Delay Time Tomography of the Iberian Peninsula

Tomografía con residuos de la Península Ibérica

María José Blanco
Instituto Geográfico Nacional.
Santa Cruz de Tenerife, Spain

Wim Spakman
Department of Geophysics.
University of Utrecht, The Netherlands

1. INTRODUCTION

The observed travel time of a P-wave contains information about the seismic velocity structure along the ray path. If we compare the observed travel time with a theoretical travel time, computed from the assumed reference Earth model used for the location of the earthquakes, we obtain the so-called delay time. The delay time contains information on the deviation of the actual Earth structure from the reference model. The sampling of the Earth's volume of interest with many crossing rays, allows the investigation of the 3-D velocity-anomaly structure by a tomographic inversion of the delay times. In this chapter, we discuss results for the Iberian mantle obtained with delay-time tomography. Earlier tomographic investigations of the mantle structure below the Iberian Peninsula (Spakman 1986, Granet and Trampert 1989, Nolet 1990) all have in common the relatively low level of spatial resolution of results, which hampers their interpretation. In our study we have reached a spatial resolution which allows to interpret structural details on scales on the order of 200 km or larger. In this chapter we focus our attention on a positive (high velocity) anomaly found below the Betic-Alboran region at depths between 200 and 700 km, and with a distinct SW-NE trend. The anomaly is interpreted as an image of a subducted slab. The slab can provide an explanation of the deep seismicity observed in this area (Buforn *et al.,* 1991). A more detailed account of this research can be found in Blanco and Spakman (1992).

2. DATA PROCESSING AND METHOD

The tomographic method we apply, has been discussed in detail in Spakman and Nolet (1988), and Spakman (1988, 1991). Here, we only mention some of the main characteristics of our application.

We selected 210,000 P-wave delay times from the ISC Bulletin tapes (1964-1986) for events recorded by at least 10 stations (up to 90 degrees). We used both teleseismic and local events, and teleseismic and local stations (figure 1). Delays with an absolute value higher than 3 seconds are discarded to avoid artifacts in the solution due to large valued, possibly erroneous, data. Delay times are related to (i) the slowness anomaly field, (ii) source mislocations vectors, and origin time errors, and (iii) station corrections. All these quantities depend on the reference model assumed for the computation of the delays. ISC delays have been computed relative to the Jeffreys-Bullen travel time tables. Following Van de Hilst and Spakman (1989) we applied a reference model correction to the ISC delays for a reference model called PM2 (Spakman *et al.*, 1991). Model PM2 (figure 2) is believed to be more appropriate for P-delay tomography of the Mediterranean region, in the sense that the tomographic problem can be linearized more adequately.

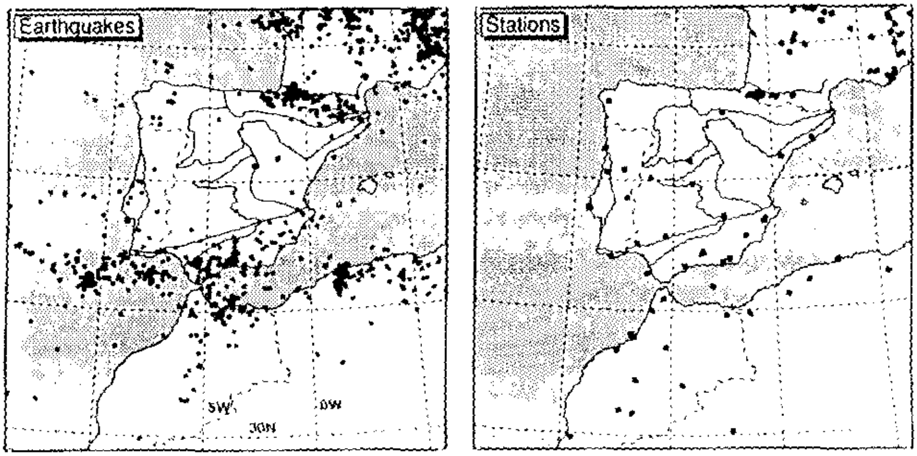

Figure 1.—The Iberian Peninsula and surrounding region. Below the area displayed, the mantle velocity structure is investigated down to a depth of 1420 km. The epicenters displayed in the left panel belong to the local subset of the earthquakes used in this study. The panel to the right shows the location of regional stations from which data is used. Note that also delay-time data are used from events and stations located outside the region displayed. Solid lines within the Iberian Peninsula delineate major tectonic units, the letters A and B denote the Alborán Sea and Betic Cordillera.

