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Seismic anisotropy in tomographic studies of the upper mantle beneath Southern Europe

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Abstract
Regional seismic tomography of Iberia, Italy, the South Balkans and the Aegean region down to about 400 km are discussed along with results of studies on the anisotropic structure of the lithosphere based on an analysis of spatial variations of *P*-residuals. The *P*-residual spheres, showing azimuth-incidence angle dependent terms of relative residuals, map lateral changes of the anisotropic structure of the subcrustal lithosphere related to large tectonic units. Isotropic velocity perturbation models correlate, in general, with models of the lithosphere thickness but in some provinces they are affected by neglecting the anisotropic propagation within the lithosphere.

Key words *subcrustal lithosphere – upper mantle heterogeneities – seismic anisotropy – velocity perturbation – residual spheres*

1. Introduction

Southern Europe and generally the Mediterranean area is a region of active tectonics manifested by the highest seismic activity of the entire European continent. Intensive tomographic research has been oriented toward this region (*e.g.* Spakman *et al.*, 1993; Amato *et al.*, 1993a) contributing to understanding both present active continent-continent collision (Serber *et al.*, 1996) and past geodynamic development (Amato *et al.*, 1993b; Papadopoulos, 1993).

Distinct high-velocity heterogeneities related to the subducting lithosphere seem to be traced down to depths of more than 1000 km in tomographies of the whole Mediterranean. The authors hypothesize slab detachments in the upper mantle resulting in a curved shape of the subductions (Wortel and Spakman, 1992). On the other hand, smaller size regional tomographies map positive velocity perturbations down to about 400-500 km, with depth-decreasing amplitudes (Babuška *et al.*, 1990; Cimini and Amato, 1993; Amato *et al.*, 1993a; Selvaggi and Chiarabba, 1995), without a need to extend the perturbations to greater depths.

Standard tomographic approaches based on isotropic 3D inversion of deviations in travel times of *P* and/or *PKP* waves suffer from unfeasibility to consider anisotropic wave propagation within the upper mantle, which have now become a commonly proved and widely accepted phenomenon. Effects due to anisotropy are of the same order as the effects due to heterogeneities (Anderson, 1989), with well-known trade-off between them. Nevertheless, in many regions the isotropic inversions can provide the first order approximation of the upper mantle heterogeneities (Gresillaud and Cara, 1996). However, we have to be

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aware of a danger of introducing possible false heterogeneities or errors in location of existing ones due to neglecting the anisotropy.

The aim of this contribution is to search for the upper mantle structures beneath Southern Europe with the use of both a standard isotropic tomographic method (ACH) and an anisotropic approach (Babuška *et al.*, 1984). Rather then performing very detailed and complicated isotropic inversion schemes (with isotropic ray-tracing), we focus on a search for detecting the upper mantle anisotropy and a discussion of possible effects caused by neglecting the anisotropy in the standard tomographies.

