Crustal and upper mantle velocity structure of Southern Iberia, the sea of Alboran, and the Gibraltar arc determined by local earthquake tomography

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Abstract
A «local earthquake tomography» of a large area encompassing the South of Iberia, the sea of Alboran, the Gibraltar arc, and Northern Morrocco, has been performed using first arrival times recorded at various Spanish and Morroccan seismic networks. A total of 52 stations and 639 earthquakes provided over 6300 first *P* arrivals and 4400 *S* arrivals. Three features of interest appear in the results: i) a continuous low velocity structure which correlates with the Betics, the Gibraltar arc and the Rif; ii) a high velocity feature which persists to a depth of approximately 30 km, positioned near the coast of Malaga on the northern margin of the Alboran sea; iii) a low velocity feature, extending to a minimum depth of approximately 40 km, which coincides with the Granada basin and a strong negative Bouguer gravity anomaly.

Key words *tomography – Alboran – Mediterranean – Betics – structure – crust – upper mantle – seismicity*

1. Introduction

A local earthquake tomography has been performed for the area lying between the North of Arica and the Iberian peninsula. This region is interesting as it contains the boundary between the African and Eurasian plates. The nature of the crust of the Alboran sea and the Western-most Mediterranean is still relatively unknown, but recently ODP Leg 161, Site 976 reached the basement in the sea of Alboran (previous holes had only sampled sedimentary layers above basement). The core samples obtained from the Alboran sea basement were metamorphic rock, of the same nature as that found in the inner Betics and inner Rif, suggesting that these formations could extend across the sea of Alboran, and that the crust is continental in nature (Soto and Platt, 1995). High heat flow values (greater than 70 mW/m^2), and intermediate depth seismicity (occurring at a depth of approximately 90 km) with a seismically quiet depth range between approximately 30 km and the intermediate depth seismicity, make the area intriguing.

2. Study area

The area studied extended from 6.0W to 2.0W and from 34.0N to 380N. This area encompasses the Alboran sea in the Western-

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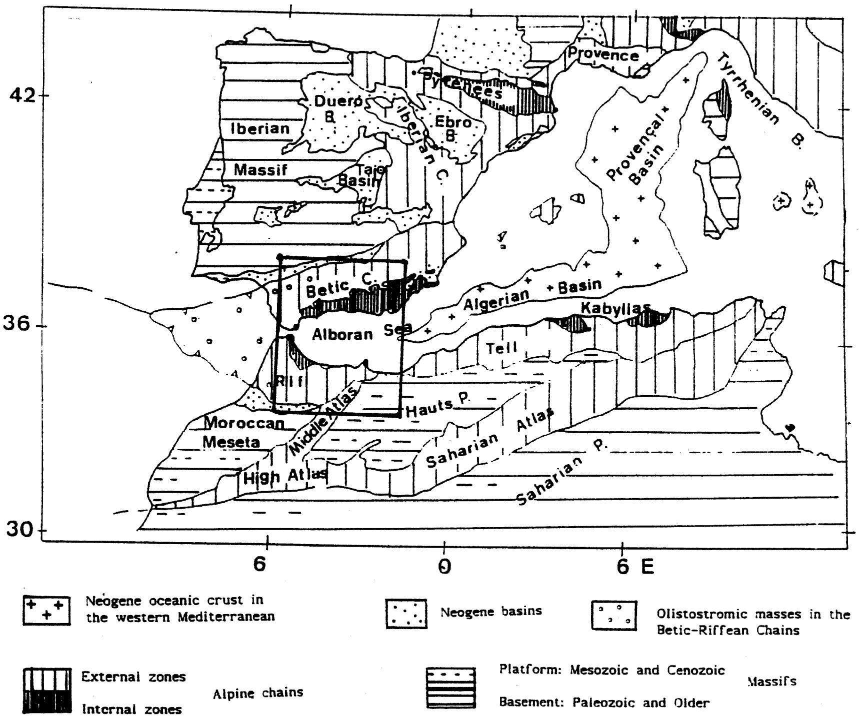


Fig. 1. Geologic and tectonic setting (Buforn *et al.*, 1995). The study area is indicated by the rectangle.

