

Imaging of subducted lithosphere beneath South America

E. R. Engdahl¹, R. D. van der Hilst², and J. Berrocal³

Abstract. Tomographic images are produced for the deep structure of the Andean subduction zone beneath western South America. The data used in the imaging are the delay times of P, pP and pwP phases from relocated teleseismic earthquakes in the region. Regionally, structural features larger than about 150 km are resolved by the data. Presentations of layer anomaly maps and cross sections reveal: (1) The Nazca slab is probably continuous laterally and at depth over most regions; (2) The offset between the north and south deep earthquake zones, containing the 1994 deep Bolivia main shock and its aftershocks, can be modelled by a northwest striking and steeply northeast dipping slab structure; and (3) The Nazca slab clearly penetrates the lower mantle beneath central South America, but is partly deflected in the southern deep zone.

Introduction

The 6 June 1994 deep Bolivian earthquake ($M_w=8.2$) is exceptional in that it is located in a region of sparse previous deep seismicity (see Figure 1). To explain its occurrence one has to better understand the structure and fate of the descending Nazca plate beneath western South America. Among the most important issues presently either ill-defined or conjectured are: (1) Is the slab continuous laterally and at depth over large regions of the implied Wadati-Benioff zone beneath South America where earthquakes are absent? (2) What are the implications for plate structure of the offset between the northern and southern deep seismic zones and of the sparse intervening deep seismicity which includes the deep Bolivian event and its aftershocks? and (3) What is the fate of the slab in these regions as it encounters the 660 km discontinuity?

Tomographic imaging is a tool that can help to provide answers to these questions. In this paper, preliminary results of a study to determine the details of plate structure beneath the South American continent are presented. First, we briefly review what is currently known about the structural setting for deep earthquakes beneath South America. Second, we describe the data and methods used. Finally, we attempt to interpret our images in relation to the questions posed above.

Structural Setting

Subduction of the Nazca plate beneath western South America is characterized by alternating intermediate-depth earthquake regions of normal and flat subduction (see Figure 1). Investigations of slab geometry in the transition between these regions beneath southern Peru show that the plate is

contorted but not torn there (Hasegawa and Sacks, 1981; Boyd *et al.*, 1984; Cahill and Isacks, 1992). Deep focus earthquakes in South America (about 500 to 650 km in depth) mainly occur in two steeply dipping, approximately straight, thin zones at $6.5-11.5^\circ$ and $16.5-29^\circ$ S (Kirby *et al.*, 1995). These zones are roughly parallel, but are offset by about 700 km at $12-16^\circ$ S.

These deep earthquakes are spatially separated from intermediate-depth events by a region nearly 4000 km long which is entirely absent of reliably located earthquakes. Early studies were equivocal about slab continuity through this aseismic part of the implied Wadati-Benioff zone. Isacks and Barazangi (1973) suggested slab continuity on the basis of high-frequency waves transmitted through the region from nearby deep earthquakes. However, Wortel (1984) argued that the slab is continuous to depths of 320 km or less and deep seismicity is due to detached slabs. Modelling of underside wide-angle reflections from the upper surface of the Nazca plate, observed by a station in Peru, provided strong evidence for continuity of the descending slab through at least part and probably all of the aseismic zone beneath central and eastern Peru at depths of 150 to 525 km (James and Snoke, 1990).

The fate of the Nazca slab at the 660 km discontinuity has been discussed in two recent papers. Lundgren and Giardini (1994) suggest that the occurrence of the isolated 28 February 1989 deep earthquake at latitude 23° S, about 230 km east of the trend of the southern deep seismic zone (see Figure 1), indicates the presence of recumbent seismogenic slab there. Grand (1994) used the travel times of horizontally polarized shear phases worldwide to resolve mantle structure beneath the Americas on the scale of a few hundred km. He found a high-velocity anomaly beneath western South America ($0-20^\circ$ S) ranging from 660 to about 1250 in depth and 550 to 825 km in width; his study did not, however, resolve small scale structure near the deep Bolivian earthquake.

