillera and subsequent crustal thickening can be easily explained by a considerable stacking of crustal slices. We emphasize that the *in situ* crustal thickening of the Western Cordillera is often under-evaluated, as the Late-Cretaceous-Paleogene deformation was certainly more intense in the western part of the Andes than generally mentioned; magmatism and other processes (which are not dicussed herein) also contributed to crustal growth. On the other hand, the upper crustal structure of the Altiplano does not indicate any significant shortening in this area (e.g. Rochat et al., 1999). Its high crustal thickness (up to 60-70 km, Beck et al., 1996) is hence to be explained invoking other mechanisms. Fig. 1 illustrates the mismatch between upper crustal shortening and crustal thickness in the Central Andes.

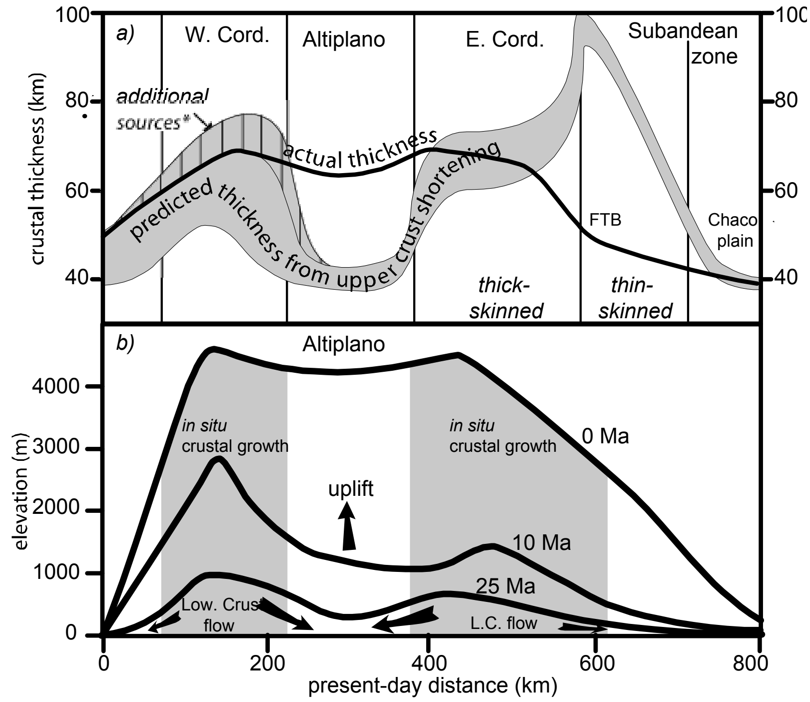

Figure : a) discrepancy between the actual crustal thickness (solid line) and predicted thickness from upper crust total shortening (shaded area) in the Central Andes (~20°S); note the volume excess in the E. Cordillera and Subandean Zone and the deficit below the Altiplano; b) crustal growth through time. Data are adapted from Rochat et al., 1999; Beck et al., 1996; Kennan, 2000.

MODELING THE ALTIPLANO UPLIFT

Homogeneous crustal thickening and lateral extrusion of the mid-lower crust constitute two end-members models which are commonly used to explain the formation of high plateaus (Medvedev & Beaumont, 2001). In the case of the Central Andes, the observations discussed above tend to suggest that the hypothesis of a lower crust channel flow can be explored. Isacks (1988) formerly suggested that the uplift of the Altiplano can be explained by a viscous lower crustal flow. Although some authors have suggested that the Altiplano could correspond to deep crustal imbrications (*e.g.* McQuarrie and DeCelles, 2001), we emphasize that evidence for a partially molten mid-lower crust (Yuan et al., 2000) more likely implies a ductile behavior at depth.

In the following model, we assume that both Cordilleras thickened *in situ* (although controversial for the W. Cordillera). As they thickened, the lateral pressure gradients drove the lower crust below the Altiplano area, inducing its uplift without shortening of the upper crust. We derive the uplift data from Kennan (2000) to calculate the crustal thickness through time assuming isostasy, only for both Cordilleras, but not for the Altiplano, where no upper crustal shortening can be invoked.

