



## RESEARCH LETTER

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## Key Points:

- GPS velocities show crustal toroidal patterns around the two slab hinges, while at depth SKS-based mantle flow field reveals an asymmetry
- Rotations occur at active lithospheric tears, currently accommodating the southeastward migration of the subduction system

## Supporting Information:

- Supporting Information S1

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## Surface imprint of toroidal flow at retreating slab edges: The first geodetic evidence in the Calabrian subduction system

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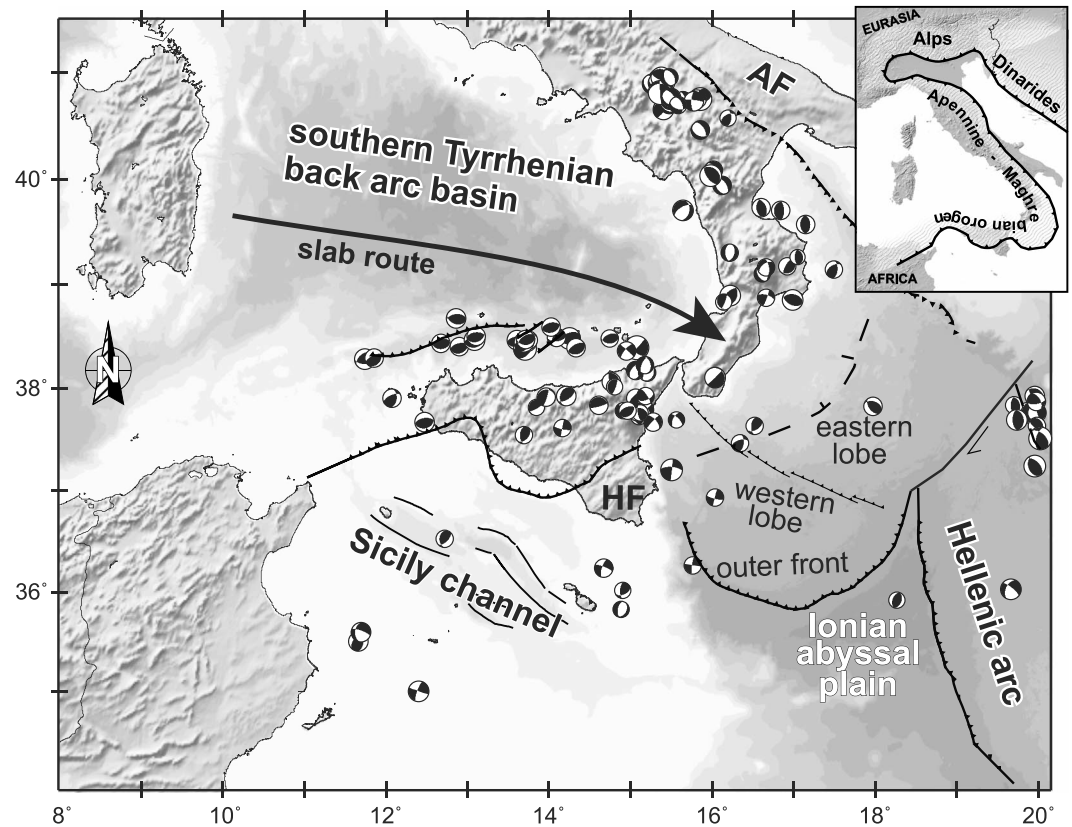
**Abstract** Dense GPS observations can help Earth scientists to capture the surface imprint of mantle toroidal flow at slab edges. We document this process in the Calabrian subduction system, where the Ionian slab rollback took place during the past 30 Ma, following a stepwise process driven by migration of lithospheric tearing. We found rotation rates of  $\sim 1.29^\circ/\text{Ma}$  (counterclockwise) and  $\sim 1.74^\circ/\text{Ma}$  (clockwise), for poles located close to the northern and southern slab edges, respectively. These small-scale, opposite rotations occur along complex sets of active faults representing the present-day lithospheric expression of the tearing processes affecting the southeastward retreating Ionian slab at both edges. The observed rotations are likely still young and the process more immature at the northern tear, where it is unable to reorient mantle fabric and therefore is unseen by SKS splitting.

