Tomographic image of the crust and uppermost mantle of the Ionian and Aegean regions

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Abstract
We present a tomographic view of the crust and uppermost mantle beneath the Central Mediterranean area obtained from *P*-wave arrival times of regional earthquakes selected from the ISC bulletin. The *P*-wave velocity anomalies are obtained using Thurber's algorithm that jointly relocates earthquakes and computes velocity adjustments with respect to a starting model. A specific algorithm has been applied to achieve a distribution of epicentres as even as possible. A data set of 1009 events and 49072 P_g and P_n phases was selected. We find a low velocity belt in the crust, evident in the map view at 25 km of depth, beneath the Hellenic arc. A low velocity anomaly extends at 40 km of depth under the Aegean back arc basin. High velocities are present at Moho depth beneath the Ionian sea close to the Calabrian and Aegean arcs. The tomographic images suggest a close relationship between *P*-wave velocity pattern and the subduction systems of the studied area.

Key words *travel time inversion – ray tracing – subduction*

1. Introduction

The dominant tectonic feature of the Central Mediterranean area is the subduction of the African plate beneath the Eurasian plate. In particular the Ionian lithosphere, supposed of continental type (McKenzie, 1978; Le Pichon and Angelier, 1979), subduces westward beneath the Calabrian arc and eastward beneath the Hellenic and Dinaric Alps (Moretti and Royden, 1988). As a result the Aegean and the Tyrrhenian basins exhibit the characteristic structure of marginal seas with volcanic activity, isostatic anomalies, and relevant heat flow (Cermák, 1982).

The seismicity, much higher than in the surrounding zones, is mainly associated with the Apennine-Maghrebides and Hellenides orogenic belts. These areas show remarkable features of island arcs with intermediate depth earthquakes down to about 200 km in the Aegean sea and down to about 450 km underneath the Tyrrhenian sea (Papazachos, 1973; McKenzie, 1978).

Due to the geodynamic evolution of the area, crustal thickness undergoes strong variations over a range of 15-25 km beneath the back arc basins to 40-60 km beneath the orogenic belts. The seismic wave velocity field is expected to be considerably complex especially in the shallower part of the Earth structure (surface down to Moho).

The results from teleseismic tomography have given a description of the *P*-wave velocity structure of the whole Mediterranean man-

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tle with a spatial resolution of about 80-100 km (Spakman *et al.*, 1993). Other studies, focused on local scale data, identified small scale structures of very restricted areas (spatial resolution of about 2-5 km) (Amato *et al.*, 1990; Chiarabba *et al.*, 1995). In both cases very few details are available on the large-scale structure of the crust and uppermost mantle.

Regional and local seismicity data make several seismic ray-path intersections available for crustal tomography. The resulting «illumination» of the structures under investigation improves the details of the velocity anomaly distribution in the crust and in those portions of the uppermost mantle sufficiently sampled by the ray paths.

Papazachos *et al.* (1995) and Alessandrini *et al.* (1995) recently presented the description of the *P*-wave velocity structure of the crust and uppermost mantle of the Aegean and Italian regions respectively obtained through the tomographic inversion of arrival times of regional events.

In the present work we used 1009 regional events, with at least 20 *P*-wave arrival times each, to find out the *P*-velocity field in the crust and uppermost mantle beneath Southern Italy, the Ionian sea, the Greek peninsula and the Aegean sea. The epicenters were in the region 34-42°N of latitude and 10-30°E of longitude. The resulting model exhibits strong velocity contrasts mainly influenced by the crust thickness. Recognisable features are the low velocity under the Apennine and Hellenides in the crust and the high velocity beneath the back arc basins. In the upper mantle a relevant high velocity anomaly extends below the Hellenides and the Hellenic arc. A similar trend, although less evident, is present below the Calabrian arc. We show east-west *P*-wave velocity cross-sections, where high velocity structures appear as the image of the uppermost portion of the slabs.

