ANNALI DI GEOFISICA, VOL. XL, N. 3, June 1997

# Seismic anisotropy: an original tool to understand the geodynamic evolution of the Italian peninsula

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**Abstract**
Anisotropy is a common property of the Earth's crust and the upper mantle; it is related to the strain field of the medium and therefore to geodynamics. In this paper we describe the different possible origins of anisotropic behavior of the seismic waves and the seismological techniques used to define anisotropic bodies. In general it is found that the fast polarization direction is parallel to the absolute plate motion in cratonic areas, to the spreading direction near rifts or extensional zones, and to the main structural features in transpressive regimes. The delay times between fast and slow waves reflect the relative strength and penetration at depth of the deformation field. The correspondence between surface structural trends and anisotropy in the upper mantle, found in many regions of the world, strongly suggest that orogenic processes involve not only the shallow crust but the entire lithosphere. Recently in Italy both shear wave splitting analysis and $P_n$ inversion were applied to define the trend of seismic anisotropy. Along the Northern Appeninic arc fast directions follow the strike of the arc (*i.e.*, parallel to the strike of the Miocene-Pleistocene compressional features), whereas in the Tyrrhenian zone fast directions are about E-W SW-NE; parallel to the post-Miocene extension that is thought to have reoriented the mantle minerals fabric in the astenosphere.

**Key words** *seismic anisotropy – geodynamics – crust – upper mantle*

## 1. Introduction

Evidence of seismic anisotropy at all scales has been accumulating during the last 30 years. Nevertheless, in most studies, the Earth is usually assumed to be isotropic for mathematical convenience. Incorporating seismic anisotropy into velocity models is a necessary step for a more realistic parametrization of the Earth and a better understanding of the geodynamic development of continents. Different geophysical fields are involved in the investigation of anisotropy of Earth materials, mineral-physics and petro-physics at the microscopic scale, and seismology, geology, and geomagnetism for larger scales. From a seismological point of view, different and independent data sets made evident that the effect of anisotropy is relevant and must be taken into account for correctly explaining the propagation of seismic waves inside the Earth (Silver, 1996 and references therein). The applications of anisotropy studies are numerous. In the crust it can be used for investigating the earthquake processes (Zollo and Bernard, 1991; Bouin and Bernard, 1994) and in exploration geophysics (Crampin and Booth, 1985). In the lithosphere it can be compared to the strain field inferred from surface tectonics: it provides fundamental information on pro-

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cesses involved in mountain building and continental collision (Nicolas and Christensen, 1987). Comparing seismic anisotropy parameters with geology allows us to understand the coupling between shallow brittle crust, lithosphere and the rest of the mantle. The study of seismic anisotropy provides a new dimension in the investigation of processes of Earth-dynamics (Silver, 1996).

In this paper we review the different possible origins of anisotropic behavior of seismic waves, the seismological techniques used to define the anisotropic layers and/or bodies, the implications of anisotropy and its relation with geodynamics in some regions of the world, and finally we describe some results recently obtained for the Apennines (Central Italy) and their tectonic implications.

## 2. Seismic anisotropy: an overview

In an isotropic elastic solid two types of elastic waves propagate: compressional or *P*-waves and shear or *S*-waves; in weakly anisotropic media, as in the Earth's crust and upper mantle, waves are neither purely longitudinal nor transverse to the direction of propagation; the *P*-wave velocity depends on the propagation direction, the *S*-wave velocity depends also on the polarization. In general, there are two shear waves that propagate with different velocities; this is known as shear wave birefringence (Anderson, 1989). For a homogeneous elastic anisotropic medium of density $\rho$, the velocities and displacement directions of the seismic waves are given by the eigenvalues and eigenvectors of the polarization matrix $V$ defined by the Christoffel equation,

$$\rho V_{il} \equiv C_{ijkl} \, v_j \, v_k$$

(Backus, 1965) where $V$ is the polarization matrix, $C$ is the elasticity tensor for the medium and $v$ is the unity vector in the propagation direction. The two basic parameters which characterize an anisotropic medium are the fast direction and the difference in propagation time between fast and slow wave.

