ANNALI DI GEOFISICA, VOL. 41, N. 1, April 1998

Teleseismic *P*-residual study in the Italian region - inferences on large scale anisotropic structure of the subcrustal lithosphere

Jaroslava Plomerová (1), **Vladislav Babuška** (2) **and Roberto Scarpa** (3)
(1) *Geophysical Institute, Czech Academy of Sciences, Prague, Czech Republic*
(2) *UNESCO, Division of Earth Sciences, Paris, France*
(3) *Dipartimento di Fisica, Università dell'Aquila, Coppito, L'Aquila, Italy*

Abstract
Jeffreys-Bullen (absolute) and relative *P*-wave travel-time residuals were analyzed over Italy and its surrounding using *P* arrival times from the ISC bulletins supplemented by the data from local observatories. We analyzed the travel-time station corrections by two independent methods to obtain information on lateral variations of the velocity structure over the area and a view of possible upper mantle anisotropy. In the first method, the station corrections are computed as a constant and two cosine terms with appropriate phase shifts. Besides a static term, the second method allows us to study the relative residuals in dependence both on azimuths and incidence angles and thus to investigate their spatial variations and to map lateral variations of anisotropic structure of the subcrustal lithosphere. The high and low-velocity directions inferred from the spatial distribution of the relative residuals as well as the high- and low-velocity upper mantle heterogeneities reflect the geodynamic development of the region, governed by the collision between the African and Eurasian plates.

Key words *teleseismic P residuals – lateral variations of mean residuals – azimuth and spatial variations of the residuals – 3D anisotropic structure – subcrustal lithosphere*

1. Introduction

The Italian region is characterized by a complex tectonics which is reflected at depths by a significant distortion of the lithospheric structures (Panza and Mueller, 1978; Calcagnile and Panza, 1981). The study of the physical properties of the lithosphere-asthenosphere system is consequently very important for understanding the geodynamic processes active in this region. The spatial reconstruction of the deep roots of the Alps and the Apennines as well as the geometry of the Calabrian arc and the subducted Benioff zone dipping in the Tyrrhenian Sea are significant tasks which still need a proper solution.

A detailed investigation of the deep velocity structure of the Alps, Apennines and Calabrian arc (*e.g.*, Calcanile and Scarpa, 1985; Spakman, 1986; Babuška and Plomerová, 1990; Babuška *et al.*, 1990; Cimini and Amato, 1993; Amato *et al.*, 1993a,b; Cimini and De Gori, 1997; Plomerová, 1997) shows relatively high velocities for the deep roots of the Alps, which are interpreted as a result of the collision be-

Mailing address: Dr. Jaroslava Plomerová, Geophysical Institute, Czech Academy of Sciences, Boční II/1a, 141 31 Praha 4, Czech Republic; e-mail: jpl@ig.cas.cz

tween the African and Eurasian plates. The deep structure of the Apennines is more complex in tomographic reconstructions. Some of which show low velocity anomalies in their northern part extending towards the Adriatic Sea (Plomerová, 1997). The Calabrian arc, where deep and intermediate earthquakes still occur, is of particular geodynamic importance. At local stations the residuals of teleseisms and deep earthquakes of this region indicate the presence of a high velocity and probably anisotropic body in the mantle.

The aim of the present study is to document results on a quantitative assessment of the anomalies of the compressional wave velocities, as achieved by an analysis of several data sets of the teleseismic *P*-arrival times covering a 24 year interval. Though simple, the methods, if properly used, may offer a valuable tool for investigating the anomalies in seismic wave propagation in the lithosphere-asthenosphere system. A modern telemetric network of digital stations built over Italy during the last decade provides a new generation access to high-quality data and their processing. However, carefully processed obsolete data also contribute to general knowledge of the deep structure of the region. The results may also be useful for improving location of teleseismic events of an adequate period by introducing appropriate station corrections or in long time-term studies frequent in the tectonically active regions, in which time changes of various parameters are investigated. Contrary to standard tomographic schemes which map velocity heterogeneities within a large volume of the mantle, we concentrated our research of teleseismic *P* residuals on the structure of the subcrustal lithosphere and especially its seismic anisotropy.

2. Data and method

As a first step Jeffreys-Bullen (JB) travel-time residuals were computed for most of the Italian seismic stations operating in the period 1962-1982. Hypocentre coordinates and origin times from the International Seismological Centre (ISC) were used. We selected 20% of the data considering only the events recorded by at least 5 seismic stations, with JB residuals within ± 5 s. The resultant data set amounts to 16 756 *P*-wave arrivals, corresponding to 2362 earthquakes with epicentral distances ranging from 20° to 100°. The azimuthal distribution of earthquakes is not homogeneous, with most events coming from the NE quadrant. This data set surpasses in quality and quantity that analyzed previously by Scarpa (1982), with its higher number (> 70) and more homogeneous distribution of seismic stations on the Italian territory due to the improvement of the seismic network since 1978. A test on the stability of results by adding bulletin data in the period 1982-1996 is currently in progress. Apparently, no significant improvement on the quality of available information, and the azimuthal and spatial distribution of data results from this additional data set.

To diminish the still existing inhomogeneity in the azimuth-distance distribution of the earthquake epicentres relative to the Italian peninsula and to improve the station coverage within a data set, a method similar to that described in detail, *e.g*,. in Babuška *et al.* (1984,

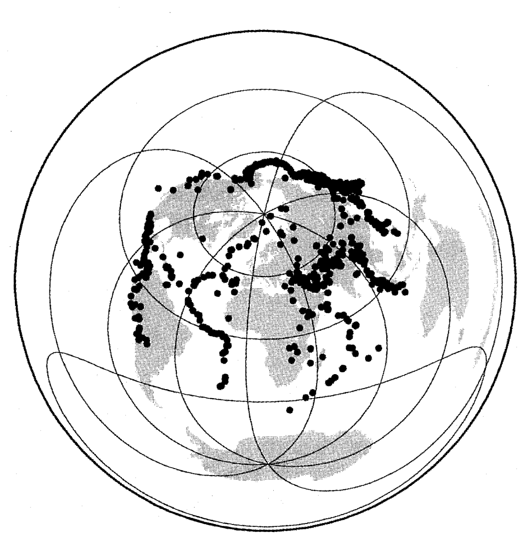

Fig. 1a. Distribution of 994 earthquakes with $\dot{P}$ arrivals included in the 1972-1985 data set. The azimuthal equidistant projection is centred in Italy at 13°E, 42°N.

Fig. 1b. Distribution of seismological stations.

1988), was applied to a data set for a period 1972-1985. This data set is formed by 994 events (fig.1a) and 16819 *P*-arrival times, which represents 17 *P*-arrivals per event, on average. This value approximately doubles a value of 7 for the data set of 1962-1982. This means we also obtained a more homogeneous and stable distribution of the residuals over the array of the stations (fig. 1b). The method works with average relative residuals of events grouped according to epicentral distances and azimuths, with steps of 10 in the distance, and 20 in azimuth, relatively to the centre of the region (13°E, 42°N).

Effects of crustal inhomogeneities were reduced by using all available information from seismic refraction data on crustal and sediment thicknesses and velocities. Single residuals were corrected for the variations relative to the JB model. Effects from source regions and deep mantle paths were minimized by subtracting an event mean residual.

