Lithospheric Structure and Along-Strike Segmentation of the Central Andean Plateau, 17 -29°S

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RESUMEN: Los datos geofísicos y geoquímicos indican que cerca del paralelo 23° S, el espesor del plateau de los Andes Centrales decrece hacia el sur a lo largo de su rumbo. Mientras una litósfera gruesa subyace el Altiplano y las Sierras Subandinas, una delgada lo hace bajo la Puna y el Sistema de Santa Bárbara. La diferencia en el estilo tectónico de estos dos segmentos puede atribuirse al cambio a lo largo del rumbo del espesor litosférico.

KEY WORDS: Altiplano, Puna, lithosphere, flexure, seismic attenuation, back-arc volcanism

INTRODUCTION:

The central Andean Plateau is a 300 km wide, nearly 4 km high plateau which is situated above a 30°E dipping segment of the subducted Nazca plate. Major along-strike variations in upper mantle structure are demonstrated by systematic changes in the topography, the upper mantle seismic Q structure, the lithospheric flexural rigidity, and the distribution and chemistry of back-arc lavas. South of 23° S, the upper mantle becomes hotter, and the lithosphere becomes thinner and weaker. This change in lithospheric thickness coincides with lateral variations in the tectonic style and timing of deformation in two distinct physiographic segments of the plateau and its adjacent foreland thrust belt to the east: the Bolivian Altiplano and Subandean ranges in the north and the Argentine Puna and Santa Barbara system in the south (see also Allmendinger et al., this volume). We conclude that lateral variations in lithospheric thickness and rheology play an important role in this segmentation.

SEISMIC WAVE ATTENUATION

One of the most sensitive indicators of variations in lithospheric structure and the thermal structure of the upper mantle is the efficiency of regional high frequency P and S wave propagation. In a recent study, Whitman et al. (1992) show that the upper mantle seismic attenuation (Q) structure varies along-strike beneath the plateau and foreland with generally low attenuation (high Q) beneath the Altiplano segment, and high attenuation (low Q) beneath the Puna segment (Fig. 1). Digital seismograms collected during deployment of the portable PANDA network near Jujuy, Argentina (24°S, 65°W) on the eastern margin of the Puna exhibit striking azimuthal variations in frequency content. Ray paths from intermediate depth earthquakes located north and northwest of the network transmit seismic waves with a higher frequency content than ray paths from earthquakes at similar depths and distances but located west and southwest of the network. In the foreland, Sn phases from crustal earthquakes in the Subandean ranges to the north propagate efficiently to the network, while Sn is not observed from shallow earthquakes at similar distances to the south.

This data when combined with previously reported observations of shear wave propagation at La Paz, Bolivia (17°S, 68°W) on the eastern side of the Altiplano (Chinn et al., 1980) define a generally low Q region in the upper mantle beneath the plateau which varies in width along strike (Fig. 1). In the Altiplano, the low-Q is confined to areas of active volcanism in the Western Cordillera, but beneath the Puna, the low Q zone spans the whole width of the plateau and is present beneath the Santa Barbara ranges to the east.

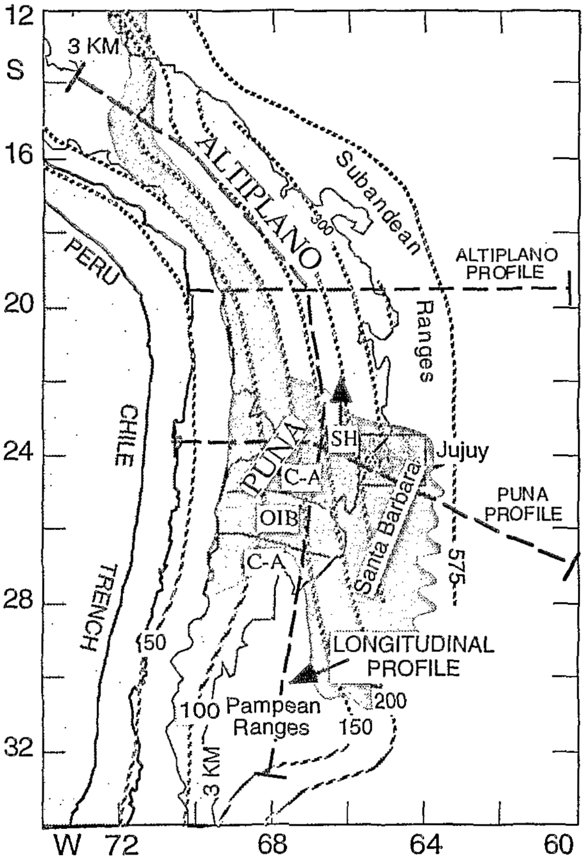

Fig 1. Map showing regions of high seismic wave attenuation (dark, shaded region) inferred to lie between the subducting Nazca plate and the overriding South American plate (after Whitman et al, 1992) and along strike variations in back arc lava composition (after Kay and Kay, 1993). SH: shoshonitic; C-A: calc-alkaline; OIB: ocean island basalt-like lavas. Also shown is depth to the Wadati-Benioff zone (50 km contours after Cahill and Isacks, 1992) and regions with average elevation over 3 km.