The mid-lower crustal flow is described by a Poiseuille flow in a channel of constant thickness *C*. The governing equations can be derived after Turcotte & Schubert (1982). After algebra, the change in elevation *h* through time writes (accordingly to *e.g.* Clark & Royden, 2000):

$$\frac{\partial h}{\partial t}=\frac{\rho_m-\rho_c}{\rho_m}g\frac{C^3}{12}\frac{\partial}{\partial x}\left(\frac{1}{\eta}\frac{\partial h}{\partial x}\right)$$

where ρ_m and ρ_c are the mantle and crust densities, *g* the gravitational acceleration, η the viscosity of the channel and *h* the elevation. The flow will mainly depends on the viscosity, which can vary by several orders of magnitude, while the uncertainties and variations in the other parameters are negligible in comparison. Changes in crustal thickness *S* can now write in a simple form as $\frac{\partial S}{\partial t}=A\frac{\partial}{\partial x}\left(\frac{1}{\eta}\frac{\partial h}{\partial x}\right)$ which emphasizes the role of the viscosity η, *A* now being a constant.

Because viscous deformation is restricted to the lower crust, this approach somehow considers that the upper crust behaves with an elastic rheology, and this model subsequently constitutes an intermediate between pure viscous and elastic deformation theories for the crust.

Creep flow law relates the strain rate $\dot{\varepsilon}$ to rheological constants (*Ea, D, n*), shear stress σ and an exponential form of the temperature *T* as $\dot{\varepsilon}=D\sigma_s^n e^{-Ea/RT}$. Temperature thus appears as the main variable in the equation. Moreover, as very little is known on both rheological constants and thermal regime of growing orogens, we assume for a first order approximation that ductility in the channel is (non linearly) depth-dependent. According to the results of Bird (1991), we assume that viscosity drastically increases with crustal thickness. The large uncertainty in rheological parameters does not allow to predict its actual temperature dependence; we prefer to invert the dynamic evolution of the Altiplano to calibrate the evolution of viscosity with depth.

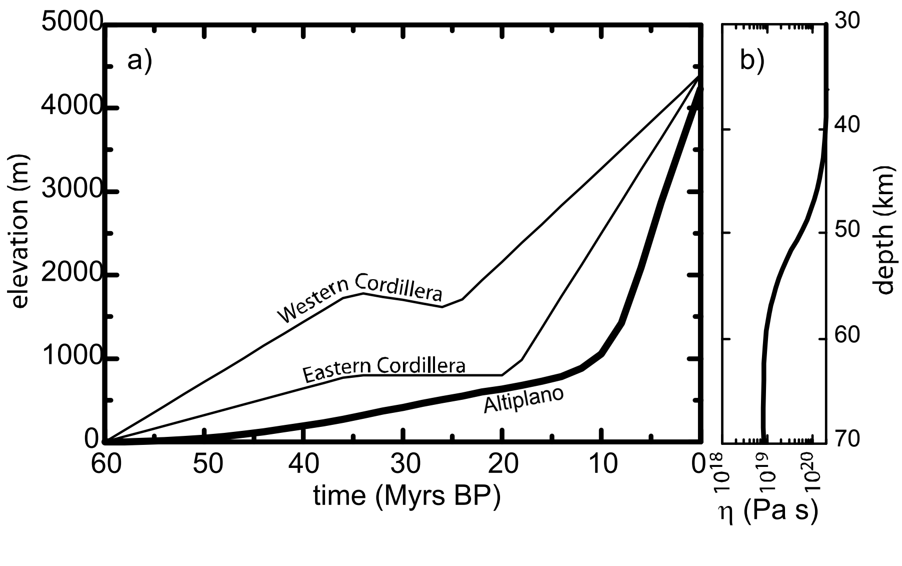

Figure 2: a) *A priori* uplift of the E. Cordillera and W. Cordillera for the model (thin lines, after Kennan, 2000), due to *in situ* crustal thickening, and predicted uplift for the Altiplano area (thick line); b) viscosity of the crustal channel as a function of crustal thickness.

In the model, the mid-lower crust flows from the surrounding growing Cordilleras towards the Altiplano. We assume that the flow from high elevation zones is instantaneously compensated.

The best fit between predicted and observed uplift histories (Fig.2) is obtained for a critical thickness of about 50 km, where the viscosity drops from 2 10^{20} Pa s to 8 10^{18} Pa s.

CONCLUSIONS

Our model confirms the possibility for a mid-lower crustal channel flow to be responsible for the Altiplano uplift. The calculated rheology is similar to the one proposed by Medvedev (2001) or Royden (1996) with the existence of a low viscosity (< 10^{19} Pa s) channel below 50 km depth.

However, the assumptions of *in situ* crustal growth for the Cordilleras raises the problem of volume balance, particularly for the Western one, where only little crustal shortening is generally mentioned. The possibility that crustal growth in the W. Cordillera might have benefited from subduction-related magmatic addition, in proportions which are difficult to assess, can also be addressed.

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