As the normalization influence both the mean residuals (static terms) and the resulting pattern of the residual spheres, various reference levels of the normalization were tested. Analogically to the analysis considering single events (see fig. 4 in the following), the residuals were at first normalized relative to the average residual computed from all stations, which recorded an event with residuals less than ± 2 s relative to the average residual in one geographic segment of grouped hypocentres. Ten stations were considered as a minimum. However, only 36 stations of the original set had enough data for the analysis.

An important requirement on the reference level for the computation of the relative residuals is to keep it as stable as possible for all events, *i.e.* the event mean (a normalizing value) should be computed from the residuals of the same group of stations for each event. Moreover, a uniform representation of different tectonic units of the region is desirable. Therefore, as a second step we averaged the residuals of 13 basic stations: AQU, CTI, CVF, DPS, DUI, FIR, GIB, LCI, MES, ORI, RMP, SAL, TRI to have more stable and representative reference levels for computing the relative residuals. Figure 2 shows residual spheres with the absolute JB residuals (corrected for crustal effects) at these 13 reference stations. The residuals are averaged over all events with the residuals in the interval $\langle -5$ s, 5 s$\rangle$. Six normalizing stations were considered as a minimum for the computation of the normalizing value.

The relative residuals generally show large directional variations at individual stations as a result of the lithosphere structure beneath them. To have a single value, which characterizes the lithosphere structure beneath each station, regardless of the direction of arriving waves, we computed representative average residuals (static term R_i). These residuals are averaged over relative residuals of selected source regions. The selection is made with the aim of having the relative residuals for one segment in each azimuth interval from which the waves arrive at the M-discontinuity at steep incidence angles, which are less influenced by possible anisotropic structures. The representative residuals were averaged over the same 19 source regions in both cases of different reference levels.

The azimuthal dependence of station corrections was studied using a procedure similar to that described by, *e.g.*, Dziewonski and Anderson (1983). Although the distribution of teleseisms is uneven, with the southern quadrants covered by a much smaller number of events than the northern ones, we were able to look at station corrections with an azimuthal dependence having the following form:

$$t = A0 + A1 \cos(\mathrm{AZIM} - E1) + \\ + A2 \cos 2(\mathrm{AZIM} - E2)$$

at 27 Italian stations. In this relation azimuths $E1$ and $E2$ as well as $E2 + 180°$ represent the slow directions.

The coefficients of this relation have been determined by the least squares, dividing the full azimuth range into 18 windows, each 20° wide. All the terms were determined if data existed for 10 or more windows. The data used were the relative residuals corrected for local crustal velocity anomalies based on published velocity models (Cassinis, 1983). We considered the crust with a single M-discontinuity taking into account its dip and including the possible existence of a sedimentary layer, which causes large positive delays at some stations of Northern Italy. We have considered the results of numerous seismic refraction experiments made in Italy (see, *e.g.*, Nicolich, 1987).

For the investigation of the spatial dependence of P residuals the residual spheres were constructed. First, the absolute JB residuals at reference stations were tested (see fig. 2) to avoid the possibility of including in the basic system of reference stations only the stations with one type of residual dependence on the

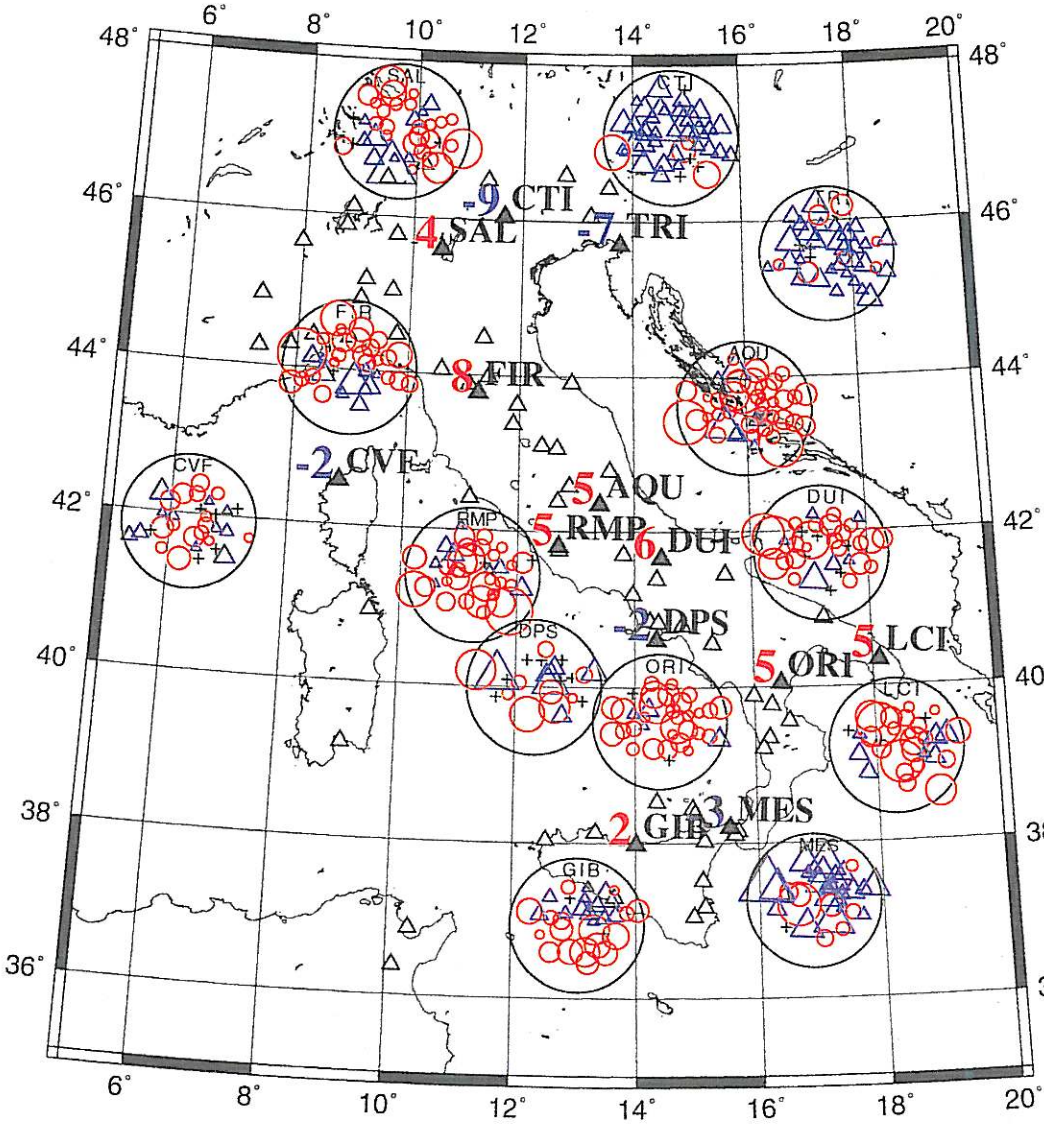

Fig. 2. Absolute JB residuals (in tenths of a second) at 13 reference stations, corrected for crustal effects, averaged over all events with the residuals in the interval ⟨−5 s, 5 s⟩ and diagrams of the spatial distribution of the absolute residuals at the reference stations. The residual spheres show smoothed absolute *P* residuals in the interval ⟨−3 s, 3 s⟩ with the use of a two-parameter linear filter (10° in the «incidence» angle and 20° in azimuth). The circle corresponds to an angle of 60° at a reference depth of 33 km. The blue triangles stand for negative residuals and red circles for positive ones. The size is related to the absolute value of the residual. Black signs mark the residuals in an interval ⟨−0.1 s, 0.1 s⟩.

azimuths and incidence angles. Second, for each station in the region, the residual sphere was constructed for azimuth-incidence angle dependent terms of the residuals, *i.e.* for the relative residuals, from which a mean residual of the station is subtracted. Therefore, these spheres emphasize the directional dependence of the residuals and are comparable among stations with different «average» structure (*i.e.* mainly the lithospheric thickness). Anisotropic structure of the lithosphere with arbitrary orientation (inclination) of symmetry axis and its lateral variations can be inferred from these diagrams. For more information on the method see, *e.g.*, Babuška *et al.* (1984, 1988) and Babuška and Plomerová (1992).