2. Methods

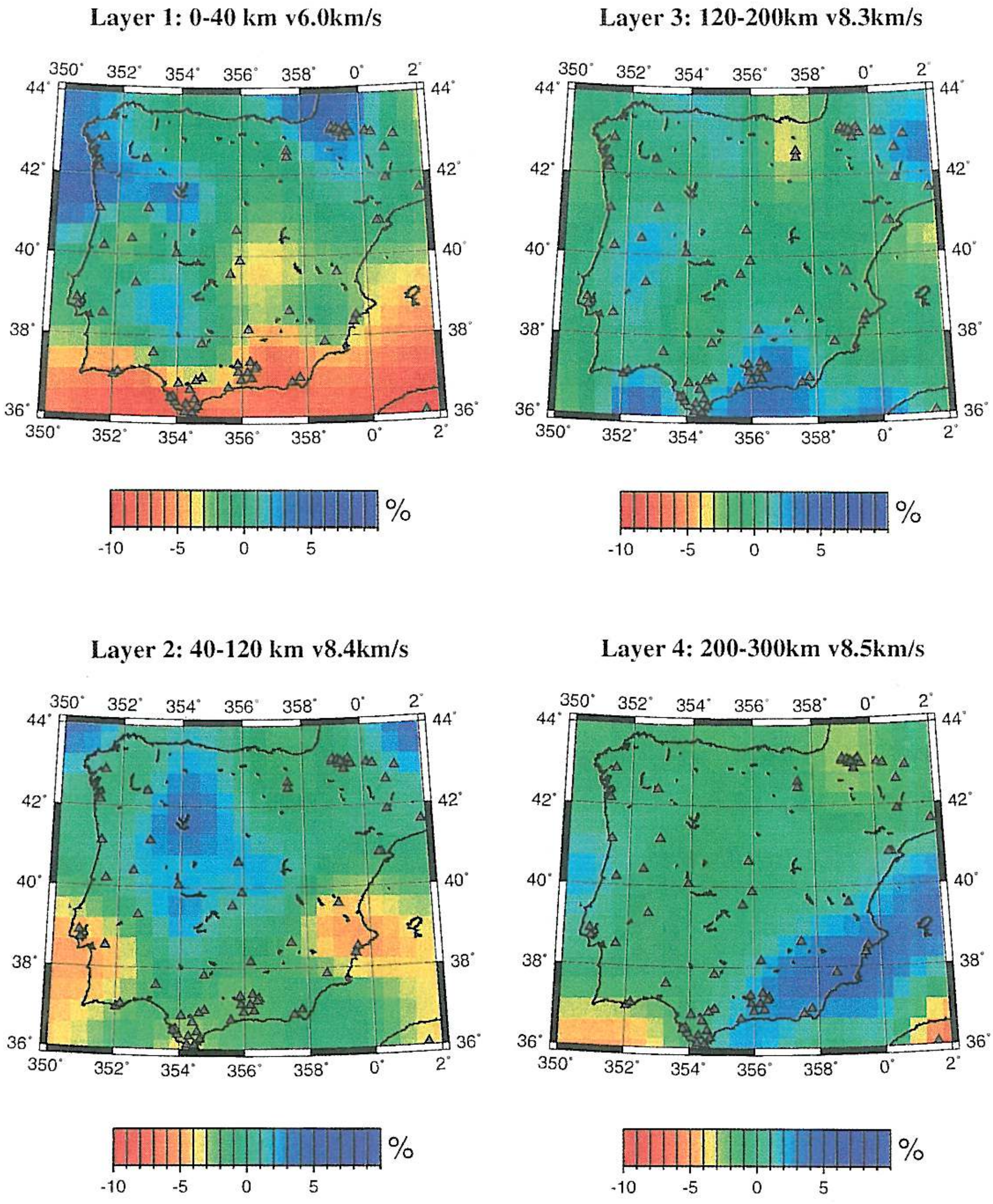
Standard tomographic studies of the Earth invert travel-time deviations of *P* waves (*P* residuals) of single events into 3D velocity perturbation or velocity models consist of *a priori* determined rectangular blocks beneath the region, down to an arbitrarily chosen depth. The well-known high noise present in the ISC bulletin data, in some cases with reading errors as high as 1 s, is the most important reason for low variance improvements, when the bulletin data of single events are used. It is usually lower than 40%, in spite of 90% or more obtained for data from local seismic networks. To decrease the effects of a data noise and uneven distribution of earthquake foci relative to the region under tomographic research, we preprocess the residuals as described below.

The residuals are pre-processed in such a way that the relative residuals are grouped within source regions, and an average residual ($R_{i,\,k}$, i stands for a station, k for a source region) and a synthetic ray are computed for the source region. Usually, a set of crustal corrections is introduced to smooth down effects from variations of crustal thickness and velocity. Besides investigating the Earth's lithosphere and the upper mantle by means of the ACH inversion technique, we analyze sets of discrete values at individual stations focused on a search for anisotropic structure of the lithosphere. A static, directionally independent term (R_i) and azimuth-incidence angle dependent terms (${}^{A}R_{i,\,k}$), related to anisotropic wave propagation within the volume, are sorted out from the relative residuals $R_{i,\,k}$. Anisotropic *P*-residual spheres show smoothed directional terms (two-parameter, azimuth and incidence angle, linear filter was applied) and map regions with similar orientation of the high velocities within the lithosphere. This allows us to map regions of similar structure of the lithosphere. As the ACH 3D inversion technique assumes an isotropic wave propagation within a model, we inverted only those relative residuals which satisfied the condition $|R_{i,\,k}-R_i| < 2$ s. For more detail about the method see *e.g.* Babuška and Plomerová (1992) or Plomerová *et al.* (1993).

2.1. *The Iberian Peninsula*

The velocity perturbation model (fig. 1) down to 300 km was obtained for a set of preprocessed *P* arrivals (Plomerová *et al.*, 1993). Thanks to this procedure the model exhibits a high value of the variance improvement (70%). The residuals without crustal corrections served as input of the inversion, but resolution of the crustal layer is rather poor due to the large spacing of the permanent observatories. The smoothed positive perturbations distinctly mark the region in the northeast, corresponding to the relatively thicker crust beneath the Pyrenees. Higher velocities are also observed beneath the Iberian Massif in the west. On the contrary, a region of distinct low-velocity perturbations has been found at very south of the Iberian Peninsula, which could be related to the crustal thinning toward the Alboran Sea (Abalos and Diaz, 1995; Badal *et al.*, 1996).