The 1994 Bolivian deep earthquake occurred in the region of offset between the northern and southern deep seismic zones where only three large events (1958, 1963 and January 1994 at $13.3-13.8^\circ$ S and $69.3-69.5^\circ$ W) had previously been located. This cluster of earlier shocks aligns roughly with the trend of the Peru-Brazil deep earthquake zone to the north. However, the 1994 mainshock and its immediate teleseismic aftershocks, located about 180 km east of this cluster (at $67.0-67.5^\circ$ W), describe a narrow (< 10 km) east-west trending zone ranging in depth from 632 to 642 km that parallels the strike of the steeply dipping nodal plane of published moment tensor solutions for the mainshock. These events and a later deep earthquake at 607 km depth (August 1994 at 13.8° S and 68.4° W), between the two clusters, imply a radical change in geometry of the Nazca slab in this area.

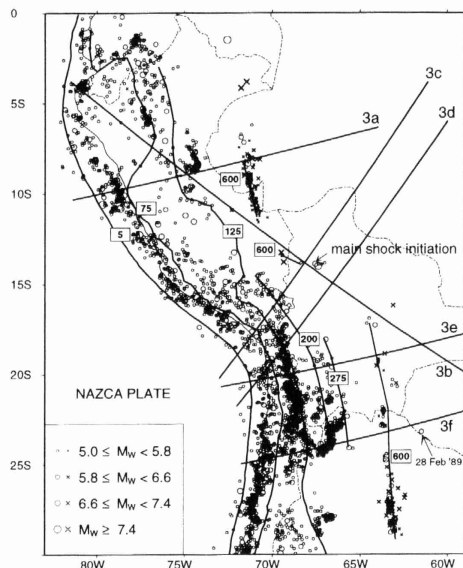
Data and Methods

A procedure that uses an improved global travel-time model (aki35; Kennett *et al.*, 1995) and the arrival times of first-arriving regional and teleseismic P phases, regional S phases, depth phases (pP, the ocean surface reflected pwP, and sP), and the PKPdf branch is used to relocate all teleseismically well-

¹National Earthquake Information Center, U.S. Geological Survey, Denver, USA

²RSES, Australian National University, Canberra, Australia

³Institute of Geophysics, University of Sao Paulo, Sao Paulo, Brazil



constrained earthquakes that have occurred during the period 1964-June 1994 in South America. Upon application of appropriate corrections and selection criteria (Engdahl *et al.*, in preparation), this procedure minimizes depth errors and the mapping of source heterogeneity into mislocation, thereby creating a powerful uncontaminated database of P, pP and pwP residuals for use in tomographic imaging.

Seismic tomography is an inversion technique that aims to interpret these travel-time residuals (or delays) in terms of structure not accounted for by the reference model used to locate the events. We use an iterative inversion method (Van der Hilst *et al.*, 1993) and linearize lateral variations in P-wave speed relative to the reference model. For the parameterization of the spatial variations in wave speed we use about 80,000 non-overlapping cells of horizontal dimension $1^\circ \times 1^\circ$ and a

Figure 1. Relocated teleseismically recorded seismicity and Wadati-Benioff zone contours (Kirby *et al.*, 1995). Open circles are plotted for relocated modern (1964-June 1994) earthquakes at all depths and x's for relocated historical (1915-1963) deep focus earthquakes. Lines labelled 3a, 3b, 3c, 3d, 3e, and 3f identify mantle cross sections displayed in Figure 3.