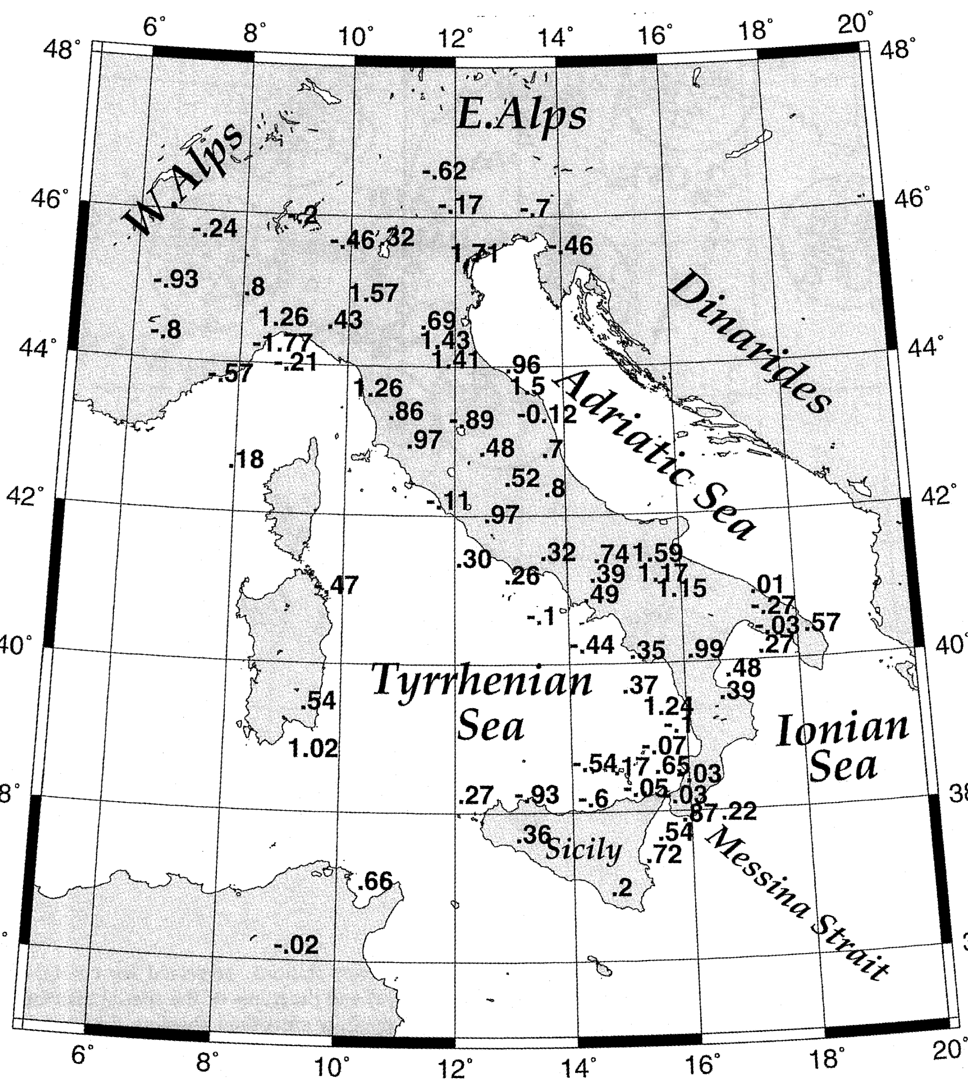

Fig. 3. Average JB *P*-wave residuals in Italy; no crustal corrections were applied.

3. Average residuals

Figure 3 reports a map of mean absolute JB *P*-wave residuals, obtained without any other correction on the whole data set (1962-1982) except the correction for the Earth's ellipticity. Many tests were performed to obtain relative residuals (Scarpa, 1982). As a rule, average values computed over the whole set of stations are subtracted from all residuals. The mean relative residuals (fig. 4), although computed only for the best recorded teleseisms, defined as those recorded at more than 10 stations of the network with the residuals within ± 2.5 s from the average value, display high lateral variations.

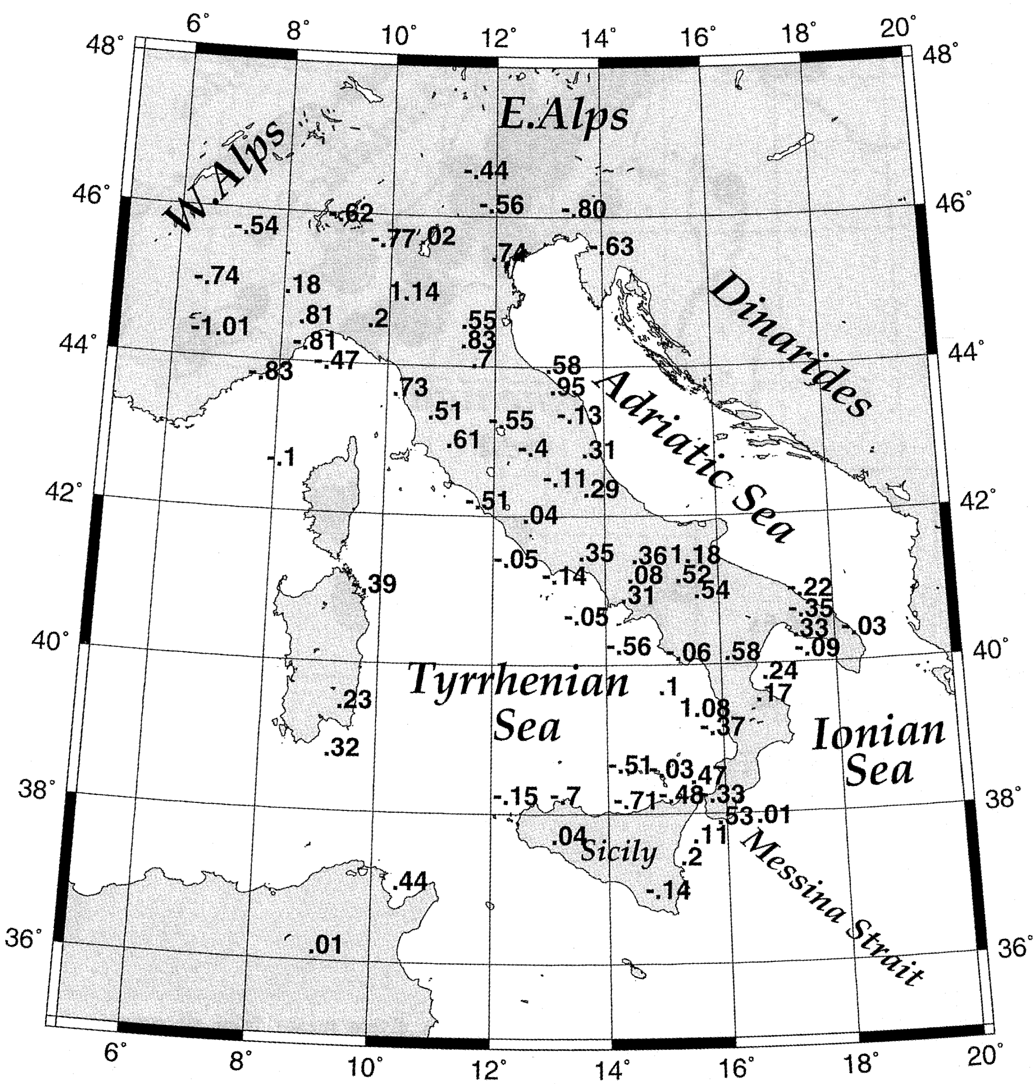

Fig. 4. Average relative (mean-subtracted) *P*-wave residuals in Italy; no crustal corrections were applied.

