NEOGENE THRUST GEOMETRY AND CRUSTAL BALANCING IN THE NORTHERN AND SOUTHERN BRANCHES OF THE BOLIVIAN OROCLINE (CENTRAL ANDES)

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KEYWORDS : Andes, Bolivia, thrust tectonics, crustal balanced cross-sections, crustal thickening, Neogene.

INTRODUCTION

The Central Andes, between 10 and 28°S, are characterised by the elbow shape of the mountain range (The Bolivian orocline), a thick crust (55-75 km), high relief (several summits over 6000 m) and an enigmatic high plateau (the Altiplano) with an average altitude of 3650 m.a.s.l.. Recent works have shown the importance of crustal shortening for the development of the structural pattern of the Central Andes [Allmendinger et al., 1983; Isacks, 1988; Roeder, 1988; Roeder and Chamberlain, 1995; Sheffels, 1990; Baby et al., 1989, 1992a, 1992b, 1995; Gubbels et al., 1993; Schmitz, 1994; Kley et al., 1995].

The purpose of this paper is to present two crustal balanced cross-sections across the northern and southern branches of the Bolivian orocline, which show the Neogene thrusts geometry of the back arc system and the Neogene shortening contribution to crustal thickening.

TECTONIC SETTING

In Bolivia, the Andean thrust tectonics started in Late Oligocene [Sempere et al., 1990] and is still developing. The sediments involved in thrusting consists of an pre-orogenic series from Cambrian to Oligocene and an Oligo-Miocene to recent continental syn-orogenic infill.

The back arc system of the Bolivian orocline is divided from east to west into five morphotectonic units (cf. Fig.). The Chaco and Beni plains correspond to a poor deformed Neogene foreland basin underlain by the Brazilian shield. It is overthrusted by the Subandean Zone, a complex thin-skin fold and thrust belt characterised in its central part (Santa Cruz elbow) by important transfer zones, and which developed since 10 My [Gubbels et al., 1993]. The pre-orogenic sedimentary series presents (Ordovician to Cretaceous) lateral variations of facies and thicknesses which play an important role in controlling the structural geometry. The Interandean zone and the Cordillera Oriental correspond to thick-skin fold and thrust belts. The Interandean zone is only built of Devonian and Silurian sediments. In the Cordillera Oriental - built mainly of Ordovician anchimetamorphic sediments - the Neogene thrust system is superimposed on a deeply eroded pre-Cretaceous fold belt. The Altiplano is a complex intermontane basin overthrusted by the Cordillera Oriental, and characterised by a thick Cenozoic sedimentary infill deformed by a Neogene thrust and tectonic inversions. Maximum crustal thicknesses of 70-74 km under the Altiplano and Cordillera Oriental thin to 32-38 km 200 km east of the Andes in the foreland basin [Beck et al., 1995].

SURFACE AND SUB-SURFACE THRUST STRUCTURES

Subandean zone

The northern branch of the Subandean Zone is characterised by important thrust sheets (10-20 km) and broad synclines filled by Neogene sediments - piggy back basins with 6,000 m of syn-tectonic sediments [Baby et al., 1995]. Surface mapping, reflection seismic data, and drilling information provided by the Bolivian State Oil Company (YPFB) show that the main detachments are located in the Ordovician shales, in the Silurian shales, in the Devonian shales and in the Permian shales. The foredeep has a bottom that slopes at 4°. In our cross-section (cf. Fig.), the amount of shortening taken from tectonic balancing is 74 km, i.e. 50%.