MAGMATISM

The southward increase in upper mantle seismic attenuation beneath the plateau is reflected in the distribution of young back-arc mafic (< 60% SiO_2) flows. In the Altiplano and northern Puna, back-arc mafic centers are composed of shoshonitic lavas indicative of small degree melts of enriched mantle lithosphere. From 24°S to 27°S, back-arc mafic centers progressively increase in volume and change in composition from shoshonitic, to calc-alkaline, to OIB (intraplate)-like, to calc-alkaline lavas. (Fig. 1; SH, C-A, and OIB). The change from shoshonitic to OIB-type is consistent with a progressive increase in mantle melting percentage and a decrease in enriched lithospheric component. The largest centers with the highest melting percentages lie above a seismic gap in the subducted Nazca plate and probably reflect anomalously high temperatures in the mantle wedge. These results are consistent with a general north to south decrease in lithospheric thickness and an increase in mantle wedge temperature.

The temporal and spatial distribution of ignimbrites on the plateau suggests that the present day lithospheric thickness of the plateau has evolved since mid-Miocene. Ignimbrites erupted in the Altiplano and northern Puna ceased in mid to late Miocene while those erupted further south in the active Central Volcanic Zone are recent. If the large-scale crustal melting associated with these ignimbrites is due to anomalously thinned lithosphere, then since mid-Miocene, the lithosphere beneath the Altiplano and northern Puna has thickened, whereas the lithosphere of the southern Puna has thinned.

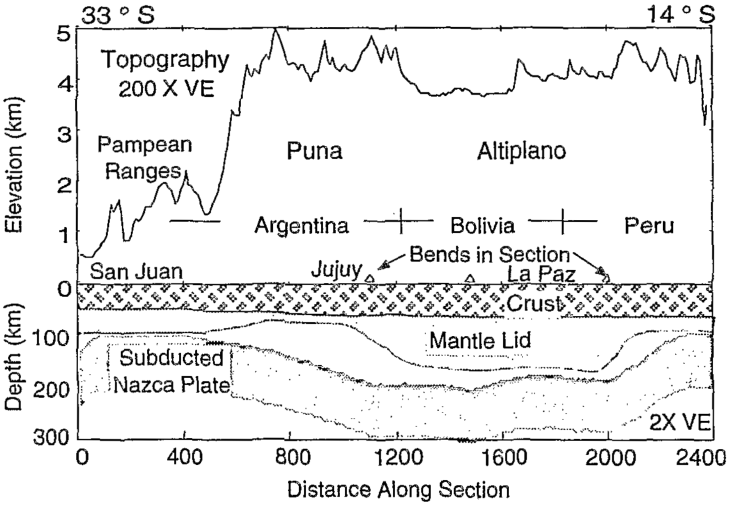

Fig 2. Longitudinal cross section through the central Andes. Location of section is shown in Figure 1. Top shows averaged topography projected into a along a 50 km wide swath along line of section. Bottom shows inferred crust and upper mantle structure along section. Thickness of mantle lid is inferred from the patterns of upper mantle seismic wave attenuation (Chinn et al., 1980; Whitman et al., 1992). Top of the subducted Nazca plate along the section is 15 km above the projected WBZ contours of Cahill and Isacks (1992).

ISOSTASY OF THE PLATEAU AND FLEXURE OF THE FORELAND LITHOSPHERE

The mode of isostatic compensation changes along-strike beneath the plateau. Near 22°S, the average elevation of the plateau increases abruptly from 3.8 km in the Altiplano to around 4.4 km in the Puna (Figs. 2 and 4), and is a consequence of a thinned lithosphere beneath the Puna. Assuming typical thermal parameters for the lithosphere, the increase in elevation in the Puna can be explained by a decrease in lithospheric thickness of 50 - 100 km, depending on whether the thin Puna lithosphere reflects a long standing difference from that of the Altiplano, or is due to a fairly recent (0-10 Ma) rapid removal or delamination of lithospheric material beneath the Puna. The elevation of the Altiplano is compensated primarily by crustal thickening, whereas the Puna is supported by both a crustal root and a thermal mantle root.