2. Data and method

We selected from the ISC catalog (years 1964-1992) 12500 events falling within 34°N and 42°N of latitude and 10°E and 30°E of longitude. All the selected earthquakes occurred at a depth not exceeding 280 km and were recorded by at least 20 stations falling within 32°N and 44°N of latitude and 8°E and 32°E of longitude. After sorting the events by decreasing number of phases, we considered all the pairs of events having both a difference in depth under 5 km and an epicentral distance under 50 km (retaining the event with a greater number of first arrivals and discarding the other). This was done to reduce the total number of events and to avoid the same ray path being weighted twice. This selection resulted in a dataset of 1009 events and 49072 first arrival times.

The velocity distribution is modeled with a 3D rectangular grid with velocities assigned to each grid-point and computed at any other point within the model through a linear interpolation. Hypocenter locations and 3D velocity distribution are jointly determined with the progressive inversion method developed by Thurber (1983). At each iteration the inversion scheme solves a linearized system of equations relating travel time residuals, hypocenter parameters (location and origin time) and model parameters (the adjustments to the velocity of the nodes). The model parameters and the hypocenter parameters were decoupled with the method of Pavlis and Booker (1980). The rays were traced at each iteration with the pseudo-bending method of Prothero *et al.* (1988). The inversion proceeded for five iterations with significant reduction of the variance, as computed with an *F*-test.

To give a quick view of the reliability of the results we computed the spread function F_i as defined by Toomey and Foulger (1989):

$$F_i = \frac{\Sigma_{j=1}^{N} R_{ij}^2 \, d_{ij}}{\Sigma_{j=1}^{N} R_{ij}^2}$$

where R_{ij} is an element of the resolution matrix, d_{ij} is the distance between pairs of nodes and N is the number of inverted nodes. Well solved areas are characterized by low values of the spread function.

The starting *P*-wave velocity model (table I) has been previously used in tomographic studies

Table I. 1D starting model.

Depth (km)	Velocity (km/s)
0	6.4
25	6.7
37	6.9
40	8.0
100	8.1
180	8.3
280	8.6

of the Italian region (Alessandrini *et al.*, 1995) and Southern Tyrrhenian basin (Selvaggi and Chiarabba, 1995). We extend the model to the Aegean region that is geodynamically similar to the Southern Tyrrhenian area.

The data variance in the starting model is 0.82 s^2. The two-point 3D ray-tracing algorithm by Prothero *et al.* (1988) has been adopted, being satisfactorily fast and suitable for our model parametrization (Alessandrini *et al.*, 1995).

3. Results

The region examined in this work has attracted the interest of many authors because of its tectonic complexity due to the interaction of the African and the Eurasian plates and the intense seismic activity.

We investigated the region making use of local and regional earthquake data. We focussed our attention mostly on the crustal part of the area even though the results concerning the Calabrian and Hellenic arcs are explored down to about 200 km of depth.

There is not much literature on the regional scale structure of this area mostly for the first tens of kilometers of depth (see for the Italian region Alessandrini *et al.*, 1995; for the Greek and Aegean region, Papazachos *et al.*, 1995).

The velocity anomaly distribution we found in this work presents similarity with the results produced with different techniques and data for the same area (see for example Drakatos and Drakopoulos, 1991; Ligdas *et al.*, 1990; Spakman *et al.*, 1993) although a full comparison cannot be straightforwardly performed, because of the different Earth structure sampling and the different techniques used.

A large anomaly structure following the Hellenides and the Hellenic arc is immediately evident: it is a low velocity anomaly in the shallower part of the crust and a high velocity anomaly at Moho depth. The same anomaly pattern is slightly recognisable beneath the Calabrian arc.

These two zones characterised by very intense seismic activity extend along the plate contact zones. The plot of the results is presented with the corresponding spread function.

Each of the following figures includes the top or the cross-section view of the velocity field on the left and the corresponding spread functions on the right. In the color bar below the velocity model plots, the red and blue colors indicate low and high velocity respectively. In the top view the velocity variations span a range of ± 8% with respect to the value assigned in the starting velocity model at that depth. The velocity variations in the cross-sections span a range of ± 22% with respect to an indicated mean value. In the color bar below the spread fuctions the red colors show the minimum values (in km).