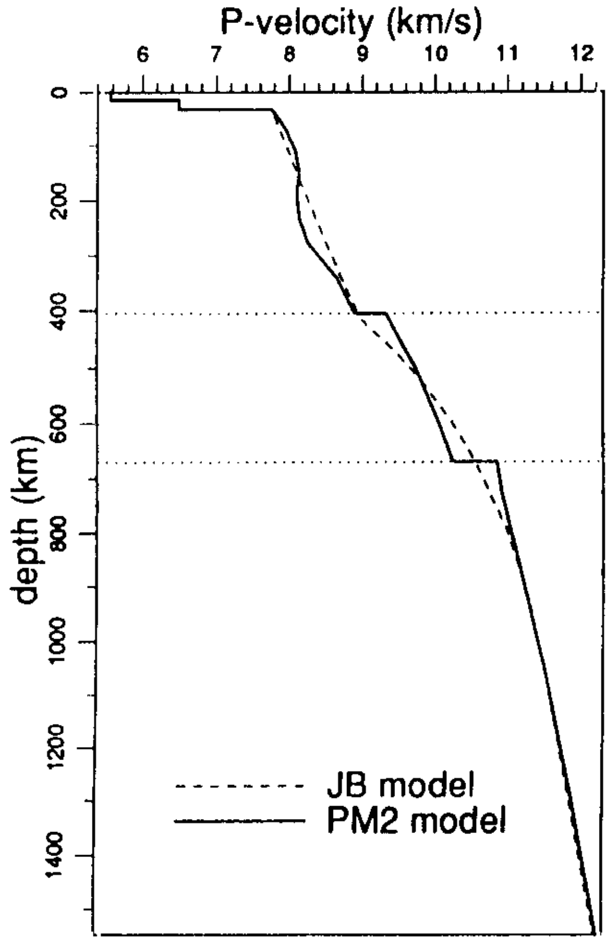

Figure 2.—Radial P-velocity models: Jeffreys-Bullen (JB) and PM2. The latter model is determined by Spakman *et al.* (1991) and serves as a better reference model for delay-time tomography of the European-Mediterranean mantle including the mantle below Iberian Peninsula.

The mantle below the region shown in figure 1 is divided into 20 layers to a depth of 1400 km, and each layer is divided into 18x18 blocks of approximately 1 by 1 degree in size. For the actual tomographic inversions we used the LSQR-algorithm of Paige and Saunders (1982) (also see Nolet 1985, and Spakman and Nolet 1988).

3. RESULTS AND TESTS

After 25 iterations with the LSQR algorithm, we obtained a 20 % reduction in RMS value. The solution obtained is addressed as IP1 (figure 3). The velocity anomalies are contoured as percentage deviations from the PM2 reference model. For us the most interesting pattern found in this region is a positive anomaly below the Betic-Alboran region at depth between 200 and 700 km. In map view the anomaly exhibits a SW-NE trend. We interpret the anomaly as resulting from a subducted slab. In figure 4 we display two cross-sections through the slab together with the cell hitcount (number of rays sampling a particular cell). Smearing of anomalies can be observed along main directions of ray-illumination. Above the slab low (negative) velocities are found. We remark that Blanco and Spakman (1992) present arguments which practically exclude the possibility that the slab anomaly may be an erroneous mapping of mantle structures actually located outside the cell model.

An impression of the spatial resolution can be obtained by applying sensitivity analysis (Spakman and Nolet 1988). We first performed a cell-spike test, from which we obtained a very poor resolution in the deeper mantle, indicating that cell-scale anomalies cannot be detected reliably. Only in some parts of the model, in cell layers centered at depths of 51, 95, and 145 km the cell spike models are well retrieved. To study the possibility that larger scale anomalies may still be resolved reasonably well, we performed a different test with anomalous blocks on the size of 2x2x2 adjacent cells (figure 5). From this test, we conclude that the spatial resolution may be sufficient for anomaly details on the order of 200-300 km in size. Hence, we only have to consider anomaly patterns in IP1 with spatial dimensions larger than say 200 km.