The origin of seismic anisotropy is non-unique, a range of phenomena may cause Earth materials to display seismic anisotropy (Crampin *et al.*, 1984). The anisotropy may be strongly dependent on wavelength if it is due to the average properties of aligned or partially aligned heterogeneity. A solid has intrinsic anisotropy when is homogeneously and continuously anisotropic down to the smallest particle size, which may be due to crystalline anisotropy (anisotropic crystals aligned). When an otherwise isotropic rock contains a distribution of dry or liquid-filled cracks which have preferred orientation it is named crack induced anisotropy. These two main mechanisms for generating anisotropy are both related to the present strain and the strain history of the medium.

The presence of aligned cracks, either open or filled with some different material, is an important mechanism at shallow depths, in the crust. In general, the fast direction of propagation is parallel to the crack strike which, in an extensional tectonic regime, is perpendicular to the minimum compression ($\sigma 3$). Relevant crystallographic anisotropy can be found in the crust close to major tectonic features where consistent regional fabric develops (Zhang and Schwartz, 1994). The orientation of the fastest *S*-wave polarization plane is parallel to the foliation in rocks which contain mica minerals. At upper mantle depths there is no reason to suppose the presence of aligned cracks filled with different materials. Here the most likely mechanism is crystallographic alignment due to finite strain (Ribe and Yu, 1991). For example olivine, the most abundant upper mantle mineral, is extremely anisotropic for both *P*-wave and *S*-wave propagation and it appears to be relatively easily oriented by the ambient stress or flow field. Mobility of olivine crystals at temperatures below 900°C is low, but it is sharply enhanced at higher temperatures (Estey and Douglas, 1986). In general, the seismically fast axes of olivine are in the plane of the flow with the *a* axis, the fastest direction, pointing in the direction of flow. The *b* axis, the minimum velocity direction, is generally normal to the flow plane. Pyroxenes are also very anisotropic (fig. 1a,b). Most of the lower mantle

