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Anisotropy beneath the Iberian Peninsula: The Contribution of the ILIHA-NARS Broad-band Experiment

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Abstract—The presence of anisotropy beneath the Iberian Peninsula and its main distinctive features can be established through the analysis of teleseismic shear-wave splitting observed in the ILIHA-NARS experiment. In this experiment, an homogeneous data set is provided by a network of 14 broad-band stations deployed over the entire peninsula for about one year. Even if technical problems led to an amount of data smaller than expected, significant variations in the inferred fast velocity direction are observed for stations located in different Iberian domains. The stations in Central and East Iberia show a fast velocity direction oriented roughly E–W, coincident with previous results in Toledo. A clearly different NE–SW direction is observed in the Ossa-Morena zone, supporting the image from a previous regional experiment. The observed delay times lie between 0.5 and 1 s. Although large-scale mechanisms, such as the absolute plate motion of Eurasia, can be invoked to explain the origin of anisotropic features in many sites, the regional variations observed in some domains imply that differentiated origins of the anisotropy have to be considered, probably related to the particular tectonics in the area. An interesting example of this fact is provided by the stations in the Betic chain; the fast velocity direction inferred for a station located in the limit of the External Betics (South Iberian domain), oriented N80°E, is clearly different from the N15–35°E direction observed in the Internal Betics (Alboran crustal domain), the origin of which has to be related to the Alpine building of the chain.

Key words: Anisotropy, shear-wave splitting, Iberian Peninsula, regional variations.

Introduction

The Iberian Peninsula provides a suitable framework to explore the presence of lithospheric anisotropy and to try to discern the mechanism responsible for the lattice preferred orientation (LPO) of the mantle minerals. A large area of the central and western Iberian Peninsula is covered by the Variscan Iberian Massif, a large, old and geologically stable block of continental lithosphere (DALLMEYER and MARTÍNEZ GARCÍA, 1990). On the other hand, the margins of Iberia have suffered a number of more recent tectonic events: late Triassic/Late Jurassic rifting

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to the west, Eocene collision with Europe to the north, Neogene rifting of the Valencia Trough to the east and the Miocene Betic orogeny and Neogene Alboran Sea extension to the south (VEGAS and BANDA, 1982) (Fig. 1). Evidence of the presence of anisotropy in the subcrustal levels of the Iberian lithosphere has been reported in a number of studies that will be reviewed in the next section. However, these anisotropy observations are geographically too scarce to allow for a comparative discussion of the anisotropic parameters.

Conceived as a part of the Iberian Lithosphere Heterogeneity and Anisotropy (ILIHA) project, in the ILIHA-NARS experiment fourteen broadband stations of the portable Network of Autonomously Recording Stations (NARS) were deployed for a period of one year (PAULSSEN, 1990) to record body and surface waves of teleseismic and local earthquakes (Fig. 1). The objective of this experiment was to provide a comprehensive set of seismological data which would allow the establishment of the main structural features of the Iberian lithosphere and upper mantle. In our study we have analysed the splitting of teleseismic SKS and SKKS waves recorded by the ILIHA-NARS array in order to investigate the presence of anisotropy beneath the Iberian Peninsula, as well as the existence of possible regional variations in the anisotropic parameters.

Previous Observations of Anisotropy in the Iberian Peninsula

Prior to the present study, information regarding the presence of anisotropy beneath the Iberian Peninsula was restricted to three specific regions: SW Iberia, Toledo (central Iberia) and the area around the ECORS profile in the eastern Pyrenees.

By analysing the azimuthal variations of the P-wave velocities from the ILIHA deep seismic sounding profiles, DÍAZ *et al.* (1993) inferred a fast velocity direction oriented roughly N10°E beneath the Ossa-Morena zone (SW Iberia). This anisotropy was restricted to well-defined depth levels between 60 and 90 km. Splitting observations on teleseismic shear waves recorded by a portable network installed in SW Iberia, in the same area explored by the ILIHA DSS profiles, suggested a NE–SW to E–W fast velocity direction (DÍAZ *et al.*, 1996). The possible origin of this anisotropy has been discussed in ABALOS and DÍAZ (1995). Using data from the permanent station located in Toledo (central Iberia), SILVER and CHAN (1988) and VINNIK *et al.* (1989) inferred, also from the analysis of teleseismic shear-wave splitting, a fast velocity direction oriented close to N90°E. Finally, BARRUOL and SOURIAU (1995) reported a fast velocity direction beneath the eastern Pyrenees, oriented N100°E from a temporary network around the ECORS profile. At a larger spatial scale, MAUPIN and CARA (1992), using the surface waves recorded by the ILIHA-NARS network, have shown that anisotropy should be present beneath depths of 100 km, although the data could not constrain a fast velocity direction. These different results are summarised and included in Figure 1.