Figure 1a,b shows the tomographic results of the mid crust (25 km). The extension of the well resolved area is confined to Greece, the Aegean basin, the Western Anatolian peninsula and the Calabrian arc. The main feature is a sharp velocity contrast in the Greek and Aegean areas. Low velocities are revealed along the Hellenic arc in correspondence with the presence of unconsolidated material (Makris, 1973). The low velocity belt coincides with the negative Bouguer anomaly as shown in the West East Europe Gravity Project Map (1996). The existence of a marked negative velocity anomaly between the Kephallina island and Northwestern Peloponnesus is supported by the absence of hypocenters and the systematically observed positive residuals of *P*-waves recorded at the stations near this region. A similar pattern is observed north of

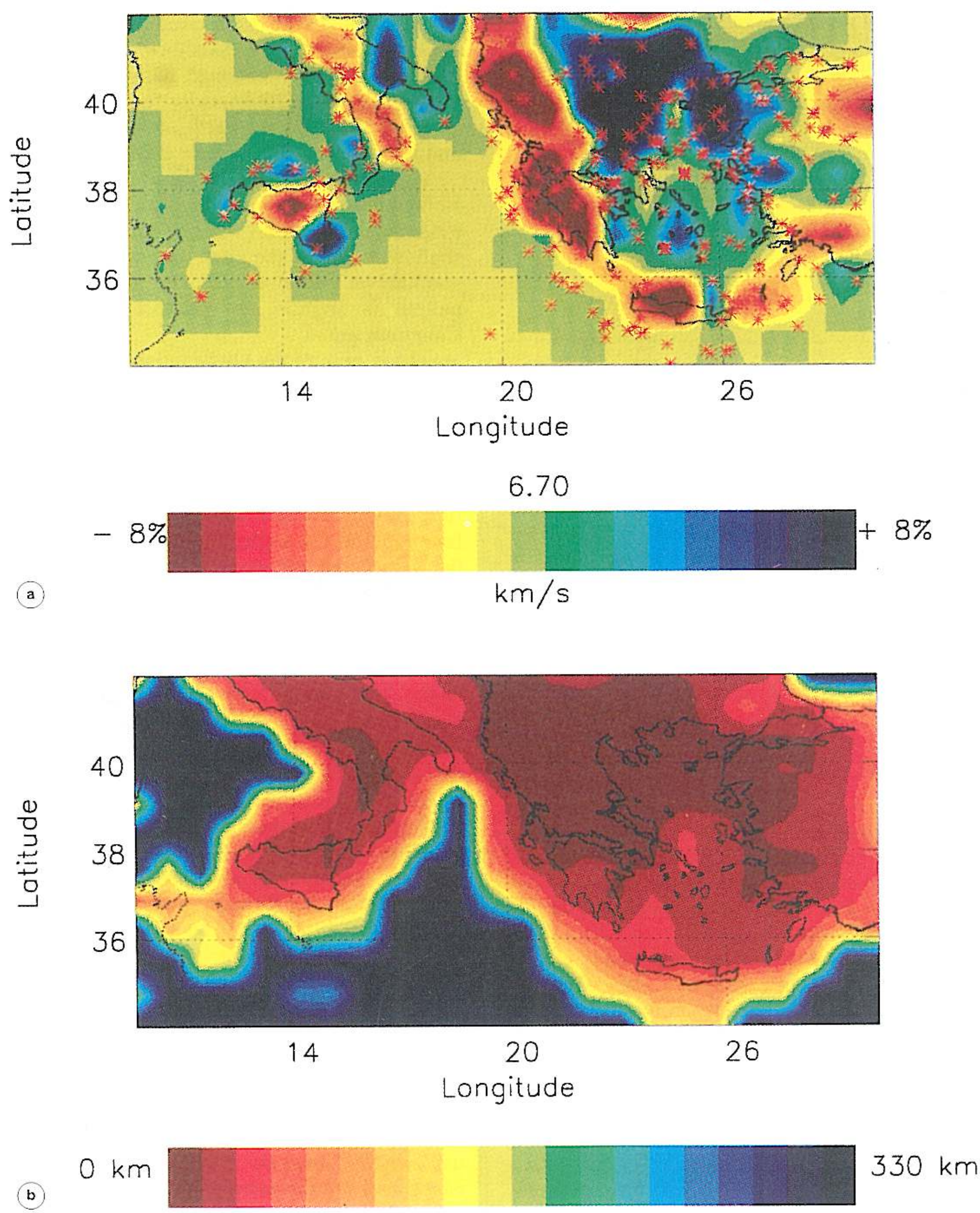


Fig. 1a,b. Map view of the resulting model at 25 km of depth: a) velocity field and hypocentres at that depth range; b) spread function.

