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Anisotropic features of the Alpine lithosphere in Northern Spain

J. Díaz, J. Gallart, and M. Ruiz
Department of Geophysics, Institute of Earth Sciences J. Almera, CSIC, Barcelona, Spain

J. A. Pulgar, C. López, and J. M. González-Cortina
Department of Geology, University of Oviedo, Spain

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[1] As part of an extensive seismic research carried out in the last years at the Northern part of Iberia affected by the Alpine compressional tectonics, the mantle anisotropic features have been investigated with the shear-wave splitting technique. Two N-S transects across the western Pyrenees and the eastern part of the Cantabrian Mountains were instrumented. In both cases the average fast velocity direction (FVD) and the delay times are remarkably consistent. The δt values are less than 1 s and the average FVD is close to E/W, subparallel to the trend of the Pyrenean belt. However, in each station the results show a significant variation of the splitting parameters with respect to the backazimuthal direction. This azimuthal dependence is compatible with synthetic models including two distinct anisotropic layers and suggests a complex distribution at depth of the anisotropic features, to be related with imprints of different geodynamic processes in the area. *INDEX TERMS:* 0935 Exploration Geophysics: Seismic methods (3025); 7203 Seismology: Body wave propagation; 7218 Seismology: Lithosphere and upper mantle; 8123 Tectonophysics: Dynamics, seismotectonics; 9335 Information Related to Geographic Region: Europe. **Citation:** Díaz, J., J. Gallart, M. Ruiz, J. A. Pulgar, C. López, and J. M. González-Cortina, Anisotropic features of the Alpine lithosphere in Northern Spain, *Geophys. Res. Lett.*, *29*(24), 2225, doi:10.1029/2002GL015997, 2002.

1. Introduction

[2] During the last 3 years, extensive seismic research has been carried out in the northern part of the Iberian Peninsula, in the framework of the Spanish Research Project GASPI. The aim of this project is twofold: i) the study of the seismicity and seismotectonics from the Pyrenees to Galicia, along the Cantabrian Mountains, and ii) the investigation of the lithospheric structure by passive seismic methods in relation to the mechanics of Variscan and Alpine deformation which affected the area. This contribution is focused in the latter aspect. Anisotropic parameters are retrieved from shear-wave splitting measurements and used to investigate the deformation of the lithosphere and to provide some clues on the structural geology within the mantle. The study area (Figure 1) has been affected by the Variscan and Alpine orogenies, separated by a large extensional period. During the Variscan orogeny, the northern part of Iberia corresponded to the continental margin of Gondwana involved in the collision with Laurentia [*Matte*, 1991]. The Mesozoic extensional episodes related to the opening of the North Atlantic and Bay of Biscay resulted in the formation of the Cantabrian Margin and the individualization of Iberia as a subplate [*Srivastava et al.*, 1990]. During the Alpine orogeny, in Tertiary times, the roughly N/S convergence of Iberia and Eurasia resulted in the formation of the Pyrenean Chain [*Choukroune*, 1992]. To the West, the Basque Cantabrian Basin and the Cantabrian Mountains were also reworked [*Alonso et al.*, 1996].

2. Data Acquisition

[3] The lithospheric signature in two key areas of structural differentiation has been investigated by instrumenting N-S transects along the Western Pyrenees (WPT) and the central part of the Cantabrian Mountains (CMT). These transects were operational during 15 and 9 months, respectively. Six portable seismic stations were deployed in each transect equipped with Lennartz seismometers Le20s and Le5s, with flat frequency response broadened up to 20 and 5 s respectively. Data were recorded continuously at a rate of 50 samples per second. All teleseismic events with reported magnitudes 5.5 or higher were inspected visually to identificate high quality shear wave signals, including SKS, SKKS and PKS phases. Only events with clear phase identification and signal-to-noise ratio higher than 3 have been retained. Zero-phase band-pass filters were applied, with a typical band-pass frequency range of 0.02–0.1 hz for Le20s and 0.1–0.5 hz for Le5s. 14 events and 67 individual measurements in the CMT and 15 events and 49 individual measurements in the WPT form the final data set with epicentral distances ranging from 88° to 155°. Tables with station locations, time and location of the seismic events used and individual splitting measurements are included as auxiliary material[1].