We also investigated the possibility of retrieving an anomaly with the shape and amplitude of the slab anomaly. To achieve this we constructed a synthetic velocity model similar to the actual slab anomaly, with an amplitude of 2 % located below the Betic-Alboran region. We calculated synthetic delays from this model using the actual reference ray paths, and added noise to data (signal to noise ration 0.15). The result of inverting these very noisy synthetic data is called SYN1 (figure 6), and is obtained with an RMS reduction of only 4 %. From this test we conclude that, even with the poor data fit, the synthetic model is well recovered despite some small resolution artifacts.

4. DISCUSSION

We applied delay time-tomography to study the P-wave velocity structure of the mantle below the Iberian Peninsula. We assumed a new reference velocity

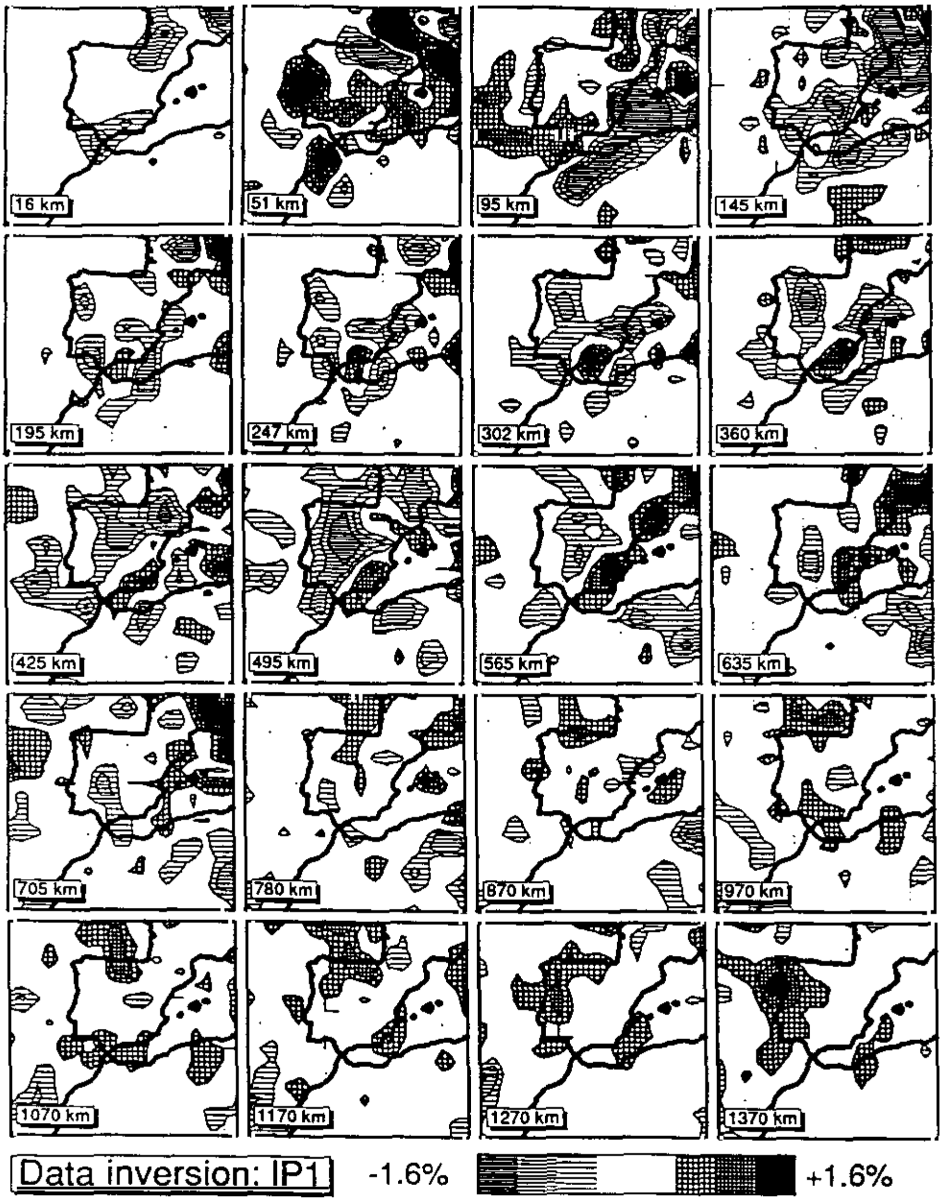

Figure 3.—Tomographic result IP1: velocity anomalies relative to model PM2. Numbers indicate the depth at the center of the cell-layer.

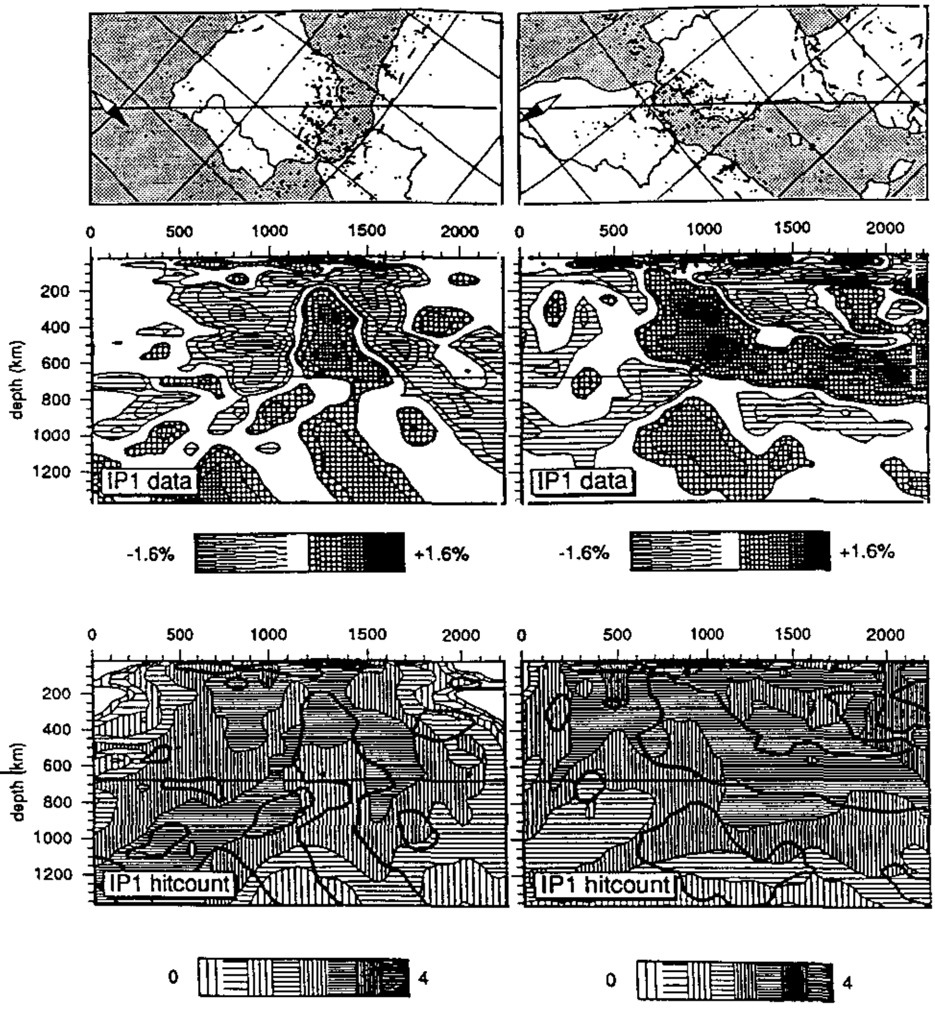

Figure 4.—Two cross-sections through the tomographic result IP1 and hitcount. The horizontal straight line in the map at the top of each column of panels, indicates the exact location of the section. The cross-section to the left is taken perpendicular to the apparent strike of the slab anomaly. The other section runs along strike of the anomaly. Dots in the maps and cross-sections indicate the location of earthquakes. Notice the deep event at 640 km near the center of the cross-sections. In the hitcount patterns, the contouring scale is logarithmic. For reference we plotted the contours of the positive anomalies obtained with IP1.

