# Neogene shortening contribution to crustal thickening in the back arc of the Central Andes

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## ABSTRACT

**To illustrate the Neogene shortening distribution in the back-arc units of the Central Andes and to estimate the contribution of the shortening to crustal thickening, two balanced crustal cross sections have been constructed across the northern and southern branches of the Bolivian orocline. Total Neogene shortening, which varies from 191 to 231 km, is accommodated by a crustal duplex below the Cordillera Oriental, but is insufficient to produce the 70 km of crustal thickness evidenced by geophysical data below the Altiplano. The best explanation for this anomalous thickening seems to be crustal underplating by material tectonically eroded from the continental margin; this process probably caused the Altiplano uplift. The subduction of oceanic lithosphere coupled with this underplating and a brief episode of gravity spreading of the Altiplano constituted the driving forces that produced Neogene shortening and development of the Central Andes.**

## INTRODUCTION

The back arc of the Central Andes, between lat 10°S and 28°S, is characterized by the elbow shape of the mountain range (the Bolivian orocline), high relief (several summits over 6000 m), an enigmatic high plateau (the Altiplano) with an average altitude of 3650 m above sea level, and a thick crust (55–75 km under the Altiplano).

Recent work has shown the importance of crustal shortening for the development of the structural pattern of this part of the Andes (Allmendinger et al., 1983; Isacks, 1988; Roeder, 1988; Sheffels, 1990; Sempere et al., 1990; Baby et al., 1992a; Gubbels et al., 1993; Schmitz, 1994; Kley and Reinhardt, 1994; Dunn et al., 1995). To illustrate the distribution of this shortening and to estimate its contribution to crustal thickening, we have constructed two balanced crustal cross sections across the northern and southern branches of the Bolivian orocline (see location in Fig. 1). To balance the whole crust, we have used the shallow structure sections constructed by the ORSTOM-YPFB (Institut Français de Recherche Scientifique pour le Développement en Coopération–Yacimientos Petrolíferos Fiscales Bolivianos) team (Baby et al., 1992a, 1992b, 1995a, 1995b, 1996; Rochat et al., 1996; Moretti et al., 1996) for the upper crust of the back-arc Neogene thrust systems and the crustal geophysical data obtained in the past decade (Allmendinger and Zapata, 1996; Beck et al., 1996; Dorbath et al., 1993; Wigger et al., 1994; Zandt et al., 1996).

## UPPER-CRUSTAL NEOGENE THRUST SYSTEMS

In the Central Andes, the back-arc thrusting started in late Oligocene (Sempere et al., 1990) and is continuing. The sedimentary section involved in thrusting consists of Cambrian to Oligocene preorogenic strata and Oligocene-Miocene to recent continental synorogenic infill. The back-arc system of the Bolivian orocline is divided from east to west into five morphotectonic units (Fig. 1).

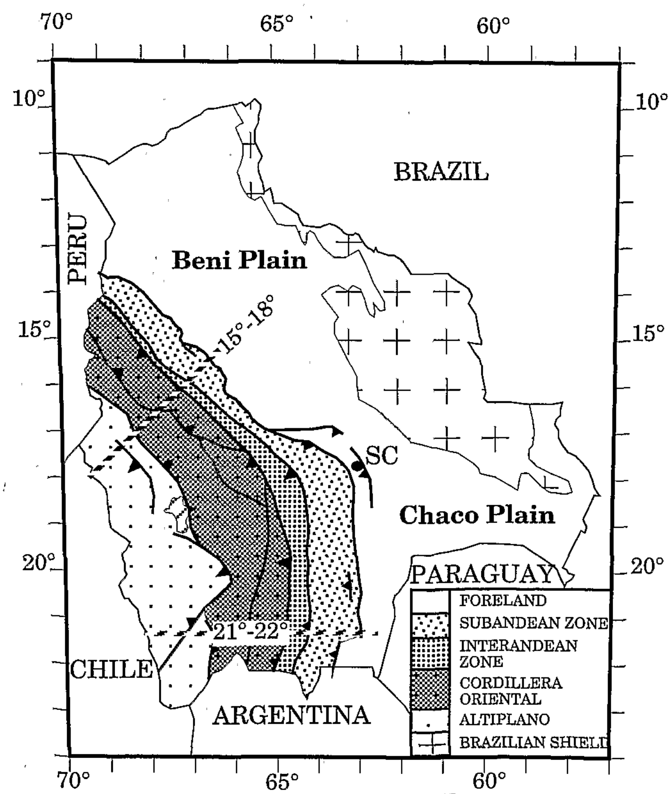


**Figure 1. Tectonic map of Bolivia and location of studied crustal cross sections.**

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### Chaco and Beni Plains and Subandean Zone

The Chaco and Beni plains correspond to a slightly deformed Neogene foreland basin underlain by the Brazilian Shield. It is overthrust by the Subandean zone, a complex thin-skinned fold-and-thrust belt characterized in its central part (Santa Cruz elbow) by large-scale transfer zones (Baby et al., 1996); the Subandean zone developed after 10 Ma (Gubbels et al., 1993).