### 1. Introduction

Tearing of the lithosphere and toroidal mantle circulation (flowing throughout slab windows) have been proposed and modeled at slab edges of a number of retreating subduction zones [e.g., *Govers and Wortel*, 2005; *Schellart et al.*, 2011; *Magni et al.*, 2014]. Slab tearing is typically related to variations in the velocity of subduction rollback along the length of the subduction system [*Govers and Wortel*, 2005]. Tear faults can be either horizontal or vertical [*Rosenbaum et al.*, 2008]. Horizontal tear faults are usually associated with a slab breakoff process and lead to the progressive detachment of a lithospheric slab. Vertical tear faults laterally decouple subducting lithosphere [*Wortel et al.*, 2009], promoting vertical motion between the subducting segment of the lower plate and the adjacent portion of the plate and strike-slip movement in the overriding plate. Slab tearing process as described in this study is associated with vertical tear faults that, over time, laterally propagate along the subduction system. In 3-D models with retreating trench, toroidal flow around slab sides develops to accommodate movement of drifting mantle material from beneath the stiff slab toward the mantle wedge [*Funiciello et al.*, 2006; *Piromallo et al.*, 2006; *Stegman et al.*, 2006]. These processes jointly contribute to the surface deformation, which may be revealed both by geodetic and geological observations [*Govers and Wortel*, 2005; *Jolivet et al.*, 2012; *Pérouse et al.*, 2012].

The history of rollback opening of the western central Mediterranean dates back to about 30 Ma [*Faccenna et al.*, 2014] and has produced a broad reorganization of mantle fabric around the southwestern edge of the Ionian slab [*Baccheschi et al.*, 2011]. The most recent evolution (younger than 2 Ma), after rapid rollback and back-arc opening, is more complex with a progressive slab migration along inherited and newly formed lithospheric discontinuities [*Wortel et al.*, 2009] coupled with a contemporaneous decrease in the lateral extent of the slab [*Faccenna et al.*, 2007; *Neri et al.*, 2009; *Giacomuzzi et al.*, 2012]. This process led to large rotations of the Neotethys margins [*Mattei et al.*, 2007] and to the accretion and stacking of sedimentary units along the Apennine-Maghrebian orogenic system [*Casero et al.*, 1988]. The gradual reduction in the lateral extent of the subducting lithosphere probably led to a slowing or even cessation of the rollback and subduction, since the middle Pleistocene [*Goes et al.*, 2004]. Consequently, these processes have caused a reorganization of the entire subduction system, from crustal to mantle depths.

Here we use a dense GPS data set to focus on the kinematics of the Calabrian subduction system (CSS) where we obtain, for the first time, a surface velocity field characterized by opposite rotations around the two slab hinges. We suggest that this signal corresponds to the geodetic surface imprint of mantle toroidal flow around the slab edges. Our observations contribute to a deeper understanding of the ongoing tectonic processes in an area that is considered among the highest seismic hazard regions of Europe.