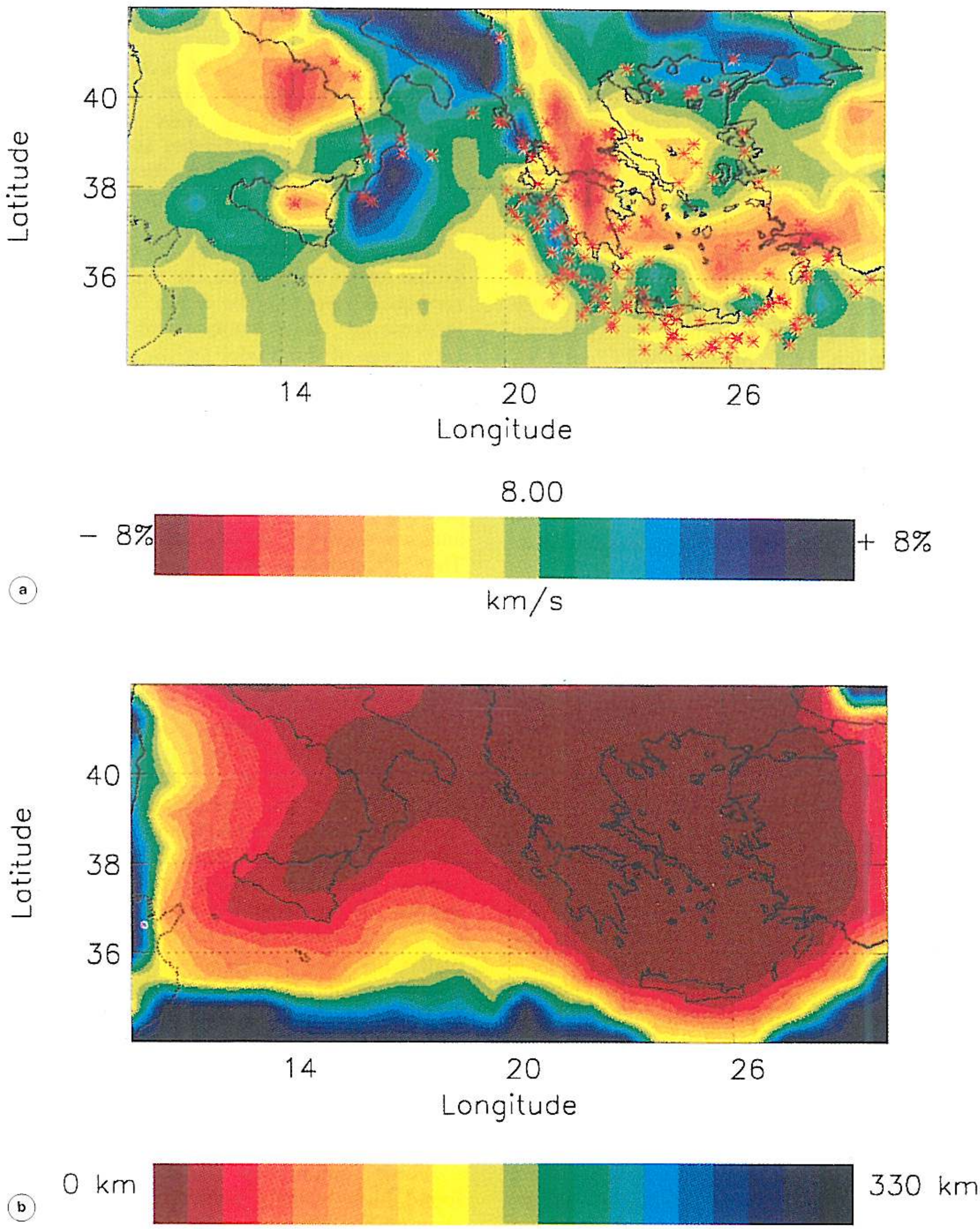


Fig. 2a,b. Map view of the resulting model at 40 km of depth: a) velocity field and hypocentres at that depth range; b) spread function.