3. Interpretation

[4] To measure the shear-wave splitting parameters, a grid search is done by projecting the horizontal components in different coordinate system orientations (every 5°) and deplacing them by 0.1 s time intervals. The fitting of the two horizontal waveforms is quantified in each case using their correlation coefficient. The coordinate system and delay time which provide a better adjustment defines the anisotropic parameters (Figure 2). Only when the transverse

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[1] Supporting material is available via Web browser or via Anonymous FTP from ftp://kosmos.agu.org, directory "append" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

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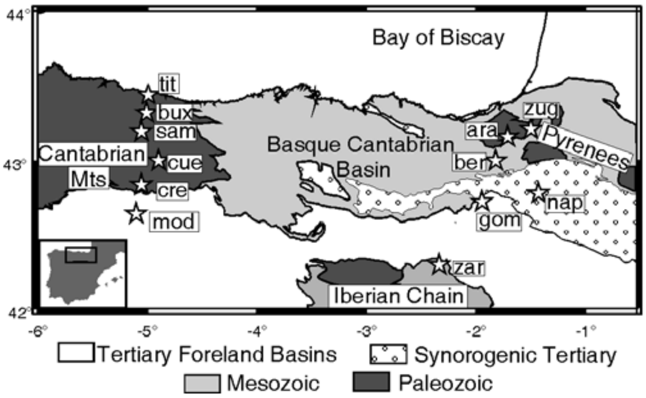

Figure 1. Structural map of the study area, showing the seismic stations deployed along the two transects.

energy can be removed, as verified in the particle motion diagrams, the measurement is retained. The mean values of ϕ and δt as well as their standard deviations, determined using standard data analysis, are reported in Tables 1 and 2. We observe a remarkable consistency in the average fast directions obtained for all the stations in both transects. Mean ϕ values lie between N85°E and N100°E in most cases. However, a spread is involved in the fast velocity directions for different events in each station, with standard deviations reaching more than 20° in some sites. The mean δt values are in most cases less than 1 s, smaller than reported in previous studies on central and eastern Pyrenees [*Barruol et al.*, 1998], where mean δt values between 0.7 and 1.8 s were found, and show also some spread. Under the usual hypothesis that waves propagate across a single layer of anisotropic material with hexagonal symmetry and horizontal symmetry axis, only minor spread related to seismic noise is expected for good-quality data. Hence, the standard deviations from our data may suggest the presence of a more complex anisotropic structure.

4. Evidence for Azimuthally-Dependent Anisotropy

[5] We checked the consistency of the spread in fast velocity directions with respect to possible ambiguities in the interpretation procedure. Figure 3 displays two events with different backazimuth, recorded on the same station. An appropriate fitting is obtained (Figure 3a) in the projections to the fast and slow directions when using the values determined for each event by the interpretation procedure, which differ in more than 50°. Figure 3b shows the effect of using in each event the anisotropic parameters inferred for the other event. It clearly illustrates that the exchange of solutions is not acceptable and, therefore, that different anisotropic parameters have to be retained for different events. We then investigate whether this spread shows any systematic azimuthal dependence. We plot ϕ and δt as a function of the backazimuth of the events and a clear variation is found (Figure 4), with ϕ increasing with backazimuth and some $\pi/2$ periodicity arising. We have verified the stability of this azimuthal dependence for the different stations along both transects. Events with a similar backazimuth give similar ϕ and δt results all over the transects. Azimuthal variation is not expected under the hypothesis of a single layer of anisotropic material with hexagonal symmetry and horizontal symmetry axis and other alternative models, such as the existence of two superposed layers of anisotropy *Silver and Savage* [1994], of different symmetry systems or of dipping axis of symmetry [e.g. *Babuska et al.*, 1993] should be considered. However, our data has a good azimuthal coverage only in the first quadrant, making difficult to discern between the latter models.

