SKS-wave splitting and upper mantle structure: results in the Southern Apennines

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Abstract
Shear wave splitting measures at six temporary stations in the Southern Apennines are computed analyzing fifteen events recorded during the spring and summer 1996, with magnitude greater than 5.8. The splitting parameters were measured using Silver and Chan's (1991) method only on *SKS* and *SKKS* phases. Evidence for strong seismic anisotropy was found at all the stations: delay times δt are generally larger than 1.5 s and fast directions ϕ are quite variable in different geodynamic domains. NW-SE ϕ average directions are found at stations on the mountain belt while at stations on the foredeep and foreland ϕ is on average N-S. Changes in splitting parameters may be related to upper mantle structure, and particularly to the geometry of a fragmented lithosphere subducting beneath the Apennines.

Key words *shear-wave splitting – SKS – upper mantle structure – Southern Apennines*

1. Introduction

Seismic anisotropy is revealed as velocity variation both as a function of propagation and polarization direction of seismic waves. Shear wave splitting, a phenomenon analogous to birefringence observed in an optically anisotropic medium (*e.g.*, calcite crystal), is the most unambiguous manifestation of polarization anisotropy (Silver, 1996). In fact, in polarization anisotropy studies based on shear wave splitting analysis, there is no trade off between the influence of anisotropic structure and laterally varying isotropic structures, as may happen in propagation anisotropy studies because these make use of seismic waves traveling along different paths. In an anisotropic medium there are two quasi-shear waves traveling, with polarization directions orthogonal to each other and propagating at different velocities. Observations of teleseismic shear wave splitting are used to monitor the thickness and the deformation field of the continental lithosphere (frozen-in, inherited from the most recent tectonic episode) and to understand its geodynamic development, on the assumption that anisotropy may be due to vertically coherent deformation of crust and subcontinental mantle during orogenesis (Barruol and Souriau, 1995; Helffrich, 1995; Silver, 1996), and to infer mantle flow directions in the asthenosphere, considering an asthenospheric source of the anisotropy (Russo and Silver, 1994; Silver, 1996). The splitting of teleseismic shear waves has this versatility thanks to its ability to monitor strain, which, through lattice preferred ori-

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entation of olivine, imparts a fabric and hence anisotropy to the upper mantle (Nicolas and Christensen, 1987).

The Southern Apennines mountain belt is part of the African-Eurasian convergent plate boundary (Patacca and Scandone, 1989); the protracted collision along this irregular margin led to a complex pattern of rapidly changing surface tectonics: extensional basins and compressional belts generally corresponding at depth respectively to upwelling mantle and descending slabs or lithospheric roots as enhanced by tomographic studies (Piromallo and Morelli, 1997). The formation of the Apennines and the opening of the Tyrrhenian backarc basin result from the incomplete subduction of the Adriatic and Ionian micro-plates; the articulate, asymmetric configuration of the Apenninic belt-Tyrrhenian basin system, possibly reflects a complex development of the subduction process. I overlaid the shear wave splitting results found in this study at the Southern Apennines transect over tomographic images of upper mantle (Lucente *et. al.*, 1998) to try to understand the relation between the two. I compared these new results with the anisotropic trends found in the Italian region (Margheriti *et al.*, 1996; Amato *et al.*, 1998, Margheriti and Pondrelli, 1998).

2. Method to measure shear-wave splitting parameter

The splitting parameters of teleseismic *SKS* and *SKKS* waves were measured using Silver and Chan's (1991) method, in which interaction of the wavefront into a single anisotropic layer with a horizontal symmetry axis is assumed; this simplifying assumption may result in the observed complexity of the measures. *SKS* and *SKKS* waves are polarized in the radial direction by the *P* to *S* conversion at the core mantle boundary, so the initial polarization is known. The two parameters fast polarization direction, ϕ, and delay time, δt, between arrivals polarized in the fast and slow directions, can be estimated through a grid search, looking for the pair that best retrieves the original polarization direction.