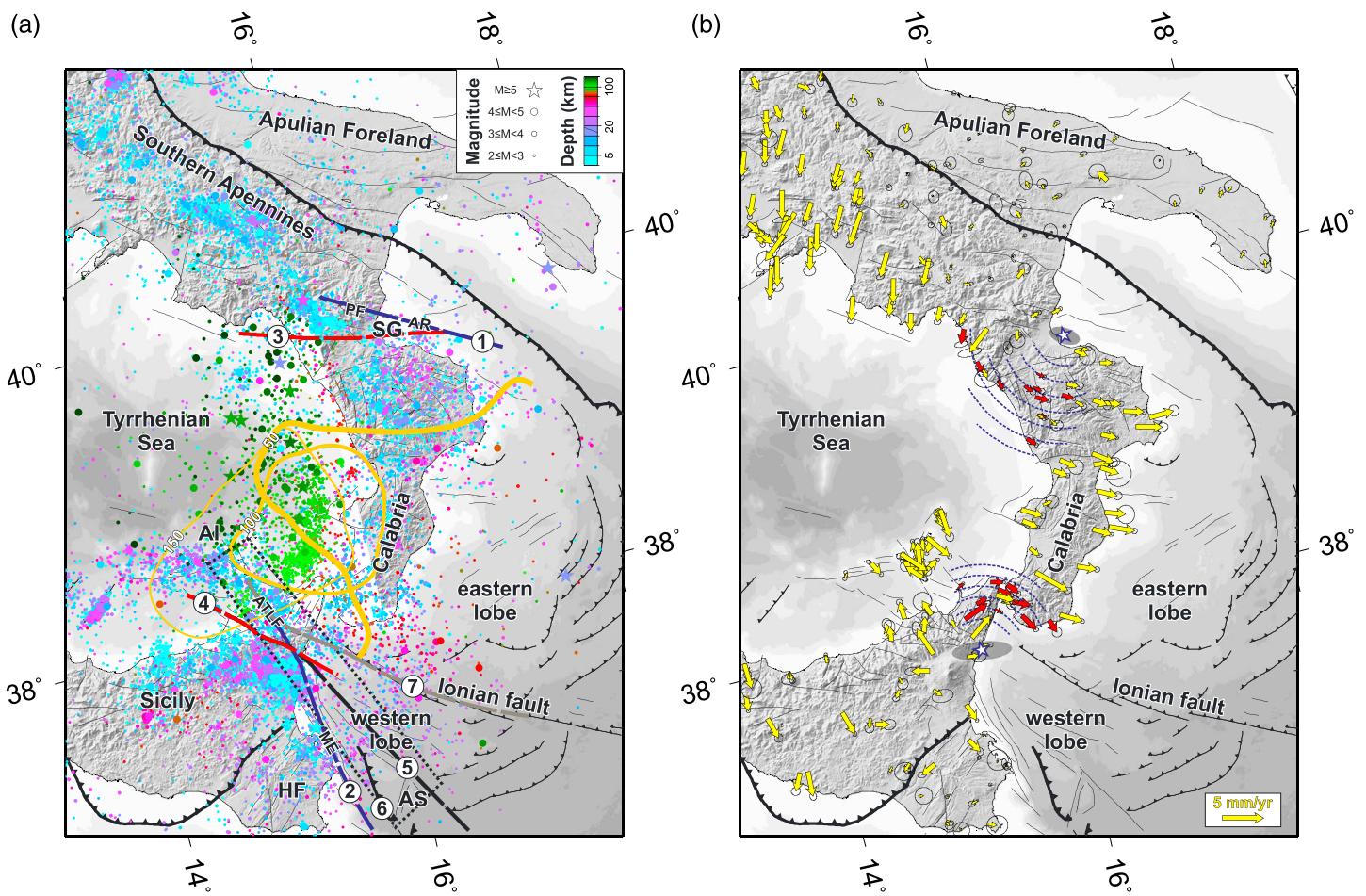
**Figure 1.** Sketch map of central Mediterranean. The route of the Calabrian subduction system is reported: the trajectory approximately follows the direction of maximum back-arc extension, according to *Faccenna et al.* [2007]. Focal mechanisms of earthquakes with magnitude  $M \geq 4$  are also reported (<http://www.globalcmt.org>). The Africa-Eurasia plate configuration is shown in the inset.

## 2. Background Setting

The CSS is a tightly curved arc belonging to the eastward migrating Apennine subduction system and connecting the Apennine chain (NW striking) with the Maghrebian thrust belt (EW trending) [*Patacca et al.*, 1990] (Figure 1). It is characterized by the presence of a narrow trench (roughly 200 km wide) where the steep, NW dipping Ionian lithosphere is subducting beneath the Eurasian plate. The Wadati-Benioff plane is characterized by approximately continuous seismicity from crustal depth down to about 500 km, in the central part of the arc [*Neri et al.*, 2012]. West of the central Aeolian Islands deep and intermediate seismicity is almost absent, occurring mainly to the east (Figure 2a) [i.e., *Chiarabba et al.*, 2015], where also seismic velocity anomalies show a continuous slab down to the mantle transition zone depths [*Piromallo and Morelli*, 2003; *Neri et al.*, 2009; *Giacomuzzi et al.*, 2012]. Crustal seismicity (depth  $\leq 30$  km) is mainly active along two belts: one running EW offshore northern Sicily and one southeastward oriented from the Aeolian Islands. East of the Aeolian Islands crustal seismicity is scattered, in the accretionary wedge and in the Apennines [*Chiarabba et al.*, 2015].

