

## CRUSTAL THICKENING IN THE CENTRAL ANDES - RESULTS FROM SEISMIC REFRACTION AND CRUSTAL BALANCING

Michael SCHMITZ\*, Peter GIESE\* and Peter WIGGER\*

\* Institut für Geologie, Geophysik und Geoinformatik, FR Geophysik, Freie Universität Berlin, Malteserstraße 74-100, W-1000 Berlin 46

**RESUMEN:** Las estructuras tectónicas de sobrecorrimiento y el espesor actual de la corteza derivados de los resultados de sísmica de refracción han sido modelados por medio de un balanceo tectónico con un acortamiento cortical de 320 km desde el Cretasico superior con un espesor inicial de 35 km. El volumen de la corteza inferior en el antearco y debajo del arco magmático, aproximadamente el 20% del volumen cortical actual, no puede ser explicado por este acortamiento. La litósfera subcortical debe haber sufrido un acortamiento en el mismo rango que exige un transporte de material hacia el manto más profundo.

**KEY WORDS:** Central Andes; crustal balancing; seismic refraction; crustal doubling.

### INTRODUCTION

The Central Andes are part of the convergence system between the oceanic Nazca plate and the South American plate. Elevations of about 7000 m above sea level in the central parts of the mountain belt are observed where the crustal thickness reaches about 70 km. The importance of tectonic shortening for the thickening of the Central Andean crust has been emphasized by various authors (Suárez et al. 1983; Allmendinger 1986; Reutter et al. 1988; Roeder 1988; Sheffels 1990).

Within the frame of the research group "Mobility of Active Continental Margins", new data on the crustal thickness and the velocity structure of the Central Andean crust on a transect at 21°S, derived from seismic refraction observations, allow to derive a model which combines data from cross-section balancing with seismic refraction data. Calculations about the portion, that contributes tectonic shortening to the thickening of the Andes, are presented.

### METHOD

Based on the velocity structure and crustal volume of the Andean crust derived from seismic refraction experiments, the amount of thickening caused by tectonic shortening could be determined. The crustal development was modelled with the program TRUSTBELT II (Linsser 1991), and a regional isostatic compensation following Airy's principles (Buness 1991) was applied to allow the application of cross-section balancing on a crustal scale, here called "crustal balancing" (figure 1). In a forward modelling procedure detachment horizons and thrusts have been changed iteratively until satisfying the observed crustal structures from seismic refraction observations. Further geophysical data were used as boundary conditions and the derived structure was checked by raytracing and gravimetric model calculations.