Shear wave splitting analysis is generally made by computing the two dimensional time domain covariance matrix of particle motion in the horizontal plane, as its eigenvalue may then be used as a measure of linearity. The covariance c_{ij} is defined between any two orthogonal components of ground motion (u_i, u_j) making angles ϕ and $\phi + \pi/2$ with the original polarization direction for a lag δt

$$c_{i,j}(\phi, \delta t) = \int_{-\infty}^{\infty} u_j(t)\, u_j(t - \delta t)\, dt \qquad i, j = 1, 2. \tag{2.1}$$

In the absence of anisotropy c_{ij} has one non-zero eigenvalue corresponding to the polarization direction. In the presence of anisotropy c_{ij} will have two non-zero eigenvalues, thus one may search for an operator such that the corrected seismogram $\tilde{u}$ possesses a singular covariance matrix. In the presence of noise c_{ij} will not be singular so the fast polarization direction ϕ and delay time δt are the ones which minimize the lowest eigen value λ_2 of the covariance matrix. The importance of the minimum λ_2 is that it constitutes a measure of variance of the noise process. As such, it provides the basis for calculating a confidence region for the two splitting parameters. Confidence bounds (σ_ϕ and $\sigma_{\delta t}$) are obtained from the extent in angle and time of a contour of misfit related to the degrees of freedom in the signal through an *F* test (*e.g.*, fig. 1c) (see Silver and Chan, 1991).

In the *SKS* particular case original polarization direction is known to be radial; therefore the search is simply made by minimizing the energy E_t on the transverse component (u_t)

$$E_t = \int_{-\infty}^{\infty} \tilde{u}_t^2(t)\, dt \tag{2.2}$$

where $\tilde{u}_t$ is the corrected transverse seismogram (*e.g.*, fig. 1a).

