MAPPING THE CONTINUITY OF THE NAZCA PLATE THROUGH ITS ASEISMIC PART IN THE ARICA ELBOW BY TELESEISMIC TOMOGRAPHY

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INTRODUCTION

The western part of South America is one of the major plate boundaries on the Earth. It is the largest region in which ocean-continent convergence is happening today. The Andes are the result of the subduction of the Nazca Plate beneath the South American Plate along the Peru-Chile trench since the Cretaceous. This continental margin orogenic belt, continuous for more than 7,000 km, presents distinct broad scale tectonic segments, which remarkably correlate with the variations in the geometry of the subducted Nazca Plate (Barazangi and Isacks, 1976, Jordan et al., 1983). The most noticeable of these segments is certainly the Central Andes (15°S to 27°S): the range is at its widest part (Bolivian Orocline) including the Altiplano-Puna high plateau and the general strike of the structures changes from N320°W to nearly NS (Arica Elbow) (Figure 1).

Along the Peru-Chile trench, the subduction of the Nazca Plate under South America is well underlined by the Wadati Benioff zone. In the Central Andes, the seismicity defines a moderately deeping slab down to about 325 km. The occurence of a scarce seismicity in the 550-650 km depth range, after a complete seismic quiescence, arises the question of the continuity of the slab. To answer this question we performed a 3-D teleseismic tomography of the mantle at 20° S.

DATA PROCESSING

From June to Novembre 1994, 41 vertical short period stations from the french Lithoscope network were operated along a 700 km long profile crossing the Andean chain in its entirety. Therefore, this profile was placed above the subducted plate from the coast, where its upper part is at a 50 km depth, to its eastern limit as it is defined by the Wadati Benioff zone; the profile ended at the subandean front of deformation, above the very deep seismicity. The profile was designed to be as perpendicular as possible to the structures. The spacing between the stations was about 20 km (Figure 1).

Among the 250 teleseismic events recorded during the 6 months experiment, we selected 120 events which provided clear P-wave arrivals at more than 10 stations. They were evenly distributed in distance and azimuth relatively to the seismic network. Absolute travel-times were calculated using hypocentral data from the USGS's Preliminary Determination of Epicenter's bulletin and Herrin's tables (1968). Next we calculated residuals at every station for every selected event, and then we computed the value of these residuals relatively to the same reference station situated in the Altiplano.

A study of the variation along the profile of these relative residuals shows the strong azimuthal variations of P relative residuals and particularly the difference between the north-eastern quadrant and the other azimuths. For the azimuths between 0 and 40°E, the more we go west, the more the relative residuals are negative, therefore the more rays cross high velocity structures. The decrease from east to west along profile is more gradual for northern than for north-eastern azimuth, but on both profiles the variation reaches 4 s, twice what is observed in others azimuths. Such large scale differences emphasize at the same time that the anomalous structures are deep and that the region sampled by the rays is far from the axial symmetry. This assertion has to be sustained by the tomography.

The travel time residuals are inverted using a version of the "ACH" inversion technic (Aki et al., 1977), extensively described in published litterature. The initial velocity model included 12 layers of blocks of incrasing size with depth. In order to obtain a satisfactory explaination of our data, it is a large reduction in the data variance, we were led to build a 3-D thick initial model. In effect, the reduction of the variance is less than 50% for a 2-D 420 km thick model; it goes up to 73% for a 3-D model of the same thickness, and reaches 82% when we use a 3-D 660 km thick model. Therefore, our initial model includes the complete upper mantel and the transition region down to the 650 km discontinuity.

TOMOGRAPHIC IMAGES

A vertical EW cross-section at 19.5°S through the smoothed velocity perturbation model is presented in Figure 2, together with the historical seismicity reported by the National Earthquake Information Service for the time period 1974-1994

The crust

Within the continental crust, the results of the tomography can be compared to the results of seismic refraction profiles recorded at 21°S by the Freie Universität Berlin (Wigger et al., 1993; Schmitz, 1993 and 1994). Because the teleseismic inversion has a poor resolution in the vertical direction, we restrict the comparison to the global structure of the crust i.e. its thickness and average velocity.

The teleseismic tomography gives a smoothed image of the lateral velocity variations within the crust that matches the structure determined from refraction surveys. The highest velocities are observed beneath the western end of the profile, below the Coastal Cordillera of Chile. Further east, the positive velocity anomaly decreases rapidly when entering the Axial Valley. The active volcanic arc (Western Cordillera) is characterized by a negative velocity anomaly. A weak (negative) anomaly is observed under the Altiplano, then the eastern part of the Eastern Cordillera is characterized by a positive velocity anomaly. Finally, at the eastern end of the profile, a weak negative anomaly is observed in the Sub-Andean Zone.

