SKS splitting in Southern Italy: anisotropy variations in a fragmented subduction zone.

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Abstract

In this paper we present a collection of good quality shear wave splitting measurements in Southern Italy. In addition to a large amount of previous splitting measurements, we present new data from 15 teleseisms recorded from 2003 to 2006 at the 40 stations of the CAT/SCAN temporary network. These new measurements provide additional constraints on the anisotropic behaviour of the study region and better define the fast directions in the southern part of the Apulian Platform. For our analysis we have selected well-recorded SKS phases and we have used the method of Silver and Chan to obtain the splitting parameters: the azimuth of the fast polarized shear wave (φ) and

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delay time (δt). Shear wave splitting results reveal the presence of a strong seismic anisotropy in the subduction system below the region. Three different geological and geodynamic regions are characterized by different anisotropic parameters. The Calabrian Arc domain has fast directions oriented NNE-SSW and the Southern Apennines domain has fast directions oriented NNW-SSE. This rotation of fast axes, following the arcuate shape of the slab, is marked by a lack of resolved measurements which occurs at the transition zone between those two domains. The third domain is identified in the Apulian Platform: here fast directions are oriented almost N-S in the northern part and NNE-SSW to ENE-WSW in the southern one. The large number of splitting parameters evaluated for events coming from different back-azimuth allows us to hypothesize the presence of a depth-dependent anisotropic structure which should be more complicated than a simple 2 layer model below the Southern Apennines and the Calabrian Arc domains and to constrain at 50 km depth the upper limit of the anisotropic layer, at least at the edge of Southern Apennines and Apulian Platform. We interpret the variability in fast directions as related to the fragmented subduction system in the mantle of this region. The trench-parallel φ observed in Calabrian Arc and in Southern Apennines has its main source in the asthenospheric flow below the slab likely due to the pressure induced by the retrograde motion of the slab itself. The pattern of φ in the Apulian Platform does not appear to be the direct result of the rollback motion of the slab, whose influence is limited to about 100 km from the slab. The anisotropy in the Apulian Platform may be related to an asthenospheric flow deflected by the complicated structure of the Adriatic microplate or may also be explained as frozen-in lithospheric anisotropy.

Keywords: Shear wave splitting; subduction; mantle flow; Southern Italy

Introduction

Crystals and most common materials are intrinsically anisotropic, with seismic wave velocities varying for different propagation and polarization direction. The knowledge of the anisotropic behavior of the mantle is an important tool in deep earth studies as it is an indicator of mineral orientation and thus mantle flow. Anisotropy has been used to discuss whether plate tectonics is driven from below by mantle flow or from above by plates (*Silver and Holt, 2002).* It aids in investigations of the relationship between plate motions, mantle flow at depth and the tectonic deformation. In recent years, numerous studies have been carried out to characterize the strain pattern of the mantle. Studies of mantle deformation are particularly focused on the anisotropic behaviour of the upper mantle and there is a growing number of anisotropic studies in active tectonic regions, such as subduction zones (*Ando et al*., *1983*; *Fischer and Yang*, *1994*; *Russo and Silver*, *1994*; *Fouch and Fischer*, *1996*; *Fischer et al*., *1998*; *Savage*, *1999*; *Peyton et al. 2001*; *Hatzfeld et al. 2001*, *Park and Levin*, *2002*). It is widely accepted that in the upper mantle, the most likely mechanism that generates seismic anisotropy is lattice preferred orientation (LPO) of the anisotropic olivine crystals. The alignment of the olivine crystals in the mantle flow direction and the direct relationship between splitting parameters and the crystallographic fabric of the mantle make the subduction zones one of the best places to map the mantle deformation and to constrain the interaction between the rigid subducting plate and the ductile mantle. Several studies show that subduction zones exhibit a broad range of splitting directions. Many convergent margin zones are characterized by arc-parallel fast directions, as in the Tonga (*Fischer and Wiens, 1996*) and in the Mariana subduction zones (*Fouch and Fischer, 1998; Pozgay et al., 2007*). Trench-sub-parallel fast directions are found in New Zealand (*Audoine et* *al., 2000*), in the Ryukyu arc (*Long and van der Hilst, 2006*), in Japan (*Long and van der Hilst, 2005*) and South America (*Polet et al., 2000*). Other subduction zones exhibit both trench-perpendicular and trench-parallel fast directions, as in Lau back-arc (*Smith et al., 2001*) and Kamchatka (*Peyton et al., 2001*). This variable pattern of shear wave polarization direction can be explained considering the large and extremely different factors which affect and complicate the anisotropy, such as the influence of water on olivine deformation (*Jung and Karato, 2001*), effects of dynamic recrystallization (*Kaminski and Ribe, 2001*), strain partitioning between melt-poor and melt-rich regions (*Holtzman et al., 2003, Kaminski, 2006*), local scale flow in the mantle wedge induced by the subducting plate motion (*Vinnik and Kind, 1993; Gledhill and Gubbins, 1996*), and frozen lithospheric anisotropy in the slab (*Plomerova et al., 2006*). Moreover, the presence of slab edges, their geometry, tears in the slab and discontinuities may further complicate the flow pattern (*i.e., Peyton et al., 2001*).

In this study, we have analyzed a large number of events increasing the number of splitting measurements for Southern Italy. This has allowed us to better reveal the variations in the anisotropic parameters between three different geological and anisotropic domains: the highly deformed Southern Apennines and Calabrian Arc mountain belts and the weakly deformed Apulia Platform. Also, new evidence of anisotropy in the southernmost part of the Apulian Platform are found.

We describe the range of splitting behaviour over the study region. There are areas where splitting patterns are generally consistent with a simple anisotropic model, and other places where we see evidence for complexity in the anisotropic fabric. We try to relate these differences to tectonic features and to the upper mantle structure.

1.1 Geodynamics of the Calabrian Arc Subduction System

The Tyrrhenian Sea-Calabrian Arc System (Fig. 1) is part of the complex tectonic boundary between the Africa-Eurasia macroplates. The slow N-S convergent motion between these two major plates has always been invoked as the primary tectonic process in the Mediterranean area (*Wortel and Spackman, 2000*). Nevertheless, the existence of large basins with E-W extensional tectonics, such as the Tyrrhenian Sea, along with compressional arcuate mountain belts, such as the Apennines and Alps, imply the existence of forces and processes independent of the Africa-Eurasia collision (*Dewey et al., 1989; Jolivet and Faccenna, 2000*). Moreover, the rate of convergence between these two plates is on the order of 1-2 cm/yr (*Faccenna et al., 2004*), which is far slower than the rate (5-7 cm/yr) of both the opening of the Tyrrhenian back-arc basin and of the building of the Apenninic and Calabrian mountains (*Malinverno and Ryan, 1986; Patacca et al., 1990*). Numerous authors (i.e., *Gueguen et al, 1998*; *Carminati et al, 1998*; *Faccenna et al. 2001, 2003, 2004, 2005*) explain the geodynamic setting of the Tyrrhenian Sea-Calabrian Arc System as resulting from the southeast retrograde motion of the northwestward subducting Western Mediterranean slab and the associated arc migration. The rollback of the slab provided the driving force for the creation of the backarc, extensional Tyrrhenian Sea and building of the Southern Apennines and Calabrian arcuate orogenic belts.

The development of the present Tyrrhenian Sea - Calabrian Arc has been inherited from several phases of fragmentation of the Western Mediterranean subduction zone. At present, subduction may be active only in the Ionian area, beneath the Calabrian Arc, while a young slab window develops at the Southern Apennines (*Lucente and Speranza, 2001; Faccenna et al., 2003, 2005*).

Beneath the Calabrian Arc are many geophysical features that suggest the presence of subducted oceanic Ionian lithosphere. The actual existence of the slab is defined by the occurrence of many shallow and deep earthquakes concentrated along the Calabrian Arc and in the southeastern sector of the Tyrrhenian basin respectively (Fig. 2a) (*Selvaggi and Chiarabba, 1995; Chiarabba et al., 2005*). The distribution of earthquakes in vertical sections (Fig. 2b) depicts the Calabrian slab extending from the Ionian foreland in front of the Calabrian Arc to the central sector of the Tyrrhenian backarc basin (Fig. 2a,b). At shallow depth, the seismicity images a sub-horizontal seismic plane that could be interpreted as the upper portion of the subducting Ionian lithosphere (*Frepoli et al., 1996; Selvaggi 2001; Chiarabba et al., 2005; Pondrelli et al., 2004*). Beneath the northern sector of the Calabrian Arc, the slab has a gap between 100 and 200 km depth, but forms continuous body at greater depth. The lateral extent of this slab, as delineated by seismicity and tomography, is very narrow, no wider than 250 km. Several seismic tomography studies (*Piromallo and Morelli, 2003; Wortel and Spakman, 1993; Cimini, 1999; Lucente et al., 1999; Montuori et al., 2007*) describe the present-day shape and extent of the slab beyond where it is imaged by seismicity (Fig. 3). The studies agree on several features. A vertical section (Fig 3) reveals that at 100 km depth a high velocity anomaly is present only where the deep seismicity is located. At the same depth, the adjacent Tyrrhenian Sea, Sicily, the Southern Apennines and the Adriatic Sea are characterized by low velocity anomalies. At greater depth, the fast velocity anomaly broadens its size lying beneath the whole Calabrian Arc. At about 300km depth, the high velocity anomaly is a continuous body running from the Southern Apennines in the NE to the Sicily-Maghrebides in the SW, and extending from the Calabrian Arc to SE sector of the Tyrrhenian Sea. This high velocity anomaly is interpreted as the sinking slab

(*Piromallo and Morelli, 2003*). Thus, the slab is horizontal in its shallow portion on the Ionian side, it is steeply dipping (about 70°) to NW down to 400 km and then it bends towards horizontal in the transition zone, lying flat on the upper mantle-lower mantle boundary (660 km) (*Lucente et al., 1999; Piromallo and Morelli, 2003*).