In the southern branch, an important east verging thrust (Mandiyuti Thrust) divides the southern Bolivian Subandean Zone into two fold and thrust belts that differ according to their thrust system geometry. The western belt is characterised mainly by fault propagation folds and fault bend folds, whereas the eastern belt is characterised by fault propagation folds and passive roof duplexes [Baby et al., 1992a]. The main detachments are located in the Silurian dark shales, in the early Devonian shales, and in the base and top of the Middle to Late Devonian dark shales. The Silurian-Devonian succession is covered by more than 2000 m of late Paleozoic and Mesozoic sandstones with no potential detachments; in some places it is also covered by several thousan1 meters of syn-orogenic Neogene sedimentary rocks. The foredeep has a bottom that slopes at 2°. Total shortening decreases from 20° S (140 km, i. e. 50%) toward the south (70 km, i. e. 35%, at 22° S).

Interandean zone and Cordillera Oriental

They are deformed by involved basement east-vergent thrusts and associated back-thrusts. Near the surface, shortening is concentrated in the west-vergent thrust system at the western part of the Cordillera Oriental and - in the southern branch - in the Interandean zone (cf. Fig.). The Cordillera Oriental is characterised by presence of small Neogene piggyback basins which have recorded the deformation history [Hérail et al., 1996]. Surface data allowed to construct some balanced cross-sections. An amount of shortening between 80 and 100 km is estimated.

Altiplano

The combined study of field and seismic reflection data shows that the Altiplano is structured by Oligocene extensional basin partially inverted during the Neogene, and by the west-vergent thrust system of the Cordillera Oriental [Rochat et al., 1996].

The northern Altiplano (cf. Fig.) is characterised by a very thick series of Cenozoic continental sediments (more than 10 000 m) which come from the Oligocene extensional tectonics and from the Neogene uplift of the Cordillera Oriental. The southern Altiplano shows the maximum amount of shortening. It is deformed by an important east-vergent thrust system [Baby et al., 1992b]. Construction of balanced cross sections has been made possible due to surface mapping, reflection seismic data, and drilling information provided by the Bolivian State Oil Company (YPFB).

DEEP DATA AND CRUSTAL BALANCING

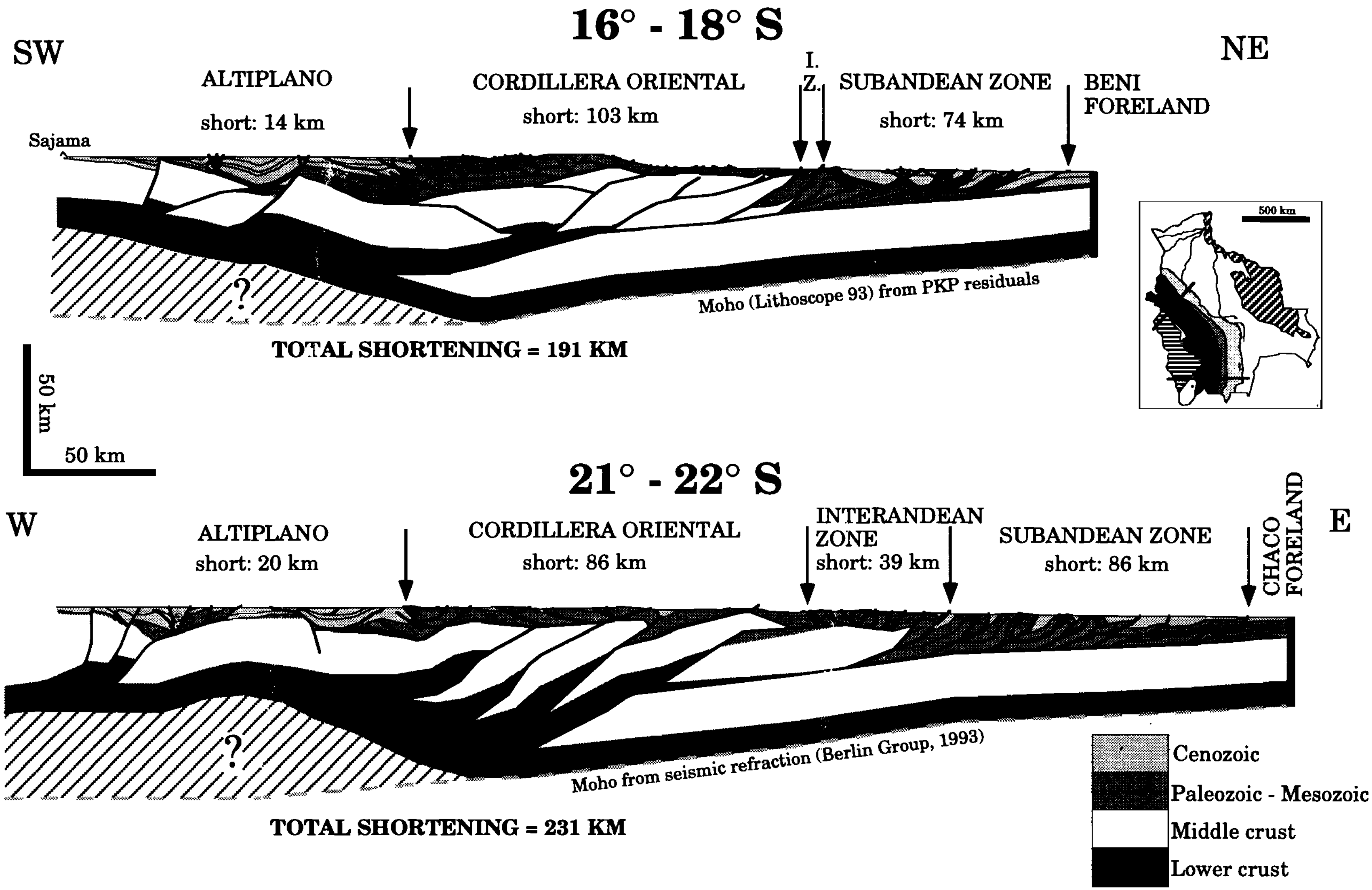
From surface and geophysical data obtained in the last decade, we have constructed two crustal balanced cross-sections (Fig.).