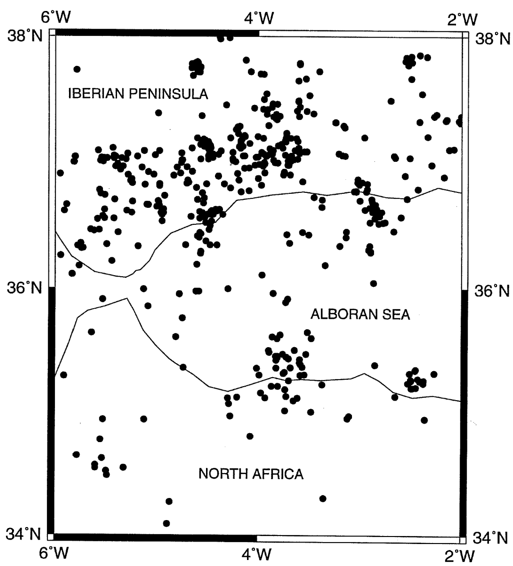


Fig. 2. Earthquake distribution.

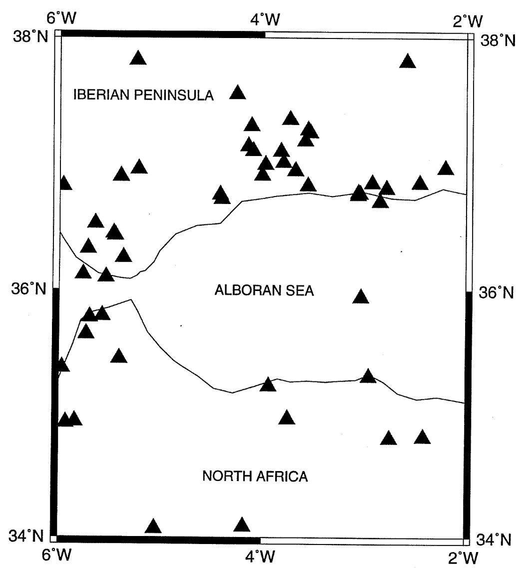
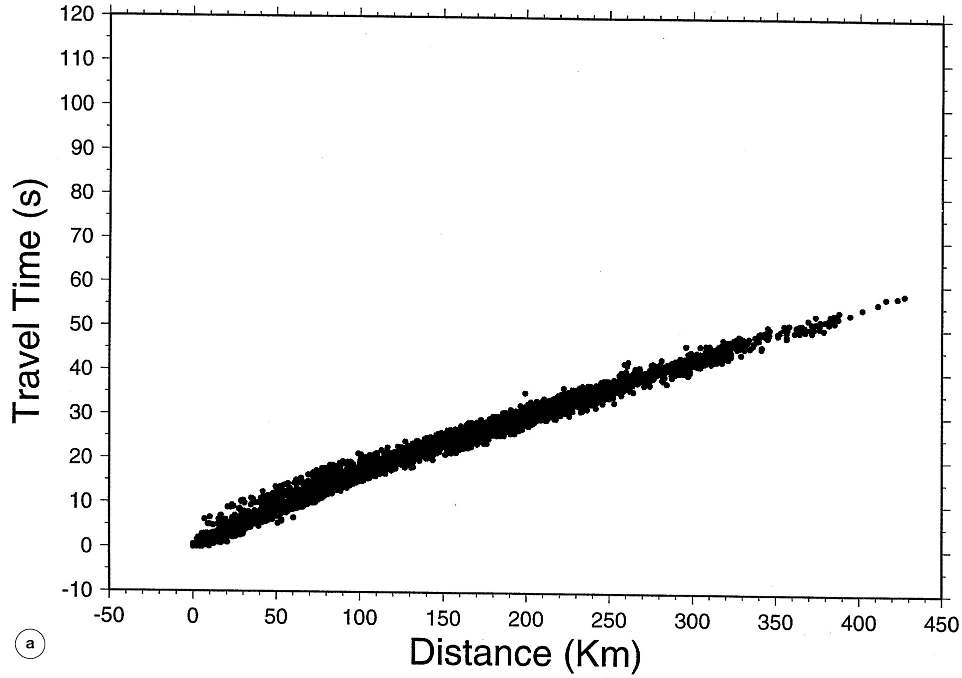


Fig. 3. Station distribution.