Geodetic data show that today the Calabrian Arc is not retreating and that back-arc extension is not active (*Hollenstein et al, 2003; D'Agostino and Selvaggi, 2004*); however, Nicolosi et al. (*2006*) by unraveling magnetic anomalies in the young Tyrrhenian Sea oceanic crust, suggest that back arc spreading was always episodic.

1.2 Geological features of the Southern Italy

The surface tectonics of the area analyzed in this study (Fig. 1) can be described by three main regions: the Calabrian Arc, the Southern Apennines and the Apulia Platform. The Calabrian Arc fold and thrust belt is part of the accretionary wedge resulting from the sinking of the old oceanic crust still present below the Ionian Sea. The top of the thrust stack in the Calabrian Arc is composed of metamorphic basement slices. These exposed Paleozoic crystalline rocks suggest that this part of Calabrian Arc is a remnant of the Europe-Iberia plate (*Rossetti et al., 2004*) that migrated southward with the subduction system (*Gueguen et al., 1998*).

A different structural style defines the Southern Apennines fold and thrust belt, resulted from the sinking of the Ionian lithosphere and from the collision with the Adriatic microplate (*Patacca and Scandone,* 1989). It was constructed by the imbrications of a succession of carbonate platforms and pelagic basins domains. The most external of these domains is the Apulia Platform which, along with the underlying basement, is partly involved in the orogenic wedge and partly forms the foreland lying below the outer front of the Apenninic chain (*Patacca et al., 2000*). The Apulian Platform is part of the Adriatic microplate considered by some authors as an African promontory (*Rosenbaum and Lister, 2004*) and by others (*Battaglia et al. 2004*) as an independent microplate. The Adriatic microplate subducted below the Eurasian plate between the Cretaceous and the Tertiary forming the SW-vergent Dinarides (*Aubouin et al., 1972*) and, during the Tertiary, the NE-vergent Apennines.

1.3 Previous studies of anisotropy in the region

Previous SKS splitting studies in the western Mediterranean subduction zone (*Barruol and Granet, 2002*; *Margheriti et al., 2003; Civello and Margheriti, 2004; Schimid et al., 2004; Barruol et al 2004; Lucente et al., 2006, Plomerova et al. 2006; Baccheschi et al. 2007; Salimbeni et al. 2007*) found quite large delay times and relate the trench-perpendicular fast directions in the mantle wedge and trench-parallel fast direction along the trench itself to the retrograde motion of the retreating slab (*Buttles and Olson, 1998*). In addition, some complications associated with the Aeolian volcanic arc have been found. Civello and Margheriti (*2004)* interpreted the trench-perpendicular fast direction around the western edge of the present-day Calabrian slab, beneath the Sicily Channel, as a return flow caused by the rollback of the narrow retreating slab. Similar toroidal mantle flow had been modelled by Kincaid & Griffiths (*2003*). In Baccheschi et al. (*2007*), such trench-perpendicular fast directions were not found at the NE edge of the slab beneath the Southern Apennines, where another slab tear is hypothesized by P-waves tomographic models (*Piromallo and Morelli, 2003*). Baccheschi et al. (*2007*) suggests that a possible return flow could be hypothesized at the boundary of the

Southern Apennines and Central Apennines. Moreover, they define that the influence of the slab rollback in the sub-slab mantle is limited to less then 100 km from the slab.

2 Data and methods

When a shear wave passes through an anisotropic medium on its path to the receiver, it splits into two pulses which travel at different speeds: these are denoted as the fast and slow components and have polarization orientations normal to each other (*Vinnik and Kind*, *1993*; *Savage, 1999; Bowman and Ando, 1987*). The splitting parameters used to describe an anisotropic medium are the polarization azimuth of the fast shear wave, φ, (the preferred orientation of the anisotropic crystals), and the delay time, δt, between the fast and slow wave arrivals, which is a measure of the thickness and of the strength of the anisotropic layer. To obtain the shear-wave polarization azimuth and delay time, we used the method described by Silver and Chan (1991), assuming that shear waves pass through a medium with homogeneous anisotropy and with an horizontal fast axis. This method is based on a grid search to find the pair of splitting parameters that best minimize the energy on the transverse component. The splitting analysis on SKS phases is simpler than for other phases. Due to SKS waves passing through the liquid core, all source-side anisotropy is removed. The P-S conversion at the core-mantle boundary provides a known polarization direction; they are polarized on the radial component. Therefore, the presence of energy on the transverse component indicates that the SKS waves have travelled through the anisotropic region on the receiver side (*Silver and Chan, 1991*). Another advantage is that SKS is an isolated phase for epicentral distances ranging between 86° and 106° (*Silver, 1996*).

We have calculated splitting parameters for 15 teleseisms (Fig. 4) with high signal to noise ratios recorded from December 2003 to March 2006 at the 40 CAT/SCAN (Calabrian-Apennine-Tyrrhenian/Subduction-Collision-Accretion Network) stations (http://www.ldeo.columbia.edu/res/pi/catscan) (Fig. 5) .

We selected earthquakes with magnitude greater than 6.0 and epicentral distance Δ° ranging from 87° to 112°. The earthquakes span all back-azimuth, but are primarily concentrated in the E to NE and in the W (Fig. 4). To obtain the best signal to noise ratio, all teleseisms are band-pass filtered with a Butterworth filter to frequencies between 0.03-0.3 Hz. We considered as good measurements only the events with waveforms that exhibit both SKS energy on the transverse component and elliptical particle motion before anisotropy correction and, those, after the correction for anisotropy, show a clear energy reduction on transverse component, rectilinear polarization of the horizontal particle motions, and a good correlation between the fast and slow waves. The final collection of splitting results includes also null measurements. We considered as nulls those measurements in which the original seismograms do not show energy on the transverse component. We did not include in the results complex waveforms not resolvable by the splitting code to avoid the ambiguity between these two different results (*Levin et al 2006*). A null direction does not necessarily mean that anisotropy is absent beneath the station, but could also mean that the shear wave is initially polarized parallel to either the fast or slow direction. This second possibility is the most likely if null directions are obtained along with non-null measurements at the same station. In Figure 6, we show an example of null measurement, an example of a well-constrained result, and an example of complex waveform for which no results are found.

3 Results: geographical variations in splitting parameters

The final collection consists of 185 new SKS high quality measurements, 43 of which are nulls. For each event (Table 1) we report the complete list of individual shear wave splitting parameters along with station and event parameters (Table 1 also includes single measurements from *Civello and Margheriti, 2004* that were not published elsewhere). Results are mapped in Figure 7 along with the splitting results obtained in the previous studies (*Margheriti et al 2003; Civello and Margheriti, 2004; Lucente et al 2006; Baccheschi et al., 2007*) to get a general picture of the anisotropy in the region.

We analyze and discuss the new splitting parameters results together with the results presented in Baccheschi et al. (*2007*). At most of the stations used, we obtained both null and non-null results. The delay time varies between 0.6 s and 3.0 s with an average value of about 1.8 s. The value of δt is in agreement with the large delay time between fast and slow components found by other authors in the Mediterranean region (*Schmid et al., 2004; Salimbeni et al., this volume*) and in other subduction zones (*Audoine et al., 2004; Anderson et al., 2004; Russo and Silver 1994*). Considering an average anisotropy of about 5%, then a delay time of 1.8 s would correspond to an anisotropic layer ~ 200 km thick (*Mainprice et al, 2000*). In subduction zone environments, anisotropy has been inferred to exist at depths as great as 400 km or perhaps deeper (*Fouch and Fischer, 1996; Fischer and Wiens, 1996*). We found the largest δt (up to 3.0 s) along the crest of the Southern Apennine chain and along the highest sector of the Calabrian Arc.

It is evident that the orientation of φ is variable and changes moving from Calabrian Arc to the Southern Apennines and to the Apulian Platform. A clear separation is present in the transition zone between the Calabrian Arc and the Southern Apennines where not only the fast polarization direction changes, but there is also a lack of measurements that is not related to the absence of stations and therefore of data. At these stations (black triangles in Fig. 5) 90% of the analyzed seismograms are either complex, and do not give clear and simple splitting results (as the CIVI example in Fig. 6), or gave a null measurements. The Calabrian Arc and Southern Apennines show a pattern of trench-parallel fast axes. In the Calabrian Arc, fast directions are prevalently oriented NE-SW parallel to the slab strike. Moving toward the Southern Apennines, especially on its Tyrrhenian side, the fast directions rotate to follow the curved contour of the slab and are oriented NNW-SSE. Toward the Apulian Platform the orientation of φ exhibits a clear rotation from N-S in the northern sector to NNE-SSW toward the central-southern sector. The splitting results in the southernmost sector of the Apulian Platform, with fast directions oriented ENE-WSW, testify to the presence of an anisotropic mantle, whereas previous studies (*Baccheschi et al., 2007*) identified only nulls. In each of the studied regions, we have found some good measurements with orientation of fast directions that differs from the prevalent trend. In the following paragraphs we try to investigate the causes of the variability of the splitting parameters. We have separated the well-constrained SKS measurements in three groups: the Calabrian Arc, the Southern Apennines and the Apulia Platform; each of these corresponds to a region with a different geological and geodynamic history. We have made frequency plots of φ for each sector (Fig. 8), obtaining 121 measurements for the Southern Apennines, 118 measurements for the Calabrian Arc and 37 measurements for the Apulia Platform. The rose diagrams show that the fast directions are quite stable in the Southern Apennines and Calabrian Arc, showing a prevalent trench-parallel direction. This trend suggests the existence of an anisotropic volume with uniform characteristics for each one. In the

Apulia Platform, fast directions are less homogeneous and might reflect a more complicated anisotropic structure. The prevalent φ is N-S, but NNE-SSW and ENE-WSW directions are also common. The N-S direction prevails in the northern sector of the Apulia Platform, while the NNE-SSW and ENE-WSW φ are found farther south together with several null measurements. The existence of regions each one with uniform anisotropic pattern, suggest a lateral variation in anisotropic structure. Even if we cannot exclude the existence of a volume with inclined fast axis, we prefer to interpret the variation in anisotropic parameters in terms of lateral or vertical variation of anisotropic volumes with horizontal fast axis following the initial hypothesis corresponding to the Silver and Chan (1991) method used.