In the northern branch of the orocline, some results of the French Lithoscope experiment - a teleseismic field experiment [Dorbath et al., 1993] - have been used to construct the deep structures. The Moho shape was established from PKP residuals. In the southern branch, the results of the Berlin Group - seismic refraction data [Wigger et al., 1994] - give a Moho shape and show that high velocity zones under the Cordillera Oriental can be interpreted as high positions of lower crustal material.

In the two crustal balanced cross-sections, the total amount of shortening in the Paleozoic, Mesozoic and Cenozoic cover, calculated from our regional studies, is accommodated by the development of a duplex of middle and lower crust. This duplex can explain the crustal thickening under the Cordillera Oriental, but not under the Altiplano. These results are in accordance with the balanced model of Schmitz (1994) in the southern Central Andes.

CONCLUSIONS

From north to south, our balanced cross-sections show that, in the back arc system of the Bolivian orocline, the total amount of shortening varies from 191 km to 231 km. These values are in



Crustal balanced cross-sections
in the northern and southern branches of the Bolivian Orocline

accordance with the amount of shortening (210 km) calculated by Sheffels (1990) in the central part of the Bolivian orocline. This increase of shortening from north to south coincide with an increase in the crustal thickness [Beck et al., 1995] and an increase in the width of the chain - the chain is wider in the south where the Interandean and the Subandean zones are more developed.

In the north as in the south, the Neogene shortening is insufficient to produce the crustal thickening evidenced by geophysical data under the Altiplano. This crustal thickening can be explained by a pre-Neogene shortening, but we have not evidence of other important shortening later than the pre-Cretaceous erosion. Other processes of crustal thickening must been suggested.

REFERENCES

Allmendinger R. W., Ramos V. A., Jordan T. E., Palma M. and Isacks B. L. 1983. Paleogeography and Andean structural geometry, Northwest Argentina. *Tectonics*, 2, 1, 1-16.

