

Seismic anisotropy reveals focused mantle flow around the Calabrian slab (Southern Italy)

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[1] SKS splitting at the Calabrian subduction zone, with delay times (δt) up to 3 s, reveals the presence of a strong anisotropic fabric. Fast directions (ϕ) are oriented NNE-SSW in the Calabrian Arc (C.A.) and rotate NNW-SSE to the north following the arcuate shape of the subducting plate. We interpret the trench-parallel ϕ as local-scale mantle flow driven by the retrograde motion of the slab; the absence of trench perpendicular ϕ below the Southern Apennines (S.A.) excludes the presence of a seismically detectable return flow at its NE edge. This may be due to the relative youth and limited width of the S.A. slab tear. A possible return flow is identified farther north at the boundary of the S.A. and Central Apennines. Different and weaker anisotropy is present below the Apulian Platform (A.P.). This implies that the influence of the slab rollback in the sub-slab mantle is limited to less than 100 km from the slab. **Citation:** Baccheschi, P., L. Margheriti, and M. S. Steckler (2007), Seismic anisotropy reveals focused mantle flow around the Calabrian slab (Southern Italy), *Geophys. Res. Lett.*, 34, L05302, doi:10.1029/2006GL028899.

1. Tectonic Framework and Previous Hypothesis of Flow Around the Calabrian Slab

[2] The Calabrian Subduction System (Figure 1) resulted from the fragmentation of formerly continuous Western Mediterranean subduction zone. It developed in a geodynamic setting characterized by N-S convergence between Africa and Eurasia, and by a strong rollback of the slab that induced the opening of back arc extensional basins [Gueguen *et al.*, 1998; Faccenna *et al.*, 2001]. Recent geodetic data show that the Calabrian Arc (C.A.) at present is no longer retreating toward the trench and back-arc extension is not active in the Tyrrhenian Sea [Hollenstein *et al.*, 2003; D'Agostino and Selvaggi, 2004].

[3] The study area includes the C.A., where subduction is still probably active, and the Southern Apennines (S.A.) (Figure 1); these two regions are both part of the Western Mediterranean subduction zone but underwent different evolutions. The S.A. fold and thrust belt is part of the accretionary wedge, constructed by the imbrication of a succession of carbonate platforms and pelagic basins. The most external of these domains, the Apulia Platform (A.P.), constitutes the foreland of the orogen [Patacca *et al.*, 2000].

The C.A. foreland is the old oceanic crust present below the Ionian Sea. The top of the thrust stack in the C.A. is composed of metamorphic basement slices, absent in the S.A., indicating that the C.A. is a remnant of the European plate [Rossetti *et al.*, 2004] that migrated southward with the subduction system [Gueguen *et al.*, 1998]. The differences between C.A. and S.A. extend beyond their crust; the Benioff plane below C.A. (Figure 2) is well defined down to 600 km [Chiarabba *et al.*, 2005, and references therein] while no intermediate earthquakes occur below S.A. Tomographic studies [Piromallo and Morelli, 2003, and references therein] reveal the existence of a narrow, high velocity body, ~ 100 km thick, interpreted as the sinking slab. Below the C.A. the slab can be followed continuously from its shallow horizontal portion steeply dipping to the NW down to 400 km and finally bending horizontal at the 660 km discontinuity below the Tyrrhenian Sea (Figure 1). Beneath the S.A., the fast velocity anomaly loses its strength at depths shallower than 200 km. This has been interpreted as a slab tear, although the geometry of the tear is still matter of debate [Cimini *et al.*, 2005].

[4] Several recent studies analyzing SKS splitting in the western Mediterranean [Lucente *et al.*, 2006, and references therein] found a significant correlation between the geodynamic evolution of the Western Mediterranean subduction system and its anisotropic parameters. In particular, Civello and Margheriti [2004] hypothesized the presence of a toroidal mantle flow induced by the rollback of the narrow Calabrian slab. They clearly identified the return flow around the western edge of the slab beneath the Sicily Channel, but their data did not resolve possible return trajectories at the NE edge beneath the S.A. Faccenna *et al.* [2005], through geological and geochemical considerations, hypothesized that the tear below S.A. is younger (<700 ka) than the one below the Sicily Channel and, consequently, the mantle flow may not have had sufficient time to reorganize to the point of being seismologically and geochemically detected.