3.1. Splitting parameters variability versus back-azimuth

In order to check for possible dependence between the back-azimuth and the anisotropic parameters we have grouped the stations of each anisotropic domain and we plot fast directions and delay times versus back-azimuths (Fig. 9). The results obtained in this study are combined with the splitting measurements in Baccheschi et al. (*2007*). Analysis of several events coming from different back-azimuth are needed to clarify the complex fabric of the anisotropic structures at depth (*Levin et al. 2006; Long and van der Hilst, 2005*). Consideration of the distributions of φ and δt versus the back-azimuth on the diagrams (Fig. 9) should be viewed with caution since each plot includes a large number of stations. We discuss the plots for the Southern Apennines and for the Calabrian Arc, while for the Apulian platform the number of non-null measurements is not sufficient for such analysis. In Southern Apennines and in Calabrian Arc the measurements show a uniform pattern, suggesting that the anisotropic structure beneath the stations should be quite homogeneous. It is interesting to note that the measures that deviate from the most common fast direction are found for specific back-azimuth: measurements in the Southern Apennines with back-azimuths of about 70° and 70° +180° are much more scattered than the other measurements. In the Calabrian arc measurements coming from back-azimuth of about 20° and 20°+180° have values different from the most common. This may imply the presence of a layered anisotropic structure beneath the stations (*Rumpker et al., 1999; Silver and Savage, 1994*). For each of those two domains we have investigated the possible depth-dependent anisotropy by computing a large number of two-layer models trying to fit the observed measurements but none of the model fit the data sufficiently suggesting that the anisotropic structure in the investigated regions is more complicated than a two-horizontal-layer model.

3.2. Splitting parameter variability along an E-W transect

The pattern of SKS splitting for the Southern Italy show a change of the fast axes orientation moving from the Southern Apennines to the Apulian Platform. To constrain the position of where this change take place, we have displayed the value of φ and δt along an E-W transect (Fig. 10) running from the Tyrrhenian Sea to the Adriatic Sea at about latitude 40° (box AA’ in Fig. 7). The fast axes rotate from NW in the Southern Apennines to NE in the Apulian Platform. We observe two groups of fast directions; one with values between -50° and 20° related to the Southern Apennines domain; the other with values of φ between 30° and 70° related to the Apulia Platform domain. The rotation of fast directions takes place almost at the surface tectonic boundary between those different tectonic domains and corresponds to a distance along the profile of about 130 km. At stations located at this transition, NW-SE fast directions are found for events coming from west and NE-SW fast directions are found for events coming from east. This may imply the presence of a steep boundary between the two domains.

3.3. Lateral variation and depth of seismic anisotropy from Fresnel zones

The variability of splitting parameters at the stations located near the boundary between the Southern Apennines and the Apulia Platform for events coming from opposite back-azimuths allows us to hypothesize the existence of a near vertical boundary between these two anisotropic regions. If this assumption is correct and if we are in presence of two anisotropic domains with horizontal fast axes, it is possible to give some constrains on the depth of the anisotropic region. According to the method described by Alsina and Sneider (*1995*), we have estimated the upper limit of the depth of the anisotropic region by calculating the Fresnel zones. The size of the Fresnel zone at a given depth is given by (*Pearce and Mittleman; 2002*):

$$Rf = \frac{1}{2}\sqrt{Tvh}$$

where *Rf* is the radius of the zones, *T* is the SKS dominant period (10 s), ν is the wave velocity (4.5 km/s from the IASP91 model) and *h* is the depth. Considering two teleseismic events with opposite back-azimuth recorded at the same station and with different splitting results, the anisotropic domain is estimated to be deeper than a certain depth we note as Z_1. Above Z_1 the rays travel through the same medium and the corresponding Fresnel zones overlap. Below this depth the ray paths and Fresnel zones for the two events are distinct, as shown by the difference in splitting parameters observed for the two events. For our analysis we have used three stations (TRIC, ILCA and CRAC) located along the transect at the transition zone between the Southern

Apennines and the Apulian Platform (Fig 11). At each of those stations, we have analyzed two teleseisms with opposite back-azimuth, obtaining two different values of fast directions. We have calculated the Fresnel zones at 50, 100, 150 and 200 km depth. Our results show that the Fresnel zones partially overlap at a depth of 50 km, indicating that above that depth they will be sampling roughly the same volume. In contrast, for the other depths, the corresponding Fresnel zones are separated, indicating that the rays sample different volumes below 50 km depth. These considerations allow us to suggest that the main source of anisotropy is located below 50 km depth and that the primary source is therefore not in the crust, at least a the transition zone between the Southern Apennines and the Apulian Platform.

4. Discussion

The increased number and the close spacing of seismic stations installed in Southern Italy in the framework of the CAT/SCAN and CESIS (Centro per la Sismologia e l'Ingegneria Sismica) projects enabled us to collect a large number of shear wave splitting measurements that has helped us to characterize the anisotropy distribution and the mantle fabric of Southern Italy. The orientation of anisotropy can be altered by the water (*Jung and Karato, 2001*). For systems with very little or no hydration, LPO of olivine fast axes are aligned with the direction of flow in the dislocation creep regime (*Zhang and Karato, 1995; Tommasi et al., 2000*). Experimental studies suggest that olivine slip systems change under higher stress and hydration states (*Jung and Karato, 2001*). Since in subduction zones there are regions where these last conditions likely exist, the development of olivine LPO may be significantly influenced by them (*Kaminski et al. 2004*), especially in the forearc (*Kneller et al., 2005*). In this study, such a volume corresponds to the offshore region in the Tyrrhenian Sea between Calabria and the Aeolian Islands and, likely, is not sampled by the SKS rays analyzed. Our SKS splittings are the results of anisotropy in the slab and subslab mantle and we interpret them in terms of LPO of olivine due to strain associated with flow in the asthenospheric mantle.

4.1. Is anisotropy related to lithospheric fabric or asthenospheric flow?

The pattern of splitting parameters observed in this study seems to be consistent with a primary source of the anisotropy localized into the asthenosphere. Most of the delay time values are larger than 1.5 s. The average value is 1.8 s: if we consider an anisotropy of about 5% (*Mainprice et al., 2000*), a δt of 1.8 s would correspond to a thickness of the anisotropic layer of ~ 200 km. This implies that the main source of anisotropy cannot be contained in the lithosphere, which is not thicker than 100 km in the area (*Panza et al., 2007*). The Fresnel zone analysis seems to exclude the source of shear wave splitting from being located in the upper 50 km, at least at the boundary between Southern Apennines and Apulian Platform. Moreover, the presence of the slab rollback is a reasonable cause of an active asthenospheric flow induced by the motion of the slab and which we interpret as being responsible for most of the observed anisotropy. In Southern Apennines and in Calabrian Arc, the observation of some back-azimuthal dependence of fast directions and delay times allow us to hypothesize the existence of vertical variations in anisotropy and also suggests a possible lithospheric contribution to the anisotropy there.

4.2. Possible pattern of asthenospheric flow

If we interpret the anisotropic parameters in terms of asthenospheric flow, the trench-parallel fast directions observed in Southern Apennines and in Calabrian Arc are likely due to the pressure induced by retrograde motions of the slab (*Buttles and Olson, 1998*) which induces the mantle to move horizontally around it creating a local-scale mantle flow below the subducting plate. The slab acts as a barrier at depth, forcing the mantle to flow parallel to its strike (*Russo and Silver, 1994*). Moving from south to north fast axes rotate to follow the arcuate shape of the mountain chains and the curve of the continuous Calabrian slab. Between the Calabrian Arc and the Southern Apennines we see a great continuity in fast directions, but we also observe a lack both of null and non-null measurements in the transition zone between these two different geological domains. Geological models for the evolution of the Calabrian Arc include a left-lateral offset between the Calabrian Arc and Southern Apennines of variable size (*Rosenbaum and Lister, 2004; Faccenna et al., 2005*), which could result in a complex transition zone characterized by incoherent anisotropic fabric in the mantle (*Plomerova et al. 2001*). Mantle flow may also be complicated by the presence of tears at the edges of the Calabrian slab, as revealed by some tomographic images (*Piromallo and Morelli, 2003*). A tear in the slab may allow the mantle to flow through it, creating a return flow from behind the subducting plate to the front of the slab (*Matcham et al., 2000*). Some local studies of anisotropy (*Civello and Margheriti, 2004*) identify a mantle return flow beneath the Sicily Channel through the tear at the SW edge of the Calabrian slab. Baccheschi et al. (*2007*) did not find such a return flow also in the N-E edge of the same slab, where tomographic models identify another tear. In this study we have added measurements below the southern Apennines which show fast axes oriented prevalently NNW-SSE. This confirm the idea that any existing tear is not wide enough to allow to the mantle to flow horizontally through it (Fig. 12), or that the tear is too young to reorganize the olivine structure (*Faccenna et al., 2005*). The delay times corresponding to the slab parallel fast directions are very high (several measurements are higher than 2.0 s) suggesting that the mantle is deformed by the retrograde motion of the slab up to a depth of about 300 km, where no tear is shown by tomographic images (Fig. 12).