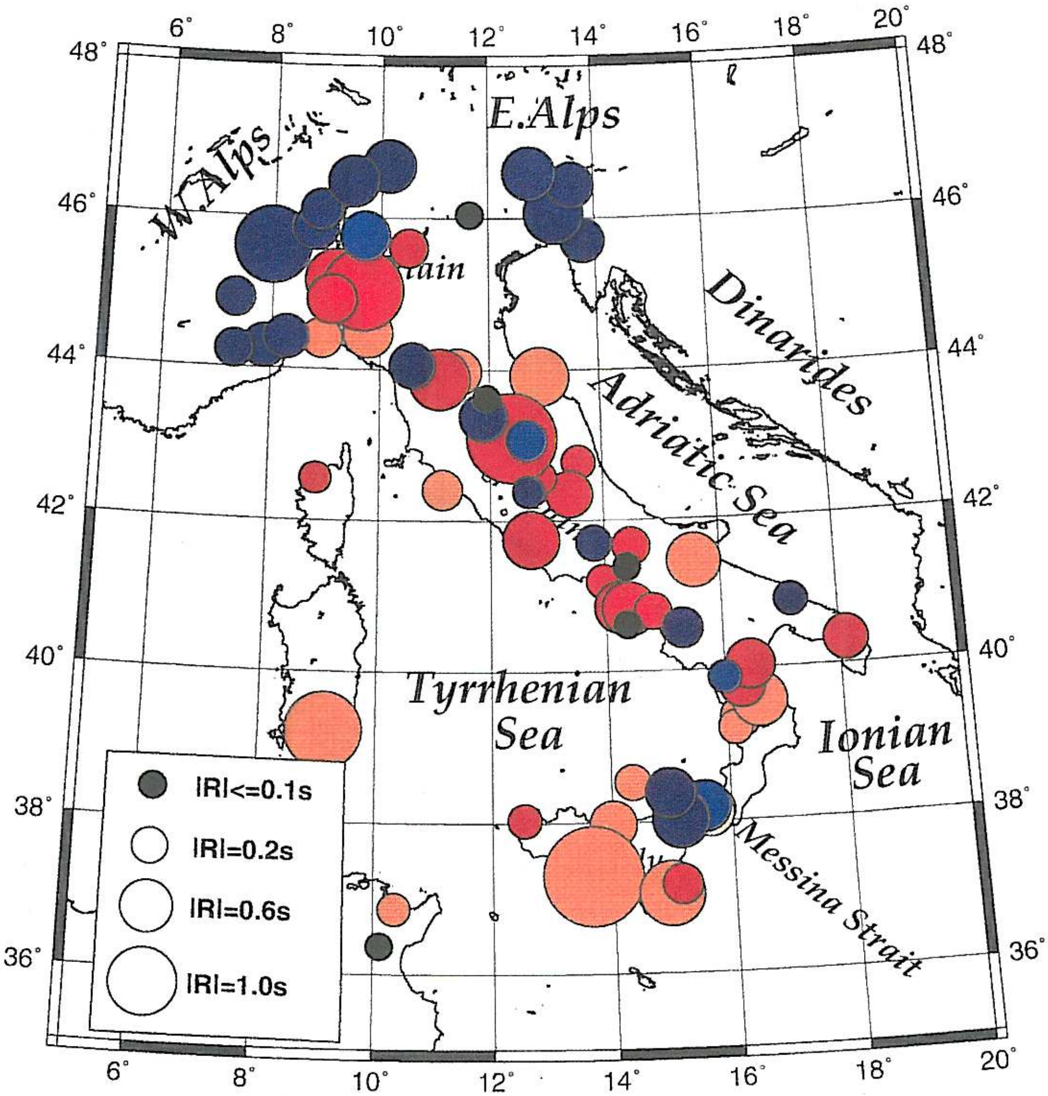

Fig. 5. Representative average *P* residuals (the static terms). Event means from all stations were subtracted and crustal corrections were applied. The size of signs is proportional to the absolute value of the residuals. Negative values are plotted in blue, positive in red. Intensity of the colours decreases with increasing Standard Deviations (SD) of the representative averages for intervals SD < 0.2 s, 0.2 s < SD < 0.35 s and 0.35 s < SD < 0.5 s. The residuals with a standard deviation larger than 0.5 s are excluded.