[5] In the current work, we seismologically test possible mantle flow models in the NE edge of the Calabrian slab (as defined by seismic tomography) where no clear evidence of this return flow has been found. We incorporate a large number of new shear wave splitting measurements obtained with the temporary seismic stations deployed in the CAT/SCAN project (Calabrian-Apennine-Tyrrhenian/Subduction-Collision-Accretion Network) and the new permanent stations of the CESIS project (Centro per la Sismologia e L'Ingegneria Sismica, INGV). These new data enables us to study in detail the seismic anisotropy around the NE edge of the slab and behind it (beneath the C.A. and A.P.) and to

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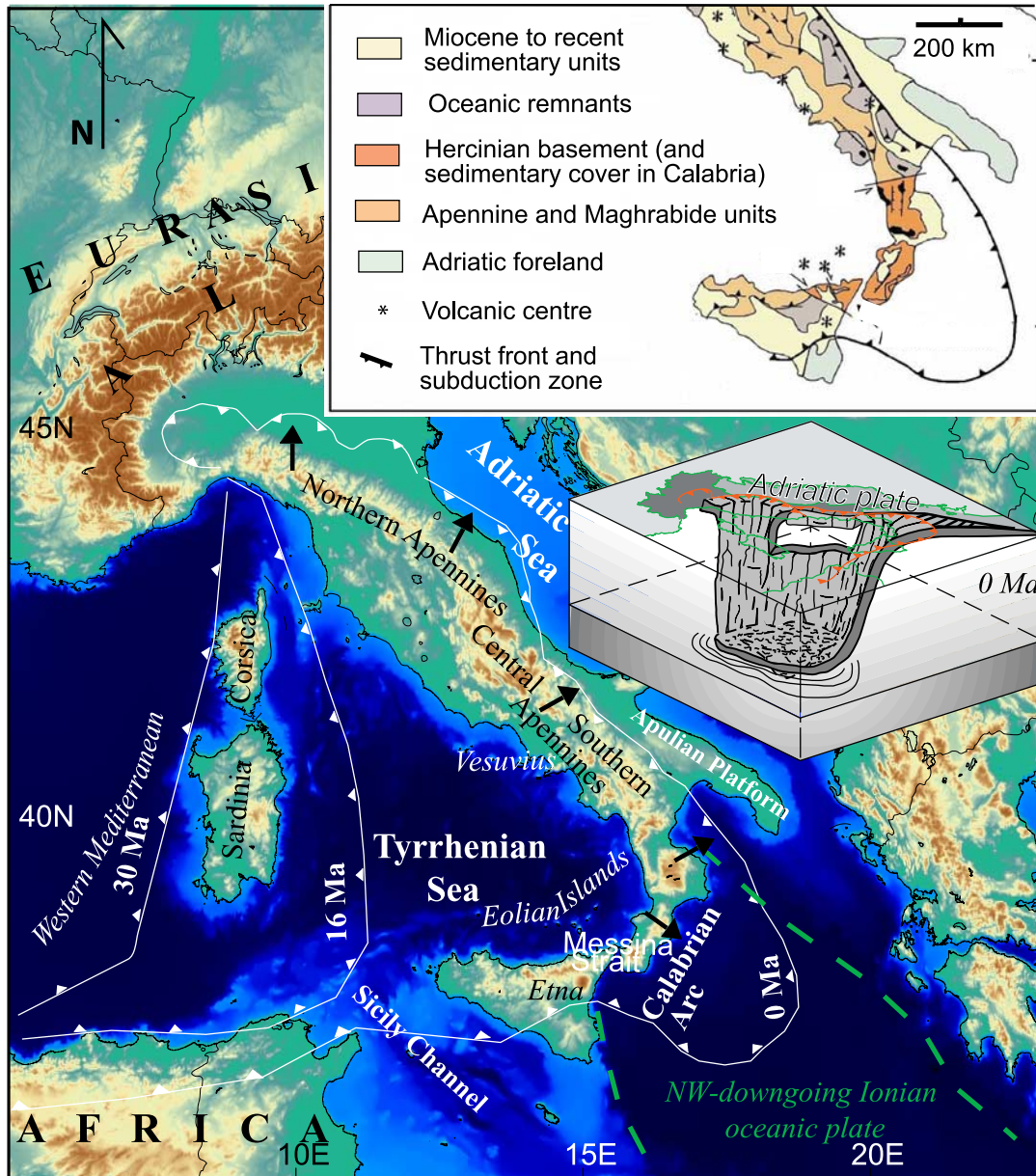