4.3. Anisotropy in the subduction foreland

Interesting results are observed in the Apulia. The main observation is the absence of fast directions parallel to the strike of the slab. This different pattern of splitting measurements could be related to previous geodynamic events frozen in the Apulian Platform lithosphere and, more generally, in the Adriatic microplate. Fast axes are oriented N-S in the northern sector, which show the same pattern of splitting measurements found by previous studies (*Margheriti et al. 2003, Schmid et al., 2004*) in the Adriatic microplate along the Italian Coast and along the Dalmatian Coast on the western flank of the Dinarides mountains. In particular, in the easternmost sector of the Northern Apennines not arc-parallel and oblique fast directions were found (*Plomerova et al. 2006*).

Moving toward the southern sector of the Apulia Platform fast axes rotate and show a prevalently NNE-SSW to ENE-WSW directions; in this sector most of the analyzed waveforms return null measurements. This change in splitting parameters between the northern and southern sector of the Apulia Platform is found around latitude 40°N which could testify some past or current deep discontinuities inside the Adriatic microplate. The orientations of fast directions found in the Apulia Platform are different from to the ones observed in the adjacent Southern Apennines. This change takes place almost at the surface tectonic boundary between those two different geological sectors. If the flow beneath the Southern Apennines represents the zone of flow induced by the rollback of the slab, then the edge of the zone where the flow is sufficiently strong to have reoriented the mantle fabric is relatively sharp. The almost trench-perpendicular splitting distributions in Apulia could be interpreted as a mantle flow not controlled by the slab presence and geometry and not involved in the retrograde motion of the slab. Together, these considerations suggest a very focused mantle flow below the slab and that the presence and the rollback of the slab horizontally influence directly the mantle deformation only in a limited zone (less than 100 km) close to the subducting plate. In contrast, the observed seismic anisotropy properties in Apulian Platform could be related to frozen-in fossil flow beneath the Adriatic microplate or to local asthenospheric flow deflected by the roots of the Dinarides away from the orogen-parallel direction. Moreover, the slightly lower values of δt and the abundance of nulls in the weakly deformed Apulian foreland would suggest a possible lithospheric contribution in this domain.

5. Conclusion

SKS splitting results collected in this study reveal the existence of strong and complex seismic anisotropy beneath the Southern Italy. Numerous and closely spaced stations allowed us to better constrain the anisotropic structure of the mantle. We observe different fast axes orientations in three different tectonic and geological domains, each one is characterized by relatively uniform anisotropic parameters. In the Southern

Apennines and in the Calabrian Arc fast axes show predominantly trench-parallel orientation. The clear rotation, from south to north, of fast directions to be parallel to the strike of the slab suggest that the anisotropy is closely controlled by subduction and by the rollback motion of the slab. The combination of those two processes would be responsible for activating mantle flow below and around the slab itself. The scarce number of trench-perpendicular φ at the northernmost stations of the Southern Apennines does not favour the hypothesis of a return flow around the NE edge of the Calabrian slab through a slab gap in the Southern Apennines. We conclude that any slab tear below the Southern Apennines is young and not wide enough to have allowed the reorganization of mantle flow. We observe a large average delay time (1.8 s) especially in Southern Apennines and in Calabrian Arc that seems to be consistent with the primary source of anisotropy localized into the asthenosphere. Moreover, the observations in Southern Apennines and in the Calabrian Arc of some back-azimuthal variations lead us to consider the existence of depth-dependent anisotropy which should be more complicated than a two-layer model. Moving from the Southern Apennines to the adjacent Apulian Platform, our results show a change in the fast direction orientations from trench-parallel to oblique with respect to the slab strike. This not trench-parallel fast axes distribution reflects the pattern observed in the larger Adriatic microplate, with fast directions ranging from N-S to NNE-SSW to ENE-WSW. Therefore in this microplate the anisotropic fabric appears not to be controlled by subduction geodynamics but could be related to a frozen-in lithospheric fossil flow or to a local asthenospheric flow determined by the interaction between Calabrian slab motion and the Dinarides roots.

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Figure captions

Figure 1. Schematic geological map of Southern Italy and Southern Tyrrhenian Sea. The lines and triangles indicate the thrust front of the western Mediterranean subduction zone at16 Ma and at 0 Ma (according to *Gueguen et al. 1998*). At present the subduction is active only in the Ionian domain with the Ionian oceanic lithosphere dipping towards the NW beneath the Calabrian Arc. 1) main thrusts; 2) normal and vertical faults; 3) fold axes; 4) Calabrian basement; 5) volcanic centers; 6a) newly-formed oceanic crust; 6b) deep basins in the African-Adriatic domain; 7) African and Adriatic foreland.

Figure 2. a) Hypocentral distributions of earthquakes characterizing the Southern Tyrrhenian-Calabrian Arc System (*Chiarabba et al., 2005*). The different depth (in km) of the events is given by the grey scale indicated on the lower left corner. The distribution of events tracks the slab subducted beneath the Calabrian Arc and the progressive increase of slab depth toward the central sector of the Tyrrhenian Sea, as also shown by the Benioff plane isobaths (black lines). The intermediate-depth earthquakes (grey circles) are confined to the front of the Tyrrhenian Calabrian coast, east of the Aeolian Islands, while the deeper events are mainly concentrated offshore in the Tyrrhenian Sea (black circles). **b)** Vertical sections oriented NW - SE across the Ionian slab from the north sector of Calabrian arc to north-eastern sector of Sicily. The lines indicates the geometry of the Tyrrhenian Moho (dashed line) and the top of the Ionian slab as inferred from deep earthquakes (solid line) (*Chiarabba et al., 2005*)

Figure 3. P-wave tomography image at 150 km depth of the entire Italian Peninsula and cross section of the Calabrian subduction zone (*Piromallo and Morelli, 2003*). There is a well defined high velocity body, interpreted as the sinking slab, which can

be followed from its shallow horizontal portion, steeply dipping (~70°) toward the Tyrrhenian Sea into the upper mantle and finally lying almost horizontal on the 660 km discontinuity. The white solid circles are the shallow, intermediate and deep earthquakes localized in correspondence with the high velocity anomaly.

Figure 4. Distribution of the epicentres of the teleseisms used in this study plotted as a function of the back-azimuth and of the epicentral distance. Map location of the events.

Figure 5. Map of the 40 CAT/SCAN temporary stations used for the splitting analysis. Black solid circles: stations used as examples in Figure 6. Black triangles: stations at which the 90 % of seismograms are either complex and did not give a clear splitting result or gave null results.

Figure 6. Examples of measurements: a null (left), a well-constrained splitting measurement (centre), an analysis where we report no result (right). The upper panels show four traces: the radial and transverse seismograms as recorded, and the radial and transverse components after correction for the anisotropy (lower two traces). The null is evident due to the absence on the transverse component of SKS energy both before and after correction. For the well-constrained measurements SKS energy is clearly present on the transverse trace before correction and it is removed after the correction. In the no result analysis, SKS energy is clearly present on the transverse trace before and after the correction for anisotropy. The time window used for the splitting analysis is shown in grey. The four middle panels show the analysis window rotated in the fast (continuous line) and slow (dashed line) components (uncorrected (left) and corrected (right) and their respective particle motion (lower row). For the null measurement, the particle motion is linear before and after the correction; for the well-determined measurement, it is elliptical before and is linearized by the correction. The last panel displays the

contour plot of energy on the corrected transverse component showing the minimum value (star symbol) of φ and δt for which the effect of stations anisotropy is best removed. The stations used in those analysis are highlighted as black solid circles in Figure 5.

Figure 7. Map of SKS splitting results displayed as single measurements for individual station-earthquake pairs and plotted at the surface projection of the 150 km depth SKS ray piercing point; this depth enable us to visually separate measurements of events coming from various back-azimuths and different incidence angles. Each measurement is represented as solid bars oriented in the φ direction with a length proportional to the delay time, δt. Null measurements are displayed with two crossing-bars, one parallel to and one normal to the back-azimuth. The thrust front is drawn as a solid black line.

Figure 8. Rose frequency plots for the three different geological domains. The trend of each petal represents the azimuth φ of the fast split shear wave and the length is proportional to the number of measurements in the same interval of φ (at 10° intervals) weighted by the delay times of the measurements.

Figure 9. Plots of the fast directions and delay times (with their errors) versus the back-azimuth of each analyzed events are presented for each of the three different domains. Grey solid squares indicate the events coming from east (rays that on average sample the sub-slab mantle); black solid squares indicate the events coming from west (rays that on average sample the slab). Null measurements are represented by empty squares and plotted as a function of back-azimuth.