Crustal deformation of CSS is demonstrated by historical seismicity (up to  $M_s = 7.5$ ) commonly ascribed to the active normal faults, which accommodate arc-perpendicular extension [*Galli and Scionti*, 2006]. High-resolution seismic and bathymetric surveys have attested active deformation also in the outermost portion of the accretionary wedge [*Gutscher et al.*, 2006, 2016; *Polonia et al.*, 2011].

Lithospheric tearing, developed during the different phases of the trench migration, has been hypothesized to affect the overriding plate at two locations: (a) between northern Calabria and southern Apennines and (b) in NE Sicily and the Ionian offshore (Figure 2a). The existence of active lithospheric tearing at the northeastern side of the slab is questioned [e.g., *Orecchio et al.*, 2014; *Chiarabba et al.*, 2016]. Tearing at the southern edge is ascribed to distinct lithospheric structures (Figure 2a): the Taormina line in NE Sicily [*Rosenbaum et al.*, 2008];



**Figure 2.** (a) Seismicity occurring during the period 1981–2013 [Chiarabba et al., 2015]. See legend for earthquake depth and magnitude. The dashed lines mark the tear faults proposed by previous investigators relative to the latest stages of the rollback process: (1) a shear zone spatially overlapping with the Pollino fault and the Amendolara Ridge, (2) the Malta Escarpment [Govers and Wortel, 2005]; (3) the Sangineto line and (4) the Taormina line [Rosenbaum et al., 2008]; (5) a fault system cutting NE Sicily and the accretionary wedge ~50 km east of the Malta Escarpment [e.g., Gallais et al., 2013]; (6) a N-NW oriented deformation belt extending from the Alfeo Seamount to the central Aeolian Islands [Argnani, 2014]; and (7) a ~400 km long shear zone, including both the Aeolian-Tindari-Letojanni fault system and the Ionian fault [Palano et al., 2015a]. The yellow lines contour the Calabrian slab ( $P$  wave velocity anomaly +0.8%) at 50, 100, and 150 km depth [Piromallo and Morelli, 2003]. Abbreviations: AI, Aeolian Islands; ATLF, Aeolian-Tindari-Letojanni fault; SG, Sibari Gulf; PF, Pollino fault; AR, Amendolara Ridge; HF, Hyblean Foreland; ME, Malta Escarpment; and AS, Alfeo Seamount. (b) GPS-based velocity field (arrows) and 95% confidence ellipses related to the local reference frame estimated in this study. GPS sites used to estimate the Euler vector components (Table S1) for both the northern and southern slab edges are reported as red arrows. Euler poles are represented as blue stars; uncertainties are at the 95% confidence level. Dashed blue lines are arcs of a circle around the pole.

the Malta Escarpment, close to the eastern Sicily offshore [Govers and Wortel, 2005, and references therein]; a NNW oriented 20–30 km wide deformation zone extending from the Alfeo Seamount (Ionian basin) up to the central Aeolian Islands [Argnani, 2014]; along a 200 km long crustal-scale fault system cutting NE Sicily and crossing the accretionary wedge ~50 km east of the Malta Escarpment [Gallais et al., 2013, and references therein], and along a ~400 km long multisegmented shear zone, including both the Aeolian-Tindari-Letojanni fault system and the Ionian fault [Palano et al., 2015a].