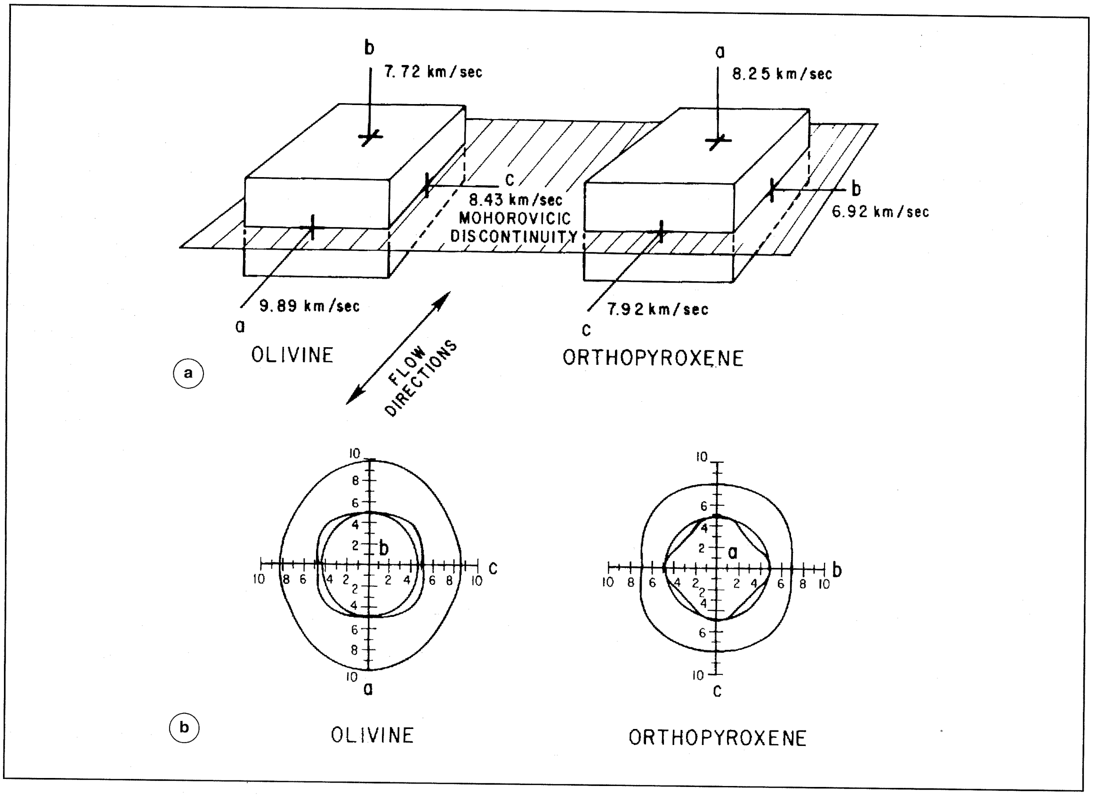

**Fig. 1a,b.** Olivine and orthopyroxene orientations within the upper mantle, showing (a) compressional velocities for the three crystallographic axes, and (b) compressional and shear velocities in the olivine a-c plane and orthopyroxene b-c plane. Two shear waves propagate with differing velocities, the difference in velocity between the two shear waves will be minimum for propagation parallel to an olivine axis (modified from Christensen and Lundquist, 1982).

seems to be isotropic except the D″ layer, here anisotropy can be related to boundary layers present in convection numerical models (Kendall, 1996). The inner core also shows evidence of seismic anisotropy (Morelli *et al.*, 1986) but the origin and mechanisms creating this anisotropy are still subject of controversy.

Difference in velocity varying propagation direction (azimuthal anisotropy) can reach 10% in the shallowest mantle (Anderson, 1989); difference in velocity for the wave polarized in different planes (polarization anisotropy) can reach up to 5%. Mainprice and Silver (1993) calculated the anisotropy of subcontinental mantle samples (peridotite-kimberlite nodules) to be about 4% for *S*-wave.

### 2.1. *Techniques to study seismic anisotropy*

The most obvious manifestations of seismic anisotropy in seismological data are:

- shear wave birefringence (or splitting) – the two polarized *S*-waves arrive at different times;
- azimuthal anisotropy – the arrival times, or apparent velocities of seismic waves at a

given distance from an event, depend on azimuth;

– an apparent discrepancy between dispersion of Love and Rayleigh waves.

The early evidence of seismic anisotropy was the discrepancy between dispersion of Rayleigh waves and Love waves (Anderson, 1961) and the azimuthal dependence of oceanic $P_n$ velocities (Hess, 1964); shear wave birefringence due to propagation in the upper mantle was first measured by Ando *et al.* (1983).

In the results obtained studying anisotropy by different techniques one should take into account that there is often a direct trade-off between the effect of heterogeneity and anisotropy. Interpretations of anisotropy observations depend on the wave-length of different types of seismic waves as well as on their directions of propagation (both as to azimuths and dips).

The most common technique to study seismic anisotropy is the analysis of seismic shear wave splitting (Silver and Chan, 1988, 1991; Vinnik *et al.*, 1984, 1992; Zhang and Schwartz, 1994) which looks at shear wave birefringence as the most unambiguous manifestation of anisotropy. Anisotropy causes shear waves to split into two pulses, one traveling faster than the other (fig. 2). The two pulses can most readily be observed for phases that have a known initial polarization before they enter the anisotropic region. One of such phases is *SKS*, which has purely *SV* polarization at the conversion from *P* to *SV* at the core-mantle boundary. Splitting of *SKS* is easily detected by examining the transverse component, which should be zero in the absence of anisotropy. If anisotropy is present elliptical horizontal polarization is observed as the fast and slow waves combine together (fig. 3). Splitting analysis was successfully applied to local earthquake *S*-waves to infer crustal anisotropy as well as to teleseismic shear waves (as *SKS*) to study the mantle structure. The *SKS* technique has little vertical resolution to contribute to the question of depth location of the anisotropy.