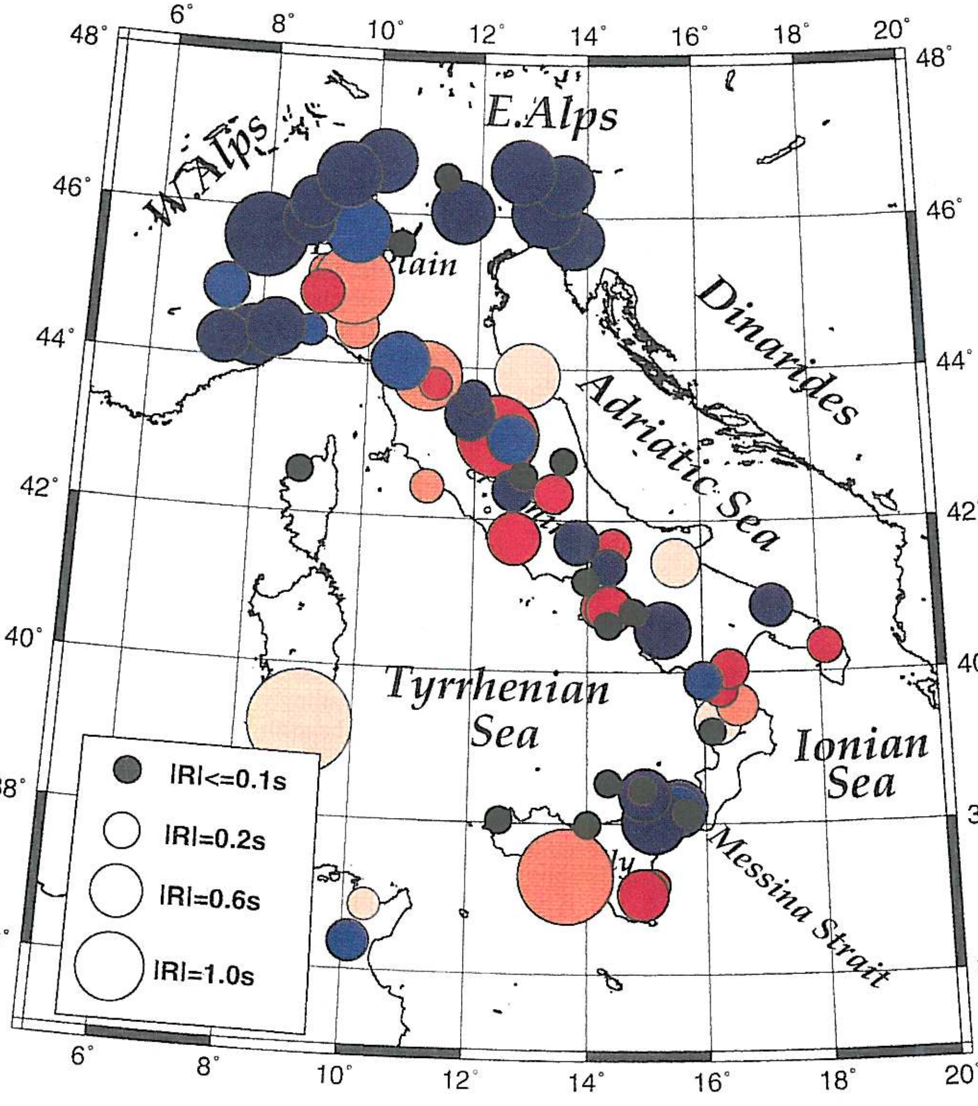

Fig. 6. Representative average P residuals when event means from 13 reference stations were subtracted (see also caption of fig. 5).

The representative average residuals R_i were computed for grouped events of the 1972-1985 data set for which the waves arrive at steep incidence angles from all azimuths (figs. 5 and 6). Corrections for the crust and sediments are included in these residuals. Both maps (figs. 5 and 6), which differ by the type of the normalization, *i.e.* the reference levels, exhibit a high degree of similarity.

Strong negative residuals, in several cases exceeding -1 s, are observed for the Alps both in the map of the mean residuals (figs. 3 and 4) and of the representative average residuals R_i (figs. 5 and 6). As the large crustal thicknesses found in this region (Cassinis *et al.*, 1979) cause delays in arrival times, the high negative residuals (earlier arrivals) cannot be accounted for by crustal effects even in the case when no crustal corrections are applied (fig. 4). The phenomenon is undoubtedly connected with the lithosphere thickening (Panza and Mueller, 1978; Babuška *et al.*, 1990; Babuška and Plomerová, 1990) which resulted from the collision of the Eurasian and the African plates.

A zone of clear-cut negative residuals follows the chain of the Alps; towards the Po plain and the North Apennines the average residuals change from negative to positive values. As the corrections for sediments were also applied, the most probable explanation of this change is a lithosphere thinning (Babuška and Plomerová, 1990).

Other domains characterized by the negative residuals are located in the Central Northern Apennines and along the inner part of the Calabrian arc (figs. 5 and 6). The high velocities in deeper structures of this region, confirmed also by the 3D inversion of *P* residuals (Amato *et al.*, 1993a,b; see also Plomerová, 1997), are obviously connected with the subduction of the oceanic lithosphere oriented to the centre of the Tyrrhenian Sea (Scarpa, 1982; Calcanile and Scarpa, 1985; Selvaggi and Chiarabba, 1995.

The mean residuals (fig. 4) generally show late arrivals in the Apennines, with a few exceptions in a zone in the central part of this mountain chain. Also the maps of representative average residuals (figs. 5 and 6) depict a large region of positive residuals reaching from the Po plain in the north to the surroundings of Naples in the south, with negative residuals along the central part of the Apennines. The negative residuals are more pronounced in fig. 6, where the event means from 13 stations are subtracted. For a small territory of negative residuals in the central part of Italy north of Rome, Calcagnile and Panza (1981) found an anomalous zone with shear velocity in a range of 4.4-4.6 km/s underlying a thin layer of a sub-Moho low velocity material. Similarly to Cimini and Amato (1993), and Amato *et al.* (1993a,b) we suppose that the negative residuals delineate a lithosphere thickening related to the Adriatic lithosphere subducted generally to the SW beneath the Northern Apennines. A higher-velocity spot may reflect a lithosphere thickening along a boundary of two different tectonic domains of the Northern and Southern Apenninic arcs (Patacca and Scandone, 1987; Amato *et al.*, 1993a,b). The low-velocity region in the North-Central Apennines (figs. 5 and 6) correlates well with the lithosphere thinning to about 60-70 km detected from low *S*-wave velocities of uppermost mantle material by Calcagnile and Panza (1981). With the exception of the northern margin (fig. 6), Sicily is characterized by positive residuals as well (fig. 5). The negative delays are concentrated around the Messina Strait and the Mt. Etna volcano.

4. Directional variations of *P* residuals

While the mean residuals or the static terms reflect prevailingly the general state of the lithosphere beneath the stations, which can be related, *e.g.*, to its thickness, the directional variations of the *P* residuals inform about the orientation of heterogeneities in the lithosphere and about its possible anisotropic structure.

An investigation of azimuthal variations of *P* residuals in a way similar to Dziewonski and Anderson (1983), *i.e.* regardless of the incidence angle of the arriving waves, is shown in fig. 7. The second azimuthal term with the π-periodicity is widely believed to reflect an anisotropy of structures. These low *P*-velocity directions obtained for the Italian peninsula are consistent with the general trend of observed discontinuities of the lithosphere-asthenosphere system (see, *e.g.*, Calcagnile and Scarpa, 1985) and they may be related to mantle anisotropy. On the contrary, this pattern does not simply correlate with the stress axes inferred from fault-plane solutions of shallow earthquakes (Gasparini *et al.*, 1985).

In general, however, the structure of the lithosphere is more complex than can be described only by the azimuthal variations of the residuals. In many regions the lithosphere con-