The continental upper mantle

Figure 2 shows that the upper mantle between 60 and 140 km has lateral variations in P-wave velocity that are smaller than ±1.5%, which is of the order of the standard deviation. The only correlation with the velocity structure in the crust is the extension of the high velocity zone under the western part of the Eastern Cordillera down to a depth of 120 km. Under the Western Cordillera, the Altiplano and the eastern part of the Eastern Cordillera, the lack of correlation between the velocity anomalies in the mantle and the crust shows that the mantle and crust probably are decoupled. We do not find any evidence for a wedge of over-heated mantle material under the thickened crust of the Altiplano and Western Cordillera which could strengthen the hypothesis of lithospheric delamination (e.g. Isacks, 1988).

Since this is the second tomographic experiment conducted in the Central Andes, it is possible to study the along strike variations in the deep structure of the chain. The previous experiment was carried out in northern Bolivia across a narrower part of the chain which included only the Altiplano and the Eastern Cordillera (Figure 1) (Dorbath et al., 1993). The two velocity models are significantly different as velocities in the shallowest layers have weaker and smoother lateral variations along the southern than along the northern transect. However, the most characteristic features are observed on both profiles: the Altiplano is characterized by low velocities down to the Moho depth, and the axial zone of the Eastern Cordillera by high velocities down to the upper mantle. The differences observed between the two models is related to along strike variations in the geometry of the underthrusting of the eastern margin of the Andes under the Brazilian craton, which occurs along steeply dipping faults in the northern narrow segment, whereas it occurs along low angle ramps in the southern wide segment.

The subducted Nazca Plate

A striking feature revealed by our tomography (Figure 2) is the eastward-dipping positive anomaly which crosses the entire profile from the coastal zone to the sub-Andean zone. This 100 km thick structure is characterized by a +2% average velocity contrast with respect to the surrounding mantle,. It is associated with the slab because it coincides with the Wadati-Benioff zone in its seismic part (Figure 2). The continuity of the high velocity anomaly down to 660 km indicates that the slab is continuous across its aseismic part. The strengthening of the velocity perturbation at 400-450 km depth and the general shape of the anomaly indicate that the dip of the descending slab increases below 400 km depth. In a recent paper, Engdahl et al. (1995) used inversion of travel time residuals of teleseismically recorded events of South America to compute tomographic images of the subducted Nazca plate. Their main result is the observation of 2.5% high velocity anomalies spatially correlated to the Wadati-Benioff zone which can be traced down to the base of the upper mantle.but do not exhibit a strong continuity.

