A VELOCITY - DEPENDENT FORCE BOUNDARY CONDITION APPROACH FOR NUMERICAL MODELS OF PLATEAU EVOLUTION - APPLICATION TO ANDEAN DEFORMATION

Robert PORTH

GFZ Potsdam, Telegrafenberg C3, 14473 Potsdam, Germany, porth@gfz-potsdam.de

KEY WORDS: numerical modelling, plateau evolution, Central Andes, velocity-dependent force boundary condition.

INTRODUCTION

Andean plateau evolution is controlled by plate driving forces and plateau induced volume forces increasing with plateau elevation. Neotectonic data and the recent stress field indicate that at present both forces are of comparable magnitude (Mercier et al., 1992; Assumpção and M. Araujo, 1993). This is supported by results of two-dimensional analytical (Froidevaux and Isacks, 1984) and elastic numerical(Richardson and Coblentz, 1994) modellings to calculate the state of stress in the Andean plateau and adjacent areas. Wdowinski and Bock (1994a and b) used a temperature dependent viscoplastic flow model to study the evolution of deformation and topography of the Andean plateau. Their model predicts many important large scale features of Andean plateau evolution such as the present day topography and migration of surface deformation from the central part of the Altiplano/Puna to the Subandean range. But, it cannot predict the decrease of indenting velocity with increasing plateau topography as suggested by Wdowinski and O'Connel (1990), because of the used velocity boundary condition (b.c.).

THE MODEL

In order to investigate the effect of growing plateau forces a velocity-dependent force b.c. was applied to geometrical simple two-dimensional lithosphere models at different stages of plateau evolution. Because of the non-linear and strongly temperature dependent viscosity (power law creep) of the lithosphere a constant force b.c. can lead to very unstable models with unrealistic high strains rates. Thus, in this study a mixed (force, velocity) b.c. was applied following Christensen (1992), who used this type of b.c. in numerical models of lithospheric extension. The force acting at the model boundary is

$$F(v) = F_0 - (F_0/v_0)\, v$$

where F_0 is the tectonic force at zero velocity and v_0 the maximum possible indenting velocity, the velocity of the right model boundary, caused by F_0. The values of F_0 chosen in this study are 3, 4.5 and 6 $\times 10^{12}$ Newton per meter lithosphere perpendicular to the two dimensional model. This is equal to an average horizontal tectonic stress acting at the 125 thick lithosphere model of 24, 36 and 48 MPa, respectively. For v_0 a value of 3 cm/a was chosen. Considering the model as a part of a larger system the physical idea behind this type of b.c. is that the finite viscosity of the "outside world" limits the indenting velocity even when the model itself is very weak.

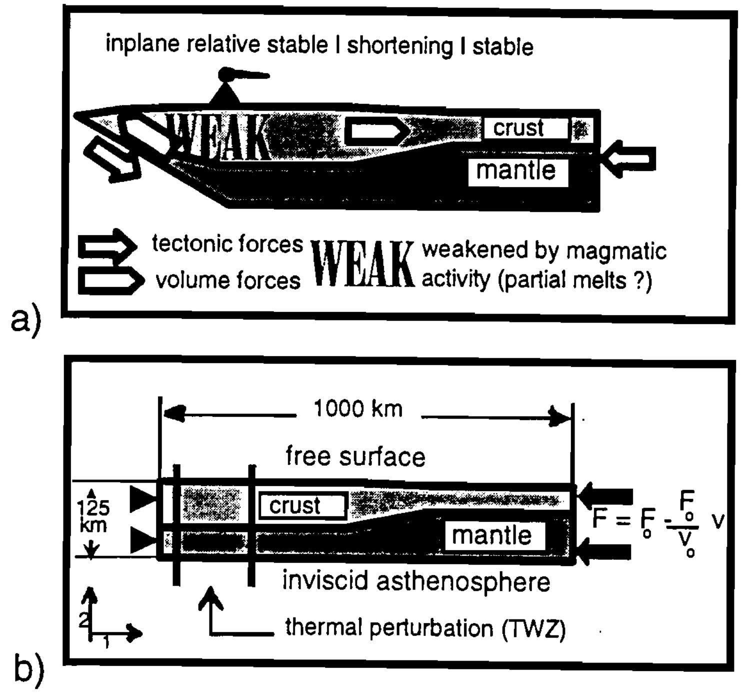

Figure 1 a) Schematic cross section showing the upper plate of the Central Andean subduction zone (vertical exaggerated). b) Geometry and boundary conditions of the numerical model. The (inplane) relative stable forearc region is not part of the model.