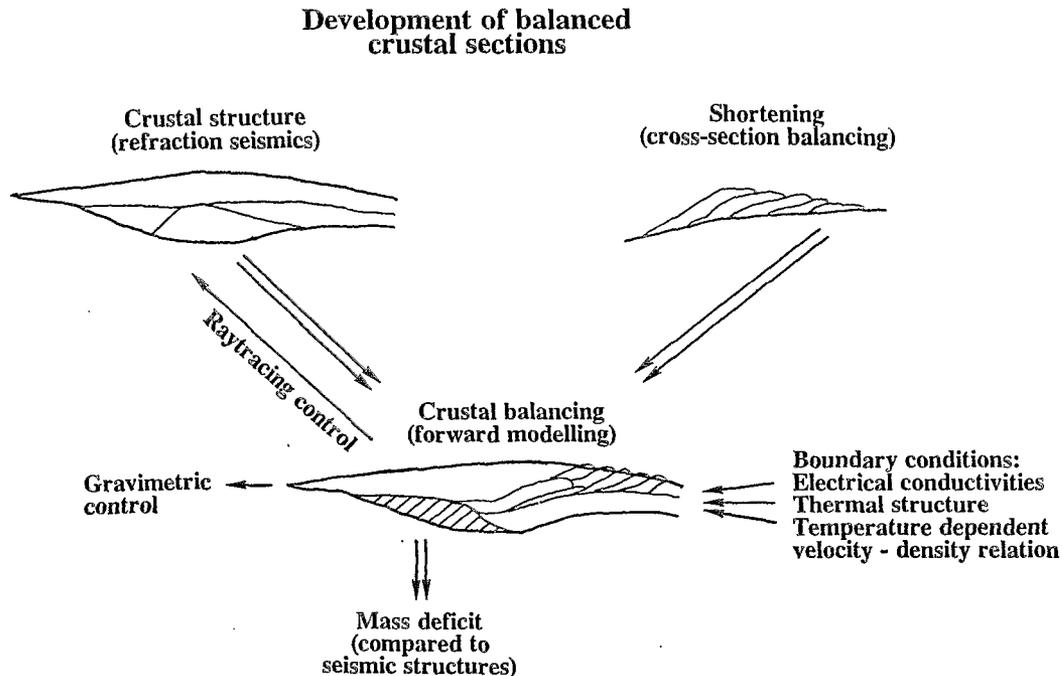


Figure 1. Development of the balanced crustal section from the crustal structure (derived from seismic refraction) and shortening from cross-section balancing.

The aim of the study was to develop an areal balanced model that should be able to explain the velocity model and the seismic discontinuities at 21°S. The program THRUSTBELT II does not allow the modelling of different rheological characteristics of the distinct crustal units. As the program only permits faults with the same vergency, no backthrusts were introduced except in the forearc, using a "pin-line" on the Altiplano.

#### GROSS CRUSTAL STRUCTURE FROM SEISMIC REFRACTION

The velocity structure was derived by observations of 4 shotpoints along a profile at 21°S with corresponding N-S profiles in the Coastal Cordillera and in the Precordillera (position map see Wigger et al., this volume). A clear discontinuity at 40 km depth in the Coastal Cordillera is interpreted as Moho of the subducted Nazca plate (Wigger et al. 1993). The continental crust in the forearc has a high average velocity of 6.5 km/s in the Coastal Cordillera, descending to 6.2 km/s in the Precordillera. A division into a high velocity upper and middle crust, dipping from 20 km depth in the coastal region to about 35 km depth beneath the Precordillera, and a deeper crust mainly represented by low velocity zones (LVZ) can be done. Strong absorption of the seismic waves in the Western Cordillera and the Altiplano area leads to a comparable low average velocity (about 6.0 km/s) down to 70 km, but a Moho is not observed. In the backarc, the Moho dips down from 40 km below the Subandean Ranges to about 70 km at the eastern margin of the Altiplano. In the Chaco the velocities increase slightly from 6.1 km/s at 10 km depth to 6.2 km/s at 30 km depth and a 10 km thick high velocity lower crust is observed. Further west, in the Eastern Cordillera, high velocity material (6.8 km/s) at 20-25 km depth is underlain by a broad LVZ down to the crustal base (see Wigger et al., this volume).

#### INITIAL MODEL AND APPLIED SHORTENING VALUES

A simple layered crust with a 10 km thick lower crust, 15 km middle crust, 5 km (Pre-)Cambrian to Ordovician rocks and a varying thickness up to 10 km of Silurian to Cenozoic sediments is taken for the initial model. Thus, the initial crustal thickness varies between 40 km in the Andean foreland and 30 km in

the Eastern Cordillera, where Cretaceous rifting took place (Marquillas & Salfity 1988). The starting point for the calculation of the modelled shortening is the onset of the strong compressional phases at Upper Cretaceous at 90 Ma (Scheuber et al. 1993).

Cross-section balancing was done for different profiles in the Central Andean backarc and the derived shortening values vary between 210 and 230 km for the Eastern Cordillera and Subandean Ranges (Roeder 1988; Sheffels 1990) at about 18°S and 140 km for the Subandean Ranges and a transition zone (Kley & Reinhardt 1993) at 21°S. In the area of the Altiplano and the recent magmatic arc the determination of tectonic shortening is somewhat more difficult because of the young sedimentary and volcanic cover. Shortening values of 55 km (Baby et al. 1990a) and 42 km (Baby et al. 1990b) for the Altiplano are reported. In the forearc region shortening is most evident in the Precordillera (Chong & Reutter 1985).