The ILIHA-NARS Data Set

The deployment of the ILIHA-NARS array was designed to cover the most significant tectonic units of the Iberian Peninsula (Fig. 1). Unfortunately, technical problems related to event detection, malfunctioning of some horizontal components and high natural noise level have reduced the number of useful recordings for anisotropy studies, especially on the stations located in NW Iberia. In our study we have only selected events with epicentral distances larger than 85° in which well-defined SKS or SKKS arrivals can be identified. Most of these arrivals provide evidence of anisotropy, allowing the determination of the fast velocity direction and the time delays induced by the anisotropy.

As in most of the published SKS studies, we assume an anisotropic model with hexagonal symmetry and horizontal symmetry axis. Under this hypothesis, a single measurement should be enough to fix the properties of the anisotropic media. Other realistic hypotheses (orthorhombic symmetry, hexagonal symmetry with inclined axis of symmetry) cannot be discussed due to the lack of good azimuthal coverage. The anisotropic parameters have been retrieved using classical cross correlation (ANDO, 1984) and/or minimum amplitude difference techniques (DÍAZ, 1994). The original signal is projected in different coordinate system orientations (e.g., every 5°) and the fitting of the two horizontal wave forms is analysed in each step. The coordinate system for which the two components are closer, is identified as corresponding to the fast and slow velocity directions. Only the records with good fitting between the fast and slow components and an acceptable minimisation of the energy in the transverse component have been retained. The resolution of the method can be estimated in $\pm 10°$ for the fast velocity direction, ϕ, and ± 0.05 s for the time delay, ∂t. Table 1 shows the records retained as well as the anisotropic parameters obtained, which are also reported in Figure 1 (white arrows). Clear arrivals that do not exhibit evidence of anisotropy are interpreted as reaching the station with a backazimuth coincident with the fast or slow propagation directions. These directions are reported as thin black arrows in Figure 1. An example of the data analysis technique is shown in Figure 2.

Anisotropy Results in Different Tectonic Domains of Iberia

The anisotropic parameters inferred from station 17, located in the Central Variscan Massif of Iberia (Fig. 1), are consistent with the previous results presented by SILVER and CHAN (1988) and VINNIK *et al.* (1989). The orientation of the fast velocity direction (N80°E to N105°E) has been related by SILVER and CHAN (1988) to the E–W strike of the Variscan orogeny over the Toledo area. This interpretation implies that the anisotropy should be "frozen" in the lithosphere, the lattice preferred orientation being induced by the last significant orogenic episode in the