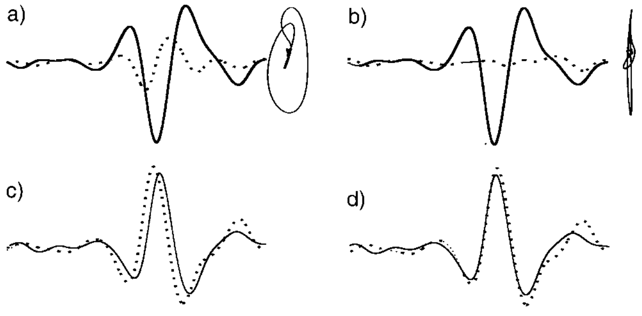

Figure 2. Example of splitting measurement. Deep Andean event (Mw = 6.9) recorded at station MOD at the Cantabrian Mountains transect. (a) Radial and tangential components and particle motion diagram. (b) Idem after removal of the anisotropic effect (ϕ = N95E, δt = 0.6 s). (c) Projection to the defined fast and slow directions (d) Restitution of the measured δt.

Table 1. Anisotropic Parameters (CMT)

sta	# events	ϕ (°)	σ_ϕ (°)	δt (s)	$\sigma_{\delta t}$ (s)
tit	13	97,3	21,0	0,7	0,3
bux	11	94,1	15,6	0,6	0,2
sam	11	95,9	15,8	0,7	0,3
cue	8	84,4	10,2	1,0	0,3
cre	15	94,3	19,3	0,8	0,2
mod	9	87,8	17,9	0,6	0,1
Total	67	93,1	17,4	0,7	0,3

[6] In the case of two distinct anisotropic layers, each with hexagonal symmetry and horizontal symmetry axis, the ϕ and δt retrieved under the assumption of a single anisotropic layer are meaningful quantities and can be used to model the real anisotropic properties [*Silver and Savage*, 1994]. These parameters display a $\pi/2$ periodicity. Hence, all the events can be projected to one quadrant, increasing the data coverage. Assuming this hypothesis, we calculate the apparent splitting parameters for 2-layered structures with ϕ_1, ϕ_2 ranging from 0 to 180° and δt_1, δt_2 ranging from 0.1 to 2 s. The synthetic models were compared to our data, and those which best fit both the ϕ and δt variations were retained. Some features of the data provide relevant constraints to validate the models, as the gentle increasing slope of ϕ between 20° and 60° and the marked differences in ϕ

Table 2. Anisotropic Parameters (WPT)

station	# events	ϕ (°)	σ_ϕ (°)	δt (s)	$\sigma_{\delta t}$ (s)
zar	14	100,4	27,3	0,9	0,3
ara	8	96,3	25,6	0,8	0,4
ber	5	98,0	19,6	0,8	0,3
nap	8	95,0	22,0	0,8	0,4
gom	7	83,6	25,6	0,8	0,2
zug	7	97,9	22,1	0,8	0,4
Total	49	95,8	23,9	0,8	0,3

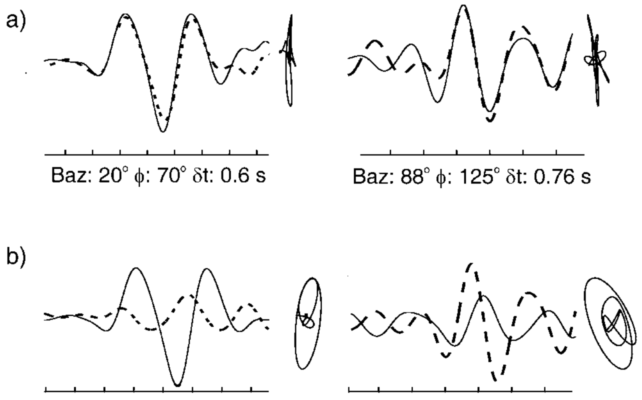

Figure 3. Events from Kuril Islands (left) and South Indian Ocean (right) recorded at station CRE. (a) Fitting obtained in the projections to the fast and slow directions when using the values determined for by the interpretation procedure. (b) Idem when using in each event the anisotropic parameters inferred for the other event.

for events ~80° (Figure 5). However, the procedure lacks unicity, as we derived a number of 2-layered models that explain our data equally well. As expected, in all the good-fitting models the main anisotropic layer has the fast velocity direction close to E/W, with δt values ~1 s. The second layer is less well constrained, but it could be located in a lower-depth layer with ϕ either not far from N/S or ~N70E and δt ~0.3 s. Figure 5 shows the fitting between our ϕ and δt results and those from the two-layer models retained. It has to be noted that most of the observations are well justified in this approach, including the rather surprising small values of δt retrieved for some events, although some features (e.g. pattern of ϕ at about 20° and of δt ~ 80°) can not be fitted accurately in any of the models considered.