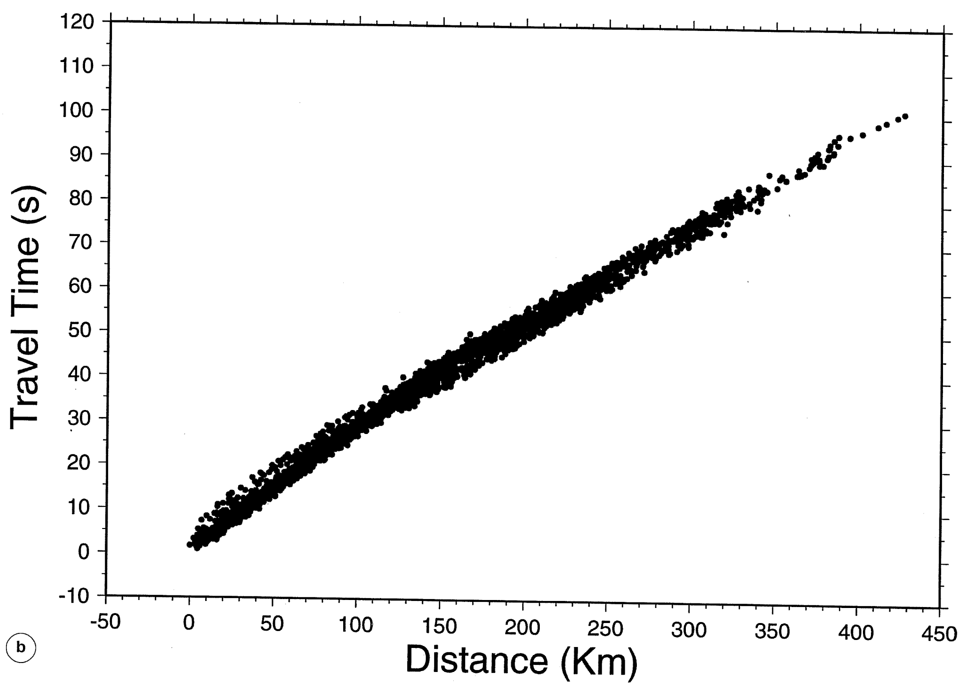


Fig. 4a,b. a) *P* distance-travel time data; b) *S* distance-travel time data.

most Mediterranean, the Gibraltar arc and the North of Morrocco (fig. 1).

Earthquake selection criteria – Earthquakes were selected according to the following criteria:

i) earthquakes having a depth < 150 km;

ii) minimum number of phases used in the initial location: 10;

iii) travel time r.m.s. error < 1.5 s.

The above criteria resulted in a set of 639 earthquakes. The study region contained 52 stations and the resulting first arrival time data consisted of 6370 *P* arrivals and 4448 *S* arrivals (figs. 2, 3 and 4a,b).

3. Method

Initial model – The study area was gridded horizontally by a 20 × 20 grid and was composed of eight layers. The initial model was the Instituto Geografico Nacional location model, which is a continental crustal model with Moho positioned at a depth of 31 km (fig. 5).

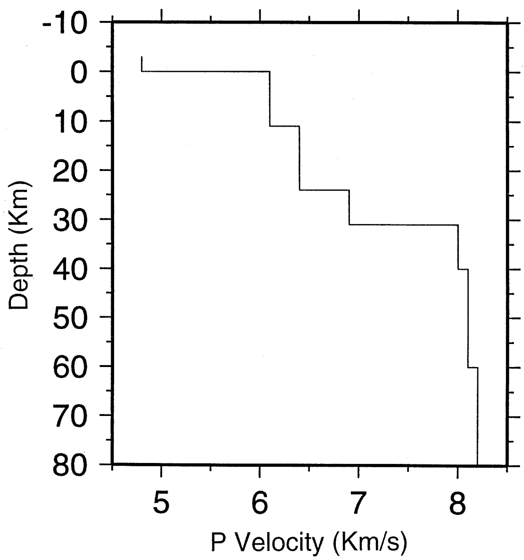


Fig. 5. Initial model employed for the linearized inversion.

The inversion code employed was developed by Thurber (Thurber, 1983), and was subsequently modified to include a Ray Tracer developed by Prothero (Prothero *et al.*, 1988). The latest version was updated by the Alessandrini-Beranzoli-Falcone-Mele group of the Istituto Nazionale di Geofisica (Alessandrini *et al.*, 1993.

The number of unknowns for the inversion of the study area was 5756, however nodes with a hit count < 15 were not inverted, hence the problem was overdetermined. Results shown were obtained with a velocity model parameter damping of 100, which was the optimum damping value determined from resolution-model variance trade-off curves. Nine iterations were performed, inverting for hypocentral and model parameters. The final average r.m.s. residual was reduced to a value of 0.68 s in the ninth iteration.

4. Discussion

Figures 6a-d show the inversion results. Information is shown only for the areas where the nodes have been inverted and correspond to a velocity parameter damping of 100.