The northern branch of the Subandean zone is characterized by large-scale thrust sheets (10–20 km of offset) and broad synclines (Roeder, 1988) filled by 6000 m of syntectonic Neogene sedimentary rocks (Baby et al., 1995a). Surface mapping, seismic reflection data, and drilling information provided by YPFB show that the main detachments are located in Ordovician, Silurian, Devonian, and Permian shales (Baby et al., 1995b). The base of the foredeep slopes at 4°SW. The amount of shortening is 74 km, i.e., 50%.

In the southern branch, a regional 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 characterized mainly by fault-propagation folds and fault-bend folds, whereas the eastern belt is characterized by fault-propagation folds and passive-roof duplexes (Baby et al., 1992a). The main detachments are located in Silurian dark shales, Lower Devonian shales, and the base and top of the Middle to Upper Devonian dark shales. The Silurian-Devonian succession is covered by more than 2000 m of upper Paleozoic and Mesozoic sandstones with no potential detachments; in some places it is also covered by several thousand meters of synorogenic Neogene sedimentary rocks (Moretti et al., 1996). The base of the foredeep slopes at 2°W. Total shortening decreases southward from 140 km (i.e., 50%) at lat 20°S to 86 km (i.e., 35%) at lat 22°S.

### Interandean Zone and Cordillera Oriental

The Interandean zone and the Cordillera Oriental are deformed by east-vergent thrusts that involve basement (Kley, 1996) and associated thin-skinned thrusts and back thrusts. Mainly Silurian, Devonian, and Carboniferous strata are exposed in the Interandean zone. In the Cordillera Oriental, the Neogene thrust system is superimposed on a deeply eroded pre-Cretaceous fold belt that deformed Ordovician anchimetamorphic sedimentary rocks. Shortening is concentrated in the west-vergent thrust system at the western part of the Cordillera Oriental and in the Interandean zone. The Cordillera Oriental is characterized by small Neogene piggyback basins (Fornari et al., 1987; Hérail et al., 1996). Good surface data allowed us to construct some balanced cross sections from which total shortening of between 80 and 100 km is estimated.

### Altiplano

The Altiplano is a complex Neogene intermontane basin deformed by both extensional and compressional tectonics. The combined study of field and seismic reflection data shows that the Altiplano is structured, in its northern and southern parts, by north-south–elongated half grabens that have been partially inverted (Rochat et al., 1996) and by the west-vergent thrust system of the Cordillera Oriental (Hérail et al., 1993; Kennan et al., 1995; Rochat et al., 1996). In the central part, the entire Altiplano is deformed by an east-vergent thrust system that overthrust the western border of the Cordillera Oriental (Baby et al., 1992a).

This intermontane basin is characterized by a very thick succession of Cenozoic continental sedimentary units (4–10 km thick) formed by five major depositional sequences (Rochat et al., 1996). The first sequence (Eocene–lower Oligocene) was laid down before the Altiplano and Cordillera Oriental development, which started during the Oligocene-Miocene (sequence 2). The middle Miocene strata (sequence 3) were deposited by very high rates of sedimentation in north-south–elongated half grabens. The upper Miocene and Pliocene sequences are contemporaneous with a tectonic inversion of the middle Miocene half grabens and uplift of the Cordillera Oriental.

Surface mapping, seismic reflection data, and drilling information provided by YPFB made possible the construction of balanced cross sections. The total shortening calculated is 20 km in the southern part and 13 km in the northern part.

## CRUSTAL GEOPHYSICAL DATA

The maximum crustal thicknesses (70–74 km) are located under the Altiplano and Cordillera