The three upper mantle layers are better resolved. A high-velocity heterogeneity related to the Pyrenees can be traced down to a depth of 200 km. This high velocity region reflects the Iberian plate subducting beneath Europe (Barruol and Souriau, 1995). Even larger in amplitudes are smoothed perturbations in the upper mantle beneath the Iberian Massif down to 120 km. Below this depth high-velocity perturbations beneath the Central and Eastern


Layer 1: 0-40 km v6.0km/s

Layer 3: 120-200km v8.3km/s

Layer 2: 40-120 km v8.4km/s

Layer 4: 200-300km v8.5km/s

Fig. 1. Velocity perturbation model of the Iberian Peninsula. Variance improvement of the model is 70%.

Betic Cordillera dominate in the upper mantle. The high-velocity heterogeneities are related to the subduction resulting from a continuing continental collision between Africa and Iberia (Houseman, 1996). Presence of the high velocity continental «root» is also indicated by recently (1954) formed deep earthquake foci.

In general, locations of the large high-velocity heterogeneities retrieved from the 3D inversion correlate with the lithosphere thickening derived from the static terms of the relative residuals (Plomerová *et al.*, 1993). However, there is an evident shift of the high-velocity heterogeneities to the NE, which is the most prominent in the region of the Betic Cordillera. This shift can be attributed to about easterly dipping high velocities in the anisotropic lithosphere (see fig. 2). Moreover, a distinct undulation of the lithosphere thickness is expected according to lateral variations of the static residual terms.

Just as in case of the *P*-residual spheres in Central and Western Europe (Babuška *et al.*, 1984; Babuška and Plomerová, 1992), the diagrams for the Iberian stations exhibit a similar pattern within individual tectonic blocks. Smoothed residual spheres for different subregions of the peninsula (fig. 2) allow us to distinguish regions with different orientation of anisotropy within the subcrustal lithosphere.

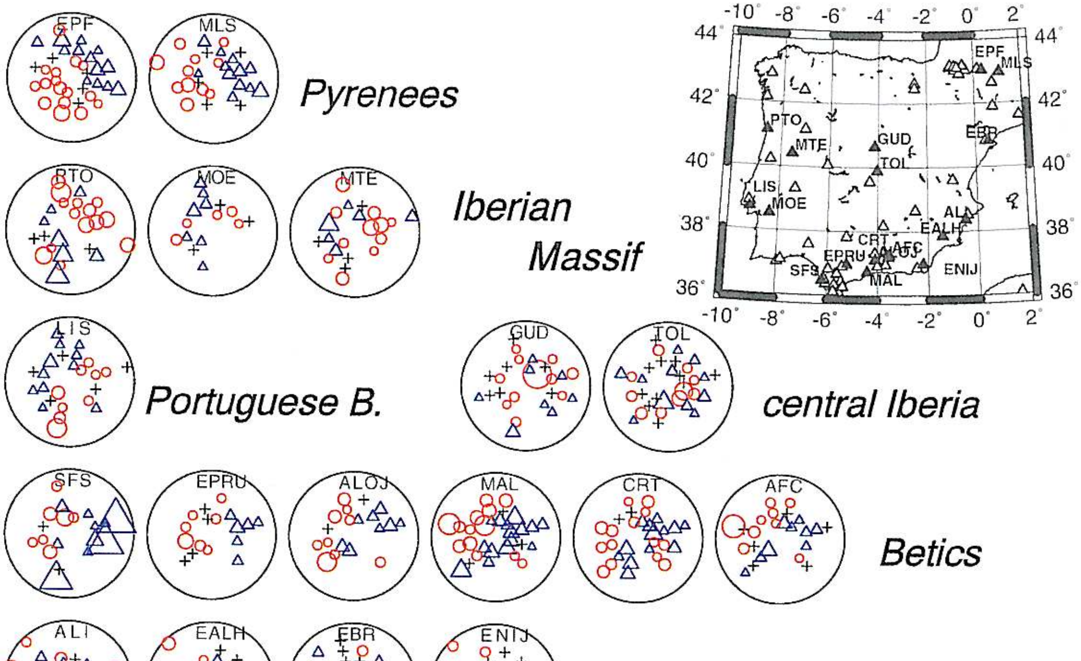


Fig. 2. Examples of smoothed anisotropic residual spheres for grouped teleseismic events at stations characterizing various Iberian regions of most probably different anisotropic structure of the lithosphere. Circles represent positive residuals, *i.e.* the low-velocity directions, triangles mark negative residuals, *i.e.* high-velocity directions. Size of the signs is proportional to their absolute value. Pluses mark values around zero (−0.1 s, 0.1 s).