In order to keep it simple the inplane relative stable forearc region is not part of the studied numerical model (Fig. 1). Since the weakened lithosphere in the area of the magmatic arc is not capable to transmit tectonic stress this simplification should have no effect on the deformation in or east of the magmatic arc, where the largest part of crustal shortening is accommodated (e.g. Schmitz, 1994). This model also assumes that mantle drag forces at the base of the lithosphere (within the modelled area) are negligible. The finite element (FE) code used in this study is an adopted version of the code written by Shimon Wdowinski, used and described by Wdowinski and Bock (1994a and b).

RESULTS

Fig. 2 shows the velocity field and the effective strain rate (the second invariant of the strain rate tensor) of the model with $F_0 = 6 \times 10^{12} Nm^{-1}$ at two different stages of plateau evolution (two and four km elevation). Similar to the models of Wdowinski and Bock (1994a and b) deformation is concentrated in a thermally weakened zone (TWZ) up to about two km plateau elevation and migrates to the non-elevated parts of models with higher plateau elevation (see also Fig. 3a). But in contrast to their models the indenting velocity strongly depends on temperature deflection in the TWZ (not shown here) and decreases with increasing plateau elevation (Fig. 3b) because of the force b.c used here. The tectonic force F_0 necessary to drive a plateau evolution of 4 km is at least 4.5 Nm^{-1}. This value which coincides with results of static models (Froidvaux an Isacks, 1984; Richardson and Coblentz, 1994) exceeds the value of the ridge push force (e.g. Bott, 1993). This supports the assumption of additional mantle drag forces acting to drive the South America Plate in western direction (Meijer and Wortel, 1992) and therefore contributing to Andean plateau evolution. The force F applied at the models increases with plateau topography and decreasing indenting velocity (Fig. 3c). In contrast to the indenting velocity the force F is remarkably independent of F_0 except for elevations between 2.5 and 3.5 km, where the transition from symmetrical pure shear compression in the TWZ (Fig. 2a) to asymmetric plateau forces controlled deformation (Fig. 2b) occurs.

CONCLUSION

The indenting velocity, the velocity of the right model boundary, decreases significantly with increasing plateau elevation. Because of the non-linear stress-strain relation of dislocation creep controlled rheology this affects not only the velocity but also the style of deformation within the model. This emphasises the importance of a force boundary condition for numerical models of plateau evolution. A comparison between the recent shortening rate and the average value over the last 26 Ma (about 1 cm/a) can be used to constrain the dynamic parameter controlling Andean deformation. The velocity of the model surface can be compared with GPS data of the SAGA 95 profile running from the coast to the undeformed Brazilian shield (at about $23°S$), provided that the data between the magmatic arc and the Brazilian shield reflect the long term deformation.

REFERENCES

Assumpção, M. and M. Araujo 1993. Effect of the Altiplano– Puna plateau, South America, on the regional intraplate stresses. Tectonophys., 221, 475–96.

Bott, M.H.P. 1993. Modelling the plate–driving mechanism. J. Geol. Soc., 150, 941–51.

Christensen U.R. 1992. An Eularian technique for thermomechanical modeling of lithospheric extension. J. Geophys. Res., 97, 2015-36.

Froidevaux, C. and B.I. Isacks 1984. The mechanical state of the lithosphere in the Altiplano–Puna segment of the Andes. Earth and Planet. Sci. Lett., 71, 305–314.

Mercier, J.L, M. Serbrier, A. Lavenu,, J. Cabrera, O. Bellier, J.-F. Dumont and J. Machare 1992. Changes in the tectonic regime above a subduction zone of Andean Type: The Andes of Peru and Bolivia during the pliocene–pleistocene. J. Geophys. Res., 97, 11,945–82.

Richardson, M.R. and D.D.Coblentz 1994. Stress modeling in the Andes: Contraints on the American intraplate stress magnitudes, J. Geophys. Res., 99, 22,015–55.

Schmitz, M. 1994. A balanced model of the southern Central Andes. Tectonics, 13, 484–92.

Wdowinski, S., R.J. O'Connel 1990. On the choise of boundary conditions in continuum models of continental deformation. Geophysic. Res. Lett., 17, 2413–16.