Crete where poor shallow seismicity occurs. The positive Bouguer anomalies beneath the Aegean basin extend in an area of high *P*-wave velocity. The small low velocity zone in the Central Aegean sea nearly corresponds to the distribution of the Neogene-Quaternary grabens. The crust of this region consists of soft materials of relatively high temperature. This suggests a large-scale absorption of seismic energy. The sharp velocity contrast beneath Southeastern Sicily can be interpreted as the transition between two different crustal domains: the Ionian plate and the Apenninic chain (Nicolich, 1989; Selvaggi and Chiarabba, 1995).

Figure 2a,b shows the *P*-wave velocity field and the spread function at 40 km of depth.

The areas with highest resolution are Southern Italy, the Southernmost Adriatic basin, Northern Ionian basin, Greece, Aegean basin, eastern part of the Balkan peninsula and Western Anatolian peninsula.

A high velocity zone is predominant along the Hellenic trench and the Southeast Calabrian arc in coincidence with the shallower part of the opposed Ionian slabs. The high velocity beneath the Hellenides extends towards north-west under the Southern Adriatic basin where the crust is supposed to be of continental type (Makris, 1978). The appearance of a high velocity zone at the north-eastern part of the Aegean basin is an evident feature obtained also by other investigators (Christodoulou and Hatzfeld, 1988).

In coincidence with the Tyrrhenian and Aegean back-arc basins a decrease in the *P*-wave velocity is observed. Inside these areas a relevant volcanic activity is also present (Etna in Sicily, Aeolian Islands, inner volcanic arc in Southern Aegean) and high heat flow, evaluated at Moho, have been associated with weakened and thin crust (Cermák, 1982).

Figure 3a,b shows as in the previous figures the result at 100 km of depth. The spread function reaches minimum values beneath Greece and the Southeast Aegean basin and, as expected, the reliability of the results is confined where deep earthquakes (red stars) occur. A sharp positive velocity anomaly extends in a north-south direction beneath Hellenides while a modest low velocity anomaly is centered in the Southeast Aegean.

A set of west-east cross sections of the velocity field are presented (see fig. 4) together with the corresponding value of the spread function. The east-west cross sections are ordered from south to north, they are labelled from 1 to 6 to indicate their position in the top map view.

The depth of the model has been set down to 280 km to include the ray paths of the deep earthquakes beneath the South Tyrrhenian and Hellenic arc; as a consequence these are the only areas of the model satisfactorily resolved down to about 200 km.

Almost all the velocity plots exhibit an evident rising of the velocity isolines from the uppermost mantle in the depth range 50-200 km along the Calabrian and the Hellenic arcs, pointing out the presence of high velocity anomalies related to the subduction systems. The corresponding small values of the spread function ensure the reliability of this result.

4. Conclusions

There is a good correspondence in anomaly signs and patterns of our results with those found by Spakman *et al.* (1993) at 51 km of depth. However the velocity anomalies of their model are lower in amplitude: these authors used an approximate iterative least-square inversion method, in which amplitude response depends on the density of ray sampling and the number of iterations performed, while a full matrix inversion is applied in this work.

The results obtained by Papazachos *et al.* (1995) also show similarity in the anomalies distribution. However the data set used garantees an adequate coverage of ray paths only for Greece and the Aegean region. So the velocity anomalies beneth the Ionian sea are not clearly visible.