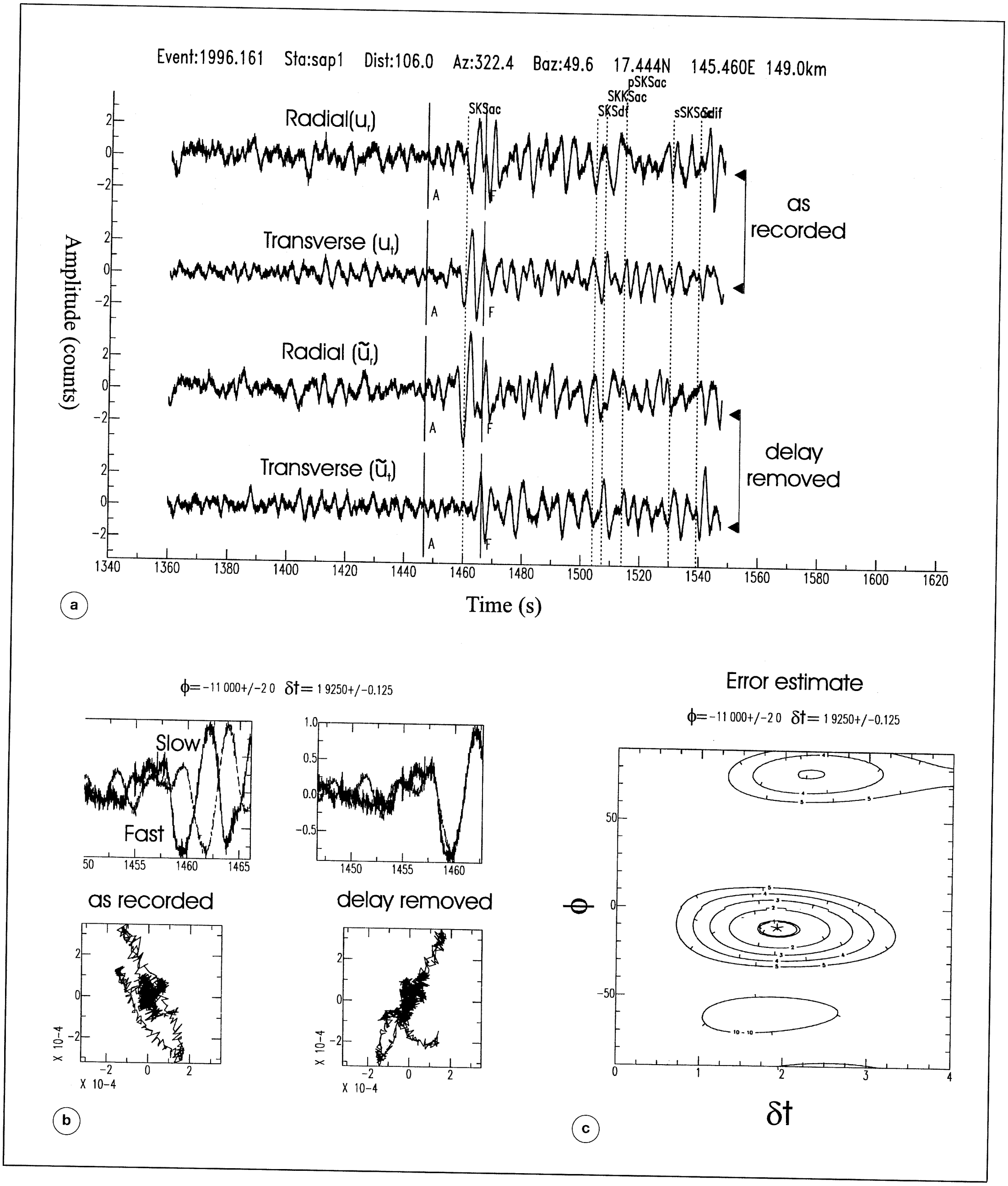

Fig. 1a-c. Example of shear wave splitting analysis at station SAP1 for the 9 June 1996 event. a) Radial and transverse components are shown before and after removing the delay time on the slow component; b) fast and slow component and their particle motion, before and after removing the delay time on the slow component; c) grid search of ϕ and δt and error estimate associated (double line include the 95% probability area).

Hence, the values reported in the next section are the combination that minimizes the energy on the tangential component, which in the absence of anisotropy should be null. Null measurements are found on seismograms which do not show any shear wave splitting; and therefore no energy on the tangential component. In presence of an anisotropic layer this happens when the polarization direction coincides with the fast or slow directions.

3. *SKS* splitting at the Southern Apennine transect

During the 1996 spring and summer (from April to September) a teleseismic transect was deployed across the Southern Apennines, from the Tyrrhenian coastal region, the Cilento area (SAP0) to the Adriatic foreland, Puglia region (SAP7). The station spacing was around 30 km (table I). This experiment was the third and the

Table I. Station locations.

Station	Location	Latitude	Longitude	Elevation (m s.l.m.)	Sensor type
SAP0	Cuccaro Vetere	40°09′44″	15°17′48″	719	CMG40
SAP1	Teggiano	40°22′11″	15°32′16″	720	LE-5s
SAP2	Sasso di Castalda	40°30′30″	15°41′12″	1030	LE-5s
SAP3	Brindisi di Montagna	40°35′59″	15°55′59″	850	LE-5s
SAP6	Gravina	40°50′57″	16°19′15″	424	CMG40
SAP7	Bitonto	40°59′46″	16°31′40″	339	CMG40

Table II. Events analyzed (IRIS data center locations and magnitude).

	Date	Time	Latitude (°)	Longitude (°)	Depth (km)	Magnitude
1	1996/06/02	09:37:46.4	27.424	128.484	42.0	5.8 m_b
2	1996/06/08	23:19:15.1	51.491	−178.128	33.0	6.3 M_s
3	1996/06/09	01:12:16.7	17.444	145.458	149.0	6.5 M_L
4	1996/06/10	04:03:35.4	51.564	−177.632	33.0	7.6 M_s
5	1996/06/10	15:24:56.0	51.478	−176.847	26.0	7.1 M_s
6	1996/06/11	18:22:55.7	12.614	125.154	33.0	7.1 M_L
7	1996/06/17	11:22:18.5	−7.137	122.589	587.0	7.9 M_L
8	1996/07/15	21:23:34.0	17.600	−100.965	18.0	6.5 M_s
9	1996/07/16	10:07:36.6	1.016	120.254	33.0	6.4 M_s
10	1996/07/22	14:19:35.7	1.000	120.450	33.0	6.9 M_s
11	1996/07/28	10:40:43.6	1.006	120.196	33.0	6.0 M_L
12	1996/07/30	17:38:30.7	14.509	119.954	33.0	6.1 m_b
13	1996/08/05	21:39:16.2	−1.996	−81.001	33.0	6.0 M_L
14	1996/09/05	23:42:06.1	21.898	121.498	20.0	6.8 M_L
15	1996/09/11	02:37:14.9	35.537	140.943	55.0	6.1 m_b

southernmost of 3 transects deployed across the Apennines (EEC project, contract EV5V-CT94-0464, GeoModAp) whose data were analyzed to recover the deep structure below the mountain belt and infer its geodynamic evolution (Margheriti *et al.*, 1996; Amato *et al.*, 1998). In this study I analyzed data recorded at 6 stations (table I), the sites were equipped with Reftek stations recording in continuous mode and Guralp (CMG40) sensors (30 s period) or Lennartz (LE-5s) sensors (5 s period).