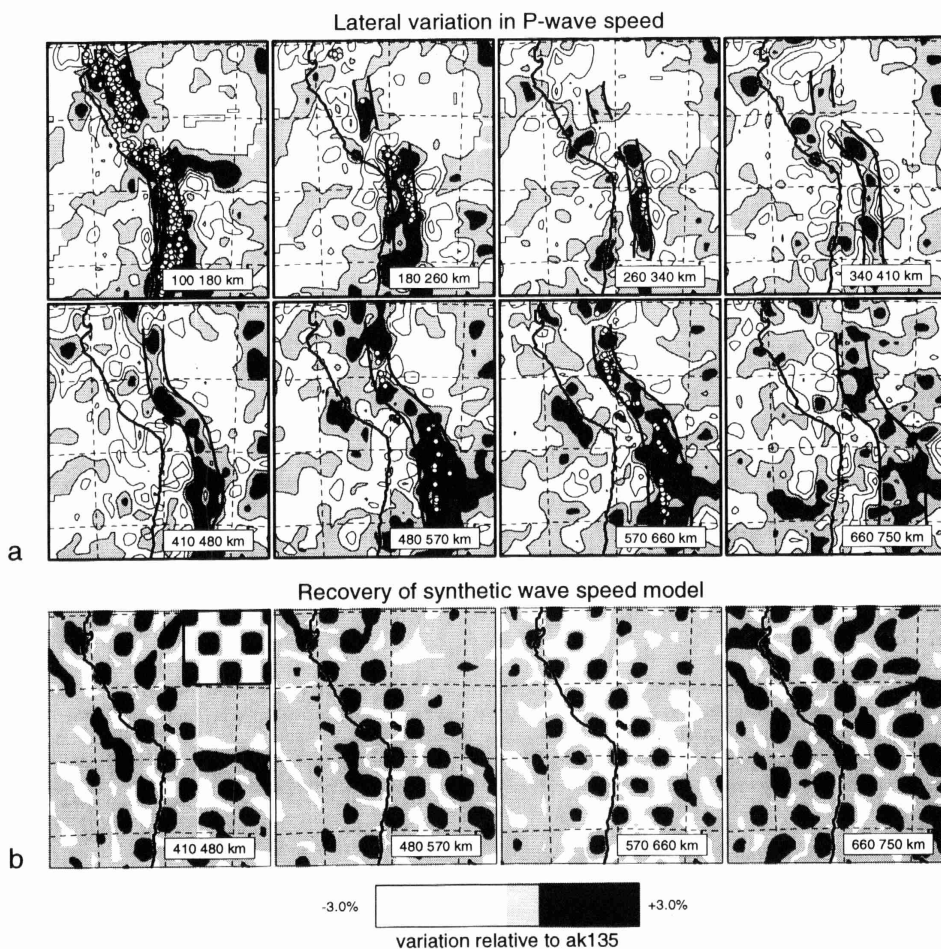


Figure 2. (a) Lateral variation in P-wave speed below the study region displayed as layer anomaly maps for eight depth intervals. Regions of fast wave propagation are depicted by shading in order to emphasize slab structure. Relocated hypocenters (Kirby *et al.*, 1995) in each layer are plotted as white dots. Implied trace of slab is shown by heavy black lines. (b) The recovery of a synthetic model of wave speed anomalies is given for four depth intervals. The regular pattern of the input model is depicted by the inset in the leftmost figure.

thickness that increases from 35 km for the crustal layer to 200 km for the layer centered at 1600 km in depth. Upon inversion of over 800,000 residuals, we determine in each cell the slowness perturbation relative to the reference value. In Figure 2a the lateral variation in P-wave speed is presented for eight intervals in depth beneath western South America. These layer anomaly maps, discussed below, reveal structures that transmit P waves up to 3% faster than the reference model. However, resolution testing shows that this amplitude may be underestimated by several percent, mainly because of the damping and smoothing required to stabilize the inversion.

To test the reliability of the wave speed images we inverted data computed from a known input model of positive wave speed variations with horizontal dimensions of about 200 x 200 km. Input anomalies were assigned to alternating layers in order to avoid the interference between the layers and to assess the vertical resolution. The match between the results of this inversion and the input model gives information about the potential recovery of mantle structure by the data and ray paths used. In Figure 2b results of this test are displayed for layers encompassing the transition zone and uppermost lower mantle. The input model of regularly spaced anomalies is satisfactorily resolved in most regions of interest. However, Figure 2 also demonstrates that target anomalies, and probably also structural features in the wave speed maps, are not resolved in some regions. Figure 2b reveals smearing along ray paths to stations in the eastern part of the continent. In general, the image quality is not as high as that obtained in our studies of western Pacific slab structure (Van der Hilst *et al.*, 1993). In particular, slab structure near mantle discontinuities is not well determined because (1) secondary arrivals in triplications were not used and (2) any variation in depth of the discontinuity relative to its depth in the reference model results in spurious structure in the images.

Interpretation

In Figure 2 the slab is not imaged as a laterally, continuous, high-velocity feature. Yet, focusing on robust features in the images it is possible to trace roughly the descent of the Nazca slab into the mantle. Our interpretation is shown by the heavy solid lines. In the transition zone (410-660 km) the slab appears to be continuous beneath most of South America and from 480 to 660 km coincident with the distribution of deep

focus seismicity. In the offset region between the northern and southern deep seismic zones there is a pronounced bend in the trace of this higher velocity feature in the transition zone with a strike similar to that of the 600 km contour in that region shown in Figure 1. In the southern deep seismic zone, slab signal is manifested over its entire length. Moreover, the