Figures 7a-d show the spread-function plots for the corresponding velocity results shown in figs. 6a-d. The spread function is simply an attempt at displaying the resolution matrix in a physical way, such that it displays how smoothed the solution is at each node. The spread function is defined as (Toomey and Foulger, 1989):

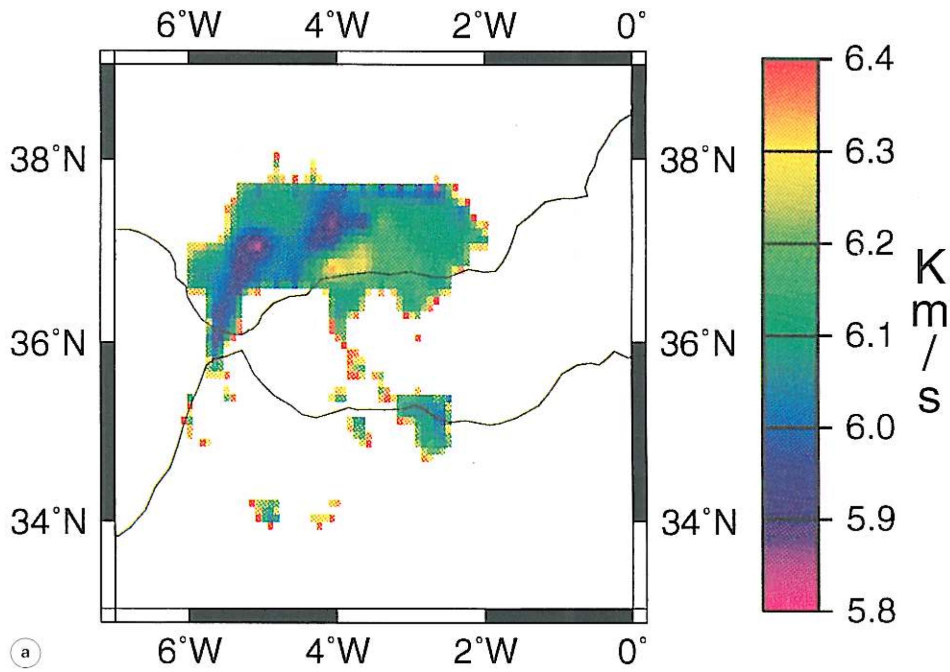
$$Sj = (\Sigma_i Dij * Rij^2)/(\Sigma_i Rij^2)$$

where:

Dij is the distance between grid nodes *i* and *j*;

Rij is the element of the resolution matrix of the *i*-th parameter (node), which corresponds to the *j*-th parameter (node).

The grid cells have an average size of 23 km in the *x* direction, and 23 km in the *y* direction, hence a «good» spread function value would be under 25 km. In the spread-function



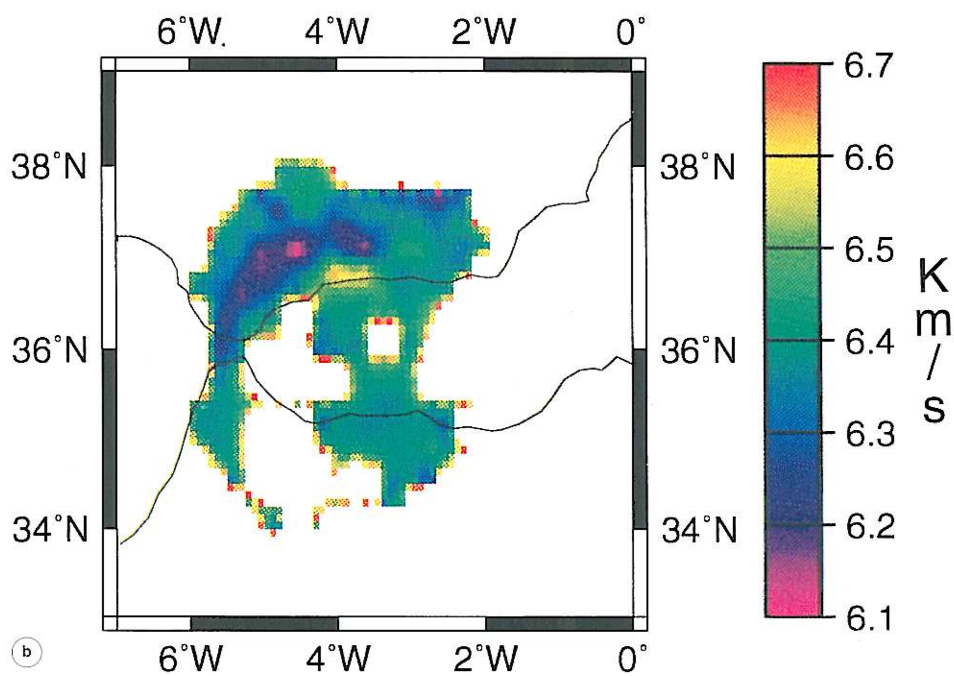


Fig. 6a,b. Inversion results: a) layer 1, depth = 0-11 km; b) layer 2, depth = 11-24 km.