Figure 1. Topographic map of Italy and surrounding regions. White lines and triangles indicate the position of the thrust front of the western Mediterranean subduction zone at 30, 16 and 0 Ma [Gueguen *et al.*, 1998]. The upper inset is a map [from Rosenbaum *et al.*, 2002] of the study region where surface geological differences between the Calabrian Arc, the Southern Apennines and the Apulian Platform are shown. The lower inset is a schematic block view of the present day subducting lithosphere beneath the Italian region (from Lucente and Speranza [2001], with permission from Elsevier).

investigate in greater detail the anisotropic properties of the region.

2. Data and Method

[6] We analyzed 15 teleseisms (Figure 2 and Table S1¹) recorded from January 2004 to August 2004 at the 40 CAT/SCAN portable digital broadband stations and at 26 CESIS and INGV permanent stations of the Italian National Network. To obtain the shear-wave splitting parameters fast

direction (ϕ) and delay time (δt) we used the method described by Silver and Chan [1991]. This method is based on a grid search to find the pair of splitting parameters that best remove the effect of the anisotropy. For SKS phases this is done by minimizing the energy on the transverse component. In this method shear waves are assumed to pass through a single, homogeneous and horizontal layer. We performed the measurements on the SKS phase. For our analysis we selected earthquakes with epicentral distance, Δ , ranging from 88.4° to 98.2° and magnitude >6 . In order to improve the signal-to-noise ratio, all teleseisms were filtered between 0.03-0.3 Hz. The dominant period of all analyzed SKS waves is in the range 8-15s. We considered

¹Auxiliary material data sets are available at <ftp://ftp.agu.org/apend/gl/2006gl028899>. Other auxiliary material files are in the HTML.