The data set (table II) includes earthquakes with magnitude between 5.8 and 7.9 and distances ranging between 87° and 107° (fig. 2). At these distances the *SKS* and *SKKS* phases are clearly distinguishable and isolated from other shear waves (fig. 1a) the magnitude of the analyzed events ensure a good signal to noise ratio on the horizontal components. Table III reports (rose diagrams in fig. 3) the singular measurements at each station; the availability of events at different stations are dependent on the operating period of the stations. The variability of splitting parameters at the same station for different events is probably related to the upper mantle structure much more complex than a single anisotropic layer with horizontal symmetry axis. Average ϕ and δt are evaluated at each station weighting the measures between 0 and 3 according to their quality, this is based on the signal to noise ratio (impulsive waveforms weight more) and on the error estimate (σ_ϕ lower than 10° and $\sigma_{\delta t}$ lower than 0.4 weight more). The average delay times are generally quite high, greater than 1.5 s, except for SAP6; this implies the presence of a thick anisotropic layer (on the order of about 170-200 km assuming an intrinsic anisotropy of 6%) or an iso-orientation of the minerals stronger than the average. The mean fast polarization directions are distinguished in two main domains: the four stations on the west, Tyrrhenian and Apenninic stations, where ϕ rotates from NW-SE to WNW-ESE, and the two easternmost stations, on the Adriatic foreland where ϕ is about N-S. These two domains correspond respectively to the orogenic belt (at this latitude the Apenninic mountain belt extends almost to the Tyrrhenian coast, Cilento area) and the Adriatic foredeep and foreland.

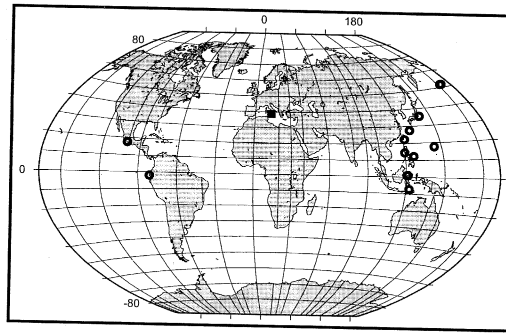

Fig. 2. Analyzed events: circles are epicentres and the solid square is the transect.

4. Discussion and final remarks

Seismic anisotropy in the upper mantle is caused by the orientation distribution function for the primary anisotropic minerals: olivine and piroxens (lattice preferred orientation) (Nicolas and Christensen, 1987), then ϕ and δt are strictly related to its strain field in the upper mantle and hence to geodynamics (Silver, 1996). The main tectonic processes candidates to impart the anisotropic pattern are lithospheric deformation (mainly inherited by orogenic processes, and frozen in the continental lithosphere) and asthenospheric flows: in the Southern Apennines both these mechanisms can be present.

Different models have been proposed to explain the geodynamic evolution of the Southern Apennines - Tyrrhenian basin (fig. 3). The main processes acting in the region are the extension in the Tyrrhenian sea started about 17 Ma (with production of oceanic crust in the internal region) (Malinverno and Ryan, 1986) and the contemporaneous subduction of the Ionian-Adriatic plate beneath the Apennines and the Calabrian arc (Selvaggi and Chiarabba, 1995 and references therein). The orogenic process which built up the Southern Apennines has been replaced by an extensional tectonic regime, since the Middle Pleistocene, as witnessed by the focal mechanisms of the largest earthquakes (Anderson and Jackson, 1987) and

Table III. *SKS* splitting measurements.