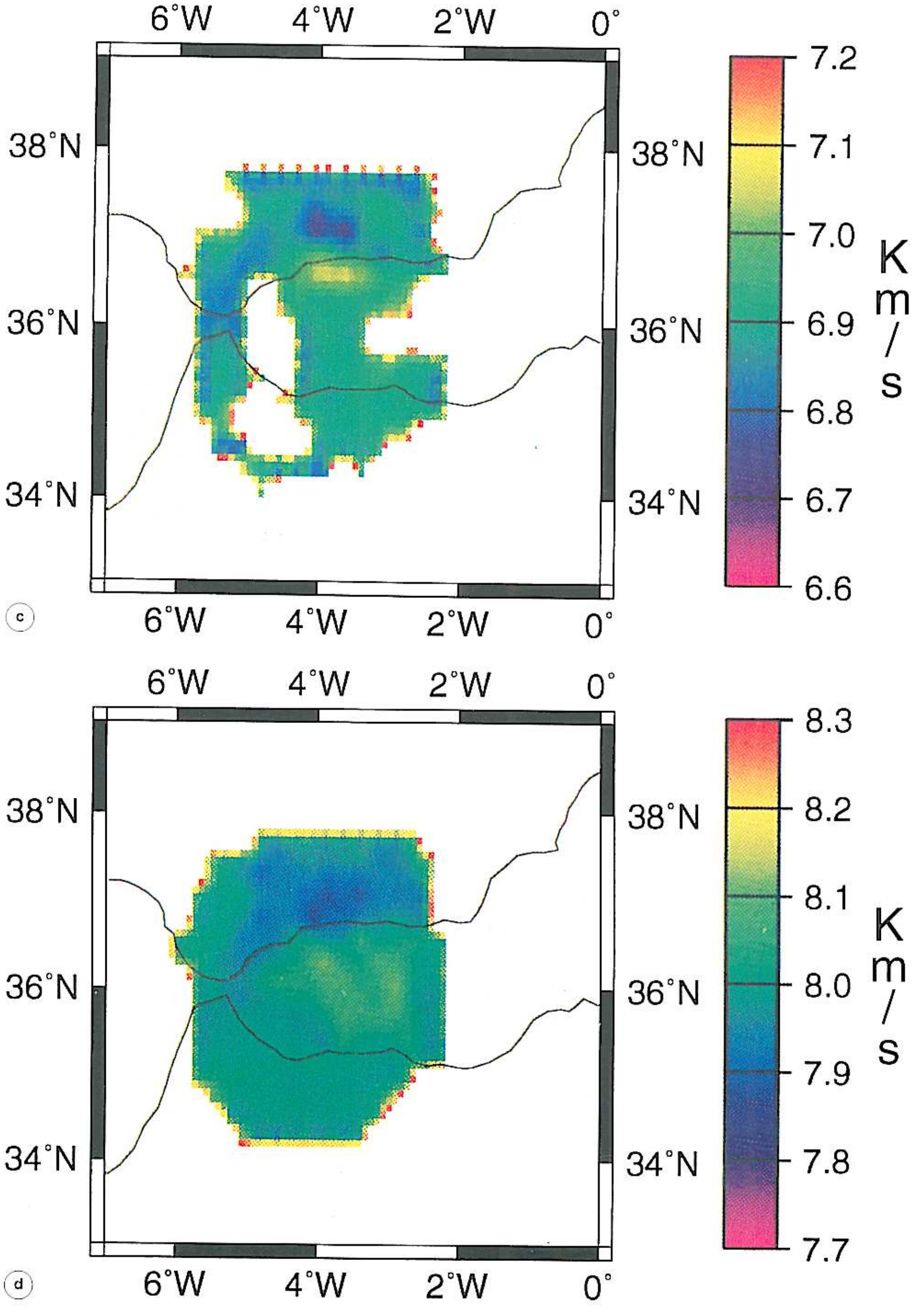
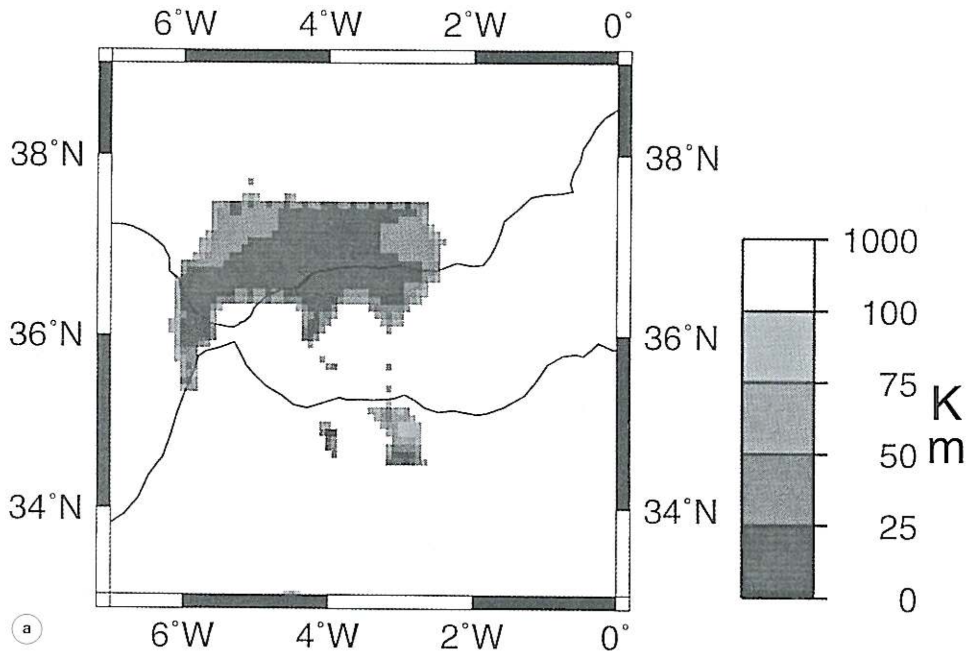