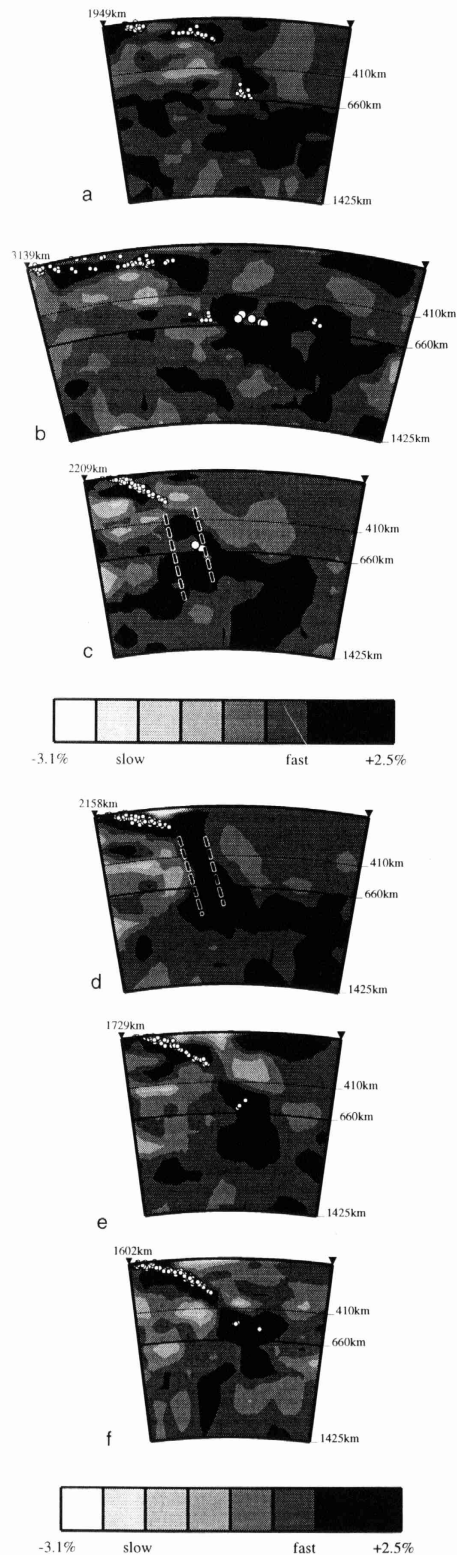


Figure 3. (a) Section normal to northern deep zone. White dots depict earthquakes within 55 km of section plane. Slab is continuous over most upper mantle regions. Note large high-velocity region in lower mantle, similar to structure described by Grand (1994) for that region. (b) Section along implied strike of slab through offset region showing presence of high-velocity material in transition zone and lower mantle. (c) Section normal to implied strike of slab just west of 1994 mainshock source region. Slab is weakly continuous through upper mantle. Eastward smearing of velocities gives false impression of slab broadening in transition zone. (d) Section normal to implied strike of slab through eastern offset region. Slab dip is 75° . Steeply dipping upper mantle higher-velocity region is 200-250 km thick, but continuous high velocity core is no more than 100 km thick. (e) Section across northernmost part of southern deep zone showing slab penetration of lower mantle. (f) Section across southern deep zone through region where large earthquake is offset eastward by more than 200 km. Ray bending effects and eastward smearing of velocities do occur, but the presence of recumbent slab in the transition zone is a strong feature of this image.

southern slab segment significantly broadens in the depth interval 480–660 km suggesting a regional emplacement of recumbent slab. Below a depth of 660 km the slab signature is less pronounced and characterized by a rather amorphous distribution of high velocity material, presumably remnant slab, in the lower mantle beneath central South America.

Several observations can be made about structures in the immediate vicinity of the 1994 Bolivian deep event. In the depth interval 570–660 km, a high-velocity region 200–300 km wide and striking about N45°W, seems to provide a continuous connection between slab segments corresponding to the northern and southern deep seismic zones. Since some expression of the slab is also seen in the depth interval 660–750 km and there is no evidence for recumbent slab in the interval 570–600, we conclude that in the region of the Bolivian deep event the slab has penetrated the lower mantle.