Some authors (see Spakman *et al.*, 1993) found high velocity values dipping down to about 600-1000 km, in coincidence with the lower crust and uppermost mantle anomalies we obtained in this work. The latter were interpreted as the images of the slabs. From the

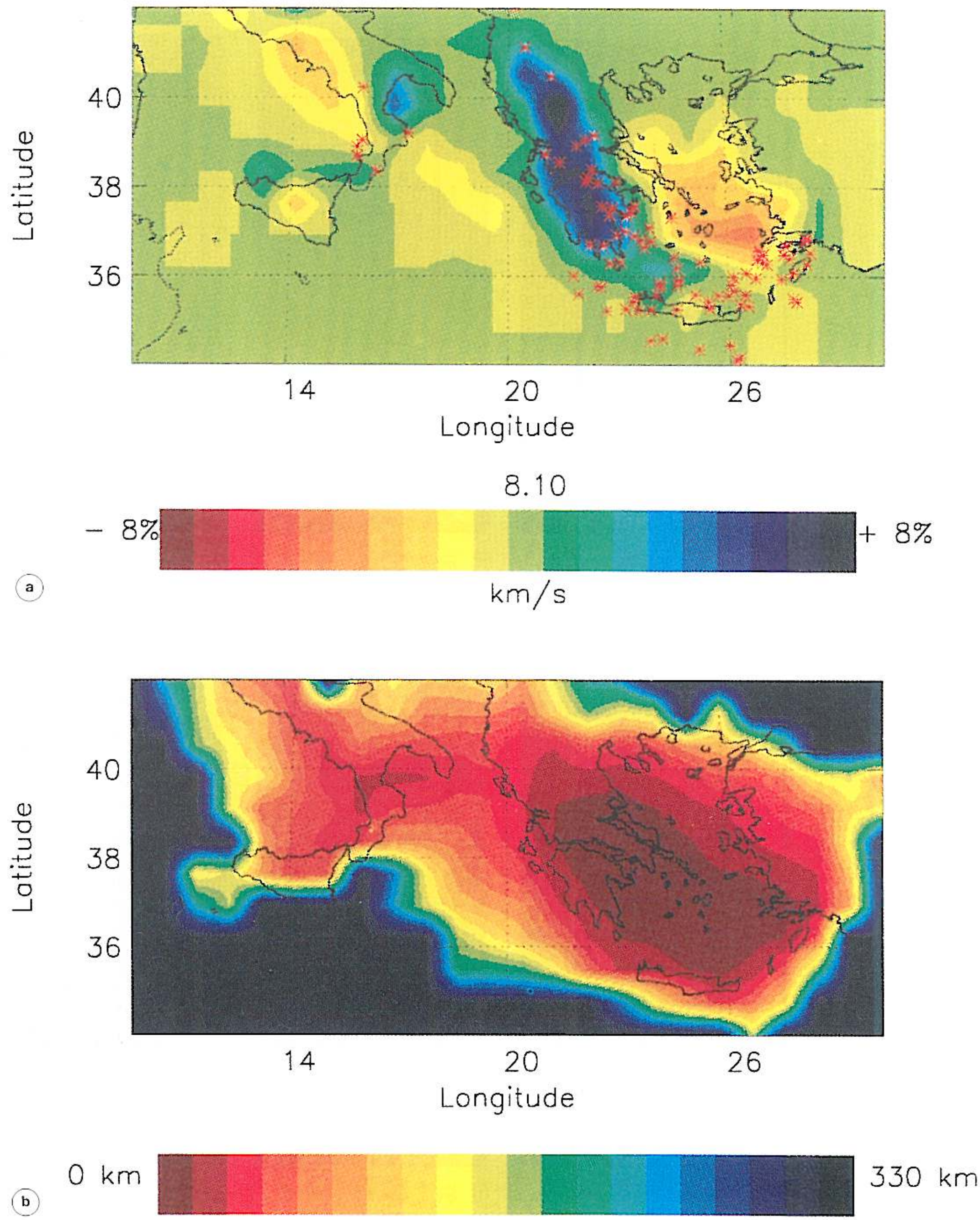
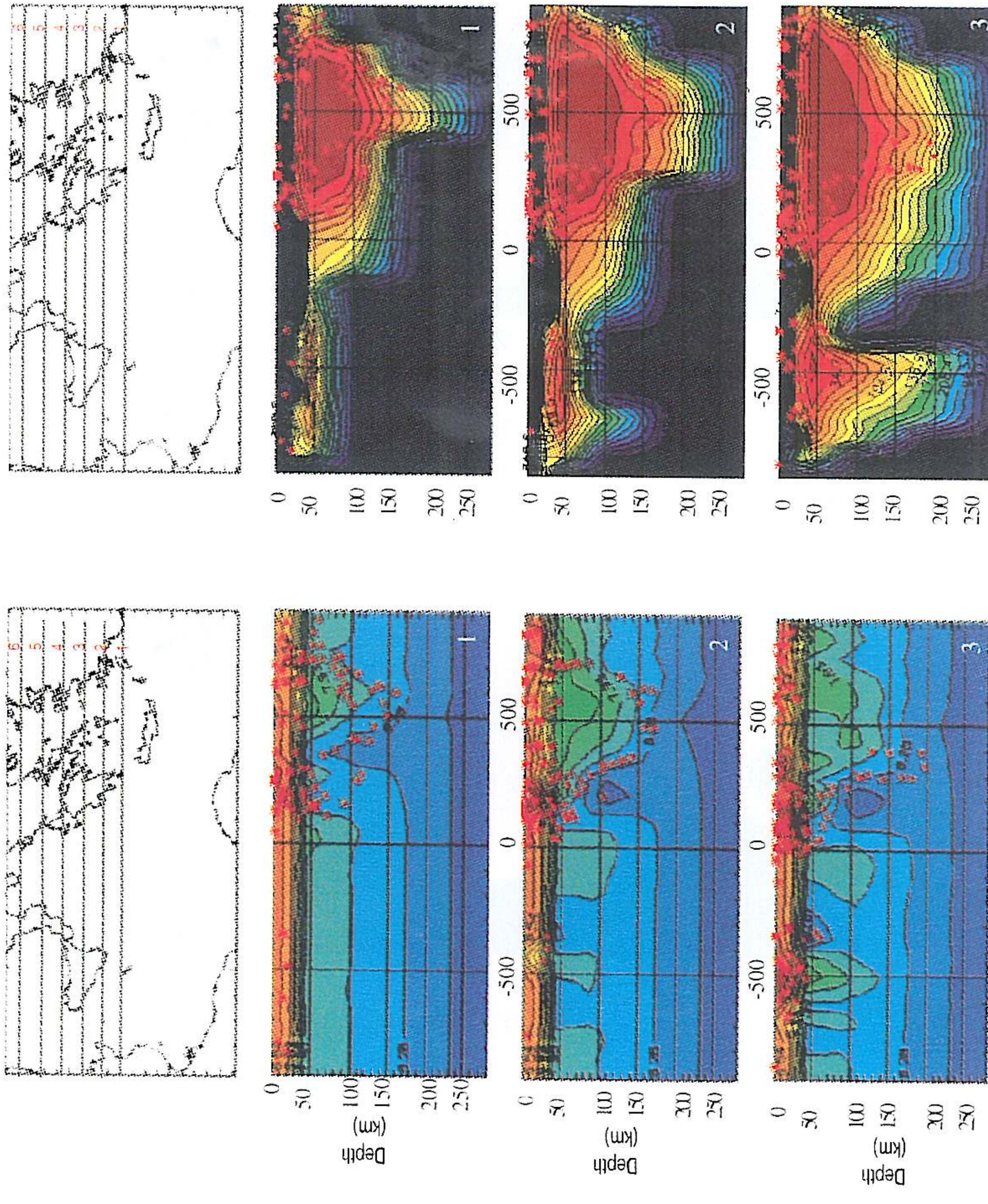