Station	Event	BAZ(°)*	Delta(°)*	ϕ(°)	σ_ϕ(°)	δt(s)	$\sigma_{\delta t}$(s)	Q_f
	6	68	96	−7	4	2.5	0.65	2
	7	85	107	−60	22	0.7	1.02	1
	8	301	98	−21	22	1.6	2.83	0
SAP0	9	80	100	−38	22	0.6	2.28	0
	10	80	100	−68	22	1.9	3.00	0
	13	273	97	−38	16	1.9	2.90	1
	Mean			−27	21	1.9	0.80	
	2	9	88	−39	20	1.4	2.73	1
	3	50	106	−11	2	1.9	0.12	3
	6	68	96	−33	22	1.0	2.00	0
	7	85	107	−64	9	0.7	0.14	3
SAP1	8	301	98	−5	7	4.0	3.97	0
	9	80	100	−28	22	0.6	2.28	0
	10	80	100	Null				
	11	80	100	Null				
	13	273	97	−12	2	2.8	0.20	2
	Mean			−30	23	1.7	0.80	
	9	80	100	−89	2	2.1	0.28	3
	10	80	100	−88	3	1.8	0.32	3
	11	80	100	−81	4	2.2	2.80	1
SAP2	12	70	91	−32	14	4.0	3.97	0
	13	273	97	−31	2	1.8	0.07	3
	14	64	87	−81	22	0.7	2.33	0
	15	42	89	Null				
	Mean			−75	24	1.9	0.10	
	1	55	88	−25	4	2.0	2.20	1
	6	68	96	−32	4	3.3	3.65	1
	7	85	107	−60	11	0.9	0.44	3
	9	80	100	−83	4	2.6	0.25	3
SAP3	10	80	100	−80	3	2.0	0.23	3
	11	80	100	−77	3	2.8	0.27	3
	13	273	97	73	4	4.0	4.03	0
	14	64	87	−3	22	0.6	2.25	0
	Mean			−70	17	2.2	0.80	

Table III (*continued*).

Station	Event	BAZ(°)*	Delta(°)*	ϕ(°)	σ_ϕ(°)	δt(s)	$\sigma_{\delta t}$(s)	Q_f
	3	50	106	3	4	1.4	0.15	3
	5	8	88	Null				
	6	68	96	29	8	1.1	0.19	3
	7	85	107	27	6	0.9	0.14	3
SAP6	8	301	98	−1	22	1.0	0.95	0
	9	80	100	8	8	1.5	0.33	3
	10	80	100	14	17	1.4	0.50	2
	11	80	100	20	20	1.0	2.53	1
	13	273	97	−12	8	1.1	1.33	1
	Mean			15	11	1.2	0.20	
	3	50	106	−64	8	3.9	3.94	1
	4	8	87	Null				
SAP7	5	8	88	Null				
	6	68	96	31	22	4.0	4.01	0
	13	273	97	−9	2	1.8	0.23	3
	Mean			−19	22	2.3	1.10	

* BAZ and delta values refer to SAP3.

the present day stress field studies (Amato *et al.*, 1995; Montone *et al.*, 1997).

A key point to understand the deep evolution of the region is whether the subduction process at present is still active in the adjacent Calabrian arc, if it was active in the Southern Apennines or not, and if, when and how the process stopped. Some constraints to this are provided by seismic tomography which recognized a complex pattern of subducted lithosphere fragments beneath Italy (Amato *et al.*, 1993; Spakman *et al.*, 1993). In fig. 4 I compare the velocity perturbations (Lucente *et al.*, 1998) in the upper mantle between 35 and 170 km depth together with deep earthquakes hypocentres, with the average splitting parameters at the Southern Apennines transect described in this work, the tomography considers an isotropic velocity model. Clear evidence of the subducting slab is present below the Calabrian arc, the high velocity anomaly and related deep earthquakes extend from Northern Sicily to Northern Calabria. In the shallower layer (35-100 km) low velocity perturbation NNW of the slab corresponds to back arc volcanism. On the other hand, an almost unperturbed mantle is present below the Central-Southern Apennines. The absence of subducted lithosphere in this region was interpreted as a slab window which extends below the Central and Southern Apennines above 250 km depth (Amato *et al.*, 1998; Lucente *et al.*, 1998).

Other shear wave splitting results are available in the Italian region (fig. 5) from two previous teleseismic transects (Margheriti *et al.*, 1996; Amato *et al.*, 1998). In the Northern Apennines a clear relationship between the fast polarization directions and the mantle velocity structures were found: the roughly E-W ϕ at the stations located on the Tyrrhenian margin abruptly rotate, corresponding with the Adriatic lithosphere subducting beneath the Northern Apenninic arc, assuming a NW-SE direction. The strongly different, E-W trending, anisotropy direction in the Tyrrhenian region, associated with the small lithospheric thickness