An amount of 320 km is taken for the shortening between the trench and the Andean foreland since Upper Cretaceous (Schmitz 1993), modelled mainly for two tectonic phases, the Incaic Phase in the Altiplano/Eastern Cordillera area and the Quechua Phase in the Subandean Ranges. The detachments are located at the base of the younger sediments, on top of the middle crust and at the base of the lower crust.

### CRUSTAL DOUBLING IN THE BACKARC

A crustal thickening from 40 km in the Subandean Ranges to about 70 km in the Eastern Cordillera is observed, representing a crustal doubling in the backarc. Material with high seismic velocities (6.8 km/s) was found in 20 to 25 km depth in the Eastern Cordillera. This can be explained by lower crustal material detached from the crustal base and overthrust to the east (figure 2). The modelled structures of the Subandean fold- and thrust belt are in good coincidence with balanced cross-sections (Kley & Reinhardt 1993). Zones of high electrical conductivities might have acted as detachments.

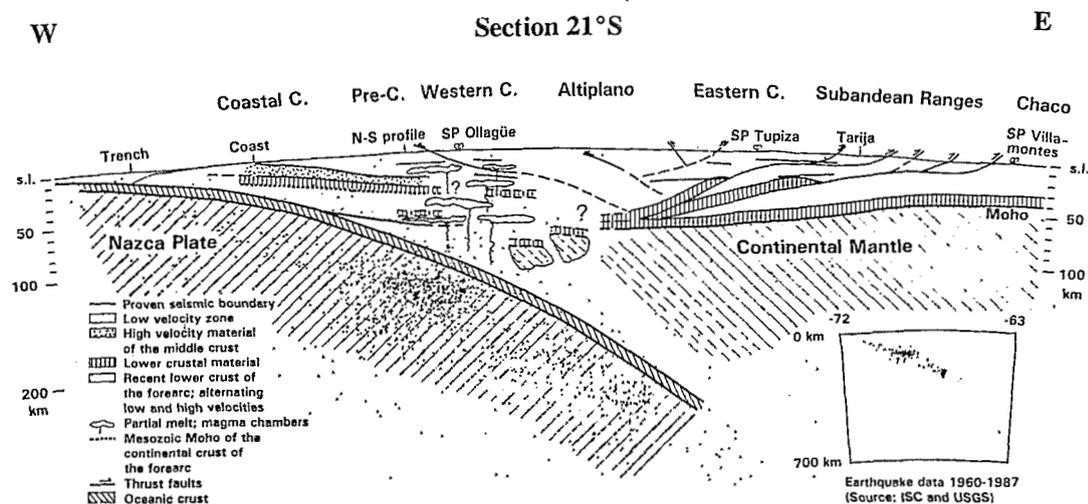


Figure 2. Interpretative cross-section at 21°S with main seismic boundaries and the tectonic structure. The position of the Nazca plate is from Cahill & Isacks (1992).

### CONCLUSIONS

Combining seismic refraction data and a cross section balancing method, new aspects on the development of the Central Andes were derived. The crustal thickening in the backarc was modelled as a crustal doubling with an overthrust of the Andean crust over its foreland (figure 2). For the arc- and forearc-region no crustal thickening could be derived which is originated by crustal shortening.

The lower crust of the forearc as well as of the magmatic arc region, which represents together about 20% of the crustal volume under study, cannot be modelled by the assumed shortening of 320 km. Other sources must be taken in account to explain these crustal parts. Tectonically eroded and later underplated material from the continental margin could fill a part of the lower crust of the westerly forearc area. Further east, transformed mantle or magmatic addition could have thickened the crust.

The lithospheric mantle must have undergone the same shortening as the crust. Thus a convergence between the oceanic lithosphere and the continental mantle is evident in the area of the recent magmatic arc. In consequence, mantle material must be transported into the asthenosphere below the magmatic arc.