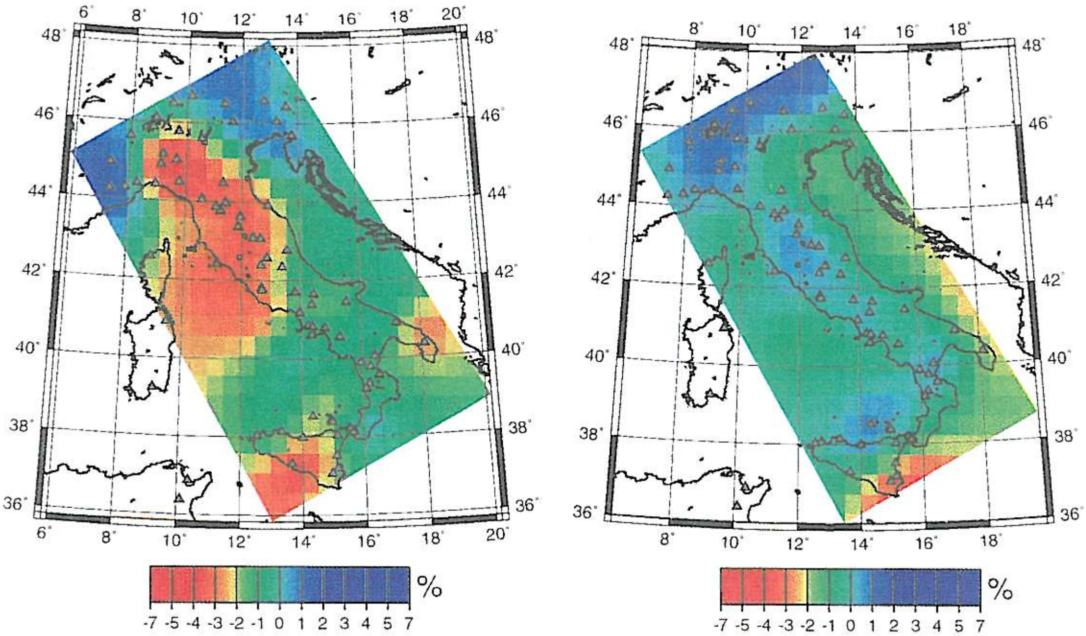
While in the Pyrenees (*e.g.* station EPF) the high-velocity directions dipping to ENE can be deduced from the residual spheres (Babuška *et al.*, 1993), *i.e.* in the direction of the subduction (Poupinet *et al.*, 1992; Barruol and Souriau, 1995), observations in the Iberian Massif and further to the south to the Portuguese Basin (station LIS) indicate the anisotropy with the high velocities plunging to SW or to NW, respectively. No characteristic pattern in the residual spheres indicating inclined anisotropy within the subcrustal lithosphere was found at stations in the central part of the peninsula (stations GUD, TOL). On the contrary, Silver and Chan (1991) found from the shear-wave splitting analysis (TOL) that there is anisotropy in the upper mantle beneath Central Iberia with the fast velocity oriented horizontally in the W-E azimuth. A very consistent «bipolar» pattern of the residual spheres, which means fast from one side and slow from the opposite one, can be observed at stations in the Betic Cordillera, along the W-E profile of stations (fig. 2). The high velocities within the lithosphere beneath the Betics plunge mainly to the E. The pattern changes abruptly at stations in the south-eastern coast of the Iberian Peninsula, indicating a distinct lateral change in the shallow upper mantle/lower lithosphere structure. This lateral change is not detected in isotropic 3D inversions (fig. 1). On the contrary, the high-velocity heterogeneity at the bottom layer of the model continues far to the east.

2.2. *Italian Peninsula (Apennines and Tyrrhenian Sea)*

The shoe-like shape of the Italian Peninsula and corresponding distribution of stations make difficult to gain a good resolution in the 3D velocity perturbation modelling the whole region (Scarpa 1982; Babuška and Plomerová, 1990; Amato *et al.*, 1993a). Figure 3 presents the upper mantle velocity perturbations in a model down to 470 km, in which the block partition is rotated W30N. The pre-processed residuals, which were also corrected for lateral changes of average crustal velocities and crustal thicknesses, as well as for sediments, served as an input of the ACH inversion.