5. Discussion and Conclusions

[7] In the western Pyrenean and Cantabrian transects studied here we obtained an average fast velocity direction subparallel to the E-W trend of the mountain belt. A similar result was already reported in previous works on the central and eastern Pyrenees [*Barruol et al.*, 1998], and interpreted as an evidence for a lithospheric anisotropy of tectonic origin. Moreover, the consistency in the anisotropic measurements from the different stations along each transect suggests that the observed anisotropy lies at subcrustal lithospheric levels. The amount of anisotropic material appears rather moderate, as most of the δt values derived are less than 1 s.

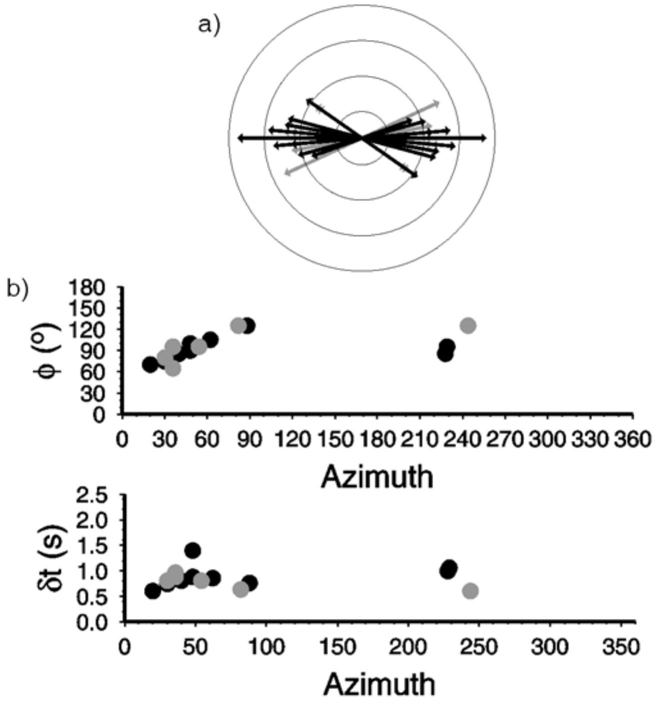

Figure 4. (a) Measured anisotropic parameters for station CRE. Each circle corresponds to 0.4 s. North is to the top. (b) ϕ and δt as a function of the backazimuth of the events. Black arrows/dots represent good measurements, gray arrows/dots correspond to fair measurements.

[8] A remarkable result of this work is that the observation of a significant spread in the anisotropic parameters determined for different events recorded in a single station, lead us to infer the existence of an azimuthal dependence of the splitting parameters which is incompatible with the hypothesis of a single anisotropy layer with hexagonal symmetry. It must be pointed out that the evidence of such a dependence would be lost if the results for each station were just averaged and afterwards discussed. We considered structures that include two distinct levels contributing to the observed anisotropy and derived models that fit the observations. Alternative anisotropic models involving different symmetry systems or dipping axis of symmetry should also be explored, although their testing would require a more comprehensive azimuthal coverage. In our two-layer aniso-