In southern Bolivia, the eastern margin of the Andes is compensated regionally due to flexural support of the foreland lithosphere. This is reflected in a high-low isostatic residual anomaly pair which tracks the location of the eastward verging Principal Frontal Thrust in the Eastern Cordillera of Bolivia (Fig 3, top). The 50 mGal high (Fig 3, ECH) is caused by a combination of high density basement rocks in the hanging wall of the thrust and local undercompensation of the topography. To the east, the -75 mGal low (Fig. 3, SAL) is coincident with the Subandean fold-thrust belt and foreland basin, and is due to a combination of low density sedimentary rocks in the foreland basin and the locally overcompensated crust of the downflexed foreland lithosphere. Forward modeling of this gravity profile (Lyon-Caen et al., 1985) indicates that the foreland lithosphere behaves as an elastic plate with thickness of 25-70 km ($D = 10^{23}$-$2 \cdot 10^{24}$ Nm) which has been underthrust beneath Subandean belt and Eastern Cordillera by at least 150 km.

Farther south, the isostatic residual across the eastern margin of the Puna and the Santa Barbara ranges is much smaller than that across the Subandean belt (Fig. 3 bottom). At the latitude of Jujuy, Argentina, modeling of the gravity anomaly and a Moho profile determined from an inversion of seismic traveltime residuals indicates that the effective elastic thickness of the lithosphere is only 6-12 km ($D = 10^{21}$-10^{22} Nm) (Whitman, in prep). This supports the model of a thinner and, hence, less rigid lithosphere beneath the foreland of NW Argentina.

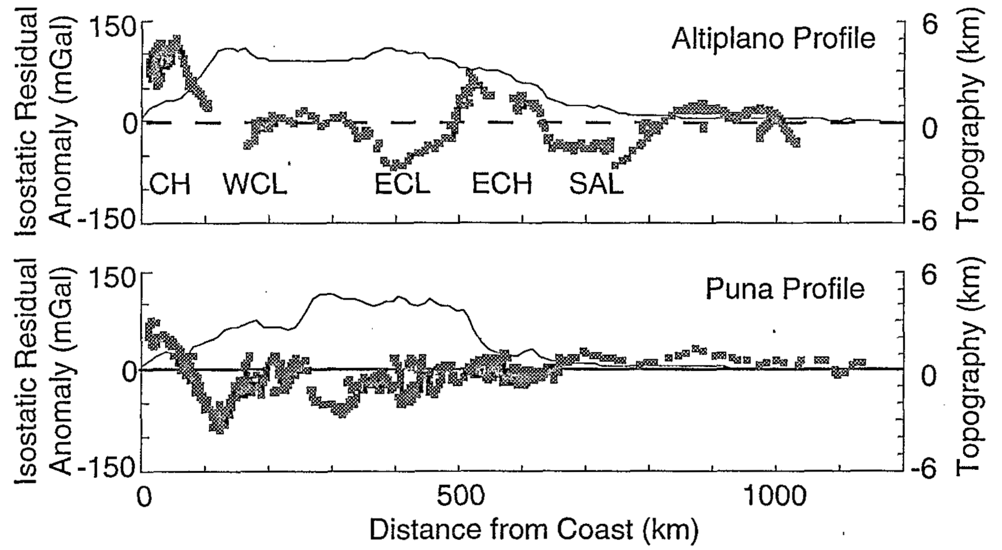

Fig 3. Profiles across the Altiplano and Puna segments of the central Andes showing averaged topography and point values of the isostatic residual gravity anomaly projected into section along a 100 km wide swath. Location of profiles is shown in Figure 1. The profiles were constructed to be approximately perpendicular to regional trends in the gravity anomalies. The isostatic residual was computed by subtracting a calculated isostatic regional and a degree 10 free air regional from the observed Bouguer anomaly. The observed Bouguer anomaly is from Götze et al. (1990) and older DMA sources. The isostatic regional was calculated at station level by assuming local Airy compensation, a zero elevation crustal thickness of 35 km, a topographic density of 2.67 gm/cc, and a density contrast at the crust-mantle boundary of 0.35 gm/cc. CH: coastal high; WCL: Western Cordillera low; ECL: Eastern Cordillera low; ECH: Eastern Cordillera high; SAL: Subandean low.