Fig. 6c,d. Inversion results: c) layer 3, depth = 24-31 km; d) layer 4, depth = 31-40 km.



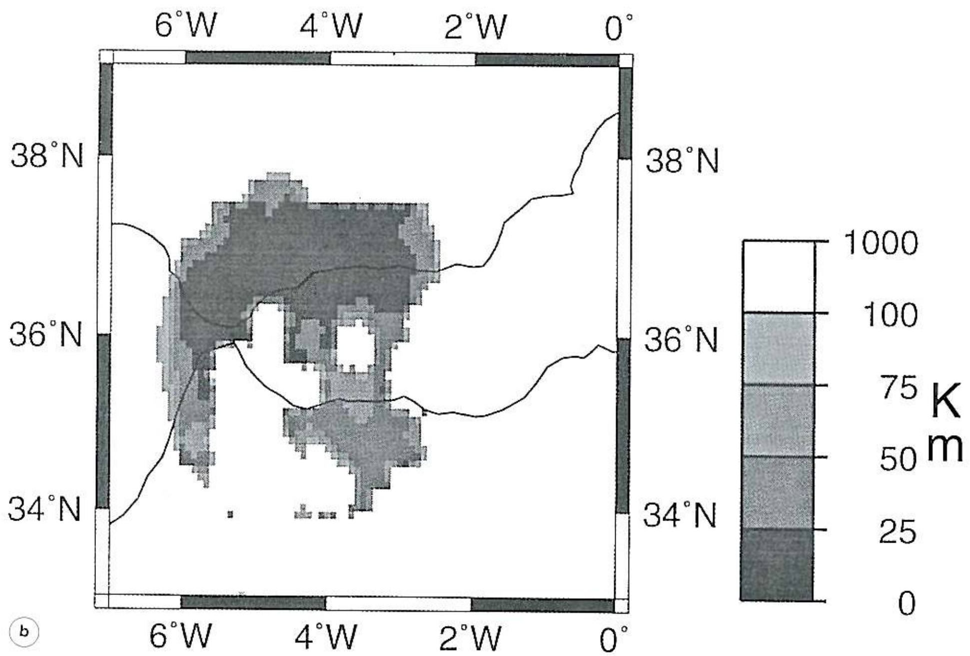
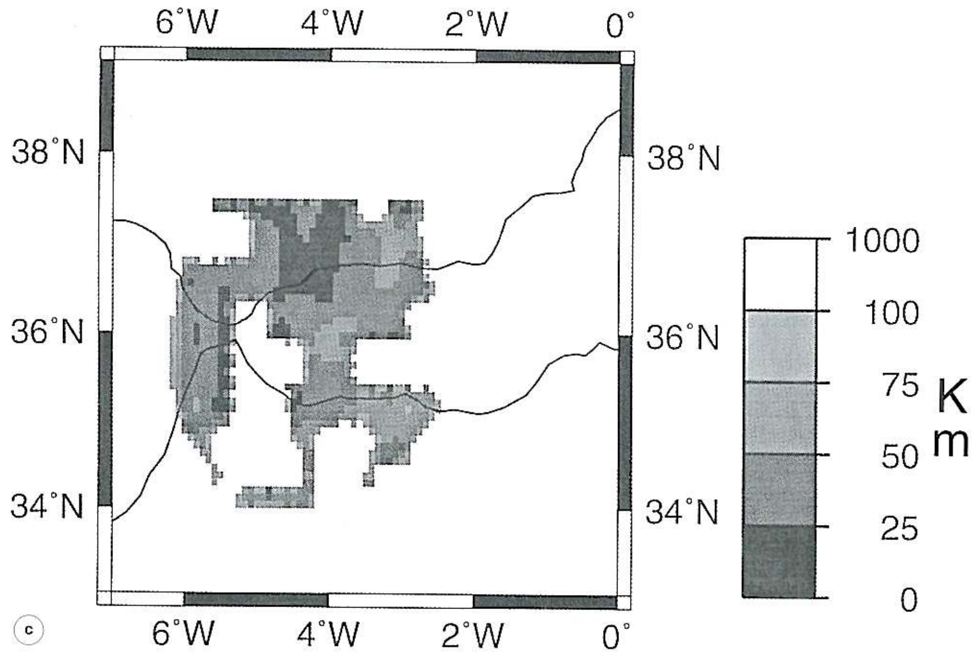