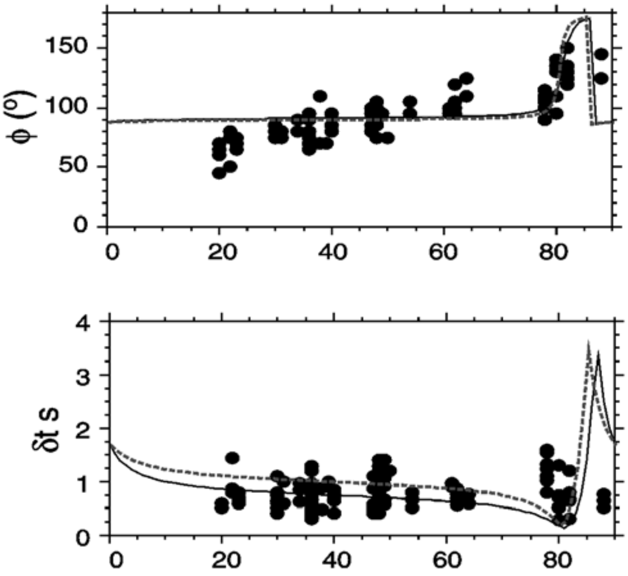

Figure 5. Fitting between our ϕ and δt results for both transects and those from the final two-layer models retained. Black solid lines corresponds to model 1 (ϕ_1 = N90E, δt_1 = 1.0s, ϕ_2 = N10E, δt_2 = 0.3s), gray dashed lines for model 2 (ϕ_1 = N90E, δt_1 = 0.7s, ϕ_2 = N70E, δt_2 = 0.3s). All the data have been projected to the first quadrant.

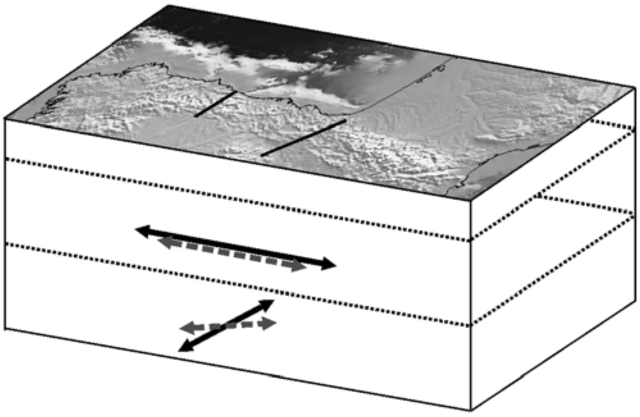

Figure 6. Anisotropic parameters for the two-layered models 1 (black lines) and 2 (gray dashed lines). The geometry of the transects and the topography of the area are displayed over the inferred fast velocity directions. Length bars are proportional to the proposed delay time induced by each anisotropic layer.

tropic modeling, the most significant contribution to the observed anisotropy comes from a layer with ϕ close to E/W and δt ∼1 s, whereas a smaller anisotropic layer located at a lower-depth level 'modulates' the result. The anisotropic parameters defining this secondary layer are not well constrained, but he preferred models have ϕ either not far from N/S or ∼N70E and δt ∼0.3 s (Figure 6).

[9] The most prominent anisotropic layer can be interpreted as 'frozen-in' anisotropy in the lower lithosphere, related to the most relevant tectonic process in the area. In the study area a similar structural E-W direction may arise from either Variscan or Alpine tectonic episodes [*Barruol et al.*, 1998]. The similarity in results obtained at stations located within or beyond the region reworked by the Alpine compression suggest that the present-day dominant anisotropic direction in the lithosphere could be mainly a signature of the widespread Variscan tectonics in North Iberia [*Vauchez and Barruol*, 1996]. If we assume an overall 4% anisotropy and an average isotropic shear velocity of 4.6 km/s, the thickness of this layer should be ∼115 km. The second anisotropic layer could be related to asthenospheric flow processes. A classical interpretation for this anisotropy origin is the passive motion of the lithosphere over a relative stationary asthenosphere, that will produce a ϕ parallel to the plate motion. The absolute plate motion (APM) direction in the study area is oriented N50E according to *Gripp and Gordon* [1990], not far from the ϕ direction of one of our preferred models. The slow displacing of the plate can explain the small amount of anisotropy in this layer. However, the uncertitudes in the determination of both the anisotropic properties of this level and the APM direction do not allow being conclusive on this point. In any case, the new seismic data set available at the Northern Iberian Peninsula reveal a complex anisotropic signature within the mantle to be related with the different imprints led by the geodynamic processes in the area.

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J. Díaz, J. Gallart, and M. Ruiz, Department of Geophysics, Institute of Earth Sciences J. Almera, CSIC, c/ Lluis Sole Sabaris s/n, 08028 Barcelona, Spain. (jdiaz@ija.csic.es)

J. A. Pulgar, C. López, and J. M. González-Cortina, Department of Geology, University of Oviedo, c/ Arias de Velasco s/n, 33005 Oviedo, Spain.