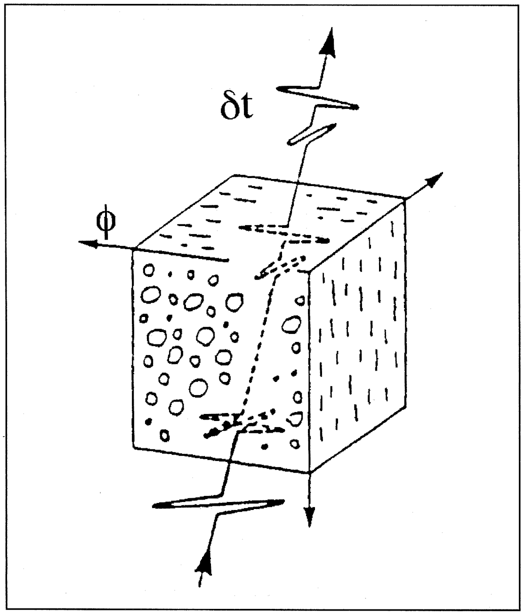

**Fig. 2.** Schematic illustration of shear wave splitting in an anisotropic medium.

The analysis of body wave relative residuals and their dependence on the azimuth-incidence angle (Plomerová *et al.*, 1996) may help in the recognition of fast and slow paths in the Earth. The azimuthal variation on $P_n$ velocity is one of the most direct indications of anisotropy (Hearn, 1996; Barazangi and Ni, 1982; Shearer and Orcutt, 1986). Such data show that both the oceanic and continental lithospheres are markedly anisotropic. The azimuthal variation of $P_n$ also depends on the dip of the Moho or the thickness of the crust.

Surface-wave data, owing to their long wavelength generally provide an average property of the different tectonic units. The technique relies on the fact that Love and Rayleigh waves related to the same path are most often found not compatible with a single isotropic structure, therefore the inversion solves the simplest anisotropic structure able to reconcile the Love-Rayleigh discrepancy. The inversion of surface-wave data (Montagner and Nataf, 1988; Montagner and Tanimoto, 1991; Gaherty and Jordan, 1995) provides a correct location at depth of anisotropy but its lateral resolution is rather poor (1500 km).

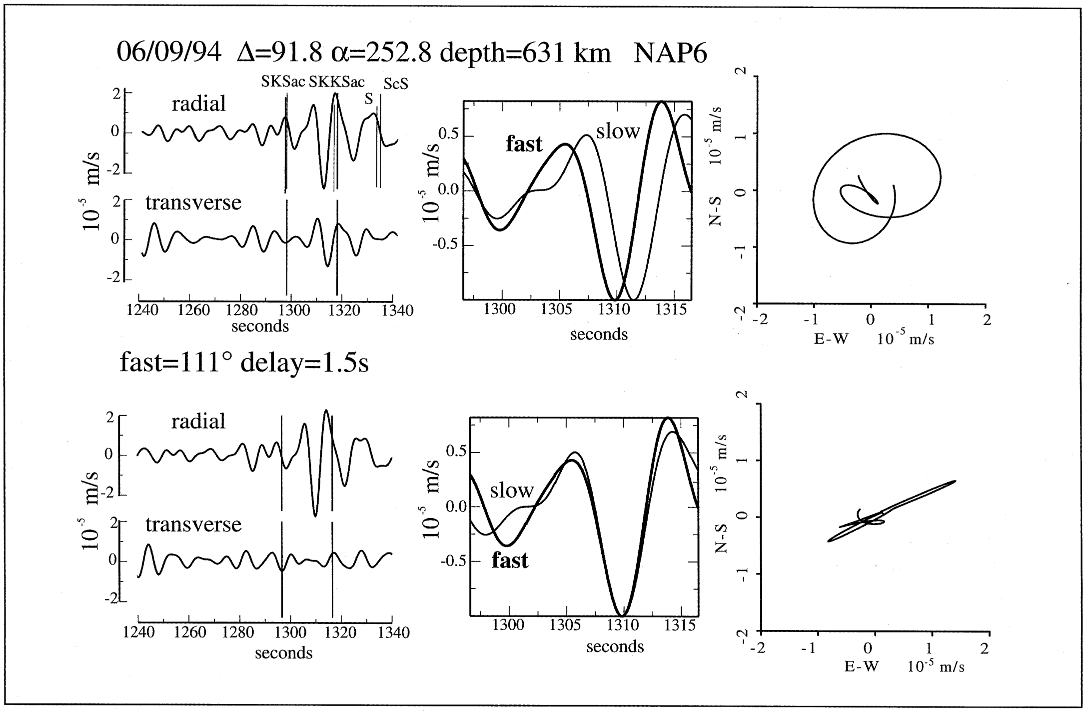

**Fig. 3.** Example of *SKS* splitting analysis. Top *SKS* radial and transverse components, waves rotated in the fast and slow reference system and particle motion in the NS-EW plane as observed at station NAP6. Bottom as top but after the removal of delay time between fast and slow waves. It is interesting to note that after removal the wave polarization direction is consistent with the back-azimuth of the event (modified from Margheriti *et al.*, 1996).