Fig. 3a,b. Map view of the resulting model at 100 km of depth: a) velocity field and hypocentres at that depth range; b) spread function.


Depth (km)
0
50
100
150
200
250
-500
0
500
1
2
3

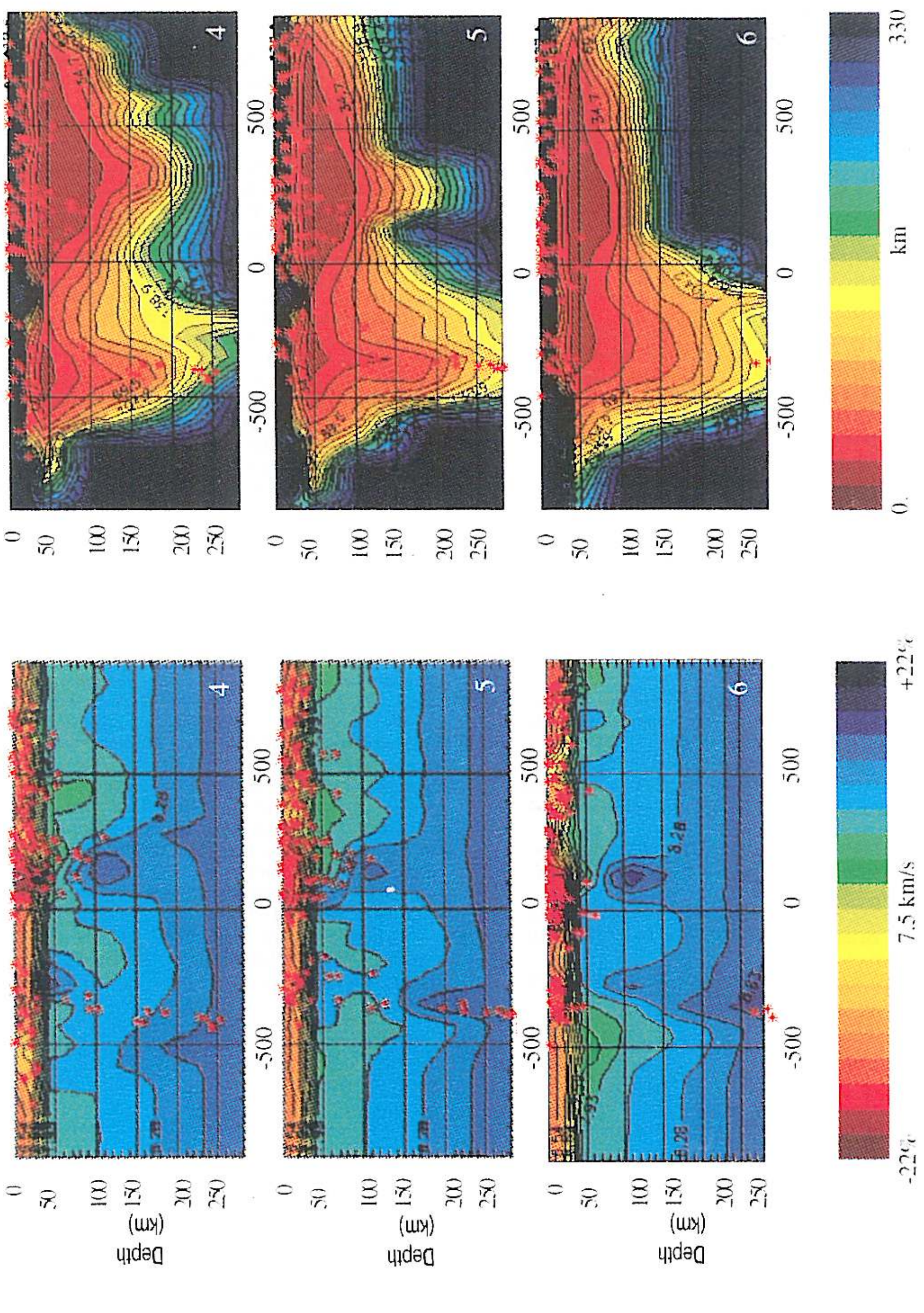


Fig. 4. East-west cross sections of the resulting model down to 280 km of depth. Velocity models at left, corresponding spread functions at right, label from 1 to 6 correspond to the cross sections.

cross sections previously presented in this work, the slope of the slabs is not visible even though the comparison between figs. 2a,b and 3a,b reveals that the high velocity anomaly along the Hellenic trench sinks eastward.

We can conclude that the lower crust and uppermost mantle anomalies we found could be interpreted as the image of the uppermost part of the subduction systems.

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