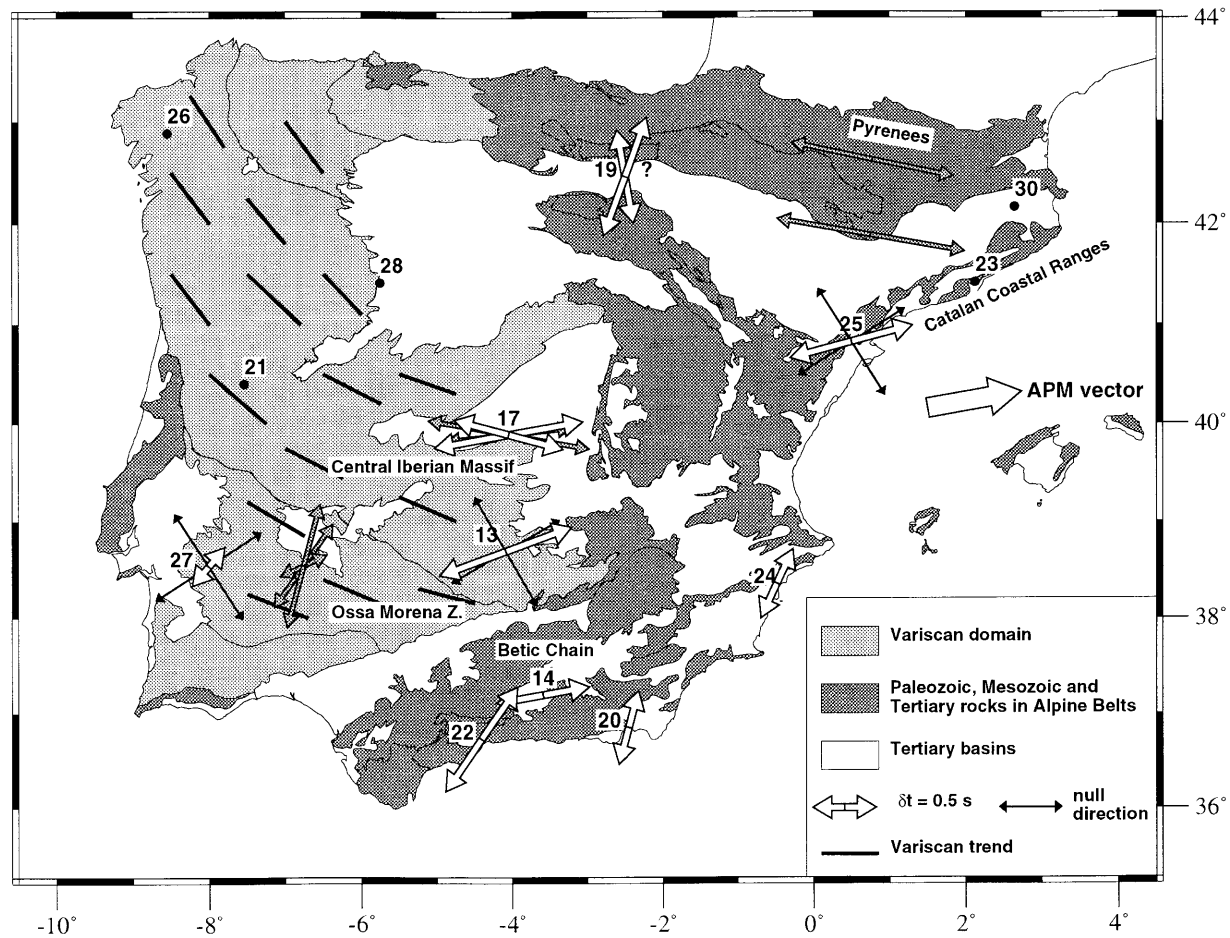

Figure 1

Anisotropic results for the Iberian Peninsula inferred from the present analysis of ILIHA-NARS data. White arrows show the fast velocity direction obtained and are proportional to the time delay. Black thin arrows show the "null measurements". Numbers identify the stations. Question mark for station 19 stands for low quality data. Previous results reported are included (grey arrows, for references, see text). Main tectonic units and Variscan trends are also sketched, as well as the absolute plate motion (APM) vector.

Table 1

Events retained in this study and anisotropic results obtained (fast velocity ϕ and splitting time ∂t)

Station	Event (yr/day)	Dist (°)	Focal Depth (km)	Phase	Baz. (°)	ϕ (°)	∂t (s)
13	88/223	155	141	SKKS	20	70	1.1
13	89/41	120	43	SKKS	60	null	–
14	88/223	155	141	SKKS	23	80	0.8
14	88/251	104	490	SKS	35	80	0.5
17	88/227	91	39	SKS	235	105	0.9
17	88/251	100	490	SKS	35	80	1.2
19	88/210	87	295	SKS	235	−10	0.8
19	88/251	99	490	SKS	35	20	1.0
20	89/41	120	43	SKKS	62	15	0.6
20	88/210	84	295	SKS	235	15	0.5
22	88/223	157	141	SKKS	21	35	1.0
24	89/41	116	43	SKKS	63	25	0.6
25	89/41	114	43	SKKS	63	null	–
25	88/223	151	141	SKKS	28	75	1.0
25	88/227	95	39	SKS	238	null	–
27	89/41	121	43	SKKS	57	null	–
27	88/223	156	141	SKKS	11	40	0.4

area. However, the fast velocity direction (FVD) inferred for station 13, located also in the Central Variscan Massif 100 km south of station 17, shows a difference of about 40° with the Variscan trend in that area.