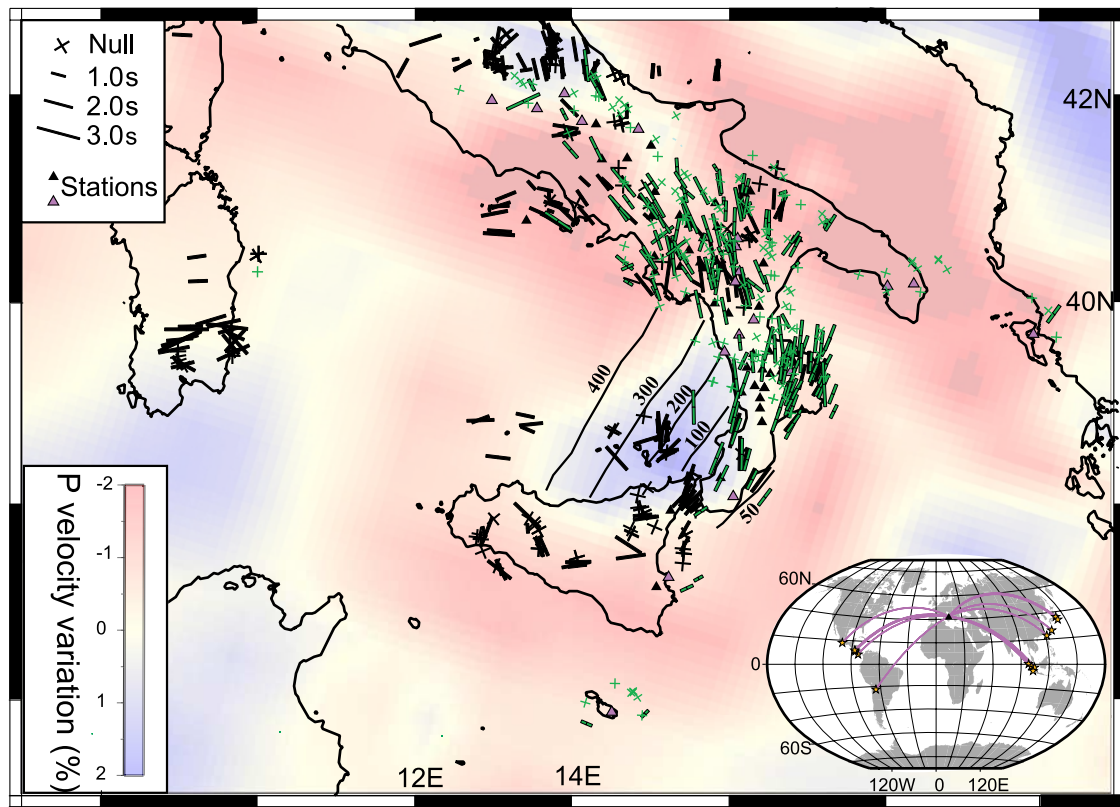


Figure 2. Compilations of SKS splitting results projected at the piercing point of the SKS ray with 150 km depth (this study green, previous black). A measure is represented by a solid bar oriented as ϕ with length proportional to the δt . Nulls are plotted with a cross oriented along the BAZ. Triangles are stations (see text for the meaning of purple ones). Benioff plane isobaths are shown over the P -wave velocity model at 150 km depth [Piromallo and Morelli, 2003]. The inset shows epicenters (stars) of the analyzed events.

good measurements to be only the results that have both a good correlation between fast and slow SKS shear wave and a rectilinear polarization of the horizontal particle motions after removing the effect of the anisotropy.

[7] The final collection of splitting measurements also includes null measurements obtained from events that do not show energy on the transverse component. A null measure does not necessarily mean that anisotropy is absent beneath the station; it can also be due to the shear wave being initially polarized parallel to either the fast or slow direction. Each measurement mapped in Figure 2 is the result of the analysis of a station-earthquake pair and is plotted at the 150 km depth piercing point of SKS ray path: the choice of this depth is done to visually separate measurements of events coming from various back azimuth and with different incidence angles.

3. Results

[8] Analysis of SKS shear waves yielded, from an initial dataset consisting of about 740 phases, 330 good splitting results, 178 of which are nulls (Figure 2 and Table S1). Most of the analyzed stations exhibit both null and non-null results (Figure S1 shows examples of “null” and “non-null” measurements). The magnitude of δt for all measurements varies between 0.5 s and 3.0 s with average value of about 1.6 s. Larger δt is found in C.A. and along the highest

sectors of the S.A., averaging ~ 2 s. In the A.P., toward the Adriatic Sea, δt decreases. Considering an average anisotropy of about 5%, then a δt of 2.0 s would correspond to an anisotropic layer ~ 225 km thick [Mainprice et al., 2000].

[9] The orientation of ϕ is complex: at stations located in the C.A. we obtained ϕ NE-SW, parallel to the slab strike and following the curvature of the mountain chain. In the S.A., especially on its Tyrrhenian side, ϕ are oriented NNW-SSE, also along the strike of the arcuate mountain range.

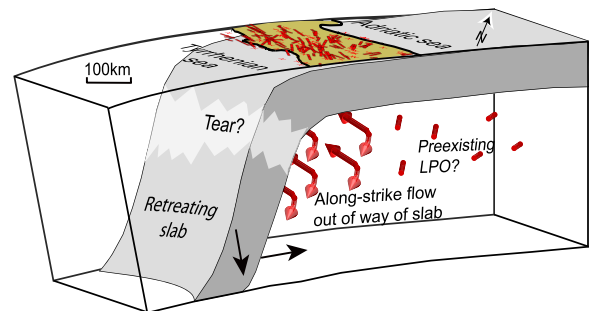


Figure 3. Interpreted mantle flow induced by subduction. The change in ϕ and δt below A.P. implies that the influence of the slab rollback in the sub-slab mantle is laterally limited and the flow and mantle deformation is focused in a zone less than 100km from the slab.