TECTONIC IMPLICATIONS

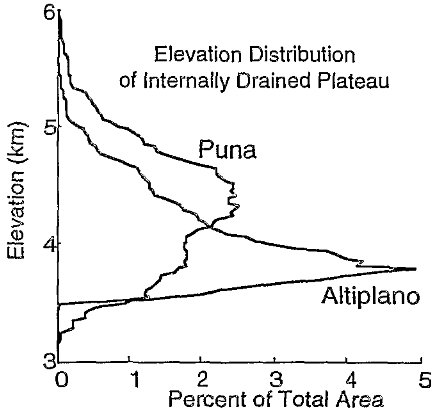

Fig 4. Differential hypsometric curves comparing the elevation distribution of the Altiplano and Puna segments of the central Andean plateau. Elevation distribution was calculated from topography contained within internally drained regions of the plateau only.

The lateral segmentation in upper mantle structure is coincident with changes in the physiography and tectonic style of the plateau. The Altiplano and Puna segments of the plateau exhibit different elevation distributions (Fig. 4). Elevations in the Altiplano are concentrated near 3.8 km, the height of the main Altiplano basin. This relatively narrow elevation distribution reflects cut and fill processes in the Altiplano basin and the lack of compressional deformation in the Altiplano and Eastern Cordillera of Bolivia since Late Miocene (Isacks, 1988; Gubbels et al., 1993). In the Puna, elevations are more evenly distributed about the mean, a consequence of the greater local relief and a longer duration of compressional deformation in the Puna than in the Altiplano (see Allmendinger et al., this volume). This longer history of compression in the Puna may be a direct consequence of thinner, weaker lithosphere.

The foreland tectonic style changes from thin skinned deformation in the Bolivian Subandes to thick skinned, basement involved deformation in the Santa Barbara ranges of northwest Argentina. We suggest the following explanation connecting the lateral changes in upper mantle structure with those expressed at the surface. The strong, thick lithosphere beneath the Bolivian foreland has allowed the Brazilian shield to be underthrust beneath the plateau margin as a coherent unit, with deformation confined to the overlying Paleozoic sedimentary wedge. A thinner weaker lithosphere beneath the Santa Barbara system of NW Argentina has lead to diffuse basement involved shortening within the crust. Since much of the shortening within the foreland is accommodated within the basement, the NW Argentine foreland has not been extensively underthrust beneath the Puna. The tectonic style of the Puna segment is similar to the thick skinned tectonics of the Pampean ranges farther south. The similarities in tectonic style in these two segments reflect similarities in lithospheric thickness and the consequent overall rheology of the plate, with the lower Pampean elevations resulting from thermal coupling between South American and subducted Nazca plates (Fig. 2)

The along-strike lithospheric segmentation of the central Andean plateau and its adjacent foreland may be due to one or a combination of the following scenarios. The change in lithospheric thickness may predate the main stage of Andean uplift, or preexisting lithospheric properties of the two segments may have at least influenced a later change in the thickness. The change in lithospheric thickness may be due to a larger amount of shortening across the mountain belt in the north with the underthrust Brazilian shield accounting for the thick lithosphere beneath the Altiplano. Finally, the lateral change in lithospheric thickness may be due to a relatively recent removal or delamination of lithosphere beneath the Puna, possibly related to the southward flattening of the subducted Nazca plate.

REFERENCES

CAHILL, T., AND B. L. ISACKS, 1992, Seismicity and shape of the subducted Nazca plate, *J. Geophys. Res., 97,* 17503-17529.

CHINN, D.S., B. ISACKS, M. BARAZANGI, 1980, High-frequency seismic wave propagation in western South America along the continental margin, in the Nazca plate and across the Altiplano. *Geophys. J. R. Astron. Soc., 60,* 209-244.

GÖTZE, H.-J., B. LAHMEYER, S. SCHMIDT, S. STRUNK, M. ARANEDA, 1990, Central Andes Gravity Data Base., *EOS, 71,* 401-407.

GUBBELS, T.L., B.L ISACKS, E. FARRAR, 1993, High-level surfaces, plateau uplift, and foreland development, Bolivian Central Andes, *Geology (in press).*

ISACKS, B.L., 1988, Uplift of the central Andean plateau and bending of the Bolivian orocline, *J. Geophys. Res., 93,* 3211-3231.

KAY, R.W, S.M. KAY, 1993, Delamination and delamination magmatism,*Tectonophysics, 219,* 177-189.

LYON-CAEN, H., P. MOLNAR, G. SUÁREZ, 1985, Gravity anomalies and flexure of the Brazilian Shield beneath the Bolivian Andes, *Earth and Planet. Sci. Let., 75,* 81-92, 1985.

WHITMAN, D., B.L. ISACKS, J-L CHATELAIN, J-M CHIU, A. PEREZ, 1992, Attenuation of High-Frequency Seismic Waves Beneath the Central Andean Plateau, *J. Geophys. Res., 97,* 19929-19947.