## 3. Seismic anisotropy and geodynamics

The main mechanisms which generate anisotropy are related to the strain field inside the Earth and consequently to geodynamics. In fact, it is the tectonic stress combined with material properties which control the crack distribution and their geometry and it is the stress, the flow and the temperature, that ultimately control the degree of orientation of individual anisotropic crystals. The crust contains strongly deformed sequences of highly anisotropic minerals. Often the contribution of the crust is ignored in geodynamics as it is deemed to be mineralogically complex and heterogeneously deformed. Such a combination is usually assumed to result in an isotropic medium, if the length scale is sufficiently long. Barruol and Mainprice (1993) showed that the crust can contribute about 0.1-0.2 s per 10 km thickness to *SKS* delay times. The mantle is the main source region of the seismic anisotropy investigated for geodynamical studies. Significant contributions to observed seismic anisotropy originate in the preferred orientation of olivine crystals in the mantle lithosphere, either «frozen» after ancient deformational episodes, or as a result of the present day stress field. An important debate is underway to establish whether the anisotropy is mainly of asthenospheric origin, and therefore related to the present-day deformation of the mantle beneath the moving plates, or if it corresponds to a past or present lithospheric deformation.

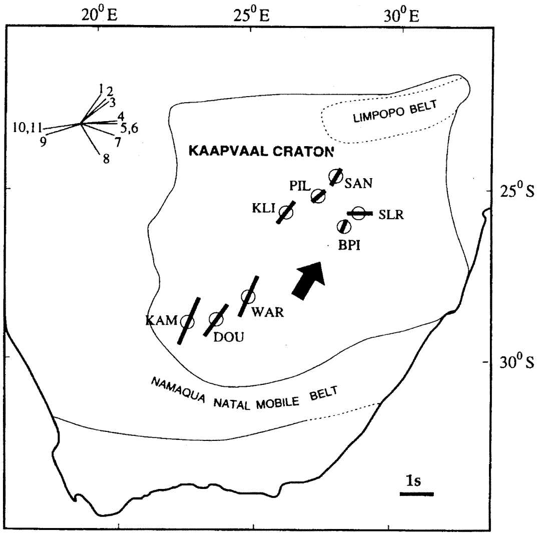

**Fig. 4.** Map of Southern Africa, the direction of polarization of the fast split wave is shown by a segment whose length is proportional to delay times. The direction of Absolute Plate Motion (APM) since the end of Jurassic period is shown by the bold arrow; fast directions seem to be roughly parallel to the APM. Back azimuth of the recorded events are shown in the upper left corner (modified from Vinnik *et al.*, 1995).

The anisotropy of subcontinental mantle samples (Mainprice and Silver, 1993) is about 4% for *S*-waves, which is considered the anisotropy necessary to explain 200-250 km thick lithosphere under shields and *SKS* delay times between the two split waves of 1-2 s (Silver, 1996). On the other hand Vinnik *et al.* (1984, 1992) suggest that the lithosphere is not sufficiently thick or anisotropic to explain the delay times of 1-2 s and prefer a significant asthenospheric contribution. In fact, considering the mobility of olivine crystals at temperature above 900°C, the survival of frozen anisotropy is very unlikely. The threshold temperature in the upper mantle of the cratons is reached at depths somewhat less than 150 km which Vinnik *et al.* (1995) regard as the limiting depth for frozen anisotropy. Understanding whether the source of seismic anisotropy lies in the frozen, strongly deformed, lithosphere or in the asthenosphere raises a major tectonic problem. Are the upper mantle and crust mechanically coupled during deformation? This question represents a major issue for increasing our understanding of both the geodynamic significance of seismic anisotropy and of lithospheric behavior in organizing its fabric. A good correlation is frequently observed between local structural trends in the continents and the parameters of seismic anisotropy (Helffrich *et al.*, 1994; Silver, 1996). A rapid variation in seismic anisotropy characteristics usually corresponds to major geological or tectonic boundaries (Hirn *et al.*, 1995). Up to now the statistical analysis of the orientation of the fast split wave with the Absolute Plate Motion (APM), the best candidate for explaining asthenospheric anisotropy underneath cratonic areas, does not show clear evidence of such a parallelism (Silver, 1996).