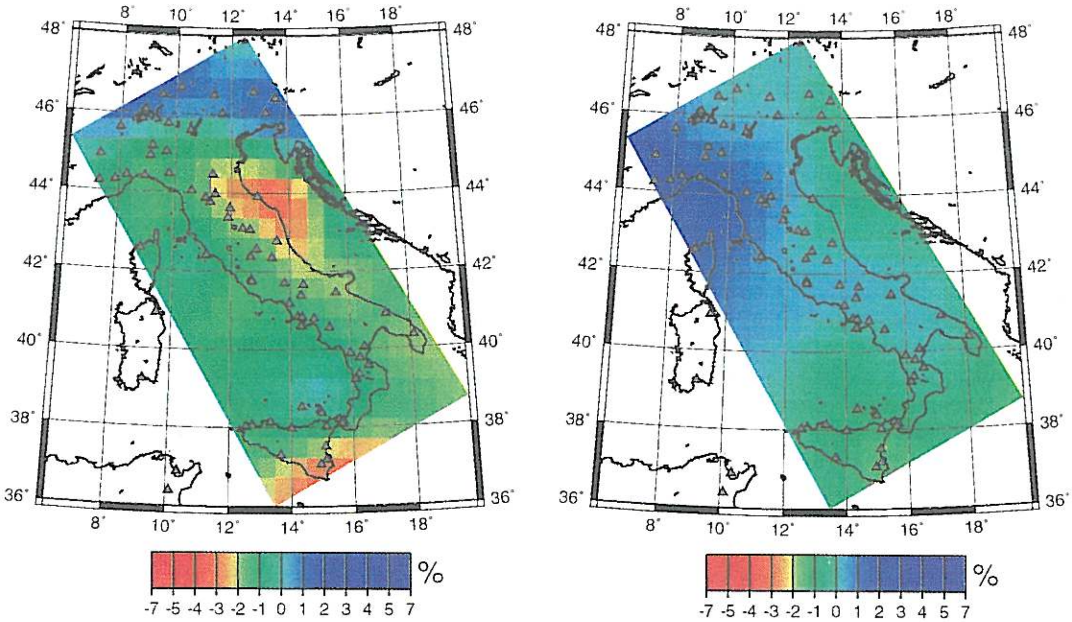
The resulting distribution of velocity perturbations marks the Western Alpine root – a product of the oblique collision between the European and Adriatic plates. This high-velocity perturbation can be traced down to 300 km, beneath the Po Plain. Negative perturbations indicate a low velocity regions beneath Sicily, and in the upper 100 km beneath the Po Plain and surprisingly also beneath the Northern Apennines. At depths between 200-300 km, the roots of the Alps, the Apennines and positive velocity perturbations related to the Tyrrhennian subduction are clearly marked. These are the most distinct features of the model. Below depths of 300 km the perturbations exceptionally exceed values of ± 1%. This is in accord with the findings of *e.g.* Gudmundsson *et al.* (1992) who found the majority of velocity heterogeneities is confined within the upper 300 km of the Earth's mantle.

As shown in the detailed analysis of both azimuthal and spatial variations of the *P* residuals (Plomerová *et al.*, 1997), various lithospheric blocks seem to exhibit consistent orientation of inclined anisotropy. Also stations in the Northern Apennines exhibit a very clear «bipolar» pattern. This pattern is independent of a dataset as well as the reference level used, *i.e.* normalization (fig. 4). From these anisotropy expressing residual spheres it is clear that the high velocities within the lithosphere plunge to the WSW beneath the Northern Apennines, in a dip-direction of a paleo-subduction proposed by Amato *et al.* (1993b). This result derived from *P* waves need not be in contradiction with the findings of Margheriti *et al.* (1996) who observed about a 1.2 s time delay in split shear waves with the fast *S* polarized along the strike of the mountain chain, on average. As we showed earlier (Babuška *et al.*, 1993), this is a typical discrepancy between results obtained from the short-period longitudinal and broad-band shear-wave analyses, which might occur if average fast shear-wave polarization azimuths are directly associated with the horizontal high-velocity direction in the anisotropic upper mantle. Due to the small



Layer 1: 33-118km v7.5km/s

Layer 3: 218-318km v8.35km/s



Layer 2: 118-218km v8.1km/s

Layer 4: 318-486km v8.6km/s

Fig. 3. Velocity perturbation model of the Italian Peninsula. Variance improvement of the model is 41%.