## REFERENCES

- Allmendinger RW 1986 Tectonic development, southeastern border of the Puna Plateau, northwestern Argentine Andes. *Geol Soc Am Bull*, 97: 1070-1082.
- Baby P, Sempéré T, Oller J, Barrios L, Héral G & Marocco R 1990a Un bassin en compression d'âge oligo-miocène dans le sud de l'Altiplano bolivien. *C R Acad Sci Paris*, 311 (Sér II): 341-347.
- Baby P, Sempéré T, Oller J, Blanco J, Zubieta D & Héral G 1990b Evidence for mayor shortening on the eastern edge of the Bolivian Altiplano: The Calazaya nappe. In: *Inst Franc Rech Scient Devel, Colloques et Séminaires, Symp Int "Géodyn Andine"*, Rés Comm: 163-166, Grenoble.
- Buness H 1991 Isostatic compensation of balanced cross sections. In: Giese P, Roeder D & Nicolich R (eds) *Joint interpretation of geophysical and geological data applied to lithospheric studies*: 181-188, Kluwer, Dordrecht.
- Cahill T & Isacks BL 1992 Seismicity and Shape of the Subducted Nazca Plate. *J Geophys Res*, 97 (B12): 17503-17529.
- Chong DG & Reutter K-J 1985 Fenómenos de tectónica compresiva en las Sierras de Varas y de Argomedo, Cordillera Chilena, en el ambito del paralelo 25° sur. *IV Congr Geol Chileno, Antofagasta, Actas 2*: 2/219-2/238.
- Kley J & Reinhardt M 1993 Geothermal and tectonic evolution of the Eastern Cordillera and the Subandean Ranges of southern Bolivia. In: Reutter K-J, Scheuber E & Wigger P (eds) *Tectonics of the southern Central Andes*: 155-170, Springer, Berlin Heidelberg New York.
- Linsser H 1991 Enhanced interpretation of crustal sections with the Thrustbelt Program. In: Giese P et al. (eds) *Joint interpretation of geophysical and geological data applied to lithospheric studies*: 165-179, Kluwer, Dordrecht.
- Marquillas R & Salfity JA 1988 Tectonic framework and correlations of the Cretaceous-Eocene Salta Group, Argentina. In: Bahlburg H, Breitzkreuz C & Giese P (eds) *The Southern Central Andes*: 119-138, Springer, Berlin Heidelberg New York.
- Reutter K-J, Giese P, Götze H-J, Scheuber E, Schwab K, Schwarz G & Wigger P 1988 Structures and crustal development of the Central Andes between 21° and 25°S. In: Bahlburg H, Breitzkreuz C & Giese P (eds) *The Southern Central Andes - Lecture Notes in Earth Sciences*, 17: 231-261, Springer, Berlin Heidelberg New York.
- Roeder D 1988 Andean-age structure of Eastern Cordillera (La Paz, Bolivia). *Tectonics*, 7 (1): 23-39.
- Schmitz M 1993 Kollisionsstrukturen in den Zentralen Anden: Ergebnisse refraktionsseismischer Messungen und Modellierung krustaler Deformationen. *Dissertation, Freie Universität Berlin*.
- Schwarz G, Chong DG, Krüger D, Martínez E, Massow W, Rath V & Viramonte J 1993 Crustal high conductivity zones in the Central Andes. In: Reutter K-J, Scheuber E & Wigger P (eds) *Tectonics of the southern Central Andes*: 49-68, Springer, Berlin Heidelberg New York.
- Sheffels BM 1990 Lower bound on the amount of crustal shortening in the central Bolivian Andes. *Geology*, 18: 812-815.
- Suárez G, Molnar P & Burchfiel BC 1983 Seismicity, fault plane solution, depth of faulting and active tectonics of the Andes of Peru, Ecuador and S-Colombia. *J Geophys Res*, 88 (B12): 10403-10428.
- Wigger P, Giese P & Schmitz M 1993 Main crustal anomalies of the Central Andean lithosphere. This vol.
- Wigger P, Schmitz M, Araneda M, Asch G, Baldzuhn S, Giese P, Heinsohn W-D, Martínez E, Ricaldi E, Röwer P & Viramonte J 1993 Variation in the crustal structure of the southern Central Andes deduced from seismic refraction investigations. In: Reutter K-J, Scheuber E & Wigger P (eds) *Tectonics of the Southern Central Andes*: 23-48, Springer, Berlin Heidelberg New York.