In the following we report some results, hypothesis and open questions regarding anisotropy at regional scale in different geodynamical environments.

In cratonic areas, despite some parallelism between the fast polarization direction and the APM that appears in some places (Vinnik *et al.*, 1995) (fig. 4), the fundamental question is related to the presence or absence of the asthenosphere as a decoupling zone in the upper mantle that could localize the deformation and therefore the anisotropy.

A relatively simple mode of formation of the oceanic lithosphere by drag-induced deformation in the asthenosphere and freezing of the deformation within the lithosphere is inferred from geological information in the ophiolite massif and from geophysical observations in the oceans (Hess, 1964). This mechanism is evident in continental and mid oceanic rift zones where the fast axes are perpendicular to the rift axes. In regions of rifting like the Red sea rift, the Baikal rift (fig. 5), the Rio Grande rift and the lower Rhine graben, the fast direction of anisotropy is oriented nearly perpendicular to the rifts and parallel to the directions of extension in the crust (Vinnik *et al.*, 1992; Gao *et al.*, 1994). Upon subduction, the oceanic plate probably retains its anisotropy, with fast

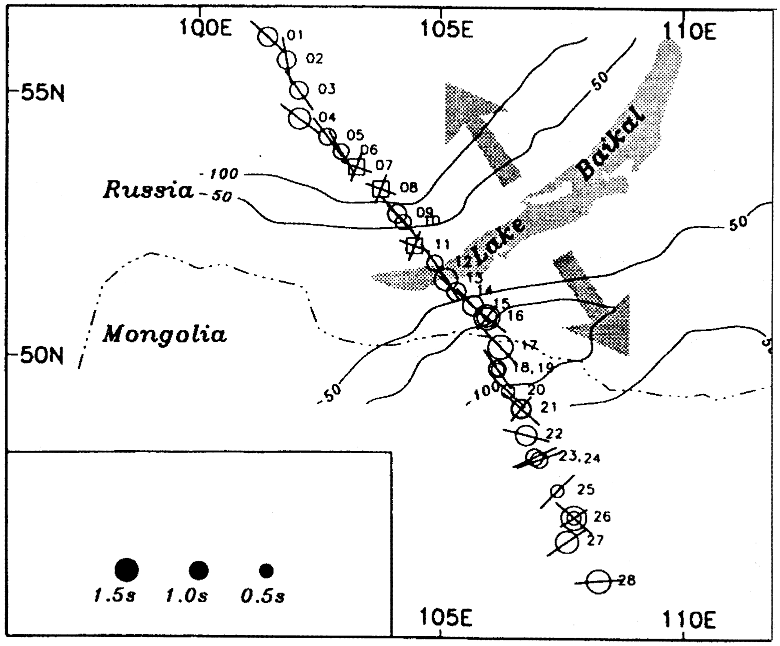

**Fig. 5.** Map showing the region extending form the Siberian platform across the Baikal rift zone into Mongolia. Stations with defined fast direction measurements are represented by single circles with size proportional to the splitting delay times; the line through the circles gives the fast polarization direction. Square and double circles represent not consistent measurements. Contour lines are the thickness of the subcrustal lithosphere in kilometers. Gray arrows are the direction of extensional stress, the fast direction is roughly parallel to the extension direction (modified after Gao, 1994).