Figure 10. Splitting parameters across the Southern Apennines and Apulia Platform along the E-W transect from the Tyrrhenian coast to the Adriatic coast (box AA' in Fig. 7). φ and δt (second and third panel) are plotted as a function of the distance of the

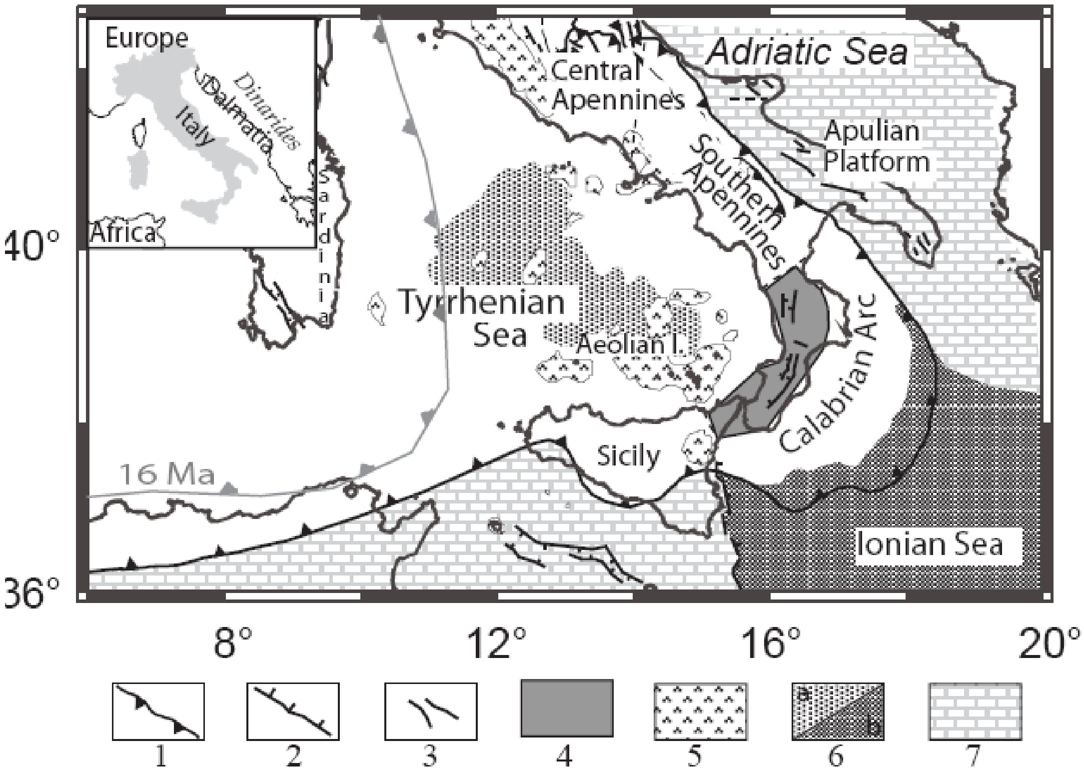
stations from the Tyrrhenian coast. Black solid circles: events coming from the west (back-azimuths between 0° and -180°); grey solid circles: events coming from the east (back-azimuths between 0° and 180°). Open circles: null measurements. The first panel shows the map location of the stations. The white line represents the thrust front. The change in the fast directions between the Southern Apennines and the Apulian Platform domains occurs at 120-150 km distance from the Tyrrhenian coast. The shaded area in the middle panel shows the most frequent fast directions in the two domains. The third panel presents the delay times versus distance.

Figure 11. Fresnel zones calculated at the stations CRAC, TRIC and ILCA close to the tectonic and geological boundary between the Southern Apennines and the Apulia Platform. For each station we used two teleseisms with opposite back-azimuth and we have calculated the Fresnel zones radius at 50 km (white circles), 100, 150 and 200 km (black circles) depth. The circles particularly overlap at 50 km depth, indicating that below this depth the path of the rays differ. This suggests that the anisotropic domain is below 50 km depth. The trench is drawn as solid black line.

Figure 12. Model of possible mantle flow trajectories induced by slab rollback and subduction. The SKS splitting measurements at 150 km depth are shown as black bars. We display the image of the slab (grey blobs) at 150 and 300 km depth, as inferred from the P-waves tomography (*Piromallo and Morelli, 2003*). At 150 km depth, two slab tears are evident, one below the Sicily Channel and the other one below the transition zone between the Southern Apennines (S. A.) and Central Apennines (C. A.). At 300 km depth, the tear below the Sicily Channel still exists, while the tear below the Southern Apennines-Central Apennines is absent and the slab forms a continuous body. The large black arrows indicate the mantle flow trajectories around the slab. According to the SKS

splitting results, mantle is hypothesized to flow around the slab, describing a ring around the SW edge of the slab through the tear imaged at 150 km and 300 km depth beneath the Sicily Channel. Our results do not identify such a return flow also through the tear at the N-E edge of the slab, where the pattern of SKS fast directions allow us to hypothesize a mantle flow parallel to the strike of the slab. The black arrows in the Apulian Platform (A. P.) indicate the possible frozen in deformation not controlled by the slab rollback, as deduced by the slightly not trench-parallel pattern of fast axes.

Table1 - We report the complete list of 185 new individual SKS splitting parameters along with the station and event parameters (Ref 1). Single measurements discussed in *Civello and Margheriti, 2004* and not published elsewhere, are also included (Ref 2).


Europe
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Apulian
Platform
Southern
Apennines
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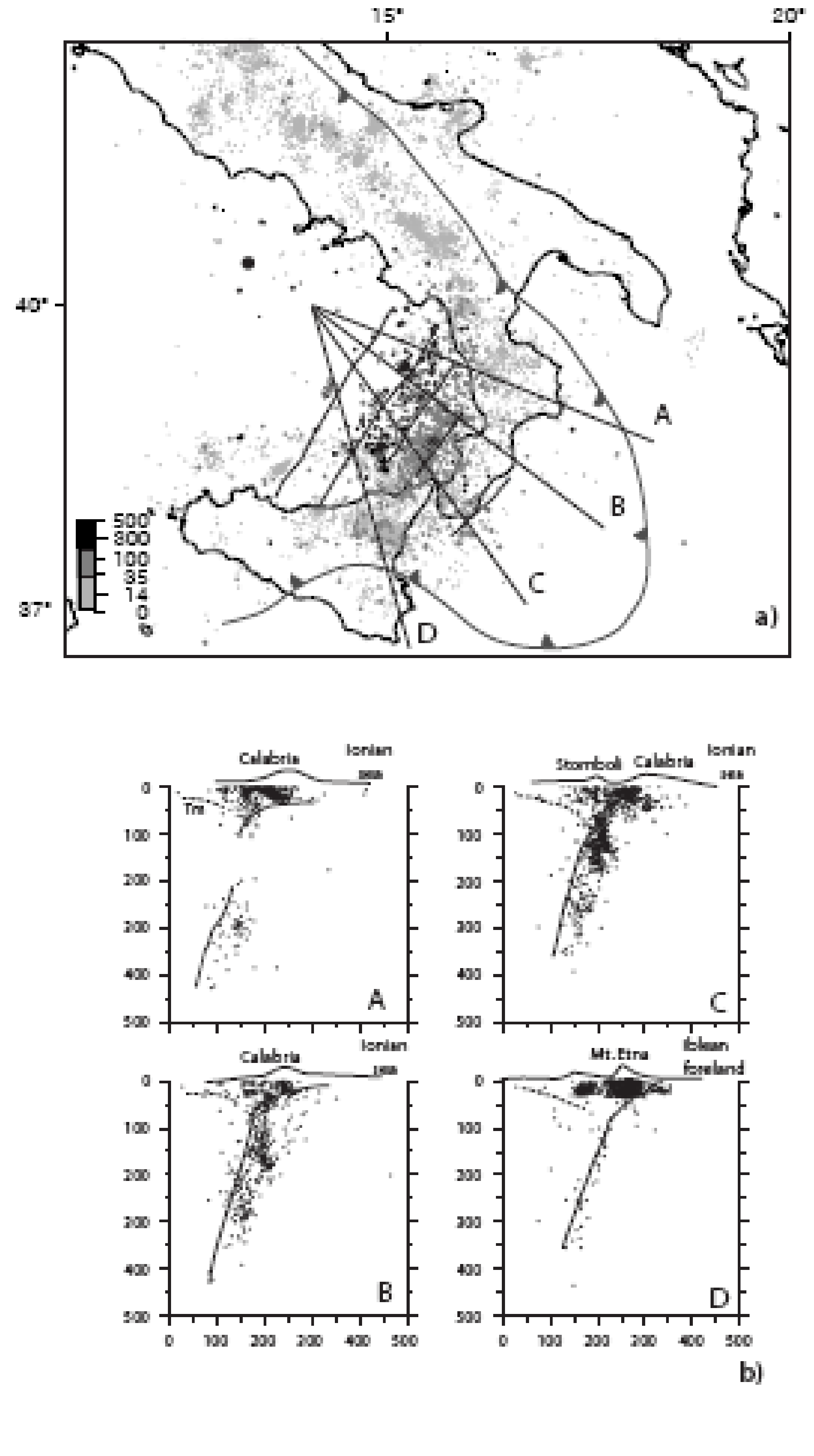
Sea
Aeolian I.
Calabrian Arc
Sicily
16 Ma
Ionian Sea
40°
36°
8°
12°
16°
20°
a
b
1
2
3
4
5
6
7