### 3. GPS Data

GPS data collected in the last two decades over the investigated area by different institutions and agencies have been processed by using the GAMIT/GLOBK software and adopting the strategy described in Palano et al. [2015b]. We first estimated GPS velocities in the ITRF2008 reference frame. In general, the kinematics of this area has been analyzed within a wider context (i.e., at the scale of the Apennine chain and/or the entire Italian peninsula) by adopting plate-scale reference frames (usually Nubia and Eurasia plates) [D’Agostino

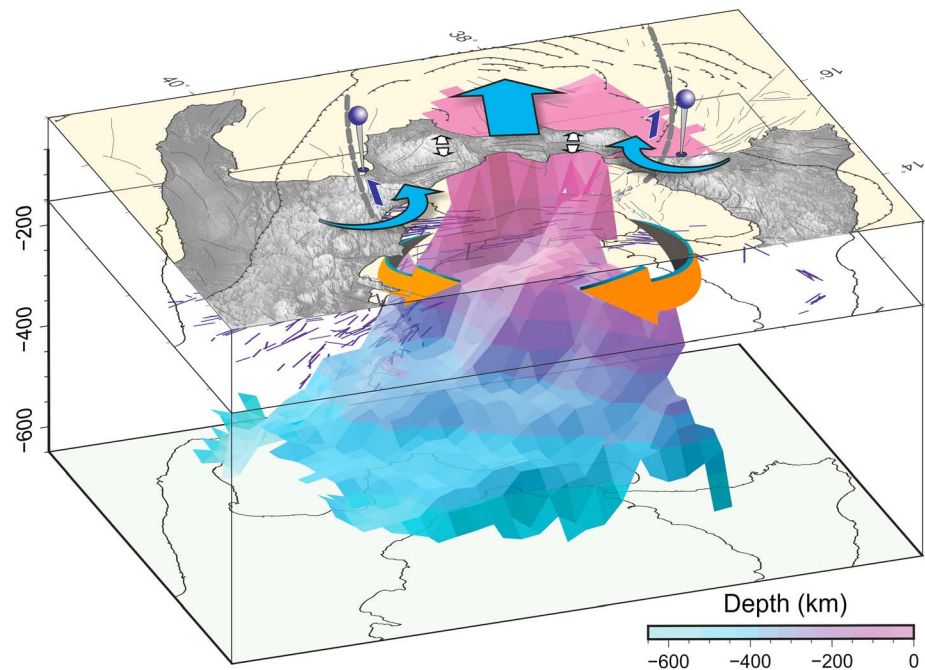
*et al.*, 2011; *Palano*, 2015, and references therein]. These studies have evidenced that the CSS and surrounding areas move independently from both Nubia (eastward with rates of  $\sim 3.5\text{--}4.5$  mm/yr) and Eurasia (north-eastward with rates of  $\sim 2\text{--}4$  mm/yr) plates. Some studies have adopted regional reference frames, more suitable to evaluate the motion of the CSS relative to the Apulian or to the Hyblean-Malta forelands (i.e., lower plate) [*D'Agostino et al.*, 2011; *Palano et al.*, 2012]. However, the scant number of GPS stations along the CSS has allowed researchers to infer only (i) its decoupling with respect to Sicily along the Aeolian-Tindari-Letojanni fault system, (ii) its southeastward motion, and (iii) the fragmentation of the lower plate in this sector of the Mediterranean region. Therefore, exploiting the dense GPS data set currently available, we derived a local reference frame by estimating the best fit Euler parameters for selected sites located on Apulian and Hyblean-Malta forelands (Figure S1 in the supporting information), under the simple assumption that these forelands behave as a single crustal block together with the Ionian domain. Indeed, the Ionian domain is considered in the literature either as part of the Apulian block or as part of the Hyblean-Malta block (see *Palano et al.* [2012] for an overview). Unfortunately, the relative motion among these blocks cannot be robustly constrained due to the absence of geodetic observations in the Ionian offshore.

The best fit Euler parameters have been estimated through a weighted least squares inversion which allows to statistically select a set of observed horizontal GPS velocities that best defines a rigid block (see also Text S1 in the supporting information for additional details). The GPS velocity field related to our local reference frame (latitude  $1.428^\circ\text{N} \pm 1.132$ , longitude  $-134.761^\circ\text{E} \pm 0.711$ ,  $\Omega = 0.355^\circ/\text{Ma} \pm 0.008$ ) is reported in Figure 2 and discussed in the following.