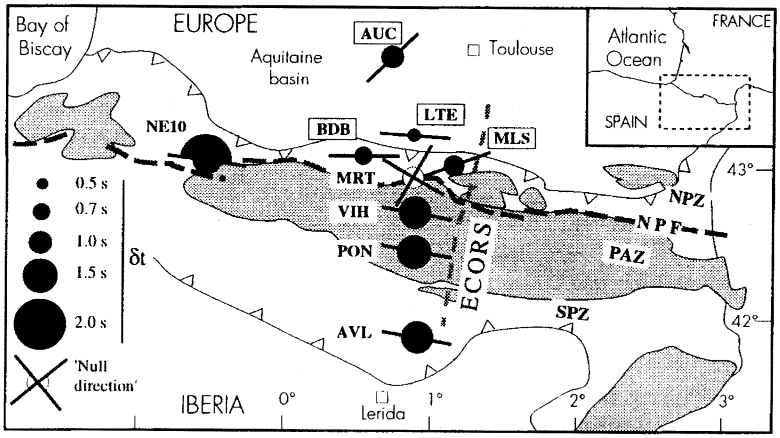

**Fig. 6.** Map of the splitting results in the Pyrenees. Circle sizes are proportional to delay times. fast polarization directions are indicated by black lines, fast directions are mainly parallel to the axis of the mountain belt (modified from Barruol, 1995).

velocities in the plane of the slab. This anisotropy is hard to detect because the problem is now three dimensional.

In mountain belts, the *SKS* splitting studies are directly compared to the extreme complexity of formation and evolution of the continental lithosphere. There is no consensus on the origin and the mode of development of the anisotropy beneath these zones; despite this, fast polarization directions observed in several places on or near major lithospheric sutures correlate with the trend of the local tectonic structures. Fast directions are often nearly parallel to the mountain range axes (fig. 6). In Eurasia this was observed in the Pyrenees, in the Balkans, in the Caucasus, in the Tien Shan, in the Pamirs and in Hindu-Kush (Vinnik *et al.*, 1992; Silver and Chan, 1991; Barruol and Souriau, 1995) and to some extent in the Apennines (Margheriti *et al.*, 1996).

In the case of strike slip faults rooting in the upper mantle (*e.g.*, San Andreas fault, see Zhang and Schwartz, 1994), a regional consistent fabric can develop and generate a regional important anisotropy with fast axes parallel to the fault.

## 4. Seismic anisotropy in Italy

Only recently were seismic measurements of upper mantle anisotropy obtained in Italy, examining shear wave splitting in *S* and *SKS* teleseismic phases (Margheriti *et al.*, 1996) from data recorded by ten stations on a 350 km long linear array, spanning from Corsica Island through the Tyrrhenian basin and the Appenninic belt to the Adriatic coast, carried out in the framework of GeoModAp (EC contract EV5V-CT94-0464) (Amato *et al.*, 1996).

From east to west three regions with different anisotropic parameters have been identified corresponding to the weakly deformed foreland, the highly deformed mountain belt, and the recently active Tyrrhenian volcanic area, respectively. The fast directions found in the different regions crossed by the array closely relate to the different tectonic environments (fig. 7). The fast directions in the Adriatic foreland and in the Apennines are approximately parallel to the strike of the mountain belt (NW-SE). The largest delay times (about 1.5 s) correspond to the highest elevations (NAP5, NAP6 and NAP7), suggesting that anisotropy is related to the compressional tectonics which built the Apennines, and that this tectonic compression involved at least the entire lithosphere. The trend of increasing delay times observed from the foreland to the mountain range can be related to increased lithospheric thickness caused by the present configuration of subduction or collision beneath the belt (Cimini and Amato, 1993). In the Tyrrhenian area fast directions are oriented about E-W, suggesting a reorientation of the mantle fabric due to asthenospheric flow responsible for the E-W post orogenic extension observed at the surface (Jolivet *et al.*, 1994); the thickness of the lithosphere in this region is supposed to be 40 km (Panza, 1984), and therefore it is too thin to account for delays as high as 1 s.

Azimuthal variation of velocity in Italy has also been studied using $P_n$ phases and interpreted in terms of uppermost mantle anisotropy (Mele *et al.*, 1995, 1996). Fast velocity directions are found along two major arcs: the Northern Apennines and the Calabrian arc. The $P_n$ fast direction is parallel to these arcs suggesting that the dynamics which generated the features is deep and involves at least the uppermost mantle.

It is interesting to note that *SKS* anisotropy and $P_n$ anisotropy find consistent results in the Apennines-Adriatic region, where the anisotropy is hypothesized to be lithospheric, and not in the Tyrrhenian area suggesting for this latter region an asthenospheric source of anisotropy, as already hypothesized, based on the observation of *SKS* delay times and the thickness of the lithosphere.