Figure 1



865 Figure 2

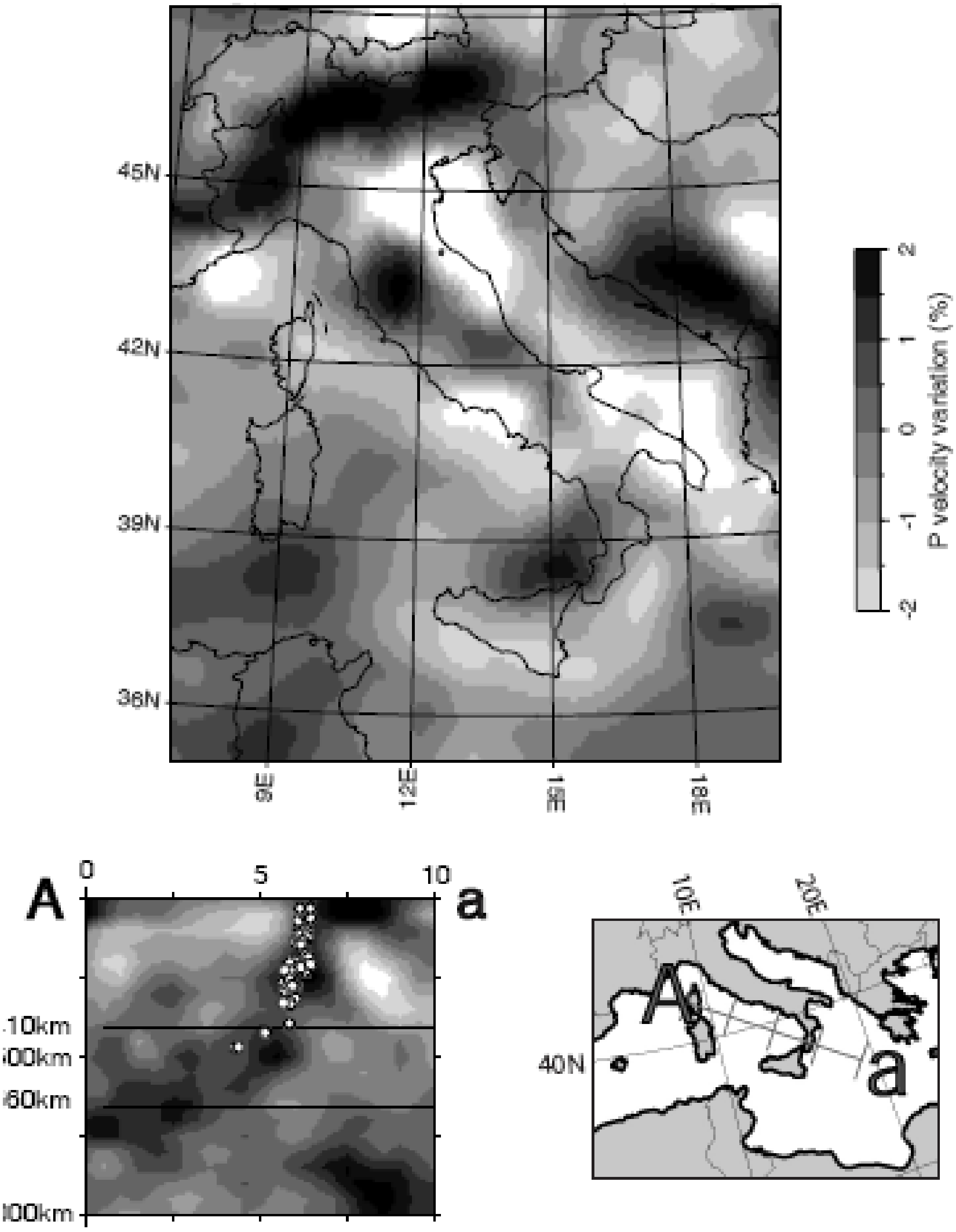

45N
42N
39N
36N
9E
12E
15E
18E
P velocity variation (%)
2
1
0
-1
-2
A
a
0
5
10
40N
10E
20E

Figure 3

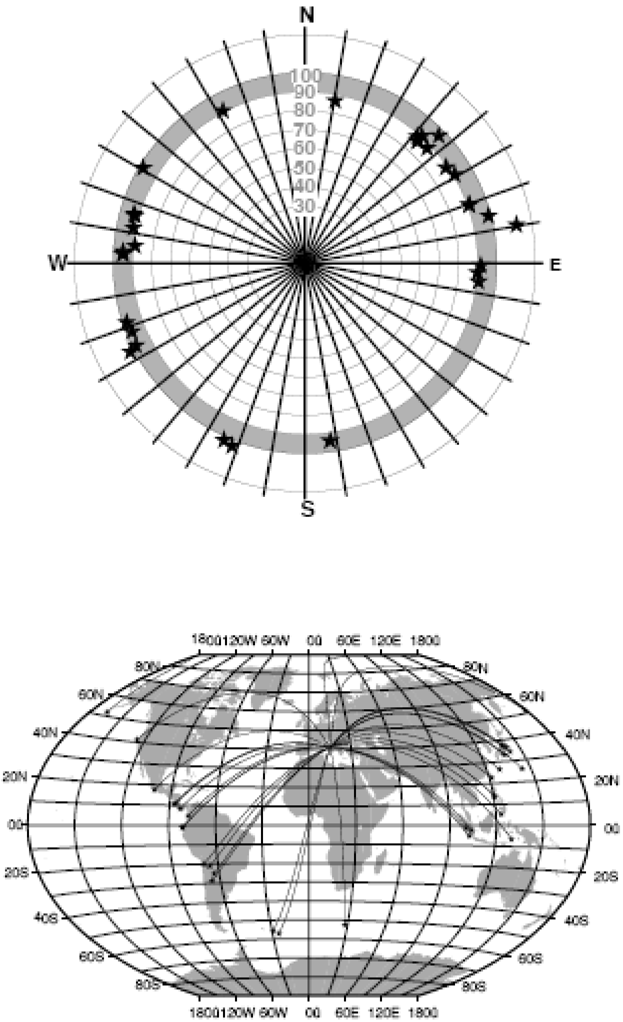
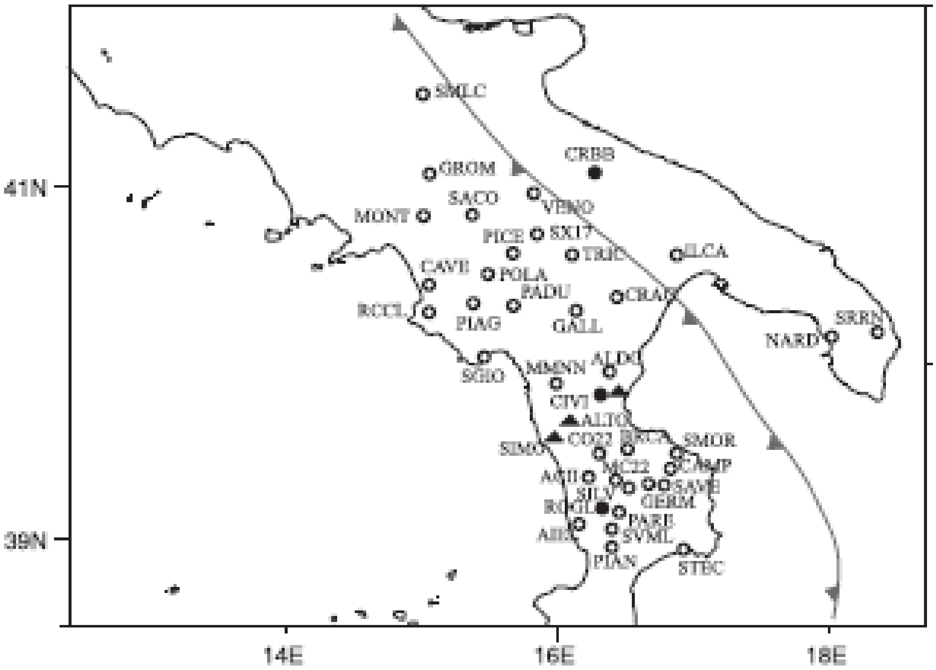
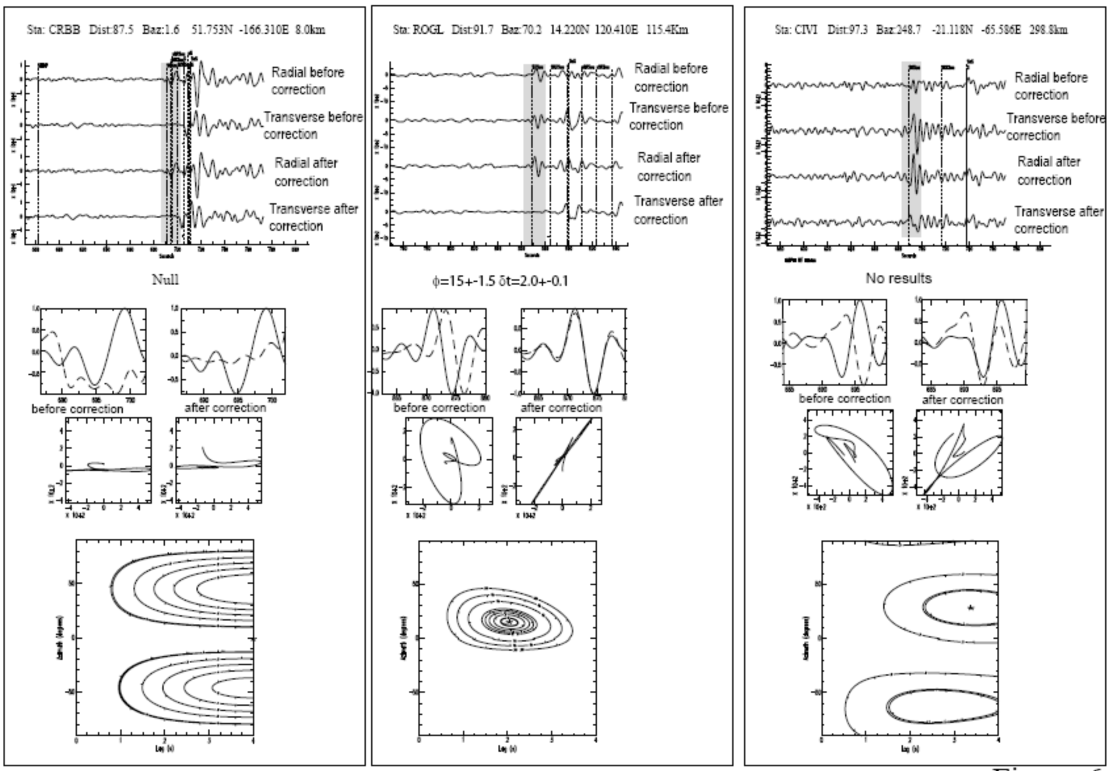