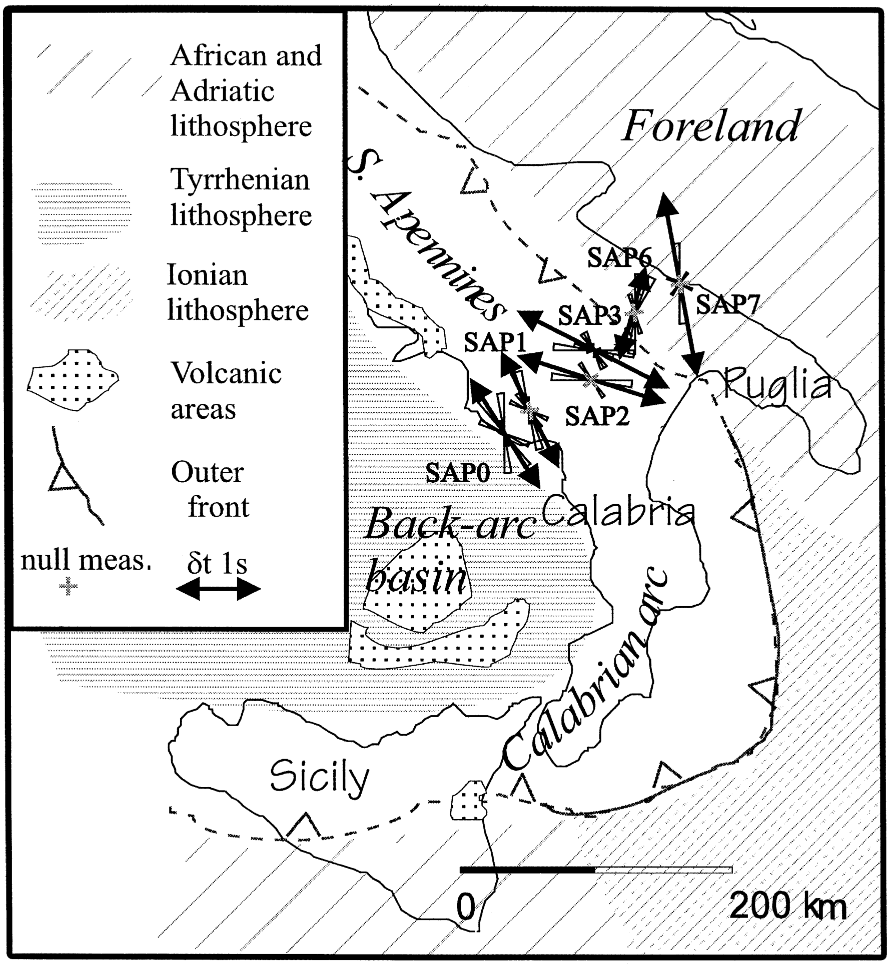

Fig. 3. Geodynamic sketch of Southern Apennines and observed fast directions and delay times across the array. Black arrows represent average fast direction at each station and their length is proportional to average delay time; rose diagrams are relative to single measures and gray crosses are null measurements.

and the correspondence with surface structural trends suggest that the Miocene to Present extension in this region was driven by deep asthenospheric flow and that asthenospheric uplift did not occur with a radial symmetry, but rather with a well defined orientation. Since this orientation is roughly parallel to the migration direction of the orogenic activity, we propose that the E-W asthenospheric flow was triggered by the slab retreat. At the stations of the Central Apennines the fast polarization directions observed are about E-W along the whole transect. Only two stations in the middle of the transect show NW-SE fast direction together with the very close AQU (L'Aquila) MEDNET station (Margheriti and Pondrelli, 1998). In this central region the absence of subducting slab down to 250 km depth was hypothesized (Lucente *et al.*, 1998), therefore the nearly constant trend of the ϕ, across the Cen-