Cross sections have been produced through the deep offset region and some examples are shown in Figure 3. Some of these sections reveal the unfortunate effects of smearing along ray paths to the few stations in eastern South America. One of the most robust features of these plots is that the slab is apparently not deflected in its descent into the lower mantle in the offset region. This results in ponding of high-velocity material up to 1400 km in depth in the lower mantle. High-velocity steeply dipping slab is also generally observed throughout the transition zone. The connection between deep slab in the offset region and slab corresponding to the active intermediate-depth Wadati-Benioff zone (at depths less than 180 km) is not as clearly defined, however, as evidence for through going slab between depths of 180 to 410 km is only weakly present in the images for the region.

Discussion and Conclusions

Earlier studies and the results presented in this paper suggest that deep earthquakes beneath western South America do not occur in detached slab, but in a descending slab which has some expression over nearly the entire extent of the implied Wadati-Benioff zone.

The southern deep earthquake zone is characterized by images which display a broad region of recumbent slab in the transition zone, as well as regions of high-velocity material beneath the 660 km discontinuity. These observations suggest that the slab is at the least partially deflected in the transition zone before continuing into the lower mantle.

In contrast, the northern deep earthquake zone and the region of offset are characterized by throughgoing slab which ponds as large areas of higher-velocity material in the lower mantle. Grand (1994) resolved similar higher-velocity shear wave structures to depths of up to 1250 in this region and invoked a model with a large increase in viscosity near the 660 km discontinuity. In this model the slab is still able to penetrate the lower mantle, but at reduced velocities relative to slab upper mantle velocity and with large lateral slab deformation in the lower mantle. The higher resolution features observed in our tomographic images of the lower mantle are consistent with this model.

The tomographic images shown in this paper provide the first high-resolution P-wave evidence for high-velocity slab material at depth and bring strong supportive evidence for the view that the slab is continuous over regions with gaps in seismicity. The June 9, 1994 deep Bolivia earthquake falls in a northwest striking and steeply northeast dipping high velocity region that connects the north and south deep earthquake zones. Slab penetration of the lower mantle clearly occurs beneath most of South America, but there is also evidence for partly deflected slab in the southern deep zone.

References

- Boyd, T.J., Snoke, A., Sacks, I.S., and Rodriguez, High resolution determination of the Benioff zone geometry beneath southern Peru, *Bull. Seism. Soc. Am.*, **74**, 557–566, 1984.
- Cahill, T., and Isacks, B.L., Seismicity and shape of the subducted Nazca plate, *J. Geophys. Res.*, **97**, 17,503–17,529, 1992.
- Grand, S.P., Mantle shear structure beneath the Americas and surrounding oceans, *J. Geophys. Res.*, **99**, 11,591–11,621, 1994.
- Hasegawa, A., and Sacks, I.S., Subduction of the Nazca plate beneath Peru as determined by seismic observations, *J. Geophys. Res.*, **86**, 4971–4980, 1981.
- Isacks, B.L., and Molnar, P., Distribution of stresses in the descending lithosphere from a global survey of focal mechanism solutions of mantle earthquakes, *Rev. Geophys.*, **9**, 103–174, 1971.
- Isacks, B.L., and Barazangi, M., High-frequency shear waves guided by a continuous lithosphere descending beneath western South America, *Geophys. J. R. Astron. Soc.*, **33**, 129–139, 1973.
- James, D.E., and Snoke, J.A., Seismic evidence of the deep slab beneath central and eastern Peru, *J. Geophys. Res.*, **95**, 4989–5001, 1990.
- Kennett, B.L.N., Engdahl, E.R., and Buland, R., Constraints on seismic velocities in the Earth from travel times, *Geophys. J. Int.*, *in press*, 1995.
- Lundgren, P., and Giardini, D., Isolated deep earthquakes and the fate of subduction in the mantle, *J. Geophys. Res.*, **99**, 15,833–15,842, 1994.
- Kirby, S.H., Okal, E.A., and Engdahl, E.R., The 9 June 94 Bolivian deep earthquake: An exceptional event in an extraordinary subduction zone, *Geophys. Res. Lett.*, *this issue*, 1995.
- Van der Hilst, R., Engdahl, E.R., and Spakman, W., Tomographic inversion of P and pP data for aspherical mantle structure below the northwest Pacific region, *Geophys. J. Int.*, **105**, 264–302, 1993.
- Wortel, M.J.R., Spatial and temporal variations in the Andean subduction zone, *J. Geol. Soc. London*, **141**, 783–791, 1984.

E. R. Engdahl, NEIC, U.S. Geological Survey, Denver, CO 80225
(e-mail: engdahl@gldfs.cr.usgs.gov)

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