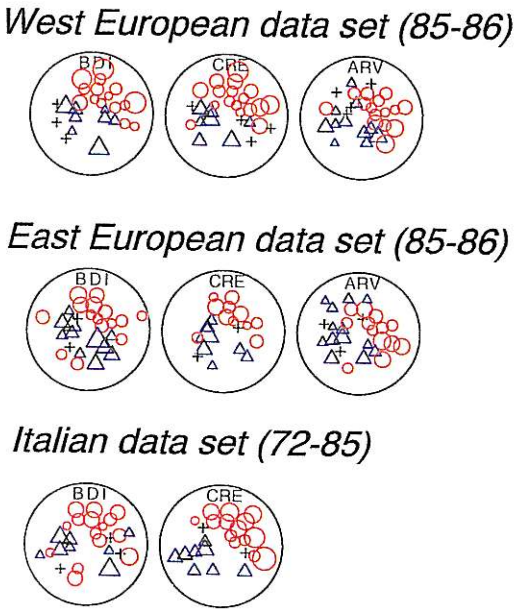


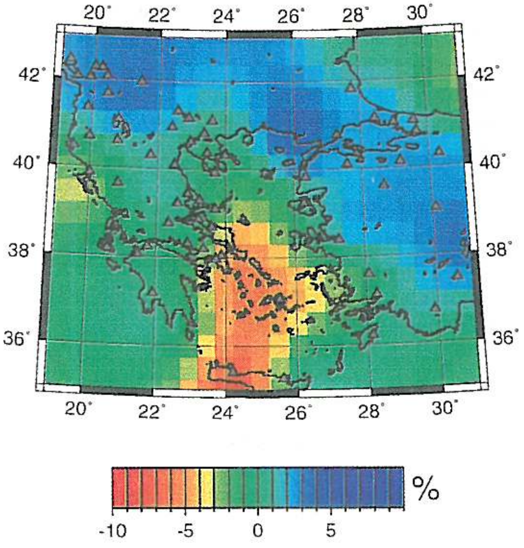
Fig. 4. Stability of the «bipolar» pattern of the anisotropic residual spheres at stations in the Northern Apennines for various reference levels and different data sets: the Western and Eastern European stations (both from 1985-1986) and Italian stations (1972-1985).

scale variability of fast *S* polarization azimuth and split time δt, and coherency of the anisotropy to surface geological features, it is evident that an important component of the observed anisotropy comes from the lithosphere (Margheriti *et al.*, 1996). Inclined anisotropic structures which can be approximated by hexagonal symmetry with the symmetry axis in the low-velocity direction, produce the *P*-residual spheres with maximum negative values in the dip direction of the dipping high-velocity plane and average fast *S* polarization azimuth along the strike of the inclined structures, *i.e.* perpendicular to the high v_p directions (Plomerová *et al.*, 1996).

Some of the low-velocity heterogeneities found in the isotropic 3D inversion of the *P* residuals may represent an artefact due to neglecting the inclined anisotropy in the lithospheric part of the upper mantle. Although when inverting the pre-processed grouped residuals, the effect of uneven distribution of earthquake foci around the region causing nonuniform spatial illumination of the box-volume decreases, the effect may remain feasible. Thus seismic active regions such as Kuriles, Japan, China, etc., with azimuths in the first quadrant supply the inversion with a great number of rays in the low-velocity directions and probably create an artificial isotropic low-velocity inhomogeneity beneath the Northern Apennines. The low-velocity heterogeneity extends towards the Adriatic Sea – in direction of the dipping low-velocities. Wortel and Spakman (1992) give an alternative explanation of the low-velocity heterogeneity beneath the Northern Apennines based on the slab detachment. On the other hand, smaller lateral-size regional inversions, which incorporate many local data, did not «see» such a low-velocity heterogeneity (Amato *et al.*, 1993a; 1996). This finding supports doubts on the real existence of the low-velocity heterogeneity as suggested in some 3D larger-scale inversions (Wortel and Spakman, 1992) including that in this study.

2.3. *South Balkans and the Aegean Sea region*

The most distinct feature of the first upper mantle layer (fig. 5) is a low-velocity heterogeneity centered at the Aegean Sea, mapping thus the low-velocity wedge above the western and eastern wings of the Hellenic subductions. A lithosphere thinning in the Central Aegean is surrounded by regions with the thick lithosphere related to the Hellenic subduction to the southwest and southeast, and to the north to the Rhodops and Anatolia (Plomerová *et al.*, 1990), and possibly to a paleosubduction beneath the Northern Aegean (Papadopoulos, 1993). The low-velocity heterogeneity in the centre of the region can be traced down to a depth of about 200 km. At depths below 100 km, high-velocity perturbations related to the subductions are located in the southern part of the second layer, whereas high velocities to the north reflect the roots of the Rhodopean Mas-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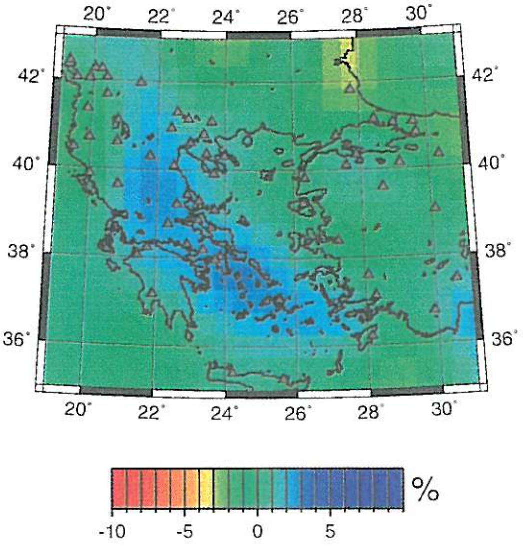
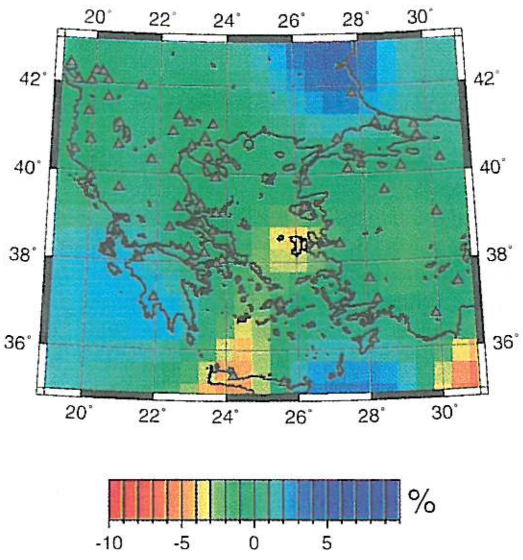