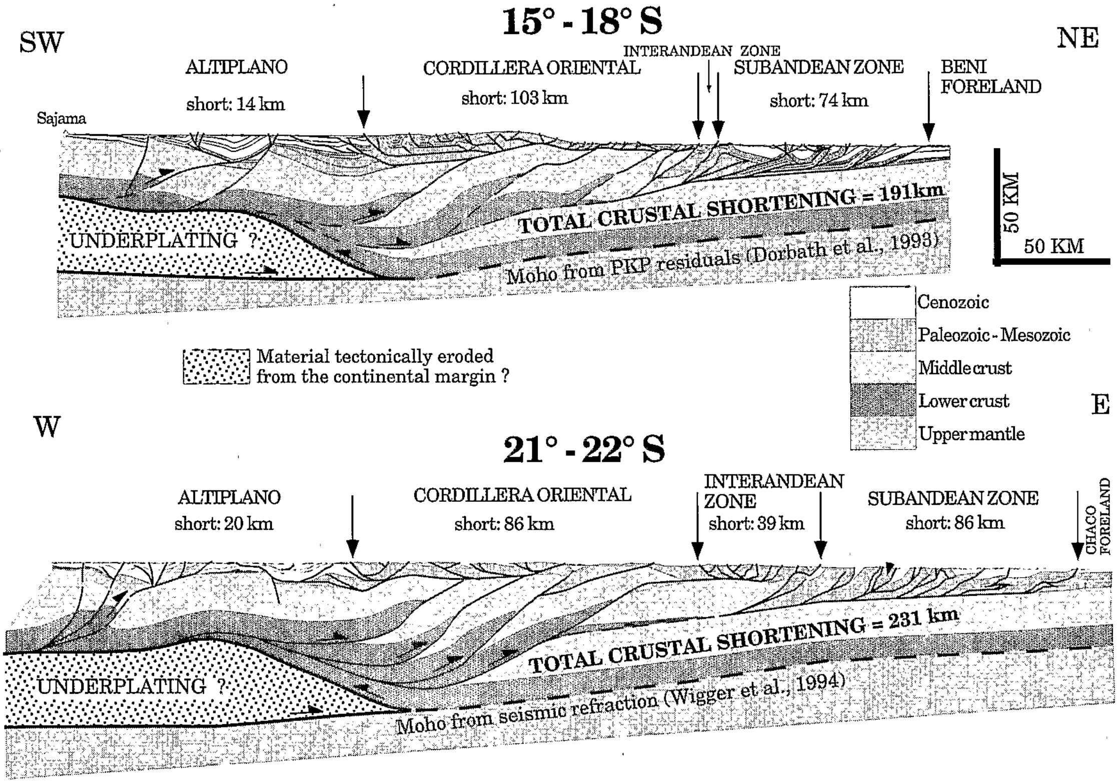


**Figure 2. Two balanced crustal cross sections constructed across northern and southern branches of Bolivian orocline (location in Fig. 1) to illustrate distribution of Neogene shortening and to estimate its contribution to crustal thickening. Mechanism of crustal underplating by tectonically eroded material is proposed to explain 70 km crustal thickness below Altiplano. "Short" refers to "shortening."**

Oriental. The crust thins to 32–38 km east of the Andes in the foreland basin (Beck et al., 1996).

In the northern branch of the orocline, the Moho shape established from PKP residuals of the French Lithoscope experiment—a teleseismic field experiment (Dorbath et al., 1993)—has been used to construct the deep structures. In the southern branch, the results of the Berlin Group (seismic refraction data of Wigger et al., 1994) give a Moho shape and show that high-velocity zones under the western part of the Cordillera Oriental can be interpreted as high positions of lower crustal material. Continuing southward, in northern Argentina, reprocessed YPF (Yacimientos Petrolíferos Fiscales, now YPF S.A.) seismic reflection data show a remarkable suite of deep reflections interpreted as a ramp in the Subandean decollement and possible duplexing of the lower crust under the Cordillera Oriental (Allmendinger and Zapata, 1996).

The Moho shapes used in the two crustal cross sections are consistent with the results of the BANJO and SEDA experiments (Beck et al., 1996), which show that the crust thickens from north (55–60 km thick) to south (70–74 km thick) along the Cordillera Oriental.

## CRUSTAL BALANCING

The deep refractions (Wigger et al., 1994) and deep reflections (Allmendinger and Zapata, 1996) observed below the Cordillera Oriental allow us to interpret a mechanism of transcrustal thrusts to achieve the shortening of the lower and middle crust. Roeder (1988) and Schmitz (1994) proposed the same mechanism in their crustal cross section.

From the balanced cross sections of the upper crust and the deep geophysical data mentioned above, we have interpreted and constructed the deep structure of the two regional cross sections (Fig. 2) by using classical crustal-balancing methods (Woodward et al., 1985; Mugnier et al., 1990). From the Coniacian to the start of the Neogene (about 60 m.y.), foreland basin conditions controlled sedimentation in what is today the back-arc of the Central Andes (Sempere, 1995). Therefore, initial crustal thickness used in the construction varies between 35 and 40 km in accordance with the geophysical data obtained by Beck et al. (1996) in the foreland basin of the Chaco plain. The Cretaceous crustal thinning proposed by Schmitz (1994) or Okaya et al. (1997) in their crustal model is poorly constrained. There is no evidence of Cretaceous rifting in Bolivia, and erosion of pre-Cretaceous sediments occurred mainly before the upper Carboniferous (Isaacson and Martinez, 1995). Studies of gravity anomalies and topography data (Lyon-Caen et al., 1985) and lack of negative velocity anomalies in the upper mantle (Dorbath et al., 1994) have led us to assume a lithosphere characterized by a cold linear thermal regime (Ranalli and Murphy, 1987), and to consider the Moho as a passive marker during Neogene shortening. In the two crustal cross sections, the total shortening calculated from the balanced cross sections constructed for the Paleozoic, Mesozoic, and Cenozoic cover is accommodated by the development of a duplex of middle and lower crust. The lower detachment is located at the crust-mantle boundary, and the upper detachment is located at the base of the Paleozoic sedimentary section.