Wdowinski, S. und Y. Bock 1994a. The evolution of deformation and topography of high elevated plateaus. 1. Model, numerical analysis and general results. J. Geophys. Res. 99, 7103–19.

Wdowinski, S. und Y. Bock 1994b. The evolution of deformation and topography of high elevated plateaus. 2 Application to the Central Andes. J. Geophys. Res. 99, 7121–30.

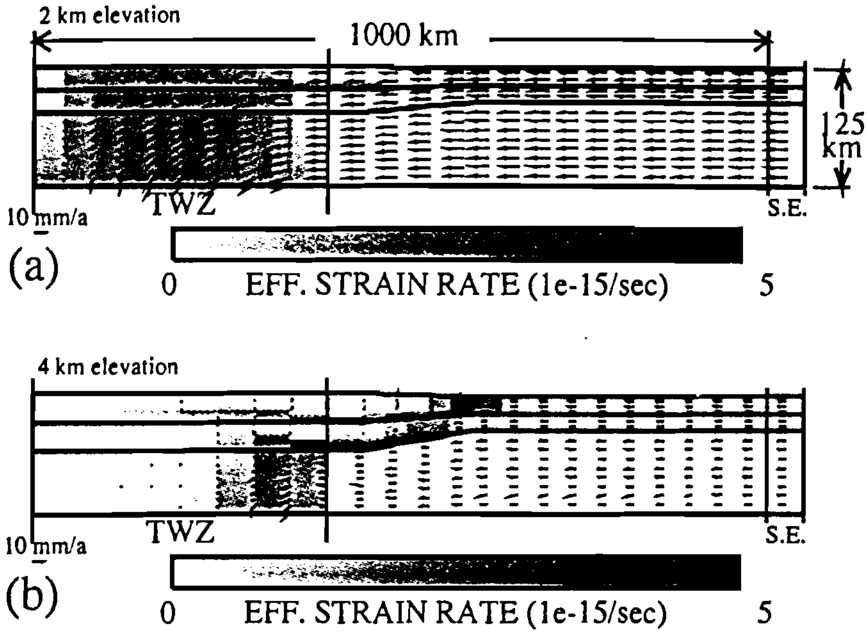

Figure 2 Effective strain rate and the velocity field of the model with two and four km elevation of the left hand side. The parameter for the mixed b.c. are: F_0 : $6 \times 10^{12} N m^{-1}$, v_0 : 3 cm/year (see text). S.E: elements with a high viscosity to achieve a no-tilt boundaty, not considered to be part of the lithosphere model.

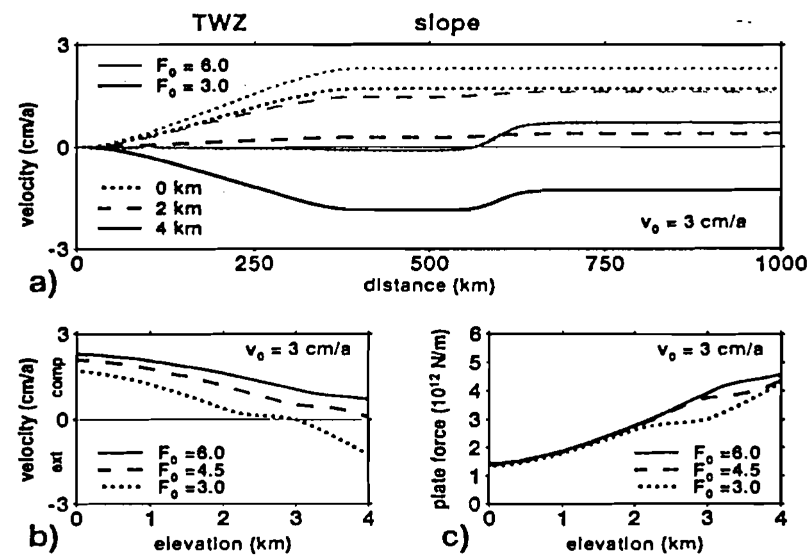

Figure 3 a) Horizontal velocity (positive to the left) at the surface of the model with the indicated parameters describing the mixed b.c. . The left model boundary is fixed. TWZ: area of a thermal deflection, slope: area of the slope. b) The velocity (positive to the left for compression of the model) of the right model boundary as a function of plateau elevation. ext: extension, comp: compression of the model. F_0 in $10^{12} N m^{-1}$. c) The force F applied at the right model boundary as a function of plateau elevation.