Fig. 7a,b. Spread function corresponding to the inversion results: a) layer 1, depth = 0-11 km; b) layer 2, depth = 11-24 km.



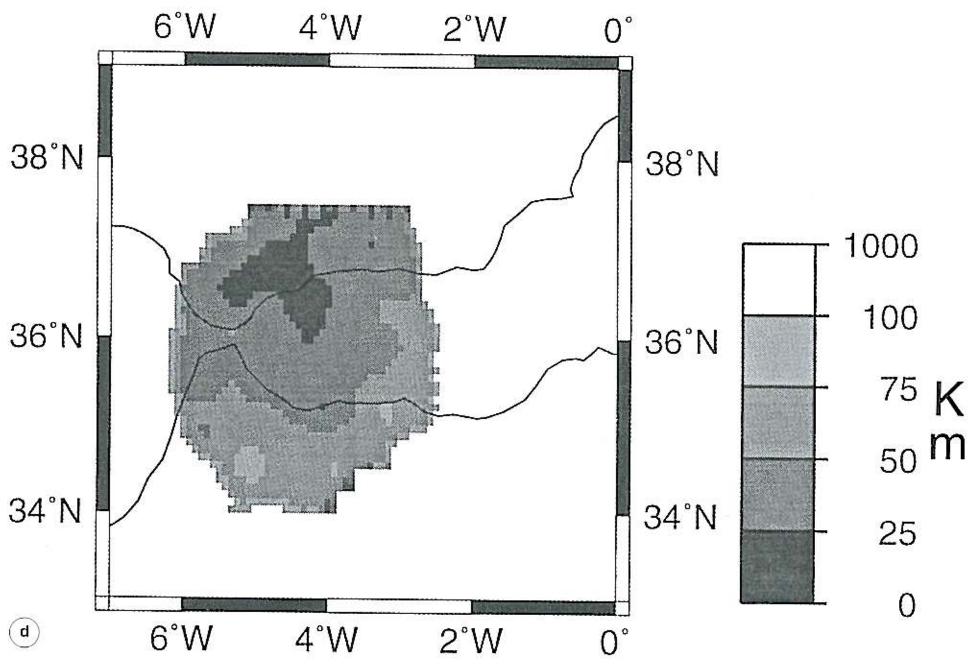


Fig. 7c,d. Spread function corresponding to the inversion results: c) layer 3, depth = 24-31 km; d) layer 4, depth = 31-40.

plots, the darkest grey tone indicates well resolved nodes.

In what follows we discuss the results shown in figs. 6a-d. One should bear in mind that the Earth model velocity features obtained are smoothed and damped and were constrained so as not to deviate too much from the initial model. This is simply a consequence of the linearization of the problem, required to perform the inversion. The velocity features should thus be interpreted as velocity features which improve the least squares fit of the travel time data for the hypocentre data set and initial earth model used, and should be interpreted only tentatively as velocity structures having those absolute velocities.

Figure 6a: depth 0-11 km – The initial model had a velocity of 6.1 km/s for this layer. We observe three main velocity features:

i) a lower velocity structure (5.9-6.0 km/s) extending along the Spanish side of the Gibraltar arc;

ii) a higher velocity feature (6.2-6.3 km/s), on the northern margin of the Alboran sea;

iii) north of the higher velocity feature mentioned in (ii) there is another lower velocity feature (5.9-6.0 km/s), which coincides with a strong negative Bouguer gravity anomaly (fig. 8).