Station 27 is also located in the Variscan domain, but in a different structural unit, the Ossa-Morena zone, which has been interpreted as an imbricated margin of the Iberian autochthon (QUESADA, 1991). For this station, the fast velocity direction is oriented N40°E, significantly different from that of the previously reported stations. The delay times are also different; 0.4 s for station 27 versus 1.0 s for stations 17 and 13. This result at station 27 is consistent with that presented by DÍAZ *et al.* (1996) from a teleseismic network covering an area located in the same tectonic unit, about 80 km east of that station. The fast velocity direction cannot be related to the Variscan main trend in the area, which is oriented roughly NW–SE (Fig. 1). ABALOS and DÍAZ (1995) have argued that the Variscan orogeny may not have affected the whole Ossa-Morena Zone, while there is evidence showing that the Cadomian one affected the entire lithosphere. The Cadomian stretching direction is oriented N30°E (ABALOS and DÍAZ, 1995), in proximity to the fast velocity direction inferred from the present data.

Station 25, located in the Catalan Coastal Ranges, constrains a fast velocity direction oriented N75°E (Fig. 2). This direction is very similar to the results inferred from the stations on the Central Variscan Massif, although the tectonic evolution is significantly different. The Catalan Coastal Ranges, oriented mainly NE–SW, are compressive structures created during the Paleogene in the eastern margin of Iberia, as the result of the NNE–SSW orientation of the convergence between the Eurasian and the African plates. Since late Miocene, the compressive direction changed to

NNW–SSE. Therefore, the fast velocity direction inferred for this station (N75°E) could be interpreted as being induced by this Alpine compressive episode. Later on, the Catalan Coastal Ranges have also been affected, since the Oligocene-Miocene transition, by extensional processes that produced a number of Neogene normal faults, oriented ENE–WSW (ROCA and GUIMERÀ, 1992). However, on a lithospheric scale the Neogene extension has mainly affected the Valencia Trough area, having limited expression inland (ZEYEN and FERNÁNDEZ, 1994). In any case, the inferred fast velocity direction does not reflect this episode, since for extensional processes ϕ is expected to be aligned with the extension direction (e.g., SILVER, 1996).

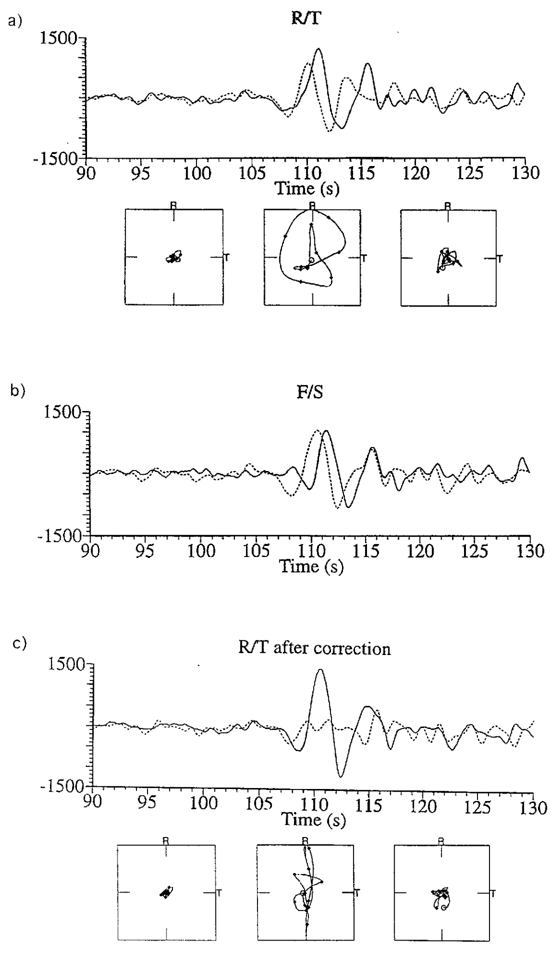

Figure 2
Data analysis of the SKKS phase from the event 88/223 for station 25. a) Radial (solid line) and transverse (dashed line) components and its particle motion diagram in the horizontal plane (5 s per square). b) Projection to the fast and slow directions derived from our analysis. c) Signal after correction of the anisotropic effect, back in the radial/transverse projection. The particle motion diagram now shows a good linearity in contrast with the original data.