N
S
W
E
100
90
80
70
60
50
40
30
180 120W 60W 00 60E 120E 180
80N
60N
40N
20N
00
20S
40S
60S
80S

Figure 4


41N
39N
14E
16E
18E
SMLC
GROM
CRBB
SACO
VENO
MONT
PICE
SX17
TRIC
ILCA
CAVE
POLA
PADU
CRAP
RCCL
PIAG
GALL
SRRN
NARD
ALDO
SGIO
MMNN
CIVI
ALTO
SIMO
CO22
SMOR
CAMP
MC22
SAVE
SILV
ROGL
GERM
PARE
SVML
PIAN
STEC

up

Figure 5



Sta: CRBB Dist:87.5 Baz:1.6 51.753N -166.310E 8.0km
Radial before correction
Transverse before correction
Radial after correction
Transverse after correction
Null
before correction
after correction
Sta: ROGL Dist:91.7 Baz:70.2 14.220N 120.410E 115.4Km
Radial before correction
Transverse before correction
Radial after correction
Transverse after correction
ϕ=15+-1.5 δt=2.0+-0.1
before correction
after correction
Sta: CIVI Dist:97.3 Baz:248.7 -21.118N -65.586E 298.8km
Radial before correction
Transverse before correction
Radial after correction
Transverse after correction
No results
before correction
after correction

Figure 6

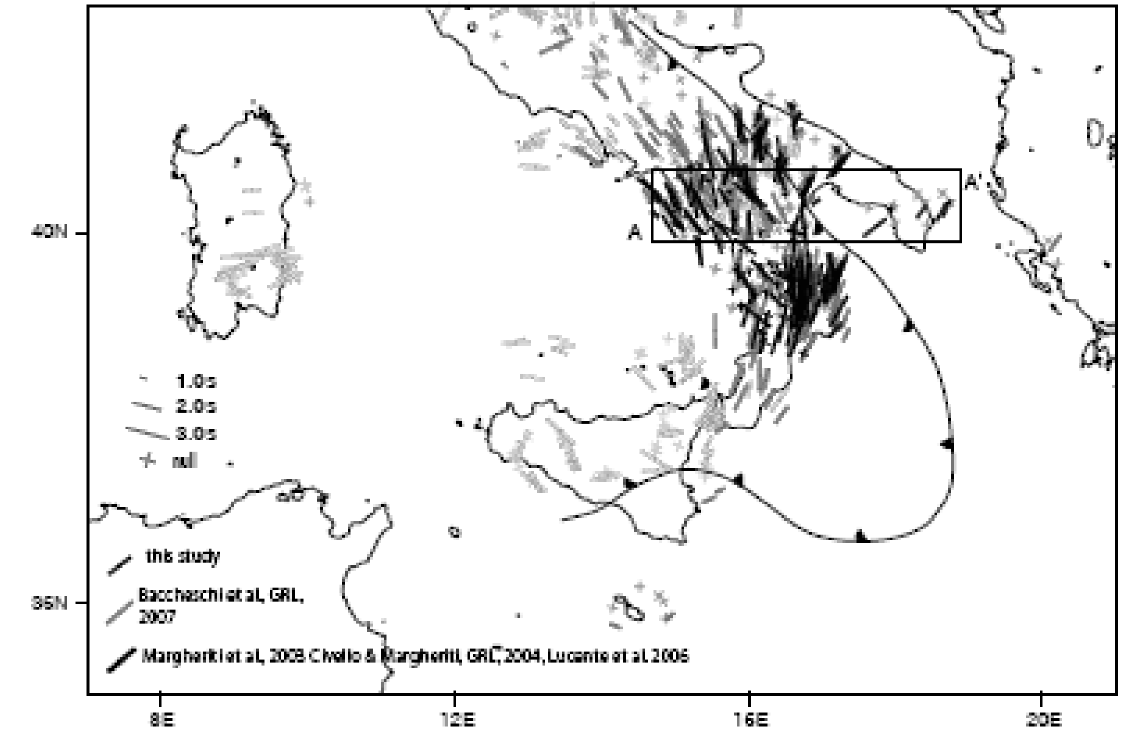

A
A'
40N
36N
1.0s
2.0s
3.0s
null
this study
Baccheschi et al, GRL, 2007
Margheriti et al, 2003 Civello & Margheriti, GRL, 2004, Lucente et al 2006
8E
12E
16E
20E

Figure 7

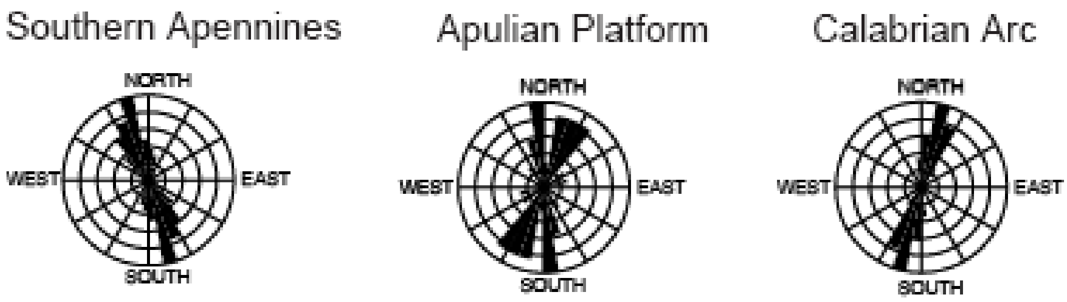

Southern Apennines
NORTH
WEST
EAST
SOUTH
Apulian Platform
NORTH
WEST
EAST
SOUTH
Calabrian Arc
NORTH
WEST
EAST
SOUTH

Figure 8

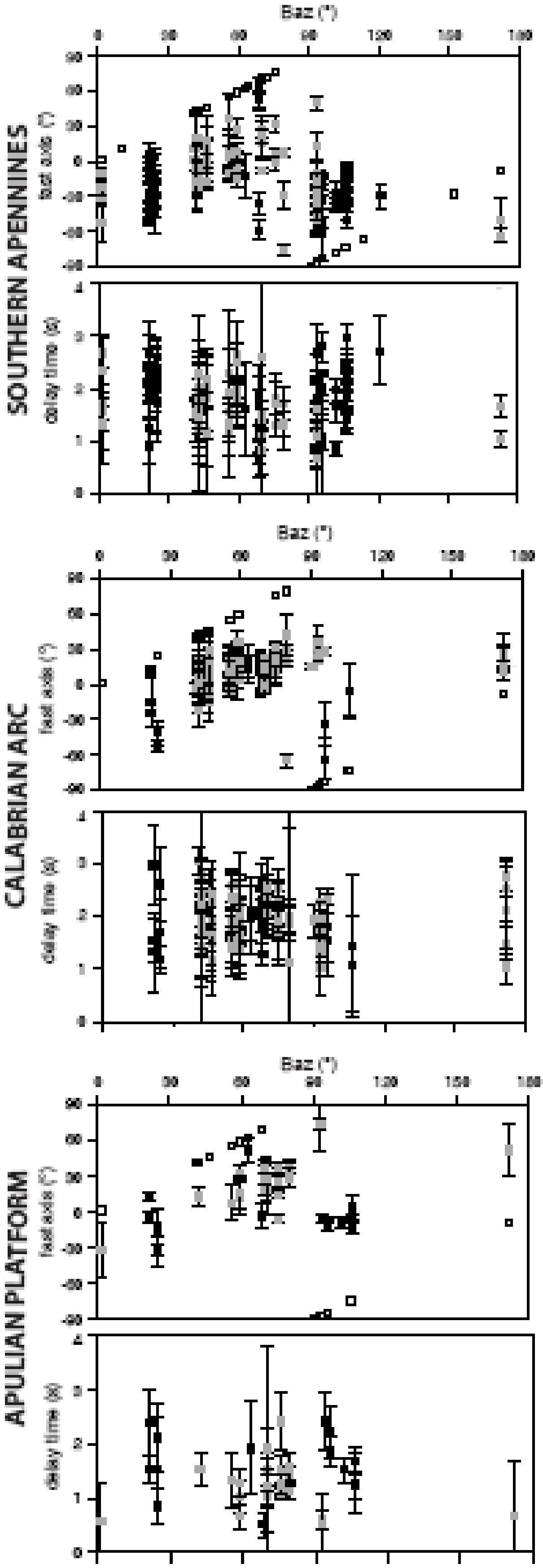

SOUTHERN APENNINES
CALABRIAN ARC
APULIAN PLATFORM
Baz (°)
fast axis (°)
delay time (s)