Layer 3: 203-289km v8.4km/s


Layer 2: 118-203km v8.1km/s

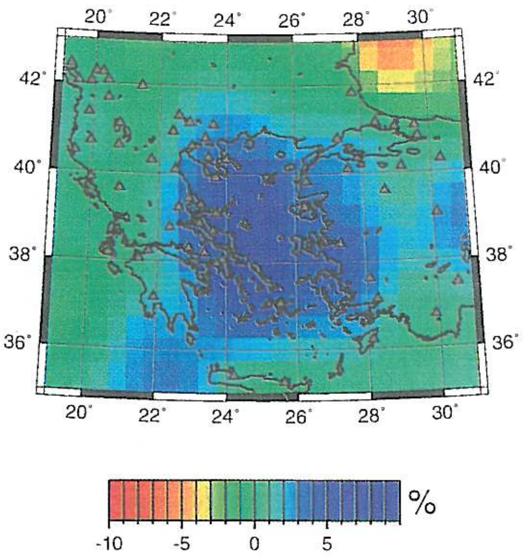

Layer 4: 289-374 km v8.6km/s

Fig. 5. Velocity perturbation model of the Balkans and Aegean region. Variance improvement of the model is 41%.

sif. At depth between about 200-300 km the high-velocity western wing of the Hellenic subduction appears as a dominant feature for the region. Below 300 km depth, the separation of the Western and Eastern Hellenic subduction disappears – all the high-velocity perturbations are concentrated in the middle of the layer. A similar effect of merging together two heterogeneities with convergently dipping high velocities at greater depths was observed for «roots» of the Western and Eastern Alps (Babuška *et al.*, 1990).

The anisotropic residual spheres (fig. 6) clearly mark the easterly dipping high velocities in the western part of the Hellenides. The pattern is preserved without distinct changes over the peninsula to the Chalkidiki region (station KNT). The high-velocity directions are oriented to the ESE. A dramatic and abrupt change of the pattern was found at the southernmost tip of Chalkidiki (station PAIG) where the pattern is almost reversed and attains a character typical for stations around the Anatolian fault and Northern Anatolia – the *P* veloci-