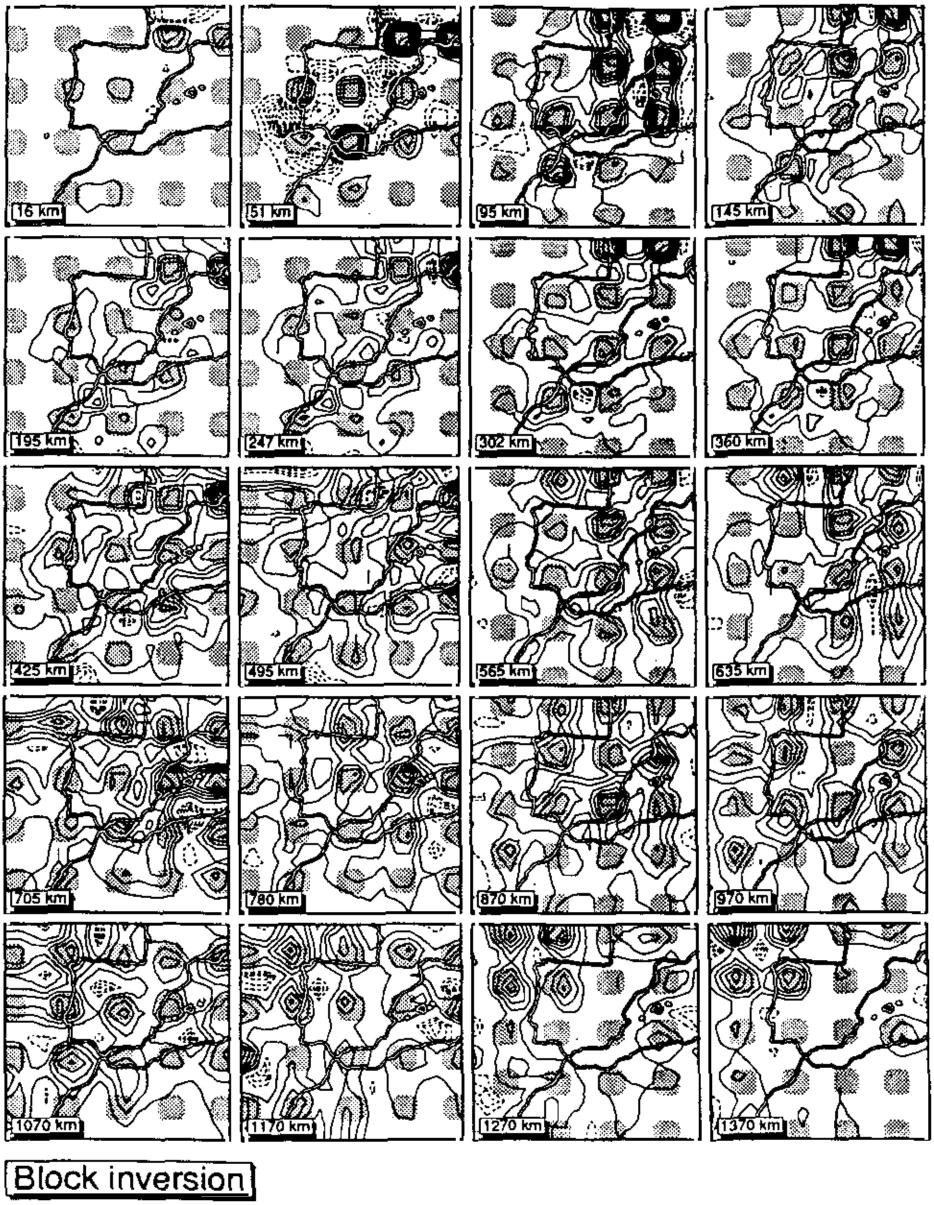

Figure 5.—Block sensitivity result. Shaded areas denote the actual location and spatial size of the block anomalies. The block anomaly value is + 5 %. The contouring is in 0.5 % anomaly value increments. Dashed contour lines indicate negative anomaly values.