The homogeneous pattern of ϕ which follows the curvature of the mountains, suggests the existence of an anisotropic volume with uniform characteristics. Toward the A.P., ϕ rotates to N-S and NE-SW. The most common ϕ is N-S, which prevails in the northern sector of the A.P. The WSW-ENE ϕ is primarily found farther south. Moreover, in the southernmost part of the A.P., all the analyzed seismograms gave null results. This is corroborated by the other null measurements at a station on the eastern side of the Adriatic Sea and testify the absence of a clear mantle texture below the Adriatic Sea around 40° latitude. There are also other stations (purple triangles in Figure 2) in which more than 90% of the analyzed seismograms gave either null measurements or seismograms that are so complicated they did not yield a good measurement; these stations are located primarily in the transition zone between C.A. and S.A. and at the transition between S.A. and Central Apennines. It is interesting to note that, even if ϕ seem to vary quite smoothly over the region, there exist stations that show anisotropic parameters dependent upon the back-azimuth (BAZ) of the analyzed earthquakes. However, none of the analyzed stations have sufficient measurements (max. 11 at GRI) to clearly define how the ϕ varies with BAZ and to check for multilayer anisotropic structure. However, some of the stations along the boundary between S.A. and A.P. have N-S ϕ for events coming from NE and a NNW-SSE ϕ for events coming from west. The presence of stations with different ϕ for events coming from about opposite back azimuth supports the existence of laterally varying anisotropy and considerations of Fresnel zones pose constraints on the depth of the anisotropic layer, which must be deeper than about 100 km, at least at the boundary between S.A. and A.P.

4. Discussion

[10] The primary mechanisms that produce seismic anisotropy in the upper mantle are the alignment of olivine crystals (LPO) [Nicolas and Christensen, 1987; Vinnik and Kind, 1993] and the alignment of melt in pockets and bands [Kendall, 1994; Holtzman et al., 2003]. The LPO of mantle olivine may be generated by active flow in the asthenosphere, or by frozen-in fossil flow in the lithosphere [Silver, 1996]. As the mantle is deformed by shear, olivine crystals are progressively rotated or recrystallize to have their seismic fast axis aligned subparallel to the flow direction [Zhang and Karato, 1995], if they have time to adjust to the local infinite strain axis [Kaminski and Ribe, 2002]. The orientation of anisotropy can be altered by the water released in subduction zones, which might change the olivine a-axis orientations to becoming perpendicular to the flow direction [Jung and Karato, 2001]. Variable water content may be appropriate for the mantle wedge in subduction zones but can explain variations in ϕ only under high stress conditions [Kaminski, 2002]. These conditions are only likely in a limited region at the top of the downgoing slab in front of the volcanic arc [Kneller et al., 2005]. This location corresponds to the offshore region in the Tyrrhenian Sea between Calabria and the Eolian Islands. Indeed, splits in S waves from local deep slab earthquakes [Baccheschi et al., 2005] show a more variable pattern in this region. For the splitting results presented here, melt

should not be a significant factor because the signal has been accrued beneath and within the slab (Figure 2). In the study region, volcanism is active at the Eolian Islands, which is the active volcanic arc, at Mt. Etna in Sicily, and at Mt. Vesuvius. The CAT/SCAN deployment lies entirely between these regions. Thus, we interpret the anisotropy measured by the SKS splittings to be the result of the LPO of olivine due to strain associated with flow in the asthenospheric mantle.

[11] The large splits observed in this study imply an average thickness of >200 km for the anisotropic region (high δt values are not uncommon at subduction zones [e.g., Russo and Silver, 1994]). This is too thick to be contained within the lithosphere (about 100 km thick in the area) and indicates that the source of the anisotropy is active flow within the asthenosphere. The mantle flow is expected to be affected at the local scale by the subducting plate motion and by the presence of tears in the slab [Peyton et al., 2001]. A tear in the slab may allow the mantle to escape through it, creating a return flow from behind the downgoing plate to the front of the slab [Matcham et al., 2000].