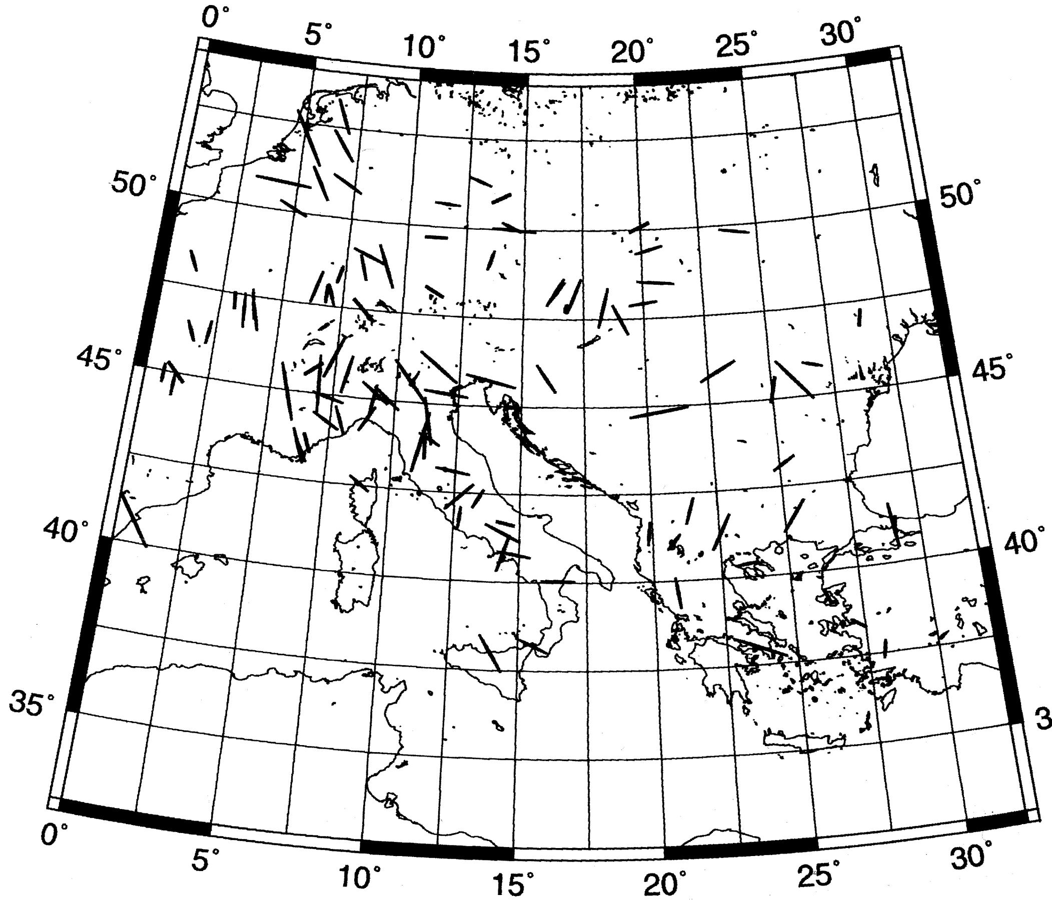

Fig. 7. Distribution of the second azimuthal term in station travel-time anomalies for Central-Southern Europe. Each line is oriented in the slow direction and its length is proportional to the anomaly. Only stations with more than 100 observations are considered.

tains large-scale inclined inhomogeneities and anisotropic structures (Babuška *et al.*, 1987, 1993; Babuška and Plomerová, 1992; Plomerová *et al.*, 1996), where the directions of velocity extremes are not parallel with the Earth surface. In such cases, the $E1$ term with 2π-periodicity detects not only inhomogeneities but also dipping anisotropic structures.

The residual spheres presented in figs. 8 and 9 describe the spatial variations of the azimuth-incidence angle dependent terms of the relative residuals. As the static terms represent the zero level in each diagram, effects of lateral variations of different «average» structures beneath the stations are minimized. This also includes the effect due to the lateral variation of the lithosphere thickness. Thus, the pattern of the distribution of positive and negative relative residuals, representing relatively high- and low-velocity directions, respectively, can be mutually compared for various stations.

The residual pattern of the spheres is not random (figs. 8 and 9), but the negative and positive residuals form groups, which indicates

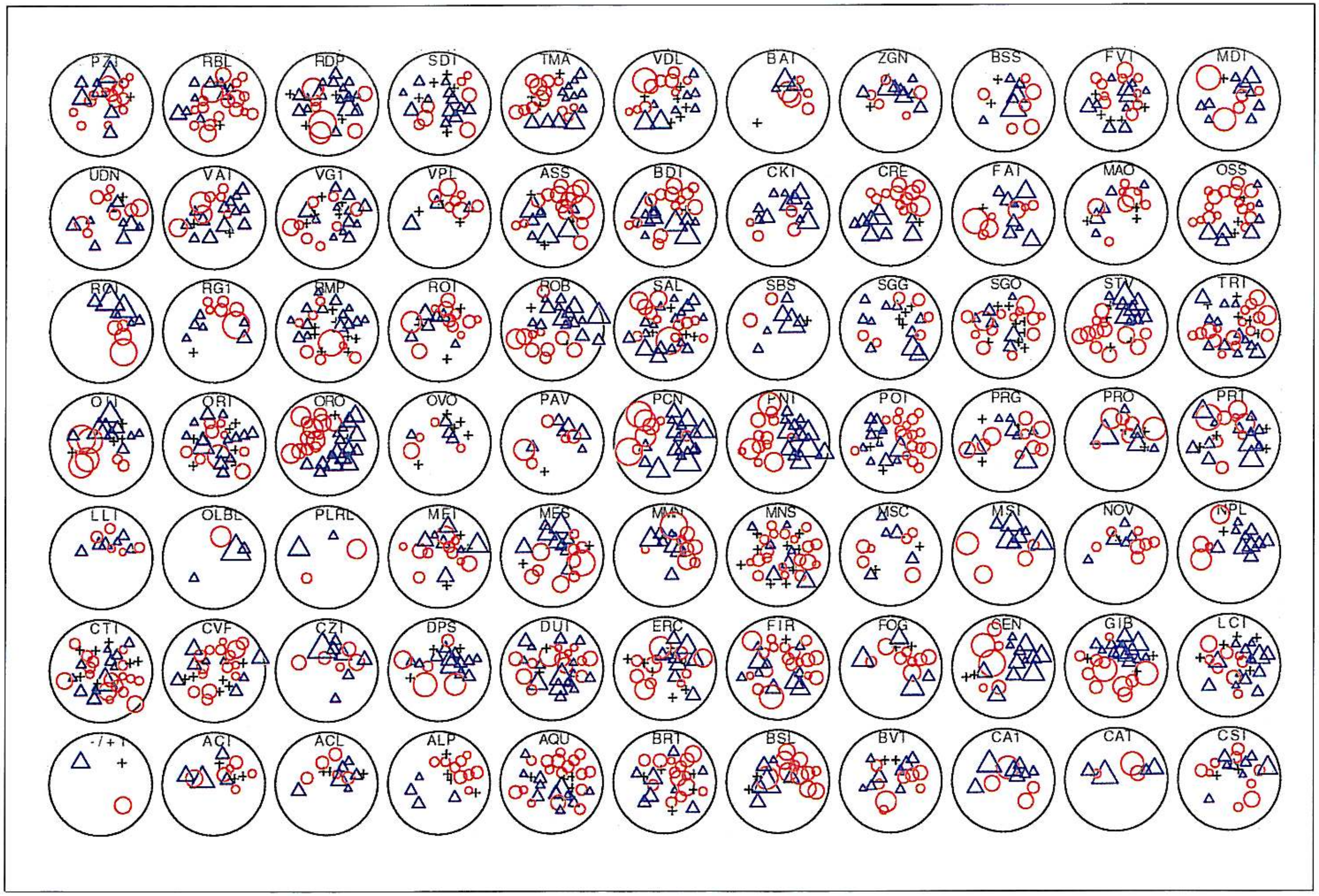

Fig. 8. The residual spheres of smoothed azimuth-incidence angle dependent terms of relative *P* residuals (event means from 13 reference stations were subtracted) with the use of a two-parameter linear filter in the majority of the stations. The signs corresponding to ± 1 s and to the interval ⟨− 0.1 s, 0.1 s⟩ are shown in the lower left (see also caption of fig. 2).