Results coming from the analysis of teleseismic *P*-wave residuals (Plomerová, 1997) show a fast velocity direction plunging WSW beneath the Northern Apennines. These results, according to the author, are not in contradiction with splitting findings, since both of them show the results expected in a three dimensional inclined anisotropic structure (Babuska *et al.*, 1993) considering that *SKS* splitting analysis only enhances anisotropy in the horizontal plane.

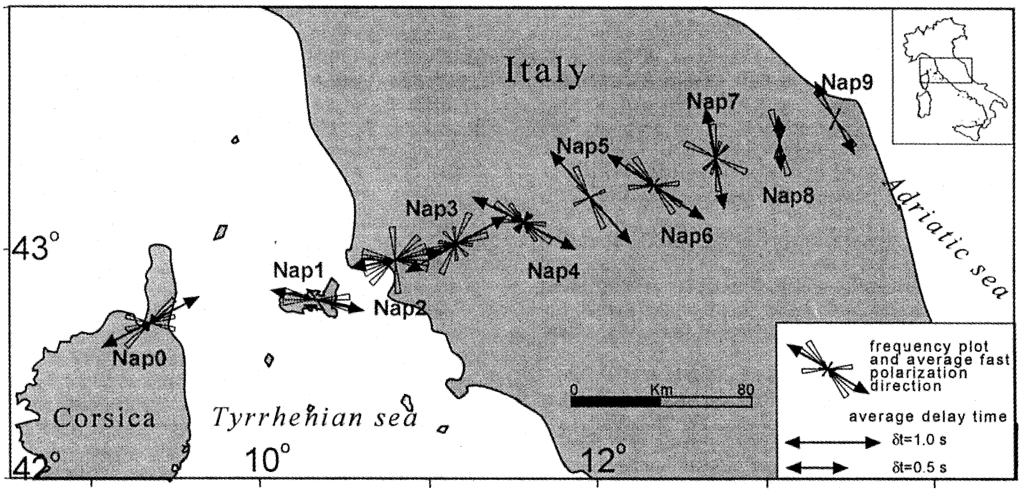

**Fig. 7.** Map of Northern Apennines transect and observed fast polarization directions and delay times. The Apennines develops roughly in the NW-SE direction. In the Tyrrhenian area fast direction is roughly parallel to the extension direction while on the Apennines and the Adriatic zone it is parallel to the strike of the mountain belt (modified from Margheriti *et al.*, 1996).

The results briefly described in this paper, though still sparse and based on few measurements, suggest that the deep processes of deformation are complex and may offer in the future a key to better understanding the three-dimensional geodynamic evolution of the region.

## 5. Conclusive remarks

The assumption that the Earth consists of isotropic shells allowed to successfully describe its gross features. Evidence of anisotropy in shear-waves and surface-waves polarization and in body-wave arrival times represent an original tool for investigating the detailed structure of the materials within the Earth. The study of seismic anisotropy is at present becoming an extension of structural geology at depth, giving the opportunity to detect the strain field at different scales. Seismic anisotropy results can be used to address geological and geodynamical questions. The relevance of mantle deformation to the orogenic process was already demonstrated, pointing out that orogeny is a phenomenon that pervasively deforms the entire continental plate and not only the crust. Moreover, seismic anisotropy studies provide clues for assessing the local stress field in the crust which can be compared with results coming from earthquake focal mechanisms and borehole breakout data. In Italy there are still only a few measurements of seismic anisotropy but the first results are promising, and will probably serve in the future to constrain the geodynamic evolution together with results from other geological and geophysical studies.

## Acknowledgements

We would like to thank R.M. Azzara, A. Basili, E. Boschi, A.C. Chiarabba, M.G. Ciaccio, G.B. Cimini, M. Di Bona, F.P. Lucente, G. Mele, S. Pondrelli, J. Plomerová, and G. Selvaggi for helping in data acquisition, for useful discussions comments, and for continuous encouragements, many thanks to D. Albarello and A. Rovelli for reviewing the manuscript. This study was partially supported by the European Community contract EV5V-CT94-0464.

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