Baby P., Hérail G., López M., López O., Oller J., Pareja J., Sempere T. and Tufiño D. 1989. Structure de la zone subandine de Bolivie : influence de la géométrie des séries sédimentaires antéorogéniques sur la propagation des chevauchements. *C. R. Acad. Sci. Paris*, 309, II, 1717-1722.

Baby P., Hérail G., Salinas R. and Sempere T. 1992a. Geometry and kinematic evolution of passive roof duplexes: examples from the foreland thrust system of the Subandean belt of Bolivia. *Tectonics*, 11, 3, 523-536.

Baby P., Sempere T., Oller J. and Hérail G. 1992b. Evidence for major shortening on the eastern edge of the Bolivian Altiplano: the Calazaya nappe. *Tectonophysics*, 205, 1-3, 155-169.

Baby G., Coletta B. and Zubieta D. 1995. Etude géométrique et expérimentale d'un bassin transporté: exemple du bassin subandin de l'Alto Beni (Andes centrales). *Bull. Soc. Géol. de France*, 166, 6, 797-811.

Beck S., Zandt G., Myers S. C., Wallace T. C., Silver P. et Drake L. 1995. Crustal Thickness Variations in the Central Andes. *Geology*, Submitted.

Dorbath C., Granet M., Poupinet G. and Martinez C. 1993. Teleseismic study of the Altiplano and the Eastern Cordillera in northern Bolivia: new constraints on a lithospheric model. *J. Geophys. Res.*, 98, B6, 9825-9844.

Gubbels T. L., Isacks B. L. and Farrar E. 1993. High-level surfaces, plateau uplift, and foreland development, Bolivian central Andes. *Geology*, 21, 695-698.

Hérail G., Oller J., Baby P., Blanco J., Bonhomme M. G. and Soler P. 1996. The Tupiza, Nazareno and Estarca basins (Bolivia): Strike-slip faulting and related basins in the Cenozoic evolution of the southern branch of the Bolivian Orocline. *Tectonophysics*, in press.

Isacks B. L. 1988. Uplift of the Central Andean Plateau and Bending of the Bolivian Orocline. *J. Geophys. Res.*, 93, 3211-3231.

Kley J. 1993. Der Übergang vom Subandin zur Ostkordillere in Südbolivien (21°15'-22°): geologische Struktur und Kinematic. *Berliner geowissenschaftliche Abhandlungen*, 156, (A), 1-88.

Rochat et al. 1996. Geometry and kinematics of the northern Bolivian Altiplano within the Central Andes, *ISAG 96*, this volume.

Roeder D. 1988. Andean-age structure of Eastern Cordillera (Provine of La Paz, Bolivia). *Tectonics*, 7(1), 23-39.

Roeder D. and Chamberlain R. L. 1995. Petroleum System of the northern and central bolivian Sub-Andean Zone. *in* : Tankard A.J., Suárez S. R. et Welsink H.J., éd., Petroleum Basins of South America, AAPG Memoir 62, 459-479.

Schmitz M. 1994. A balanced model of the southern Central Andes. *Tectonics*, 13, 2, 484-492.

Sempere T., Hérail G., Oller J. and Bonhomme M. 1990. Late Oligocene-early Miocene major tectonic crisis and related basins in Bolivia. *Geology*, 18, 946-949.

Sheffels B. 1990. Lower bound on the amount of crustal shortening in the central Bolivian Andes. *Geology*, 18, 812-815.

Wigger P. J., Schmitz M., Araneda M., Asch G., Baldzuhn S., Giese P., Heinsohn W.-D., Martinez E., Ricaldi E., Röwer P. and Viramontes J. 1994. Variation in the crustal structure of the Southern Central Andes Deduced from Seismic Refraction Investigations. *in* : K.-J. Reutter E. Scheuber P.J. Wigger, éd., Tectonics of the Southern Central Andes, Springer-Verlag, Berlin, 23-48.