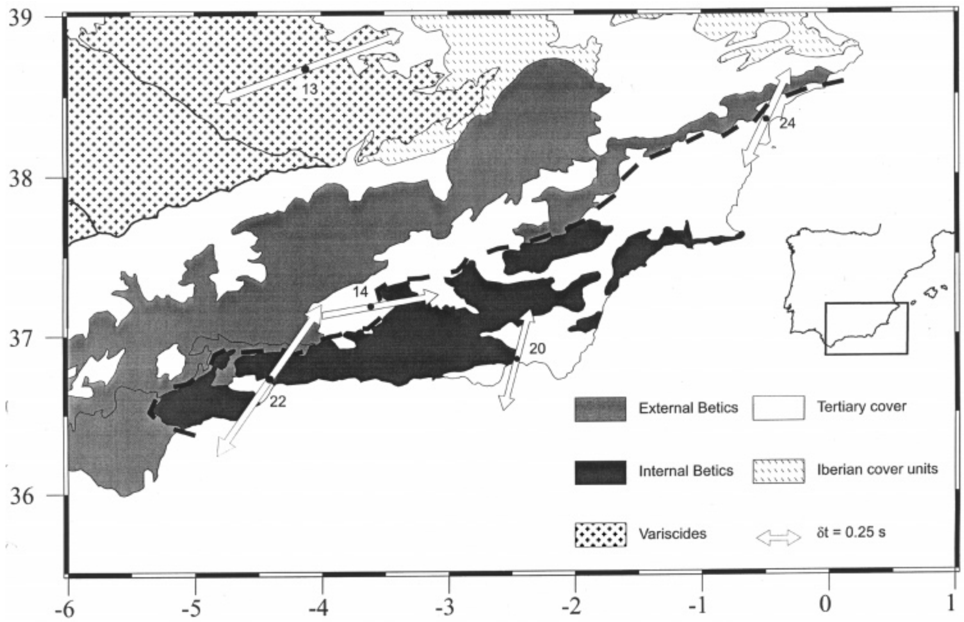

Figure 3
Anisotropic results inferred in the Betics-Alboran domain. Dashed line shows the limit between the Alboran and South-Iberian domains.

Station 19, located south of the western edge of the Pyrenees, displays a roughly N–S fast velocity direction, although more data would be needed to confirm this result, as the data quality is lower than in the remaining stations. This direction clearly differs from most other results and may be related to the particular Alpine tectonic history of this area, affected both by the formation of the E–W Pyrenean chain and the NW–SE Celtiberian chain.

The ILIHA-NARS experiment also provides for the first time, remarkable anisotropy results concerning the Betics-Alboran domain. The Granada station (14) in the External Betics, near the limit of the Internal units, shows a fast velocity direction oriented roughly E–W, similar to the results obtained in the Central Variscan Massif. In contrast, the stations in the Internal Betics (20, 22, 24) express a fast velocity direction clearly different, oriented NNE–SSW (Fig. 3). In Figure 4 this difference is illustrated by comparing, for stations 14 and 22 recording the same event, the fitting of the projections to the fast and slow directions (upper panels) and to the fast and slow directions inferred for the other station (lower panels). The figure demonstrates that the solution for the two stations is clearly different. Therefore, even if this remarkable feature should be confirmed by an enlarged data set, contrasted anisotropic properties seem to characterise these two main Betic domains.