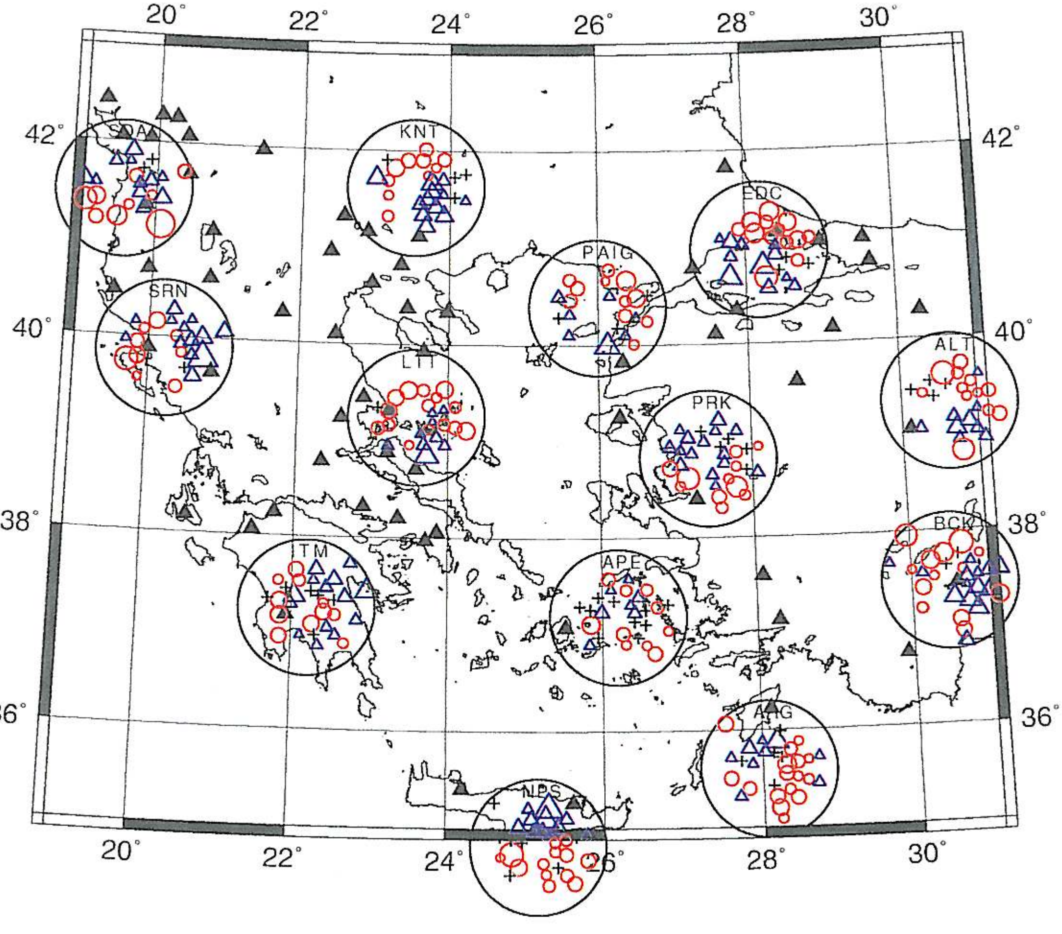


Fig. 6. Examples of the anisotropic residual spheres in the Balkan and Aegean region.

ties within the lithosphere plunge to the SW. Beneath stations in the central part of the Hellenic arc the high velocities point in the direction of the active subduction – to the N (station NPS) and NW (station ARG). As was expected, no preferential high-velocity direction can be determined for the central part of the Aegean Sea (station APE). Stations in the Taurides (*e.g.* station BCK) are located eastward of the Hellenic trench. If the anisotropic pattern of the residual spheres was affected and/or contaminated by the subductions which represent a large high-velocity heterogeneity, then early arrivals from the NW would be observed. On the contrary, the pattern of the anisotropic part of the residuals presented in the spheres is free of this effect and clearly demonstrates that the high velocities within the lithosphere beneath the Taurides plunge to the SE. Coherency of the residual pattern through the Balkans, including its central part (Babuška *et al.*, 1987) complements other geological and seismological observations supporting the idea of several or at least one successive subductions in the Aegean area (Papadopoulos, 1993, for a review).

3. Conclusions

In general, we observe a correlation between a large lithosphere thickening, derived from static terms of the relative residuals and distribution of high-velocity perturbations in the uppermost mantle layers. A decrease of amplitudes of the perturbations with depth is usually observed unless strong effects of anisotropic propagation within the subcrustal lithosphere become dominant. This also may lead to introducing possible false heterogeneities or mislocation of existing ones. The former most probably concerns *e.g.* the low-velocity heterogeneity beneath the Northern Apennines, the latter relates *e.g.* to the high-velocity heterogeneity beneath the Betics. Convergent high-velocity directions within the Hellenic subductions are responsible for the existence of only one extremely high-velocity heterogeneity at the bottom layer of the model beneath the Aegean region.

In the light of the recent findings of Amato *et al.* (1996), the single slab-detachment model of the upper mantle beneath the Italian peninsula (Wortel and Spakman, 1992) does not seem to explain the geodynamic development of the region. The double arc shape of the seismicity over the peninsula and the delineation of the upper mantle structures beneath the Northern Apennines and Southern Apennines-Calabrian arc (Amato *et al.*, 1993b), also reflected in a prominent lithosphere thinning (Babuška and Plomerová, 1990), argues rather more complex multi-subduction system.

The existence of large-scale upper mantle anisotropy is evident from various seismological data. The anisotropic residual spheres map its lithospheric part, with characteristic inclined orientation of the symmetry axes which is consistent within large tectonic units. The orientation of the anisotropic structures allows us, in combination with other geophysical and geological findings, to accept the idea of detecting paleosubductions originating during successive subduction processes in geodynamically active regions or during an accretion of various continental fragments (*e.g.* the Balkans, Aegean region or Italian peninsula). The necessity of incorporating the seismic anisotropy into the Earth's upper mantle models is inevitable for further progress in understanding geodynamic development especially of such tectonic complexes as represent the Southern Europe and Mediterranean region.

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