Figure 6.—Tomographic result SYN1 of a noisy data inversion for a synthetic slab model. The synthetic slab is designed to resemble in shape and amplitude the slab-like anomaly imaged beneath the Betic-Alborán region. The location of the synthetic slab is indicated with a thick line visible in the panels with depths between 247 and 635 km. Notice that the contouring limits are - 0.5 % and + 1.5 %. Anomalies outside line are all imaging artifacts. Note that the core of the synthetic slab is well recovered. Compare SYN1 to IP1.

model PM2 relative to which the tomographic problem is linearized. Inversion results can only be viewed as an approximation of true mantle structures. Structural details larger than 200 km seem reasonably well resolvable. A demonstration that the ray paths used sample the mantle adequately enough to resolve the slab structure even in the presence of large data errors, is given by the synthetic slab test. The positive anomaly found below the Betic-Alboran region is interpreted as a subducted slab. The presence of this anomalous mantle structure is also corroborated by the occurrence of very deep seismicity at a depth of 640 km; many authors invoked a detached piece of a subducted slab to explain this peculiar seismicity. Because of the low velocities found above the slab anomaly, we also anticipate that the subducted slab is detached from the surface. Blanco and Spakman (1992) have performed many other tests, including those for a detached-slab configuration, to demonstrate the existence of an anomalous slab-like structure below the Betic-Alboran region, and they propose that the slab has been subducted during at least part of the Oligocene and probably became detached in the early Miocene.

REFERENCES

Blanco, M. J., W. Spakman (1992): «The P-wave velocity structure of the mantle below the Iberian Peninsula: evidence for subducted lithosphere below southern Spain». *Tectonophysics* (in press).

Buforn, E., A. Udías, R. Madariaga (1991): «Intermediate and deep earthquakes in Spain». *Pageoph*, 36, N.º 4, 375-393.

Granet, M., J. Trampert (1989): «Large-scale P-velocity structures in the Euro-Mediterranean area». *Geophys. J. Int.*, 99, 593-594.

Buforn, E., A. Udías, J. Mezcua, R. Madariaga (1991): «A deep earthquake under south Spain, 8 March 1990». *BSSA*, 81, 4, 1403-1407.

Kissling, E. (1987): «Geotomography with local earthquake data». *Rev. of Geophys.*, 26, 4, 659-698.

Nolet, G. (1985): «Solving or resolving inadequate and noisy tomographic systems». *J. Comp. Phys.*, 61, 463-482.

Nolet, G. (1990): «Partitioned waveform inversion and two-dimensional structure under the network of autonomously recording seismographs». *J. Geophys. Res.*, 95, 8499-8512.

Paige, C. C., M. A. Saunders (1982): «LSQR: an algorithm for sparse linear equations and sparse least squares». *ACM Trans. Math. Soft.*, 8, 43-71.

Spakman, W. (1986): «Subduction beneath Eurasia in connection with the Mesozoic Tethys». *Geol. Mijnbouw*, 65, 145-153.

Spakman, W. (1988): *Upper mantle delay time tomography. Thesis, Geologica Ultraiectina,* 53, University of Utrecht, Utrecht, 200 pp.

Spakman, W., G. Nolet (1988): «Imaging algorithms, accuracy and resolution in delay time tomography», in: *Mathematical Geophysics: a survey of recent developments in seismology and geodynamics*, Vlaar, N. J., Nolet, G., Wortel, M. J. R. and Cloetingh, S. A. P. L. (eds), Reidel, Dordrecht, 155-188.

Spakman, W. (1991): «Delay time tomography of the upper mantle below Europe, the Mediterranean and Asia Minor». *Geophys. J. Int.* (in press).

Spakman, W., S. van der Lee, R. D. van der Hilst (1991): «Structure of the European-Mediterranean mantle to a depth of 1400 km: preliminary results from P delay-time tomography». *EUG VI, Strasbourg, Terra Abstracts,* 3, 1, 173.

Van der Hilst, R. D., W. Spakman (1989): «Importance of the reference model in linearized tomographic inversions: images of subduction below the Caribbean plate». *Geophys. Res. Lett.,* 16, 1093-1097.