The westernmost end of the Alpine orogenic belt is marked by the Betic and Rif chain and the Gibraltar Arc surrounding the Alboran basin (GARCÍA-DUEÑAS *et al.*, 1992). It is associated with the boundary between two large plates that have undergone complex geodynamics on a lithospheric scale since Mesozoic times. Even if different hypotheses have been proposed to explain the tectonic evolution of the Betics-Alboran region (e.g., PLATT and VISSERS, 1989; SANZ DE GALDEANO, 1990; SEBER *et al.*, 1996), two major domains can be identified. The internal parts of the

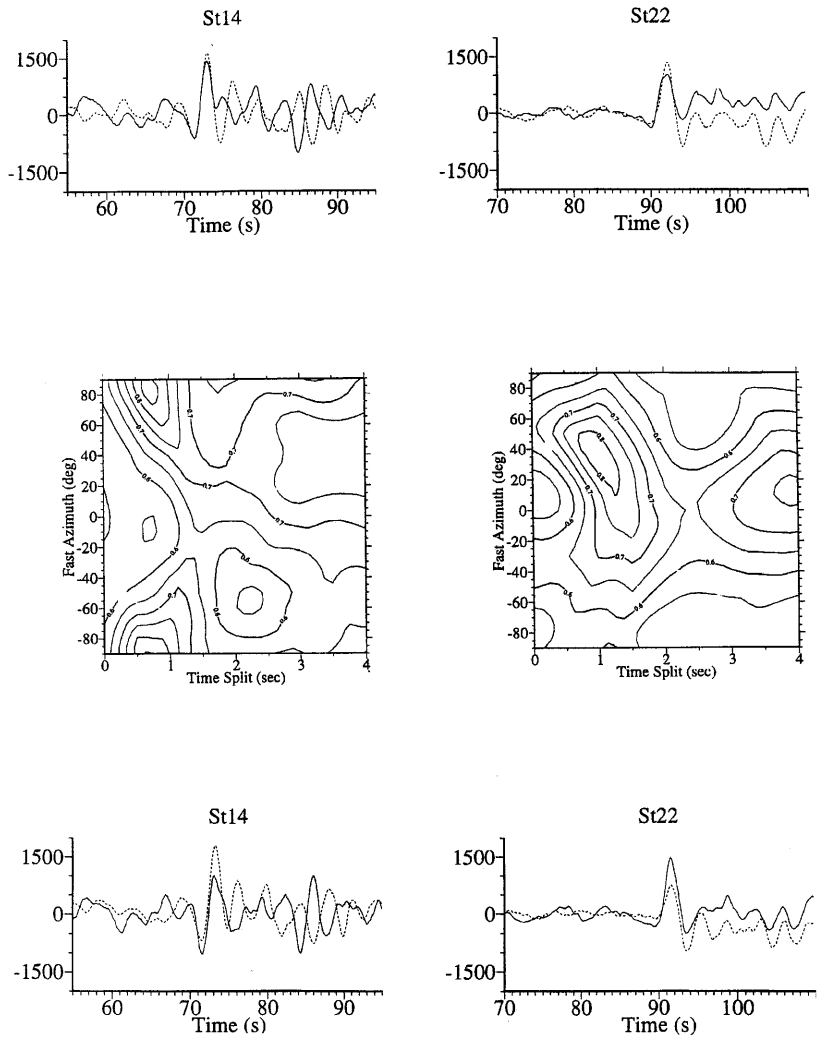

Figure 4
Data analysis of event 88/223 for station 14 (left panels), located in the External Betics (south Iberian domain) compared to station 22 (right panels), located in the Internal Betics (Alboran domain). The upper panels show the projection to the fast and slow directions obtained for each station (see Table 1) once the anisotropic effect has been corrected. The middle panels show the $(\phi, \partial t)$ dependency of the correlation coefficient. The lower panels show, for each station, the projection to the fast and slow directions obtained for the other station, and illustrate that such a test results in a clearly degraded fitting.

Gibraltar Arc (the so-called Alboran crustal domain, which includes the Internal Betics and Alboran Sea basin) are formed by paleogeographical domains not belonging to the Iberian Peninsula. The northern external part (i.e., the south Iberian domain, which includes the External Betics) is the Mesozoic margin of Iberia (e.g., SANZ DE GALDEANO, 1990). The Alboran crustal domain is character-ised at present by higher seismic activity and strong changes in lithospheric structure (CARBONELL and GARCÍA-DUEÑAS, 1997) with respect to the south Iberian domain, more similar to the stable Iberia. In this area, tomographic studies have also shown the presence of an anomalous lithospheric body, interpreted as a piece of subducted or delaminated lithosphere (BLANCO and SPAKMAN, 1993; SEBER *et al.*, 1996) resulting from the orogenic collapse.