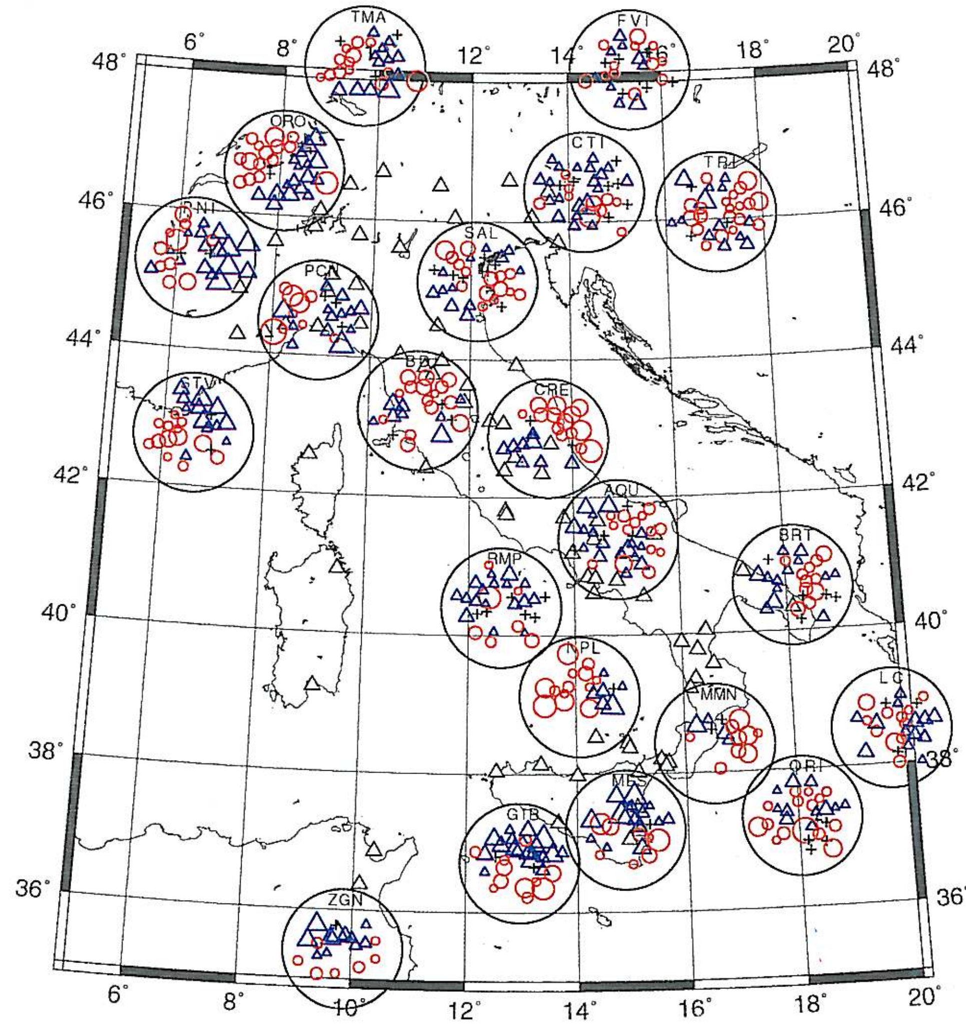

Fig. 9. A map view of representatives of the residual spheres of smoothed azimuth-incidence angle dependent terms of relative *P* residuals (event means from all stations were subtracted) with the use of a two-parameter linear filter (see also caption of fig. 2).

a systematic orientation of the high- and low-velocity directions in most of the stations. In general, the residual pattern is independent of the normalization used (see also Plomerová, 1997) which supports significance of the feature. The differences between the residuals are large, attaining as much as 2 s.

The stations in the Western Alps (ORO, PNI, STV, ROB) and stations PCN and GEN as well, show a very consistent pattern of negative residuals for waves arriving from E, SE and NE and of positive residuals for those from opposite sides. This observation agrees with the data of French and Swiss seismological stations in the Western Alps (Poupinet, 1976; Babuška *et al.*, 1990; Babuška and Plomerová, 1992) and can be interpreted in terms of the high-velocity continental lithosphere dipping to SE into the low-velocity asthenosphere beneath the Po plain (Babuška *et al.*, 1984, 1987). This is in agreement with the findings of Spakman (1986), who determined by a tomographic inversion of a large number of ISC *P*-residuals two high-velocity slabs, of which the northern one seems to thrust under the southern slab. However, in the Western Alps the complex crustal structure, namely the well known fast velocity Ivrea body, also strongly affects the directional dependence of *P* residuals (Cattaneo *et al.*, 1987; Cattaneao and Eva, 1990).

The pattern of the residual spheres in the NE is affected by the steep root of the Eastern Alps (Babuška *et al.*, 1990). A very stable pattern characterized by the high velocities plunging to the SW is observed along the Northern Apennines (Plomerová, 1997), especially in the central and outer part of the chain. «The Western Alpine pattern» turns to the «North Apenninic» one south-east of the GEN and PCN stations. Similar sharp termination of the pattern is related to the boundary between the Northern Apenninic arc and the Southern Apennines (Amato *et al.*, 1993b), south of 42°N. In this region stations RMP and especially NPL exhibit just the opposite pattern, with the high-velocity directions oriented towards NNW or ESE, respectively. Similarly, stations in the Apulian foreland (BRT) and Bradanic foredeep (ORI) are of more complex pattern, while at the southern tip of Apulia, the SE orientation of the high-velocity directions seems to dominate. On the contrary, stations in the Calabrian arc (MMN), although with less distinct spatial dependence compared to stations in Sicily (ERC, GIB, MES, RCI, OII) display similar clear-cut orientations of directions of positive and negative residuals with the high-velocity directions mostly oriented towards the Tyrrhenian Sea. This pattern can be traced to Northern Tunisia (ZGN). The diagrams show high-velocity directions plunging to the NE and N, respectively, for seismic waves propagating along the Benioff zone dipping to the centre of the Tyrrhenian basin.

The pattern of the residual spheres is distinct in many provinces of the Italian peninsula, and in spite of their complexity in some areas, they still form groups. Lateral variations of the pattern are related to the complex block structure of the region, resulting from the collision of the Eurasian and African plates and ongoing accretionary processes, especially in the south of the peninsula (Selvaggi and Chiarabba, 1995; Babuška and Plomerová, 1989). There is a well-known trade-off between an upper mantle heterogeneity and generally oriented anisotropy within the lithosphere (Babuška *et al.*, 1990; Babuška and Plomerová, 1992), which is more difficult to solve in tectonically active regions, represented, *e.g.*, by the whole Mediterranean (Plomerová, 1997). The substantial part of the anisotropic signal related to the various fragments of the continental lithosphere can be extracted from the spheres of the azimuth-incidence angle dependent terms of the relative residuals, especially if we take into account the lateral extent of the pattern, its consistency within one tectonic block, sharp change related to important tectonic boundaries and the amplitude of the variation. Joint analysis (Plomerová *et al.*, 1996) of anisotropic *P*-residual spheres with inferences about mantle anisotropy from analysis of shear wave splitting parameters (Margheriti *et al.*, 1996, 1997) intended to be performed in the near future will broaden our knowledge of the deep structure of the region.

5. Conclusions

The results discussed in the present paper furnish further proof of the complicated pattern of travel-time residuals and thus *P*-wave velocity structure beneath Italy. The deep structure of this region is split in many blocks having both high and low mean *P*-wave velocities, the variations of which are greatly pronounced also in the upper mantle. This complex structure reflects the geodynamic processes still active in the area and indicates the presence of deep lithospheric roots in the Alps, a high velocity body in the Tyrrhenian Sea, and a more complicated structure along the North and South Apennines, related to the both active- and paleo-subductions. Inferences about anisotropic structure of the upper mantle based on 3D orientation of the high *P*-velocity directions detected in the subcrustal lithosphere follow the block structure of the region and they mostly plunge in dip-directions of the subductions.

Detailed understanding the geodynamics of the region of the Italy requires a higher resolution of the structures, including a tomographic reconstruction of shear-wave velocity distribution as well as 3D interpretation of the shear-wave splitting parameters. The presented results lead to a quantification of the degree of the lateral inhomogeneities and mapping *P*-wave anisotropy in the lithosphere beneath Italy.