## IMPLICATIONS AND CONCLUSIONS

From north to south, our balanced cross sections show that, in the Bolivian orocline, the total amount of shortening varies from 191 to 231 km. These values are in accordance with the amount of shortening (210 km) calculated by Sheffels (1990) in the central part. This increase of shortening from north to south coincides with an increase in the crustal thickness (Beck et al., 1996) and in the width of the chain, which is wider in the south where the Interandean and the Subandean zones are more developed.

In the north as in the south, the Neogene back-arc shortening is insufficient to produce the crustal thickening evidenced by geophysical data below the Altiplano. The crustal duplex can explain the crustal thickening below the Cordillera Oriental, but not below the Altiplano. In the same way, Neogene shortening in the fore-arc region cannot produce this crustal thickening. The Chilean part of the Central Andes is characterized by thick-skinned tectonics with reactivated high-angle faults (Garcia et al., 1996) that accommodate a maximum shortening of 10 km. These results are in accord with the balanced model and conclusions of Schmitz (1994) in the southern Central Andes. The Altiplano crustal thickening could perhaps be explained by a pre-Neogene shortening, but in the back-arc we have no evidence of other important shortening younger than the pre-Cretaceous erosion. We did not find the early-middle Tertiary shortening that has been proposed by Roeder and Chamberlain (1995) to explain one part of the crustal thickening. During latest Paleocene–early Oligocene, what is today the Altiplano was a foreland basin (Sempere, 1995).

One other explanation for the deep position of the Moho below the Altiplano is an asthenospheric wedge overthrusting to the east over one part of the lower crust of the Brazilian Shield. This type of asthenospheric wedge has been described from other mountain chains such as the Pyrenees (ECORS Pyrenean team, 1988) or the Alps (Mugnier et al., 1990). But below the Altiplano, geophysical data are inconsistent with mantle delaminations. The thickening is characterized by anomalous P velocities of 5.9 km/s (Wigger et al., 1994) and quartz-rich, felsic bulk composition (Zandt et al., 1996). This composition is also inconsistent with significant volumes of magmatic addition. For the southern branch of the Bolivian orocline, Schmitz (1994) suggested a mechanism of crustal underplating by material tectonically eroded from the continental margin to explain the crustal thickening below the western part of the Altiplano. We propose the same mechanism to explain the crustal thickening below the entire Altiplano (Fig. 2). It is consistent with the Chilean Trench, whose morphology and lack of accretionary prism (Von Huene and Scholl, 1991) suggest subduction erosion (Cloos and Shreve, 1996). During the Neogene, a possible underplated volume of material eroded from the continental margin could have formed a tectonic wedge between the upper mantle and the lower crust; this wedge could have subsequently moved to the east and caused the uplift of the Altiplano. The driving force of this underplating coupled with the subduction of oceanic lithosphere and a brief episode of gravity spreading of the Altiplano could have produced the crustal-duplex development below the Cordillera Oriental and the concomitant shortening in its sedimentary cover. The Altiplano collapse as an important force in the Andean and Subandean thrusting has been already suggested by other authors (Roeder and Chamberlain, 1995). The structural and sedimentologic studies of the Altiplano show that this gravity force was active only in the middle Miocene when the north-south–elongated half grabens developed (Rochat et al., 1996). Subsequently, during the upper Miocene and Pliocene, the observed tectonic inversion of these half grabens reflects compressional deformation of the Altiplano.

In conclusion, the Central Andes are characterized by a unique process of mountain building that differs from the process of continental-continental convergence described for the Himalayas (Zhao and Nelson, 1993), Alps (Mugnier et al., 1990), or Pyrenees (ECORS Pyrenean team, 1988). Shortening quantification coupled with crustal geophysical data analysis shows that none of the processes of continental shortening, magmatic addition, or asthenospheric wedging can produce the uplift and crustal thickening of the Altiplano. Crustal underplating by material tectonically eroded from the continental margin seems to be the best interpretation to explain this phenomenon.

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