These significant differences between the Alboran and the south Iberian domains are also observed in our anisotropy results. The fast velocity directions in the External Betics are directed along the Mesozoic margin of SE Iberia and are similar to those obtained more internally to this margin, in the Central Massif. The fast velocity directions change clearly for stations located in the Internal Betics (Fig. 3). Therefore, the anisotropy pattern supports the structural differences between these two tectonic domains.

Discussion and Conclusions

The analysis of the splitted teleseismic shear waves recorded in the ILIHA-NARS experiment provides for the first time anisotropy constraints beneath different tectonic domains of the Iberian Peninsula from a homogeneous seismic network. Although the present data set is still rather limited, providing only a few measurements for each location and, therefore, the results cannot be considered as conclusive, they evidence the existence of significant variations in the anisotropy on a regional scale.

A classical approach is to relate the origin of the anisotropy with the last main tectonic event in the area. According to this hypothesis, the major trends of the Variscan orogeny could explain the inferred fast velocity direction for some locations (station 17 at Toledo, station 25 in the Catalan Coastal Ranges, Pyrenees). In some of these cases, more recent tectonic episodes can also be invoked as responsible for the anisotropy pattern: Alpine orogeny for the Pyrenees, Paleogene compression in the Catalan Coastal Ranges. In this latter case it must also be assumed that the Neogene extension had no major influence, on a lithospheric scale, inland on the eastern Iberian margin, as the anisotropic properties of the lithosphere have not been modified accordingly. On the other hand, this hypothesis fails to explain the results at some Variscan locations (station 27 in the Ossa-Morena zone, station 13 south of Toledo) (Fig. 1).

Another classical hypothesis submitted to explain the origin of the LPO of the mantle minerals, assumes that it is due to the progressive simple shear induced by the motion of the continental plate over a stationary mantle or, conversely, of the drag of the asthenospheric flow on the base of the lithosphere (e.g., VINNIK *et al.*, 1989). Under this hypothesis, the fast velocity direction is expected to be aligned with the absolute plate motion (APM) and should remain stable along large regions. The APM direction is poorly known for Eurasia (MINSTER and JORDAN, 1978; GRIPP and GORDON, 1990) and therefore this hypothesis is difficult to discuss. The most recent calculations of the APM in the Eurasian plate (Morgan, personal communication), show an APM motion oriented roughly N75°E in the Iberian Peninsula (Fig. 1). This is consistent with the general ENE–WSW trend for the fast velocity direction in large regions of Iberia (stations 17 and 13 in the Central Massif, station 27 in the Catalan Coastal Ranges) but it cannot explain the results at some specific domains (Betic Chain, Ossa-Morena zone). ALSINA and SNIEDER (1995) have proposed that present-day flow in the mantle, at smaller scale than APM, can also contribute to the observed anisotropic pattern and could explain regional differences.

Some of the stations where multiple measurements are available (stations 17, 19) show some dispersion in the fast velocity direction, which cannot be related to the resolution of the method. This feature has also been reported in other regional scale anisotropic experiments (e.g., BARRUOL and SOURIAU, 1995), and is sometimes hidden by statistics. In our opinion, this fact has to be interpreted as reflecting the presence of a more complex anisotropic structure, probably including dipping axis of anisotropy and/or a symmetry system other than hexagonal, which cannot be resolved with our present data.

The observed delay times are in most cases close to the usual value of 1 s. However, some stations present smaller values and in other cases there is a significant variation in the delay time measurements at single stations (see Table 1). This fact cannot be explained by the classical hypotheses of the origin of anisotropy and may be attributed to the existence of more complex anisotropic patterns.

The regional variations in the anisotropic parameters documented by the ILIHA-NARS data set imply that differentiated origins of the anisotropy have to be considered in some areas, in relation to their particular lithospheric geodynamics. A clear example of this is the Betic Chain, where a strong contrast appears in the anisotropic results between the south Iberian domain and the Alboran crustal domain. In the former the results are similar to those obtained for sites on the stable Iberia, whereas in the latter the different anisotropic properties must be related to the complex Alpine geodynamics.

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