Figure 6b: depth 11-24 km – The initial model had a velocity of 6.4 km/s. We observe the same continuous lower velocity structure (6.2-6.3 km/s, 6.3-6.4 km/s) along the Gibraltar arc. The higher velocity feature (6.5-6.6 km/s) on the northern margin of the Alboran sea, and the lower velocity feature just above it, persist.

Figure 6c: depth 24-31 km – The initial model had a velocity of 6.9 km/s. The lower velocity (6.8-6.9 km/s) arc-like structure persists, as does the lower velocity feature (6.7-6.8 km/s) associated with the negative Bouguer gravity anomaly. The higher velocity feature (7.0-7.1 km/s) on the northern margin of the sea of Alboran still exists but has shifted slightly southward with respect to its position in the previous two layers.

Figure 6d: depth 31-40 km – The initial model had a velocity of 8.0 km/s. The lower velocity structure (7.9-8.0 km/s) coinciding with the Betics, Gibraltar arc and Rif and the

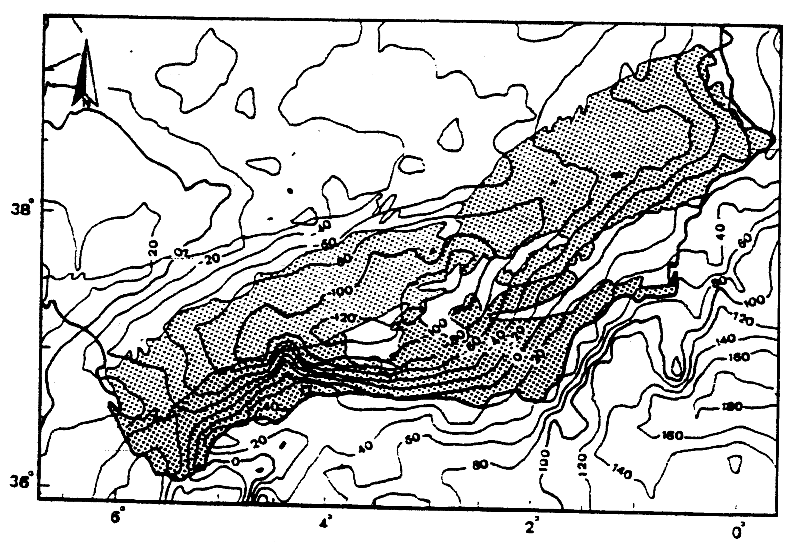


Fig. 8. Simplified Bouguer gravity anomaly map of the Betic Cordilleras, compiled from the B.G.I. database. Contour interval is 20 mGal (van der Beek and Cloetingh, 1992).

lower velocity feature (7.8-7.9 km/s), which coincides with the gravity anomaly, persist. The higher velocity feature observed on the northern margin of the Alboran sea in the previous figures, does not appear, but the Alboran sea basin itself is imaged as having a higher velocity (8.05-8.15 km/s) than the surrounding landmasses which have a velocity of 7.9-8.0 km/s.

5. Conclusions

Use has been made of the local earthquake tomography method to obtain structural information on a large area (4 degrees by 4 degrees). We obtained interesting information which correlates with the observed geology. Three interesting features are imaged in the study area: i) a continuous lower velocity feature which extends to a depth of 31 km-40 km and correlates with the Betics, Gibraltar arc, Rif and Tell; ii) a higher velocity feature which exists to a depth of 24-31 km in the northern margin of the Alboran sea; iii) a lower velocity feature which coincides with the Granada basin and a strong negative Bouguer gravity anomaly, and which can be imaged to a depth of 31-40 km, but which could extend to greater depth.

The depth of these features is uncertain as at the moment we are not able to say if there is a vertical «numerical smearing» effect. The higher velocity feature on the northern margin of the sea of Alboran could indicate a thinner crust; this higher velocity feature could be greater in extent, but the data did not illuminate the sea of Alboran equally at all the sampled depths.

Acknowledgements

This work forms part of the collaborative European Union project «Southern Europe Network for Analysis of Seismic Data», headed by the Istituto Nazionale di Geofisica, Rome and partnered by the National Observatory, Athens and the Instituto Geografico Nacional, Madrid. The authors wish to thank the very generous, warm and helpful group of the Istituto Nazionale di Geofisica: in particular Bruno Alessandrini, Laura Beranzoli, Bruno De Simoni, Claudia Falcone and Franco Mele.

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