Figure 9

916

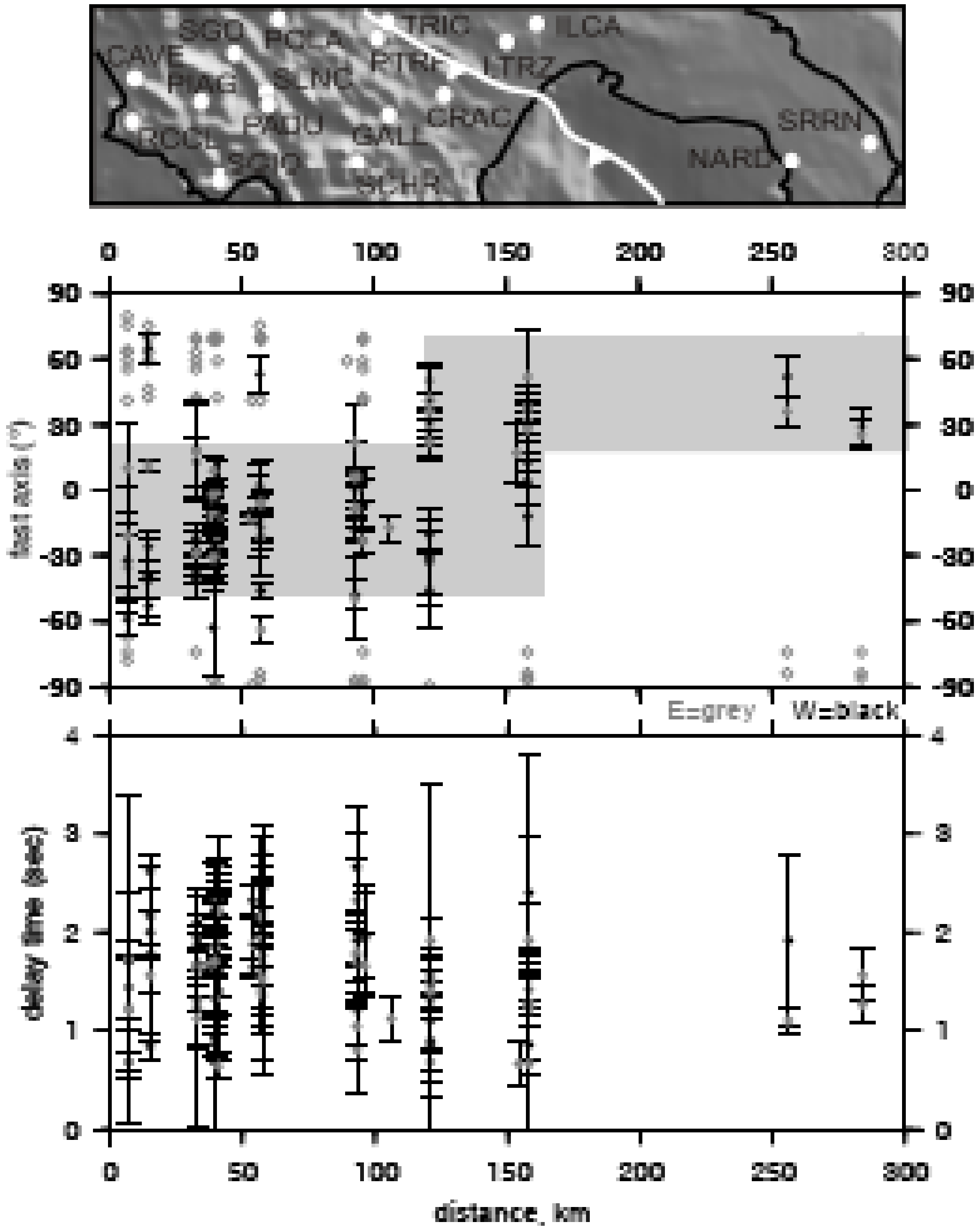

SGO
PCLA
TRIC
ILCA
CAVE
LTRZ
PIAG
SLNC
PADU
CRAC
GALL
SRRN
NARD
E=grey
W=black
fast axis (°)
delay time (sec)
distance, km

Figure 10

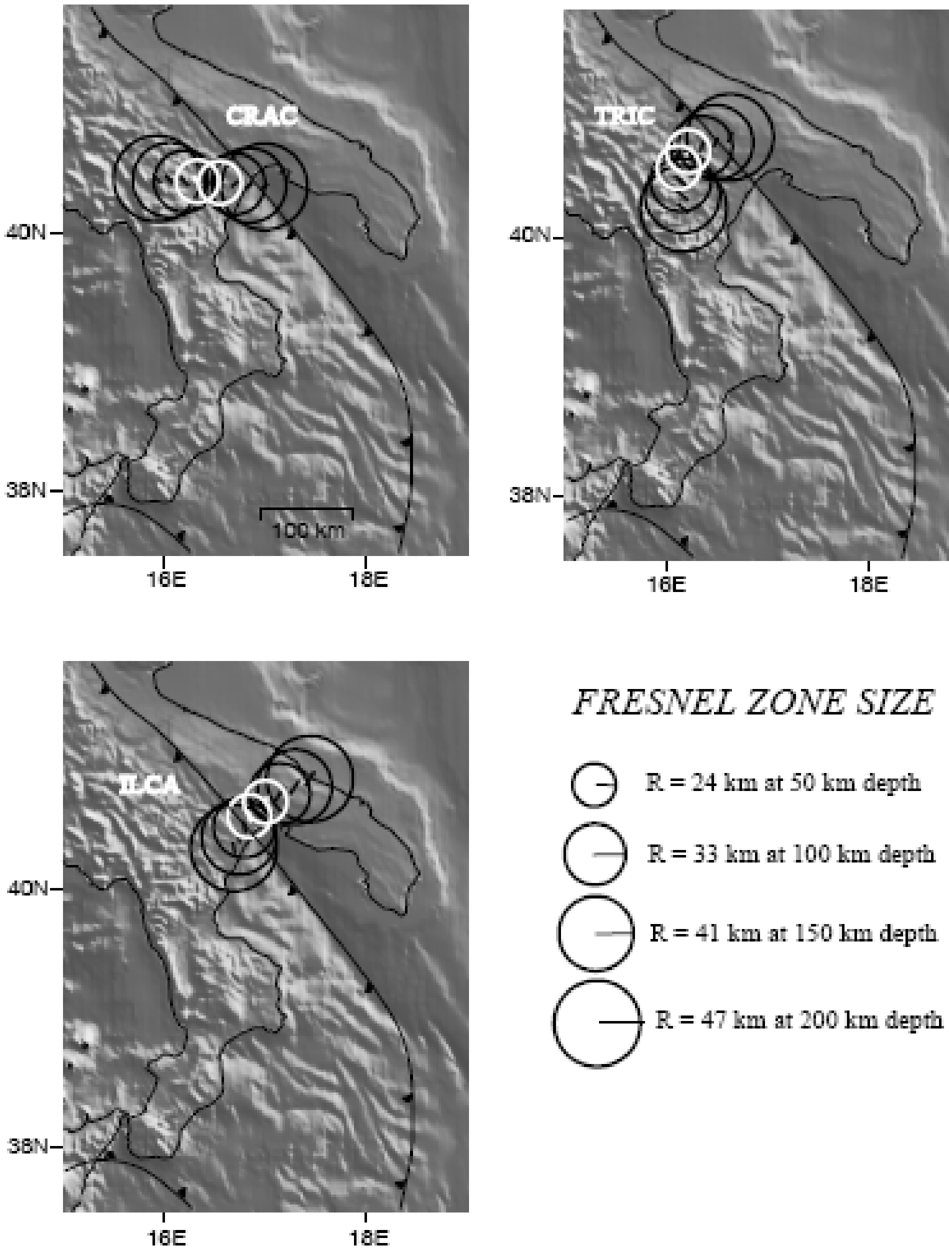

CRAC
TRIC
ILCA
40N
38N
16E
18E
100 km
FRESNEL ZONE SIZE
R = 24 km at 50 km depth
R = 33 km at 100 km depth
R = 41 km at 150 km depth
R = 47 km at 200 km depth

Figure 11

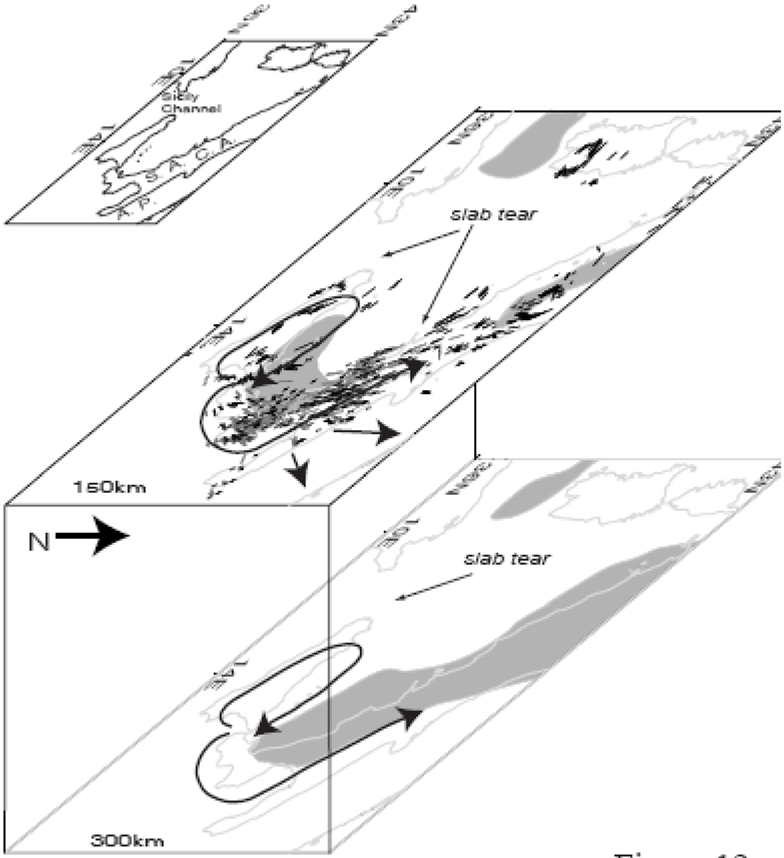


Figure 12