[12] Our results show that moving along strike from S.A. to C.A. and toward the Messina Straits, the ϕ change their orientation and rotate from NNW-SSE to NNE-SSW to follow the arcuate shape of the slab. The good correspondence with the tomographic image of the slab (Figure 2) suggests that the mantle strain is clearly guided by the curve of the slab. At all the analyzed stations, most of the anisotropy detected should lie beneath the slab. We suggest that the pattern of SKS ϕ observed is consistent with a model of local-scale mantle flow strongly controlled by the slab geometry and rollback (Figures 2 and 3). The slab acts as barrier at depth [Russo and Silver, 1994] and induces the mantle to flow parallel to the strike of the slab. We also see great continuity in the measurements between the C.A. and S.A. Some models for the evolution of the C.A. incorporate a large left-lateral offset between the C.A. and S.A. [Rosenbaum et al., 2002]. While, there are some null (purple stations) associated with the transition, there is little sign of a major discontinuity. One possibility is that the disruption between the C.A. and S.A. only dates to the stopping of the S.A. and slowing of the C.A. in the Pleistocene [Patacca and Scandone, 2001]. This could result in a complex transition zone yielding no coherent splits while the belts on either side still retain a continuous pattern of ϕ . Tomographic images reveal the presence of a slab tear below the S.A. Such a tear should allow a mantle return flow through it similar to the one observed beneath the Sicily Channel at the SW edge of the same slab [Civello and Margheriti, 2004]. If this were the case, we would expect a large number of SKS ϕ oriented almost E-W in the S.A. Our results do not identify such a return flow and show that fast axes are oriented prevalently NNW-SSE. Possible interpretations for the absence of E-W ϕ could be that any tear that exists is too narrow to allow significant mantle to escape through it or is too young to have realigned the olivine structure [Faccenna et al., 2005]. Some E-W measures associated with several nulls (purple stations in Figure 2) are found farther north at the transition between S.A. and Central Apennines suggesting that this could be the locus of a possible better organized return flow.

[13] The stations located in the A.P. show a different pattern and a strong variability from north to south. In the northern sector, ϕ , associated with δt of 1.6s, are oriented N-S. These agree with previous measurements [Margheriti *et al.*, 2003] obtained in the northern sector of the Adriatic Sea (Figure 2). It is also consistent with N-S to NE-SW splits obtained from the Dalmatian coast of Croatia, across the Adriatic Sea [Schmid *et al.*, 2004]. In the center of A.P., ϕ are SW-NE also with δt as large as 1.6 s while in the southernmost A.P. only null measures are found. These changes of directions are not easily explained, but may mark around latitude 40°N some past or current discontinuities inside the Adriatic microplate (A.P. is part of it). The southern sector of the A.P. exhibits only null measurements obtained from events from different BAZ. This testifies to the absence of a clear pattern of mantle strain in the foreland. Seismic anisotropy below the A.P. is variable and seems to not be strongly influenced by the subduction geodynamics in contrast to the C.A. and S.A. farther west (Figure 3).

5. Possible Mantle Flow Around the Calabrian Slab

[14] Shear-wave splitting results from sixty-six stations in the S.A.-C.A. region reveal the existence of strong seismic anisotropy in the mantle that is influenced by the presence of the slab. We interpret the pattern of SKS ϕ as mantle flow below the slab, parallel to the mountain chain and driven by the retrograde motion of the slab itself. Seismic anisotropy, geology and geochemistry [Civello and Margheriti, 2004; Faccenna *et al.*, 2005] support the idea of the presence of a return flow around the SW edge of the Calabrian slab. To the north, the Calabrian slab appears to be limited by a horizontal tear beneath S.A. (Figure 1), at its NE edge. However, the absence of trench perpendicular ϕ at S.A. stations testify the absence of a well-organized return flow around the NE edge of the Calabrian slab (Figure 2). This supports the idea that any slab tear below S.A., seen by tomography, is neither old nor wide enough to allow a seismologically detectable mantle flow. Possibly a better organized flow may be present at the boundary of the S.A. and Central Apennines, reflecting the boundaries of a formerly larger Calabrian slab. The anisotropic pattern changes below the A.P.; this implies that the influence of the slab rollback in the sub-slab mantle is laterally limited and the flow and mantle deformation is focused in a zone less than 100km from the slab (Figure 3).

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