Acknowledgements

Partial support of the UNESCO, Italian MURST 40% and a grant No. A3012604 of Czech Academy of Science are greatly appreciated. The authors thank to P. Pajdušák and R. Maresca, who helped us at the early stage of data processing. We thank an anonymous reviewer for his comments and suggestions which improved the manuscript.

REFERENCES

AMATO, A., B. ALESSANDRINI and G.B. CIMINI (1993a): Teleseismic wave tomography of Italy, in *Seismic Tomography: Theory and Practice*, edited by H.M. IYER and K. HIRAHARA (Chapman and Hall, London), 361-397.

AMATO, A., B. ALESSANDRINI, G.B. CIMINI, A. FREPOLI and G. SELVAGGI (1993b): Active and remnant subducted slabs beneath Italy: evidence from seismic tomography and seismicity, *Ann. Geofis.*, **36** (2), 201-214.

BABUŠKA, V. and J. PLOMEROVÁ (1989): Seismic anisotropy of the subcrustal lithosphere in Europe: another clue to recognition of accreted terranes?, in *Deep Structure and Past Kinematics of Accreted Terranes*, edited by J.W. HILLHOUSE, *Geophys. Monogr. 50*, IUGG, Washington DC, vol. 5, 209-217.

BABUŠKA, V. and J. PLOMEROVÁ (1990): Tomographic studies of the upper mantle beneath Italian region, *Terra Nova*, **2**, 569-576.

BABUŠKA, V. and J. PLOMEROVÁ (1992): The lithosphere in Central Europe – seismological and petrological aspects, *Tectonophysics*, **207**, 141-163.

BABUŠKA, V., J. PLOMEROVÁ and J. ŠÍLENÝ (1984): Spatial variations of *P* residuals and deep structure of the European lithosphere, *Geophys. J. R. Astron. Soc.*, **79**, 363-383.

BABUŠKA, V., J. PLOMEROVÁ and J. ŠÍLENÝ (1987): Structural model of the subcrustal lithosphere in Central Europe, in *The Composition, Structure and Dynamics of the Lithosphere Asthenosphere System*, edited by C. FROIDEVAUX and K. FUCHS, *AGU Geophys. Series*, 239-251.

BABUŠKA, V., J. PLOMEROVÁ and P. PAJDUŠÁK (1988): Lithosphere-asthenosphere in Central Europe: models derived from *P* residuals, in *Proceedings of the Fourth Workshop on the European Geotraverse (EGT) Project: the Upper Mantle*, edited by G. NOLET and B. DOST (European Science Foundation, Strasbourg), 37-48.

BABUŠKA, V., J. PLOMEROVÁ and M. GRANET (1990): The deep lithosphere in the Alps: a model inferred from *P* residuals, *Tectonophysics*, **76**, 137-165.

BABUŠKA, V., J. PLOMEROVÁ and J. ŠÍLENÝ (1993): Models of seismic anisotropy in deep continental lithosphere, *Phys. Earth Planet. Inter.*, **78**, 167-191.

CALCAGNILE, G. and G.F. PANZA (1981): The main characteristics of the lithosphere-asthenosphere system in Italy and surrounding regions, *Pure Appl. Geophys.*, **119**, 865-879.

CALCAGNILE, G. and R. SCARPA (1985): Deep structure of the European-Mediterranean area from seismological data, *Tectonophysics*, **118**, 93-111.

CASSINIS, R. (1983): Seismicity and crustal structure in the Italian region: a preliminary zoning, *Boll. Geofis Teor. Appl.*, **25**, 3-26.

CASSINIS, R., R. FRANCIOSI and S. SCARASCIA (1979): The structure of the Earth's crust in Italy. A preliminary typology based on seismic data, *Boll. Geofis. Teor. Appl.*, **21**, 105-126.

CATTANEO, M. and C. EVA (1990): Propagation anomalies in North-Western Italy by inversion of teleseismic residuals, *Terra Nova*, **2**, 577-584.

CATTANEO, M., M. COVIELLO, C. EVA and M. PASTA (1987): Residui di tempo delle onde *P* nell'Italia Nord-Occidentale, in *Atti V Convegno Gruppo Nazionale Geofisica Terra Solida*, CNR, Roma, 439-449.

CIMINI, G.B. and A. AMATO (1993): *P*-wave teleseismic tomography: contribution to the upper mantle structure of Italy, in *Recent Evolution and Seismicity of the Mediterranean Region*, edited by E. BOSCHI, E. MANTOVANI and A. MORELLI (Kluwer Academic Publishers, Dordrecht), 313-331.

CIMINI, G.B. and P. DE GORI (1997): Upper mantle velocity structure beneath Italy from direct and secondary *P*-wave teleseimic tomography, *Ann. Geofis.*, **40**, 175-194.

DZIEWONSKI, A. and D.L. ANDERSON (1983): Travel times and station corrections for *P* waves at teleseismic distances, *J. Geophys. Res.*, **88**, 3295-3314.

GASPARINI, C., G. IANNACCONE and R. SCARPA (1985): Fault-plane solutions and seismicity of the Italian peninsula, *Tectonophysics*, **117**, 59-78.

MARGHERITI, L., C. NOSTRO, M. COCCO and A. AMATO (1996): Seismic anisotropy beneath the Northern Apennines (Italy) and its tectonic implications, *Geophys. Res. Let.*, **23**, 2721-2724.

MARGHERITI, L., C. NOSTRO, A. AMATO and M. COCCO (1997): Seismic anisotropy: an original tool to understand the geodynamic evolution of the Italian peninsula, *Ann. Geofis.*, **40**, 759-769.

NICOLICH, R. (1987): Crustal structures from seismic studies in the frame of the European geotraverse (Southern segment) and Crop projects, in *The Lithosphere in Italy – Advances in Earth Science Research*, Accademia Nazionale dei Lincei, Roma, 1-14.

PANZA, G.F. and S. MUELLER (1978): The plate boundary between Eurasia and Africa in the Alpine area, *Mem. Soc. Geol. It.*, **33**, 43-50.

PATACCA, E. and P. SCANDONE (1987): Structural evolution of the outer margin of the Apennines and related fordeep system, in *The Lithosphere in Italy – Advances in Earth Science Research*, Accademia Nazionale dei Lincei, Roma, 139-142.

PLOMEROVÁ, J. (1997): Seismic anisotropy in tomographic studies of the upper mantle beneath Southern Europe, *Ann. Geofis.*, **40**, 111-121.

PLOMEROVÁ, J., J. ŠÍLENÝ and V. BABUŠKA (1996): Joint interpretation of upper mantle anisotropy based on teleseismic *P*-travel time delays and inversion of shear-wave splitting parameters, *Phys. Earth. Planet. Int.*, **95**, 293-309.

POUPINET, G. (1976): Sur l'existence d'un manteau à très faible vitesse sous les Alpes Occidentales et ses implications tectoniques, *Bull. Soc. Geol. France*, **28**, 1073-1083.

SCARPA, R. (1982): Travel-time residuals and three-dimensional velocity structure of Italy, *Pure Appl. Geophys.*, **120**, 583-606.

SELVAGGI, G. and C. CHIARABBA (1995): Seismicity and *P*-wave velocity image of the Southern Tyrrhenian subduction zone, *Geophys. J. Int.*, **121**, 818-826.

SPAKMAN, W. (1986): The upper mantle structure in the Central European-Mediterranean region, in *Proceedings 3rd ESC Workshop on the European Geotraverse Project* (European Science Foundation, Strasbourg), 215-221.

(received October 20, 1997;
accepted February 5, 1998)