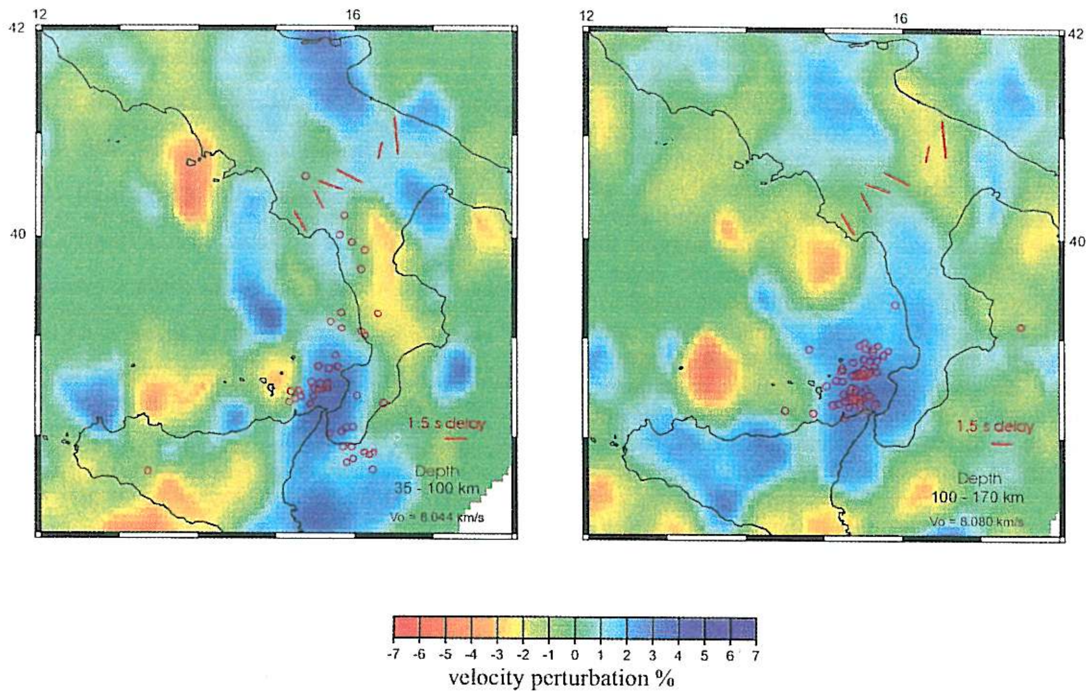

Fig. 4. Average ϕ and δt are plotted over the velocity perturbation maps of the area (from Lucente *et al*, 1998). See text for details.

tral Apennines, seems to be related to the structure of the mantle. In fact the proposed slab-less window possibly allowed the Tyrrhenian asthenosphere to flow underneath the mountain belt, determining a more diffuse pattern of trench-normal fast polarization directions. The region over which this asthenospheric flow is hypothesized (Central Apennines) is characterized by widespread extension in the crust and general uplifting suggesting that the present-day deformation is driven by deep processes.

The Southern Apennines transect cuts the Peninsula just above the northern edge of the Southern Tyrrhenian subduction zone (figs. 4 and 5); the rotation of the ϕ along the transect could be related to the geometry of the subducting lithosphere fragments similarly to what is found at the Northern Apennines transect in the portion relative to the Apennines belt and Adriatic foreland (fig. 5). No splitting mea-

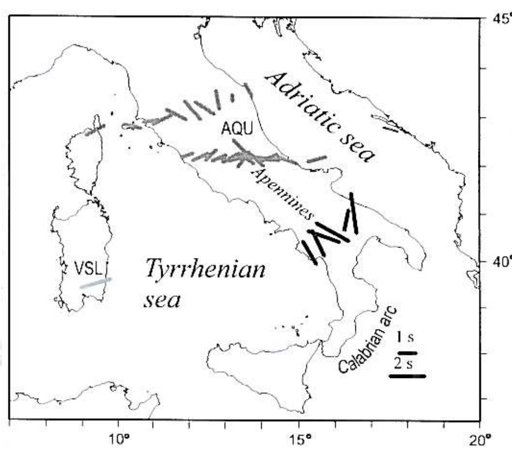

Fig. 5. Average splitting parameter available in the Italian region. Black arrows are average values found in this study, gray arrows are from Margheriti *et al.* (1996), Amato *et al.* (1998) and Margheriti and Pondrelli (1998).

surements relative to the Southern transect are on the Tyrrhenian lithosphere but the ϕ measured at the MEDNET station VSL in Sardinia (Margheriti and Pondrelli, 1998), at about the same latitude as the Southern Apennine transect, is EW as at the other stations of the Tyrrhenian plate domain. Generally the observed rapid variations of ϕ directions among close stations and the delay times suggest that the ~ 150-200 km thick anisotropic layer is shallow, confined in the uppermost mantle.

The discussed results of anisotropic study beneath the Apennines are hence related to three dimensional upper mantle structure, a more detailed study of the splitting measurements at the three Apenninic transect, looking for their variation and azimuthal dependence may, in the near future provide some constraints for understanding Italian geodynamics.

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