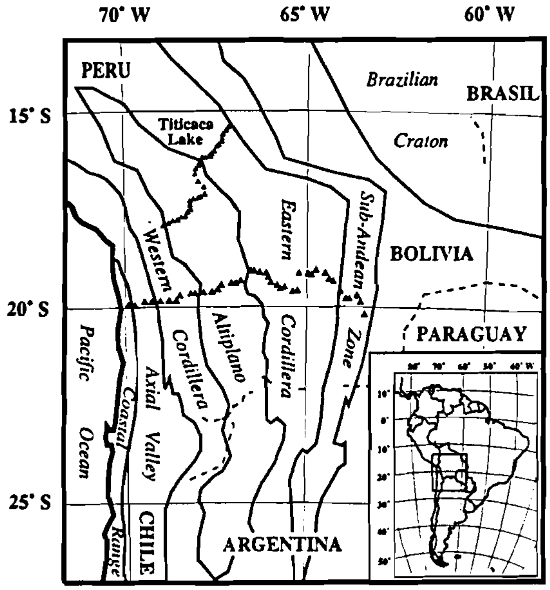

Figure 1

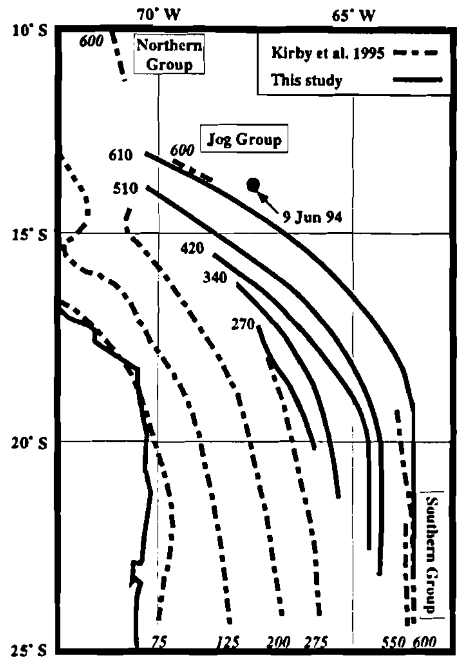

Figure 3

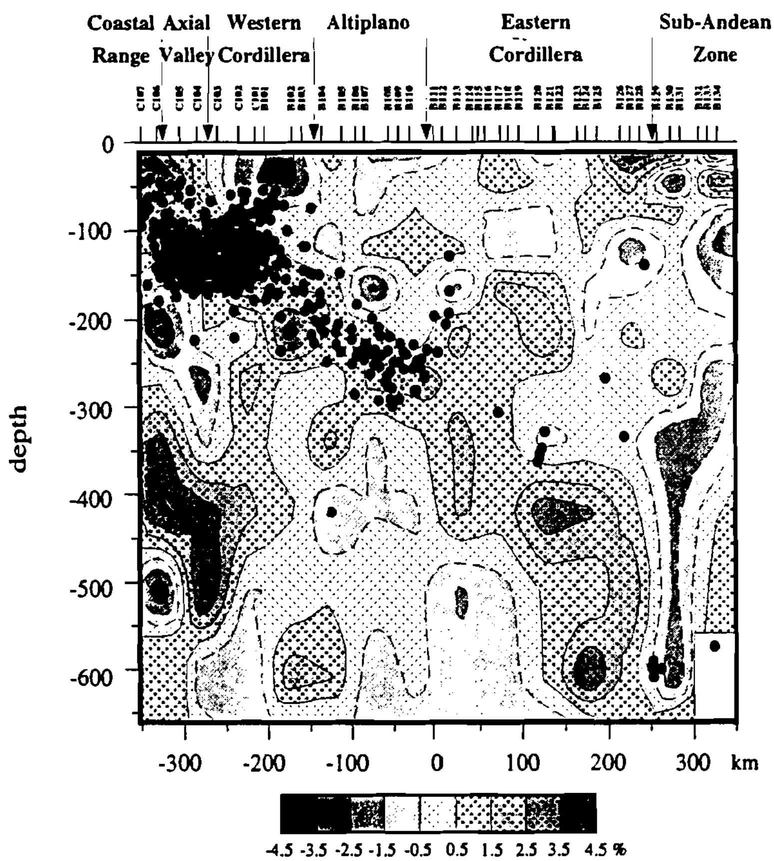

Figure 2

The images obtained by the teleseismic tomography provide a strong supportive evidence for the continuity of the slab over regions with gaps in seismicity. From the surface to 660 km depth, the slab is evidenced on the 3-D images by a laterally continuous high-velocity structure, clearly displaying a pronounced bend on the deepest layers of our final model. A complementary contribution which can only be provided by the tomography is the possibility to follow the slab deeping throughout the seismically quiescent zone. We present on the Figure 3 a schematization of the slab geometry deduced from the 3-D image. For every layer in which the slab is clearly identified by higher velocities, we have drawn a contour passing through the maximum of the positive anomaly. Doing so, we approximate the position of the slab at the mean depth of the layer. On the same figure, we have reported the seismicity of the NEIS for the past 20 years and the iso-depth contours obtained by Kirby et al. (1995). Our network layout allows us to sample only a roof-shaped zone aligned on the seismic profile and consequently the north-south extension of the layers depends on their depth. Therefore our 270 km contour is very short and does not fit well with the 275 km contour, the deepest of the Wadati Benioff zone. On the other hand, our 610 km contour is in good spatial agreement with the 600 km depth events. When drawig a cross-sections of the slab in the Arica Elbow, we observe that the dip of the slab changes with depth. From the trench to a depth of 275 km, the seismicity defines an about 30° dipping slab; then the dip, inferred from the tomography, increases to more than 50° in the aseismic part of the slab. Finally, the dip decreases to about 40° where the deep seismicity is present, suggesting a deflection of the slab at the bottom of the upper mantle.

Finally, the geometry of the deep slab in the transition zone of southern Peru is still an open question. If it is relatively easy to connect our 610 km contour with the Northern Group through a reverse bend, the closing up of the 200 and the 510 km contours at about 15°S involves a steepening of the slab. Therefore, the transition, from the 50° dip of the aseismic part of the slab deduced from the tomography, to the 70° dip inferred by James and Snoke (1990) study beneath Peru, seems to occur in this region of the Arica Elbow, and implies a very complicated geometry of the slab between 13°S and 18°S.

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