#### 4. Discussion

The GPS velocity field shows a clear southeastward migration of the whole Calabrian Arc, with values ranging from 2 mm/yr to 3 mm/yr, considering the average velocities of stations located on the inner and external side of the arc, respectively (Figure 2). These results suggest two observations: the fore-arc region is subject to a crustal extension up to 1 mm/yr and the southeastward motion of the system is absorbed in the Ionian accretionary wedge. The GPS-based crustal extension of Calabria indeed matches well the geological slip rates (0.6 mm/yr) estimated for middle Pleistocene-Holocene time for active normal faults, along the western side of Calabrian Arc [*Galli and Scionti*, 2006]. During historical times this area was struck by 20  $M_w \geq 6.0$  earthquakes [*Rovida et al.*, 2011], and most of them occurred in the past five centuries [*Galli and Scionti*, 2006]. Also, stress field estimations from the inversion of earthquake focal mechanisms have evidenced that the Calabrian Arc is subject to a NW-SE extension (see *Palano* [2015] for an overview). All these aspects confirm that the current crustal extension of the Calabrian Arc occurs along a prevailing NW-SE direction, and such a deformation is largely released seismically [see also *D'Agostino et al.*, 2011]. As far as the second observation is concerned, multichannel and single-channel seismic profiles, as well as bathymetric surveys, have recently provided evidence of ongoing compressional deformation at the outer front of the accretionary wedge coupled with widespread strike-slip faulting throughout the wedge [*Gutscher et al.*, 2006; *Polonia et al.*, 2011]. Our results agree with these evidence, since the current southeastward motion of CSS is absorbed by strike-slip faults within the wedge and contractional structures at the front.

We observe a small-scale (radius of  $\sim 65$  km) toroidal crustal pattern of deformation around a vertical axis close to each slab edge, one in northern Calabria and the second in NE Sicily-southernmost Calabria (see Figures 2b and S2 in the supporting information). By considering a total of 10 and 11 GPS sites, respectively, for the northern and southern slab edges, we estimated the Euler pole parameters for each deformation pattern (see Figure S2 and Text S2 in the supporting information for details about the computations). At the northern slab edge, we derive a pole located in the Sibari Gulf and characterized by a counterclockwise rotation rate of  $1.29 \pm 0.23^\circ/\text{Ma}$  (Figures 2b and S2). At the southern slab edge, we derive a pole located close to the NE Sicily coastal area, with a clockwise rotation rate of  $\sim 1.74 \pm 0.35^\circ/\text{Ma}$  (Figures 2b and S2). This surface toroidal pattern in the GPS-based velocity field was masked in earlier studies, due to the small number of GPS stations along the CSS, hampering the detection of relative motions of smaller blocks at low velocities [*D'Agostino et al.*, 2011; *Palano et al.*, 2012; *Pérouse et al.*, 2012]. The estimated poles are located asymmetrically with respect to the deeper and older portion of the Ionian slab subducted during Neogene, while they are symmetrical to the shallow part of the slab (see the  $+0.8\%$   $P$  wave velocity anomaly at 50 km depth in Figure 2a) more recently subducted, during late Pliocene to early Pleistocene [e.g., *Faccenna et al.*,



**Figure 3.** Simplified 3-D sketch model of the investigated area, view from NW. Calabrian slab isosurface (velocity anomaly +0.8%) down to 650 km depth is taken from PM0.5 model [Piromallo and Morelli, 2003]. Euler poles (blue pins) estimated in this study and preferred present-day tear faults (gray dashed lines) are reported on top. Blue curved arrows: rotations around poles inferred from GPS vectors. Large blue arrow: direction of trench rollback. Small half-arrows: motion along the two tear faults. White arrows: extension direction. Single measurements of SKS splitting fast directions from Baccheschi *et al.* [2011] are plotted as blue bars at the 150 km depth SKS ray piercing point (Figure S3 in the supporting information). The bars are oriented according to the fast direction, and their length is scaled to the delay time. Orange arrows: mantle flow around the slab edges.

2014]. Such symmetry is also observed in the rotation rates, whose values partially overlap within the estimated uncertainties. The slight difference in the rotation rates is likely related to the pole computation strategy and the stations geometry (see Text S2 in the supporting information for details about the computations) and might not be geodynamically significant.

These opposite direction rotations around vertical axes constrained by GPS measurements concur with those inferred by paleomagnetic observations during the late Pliocene to early Pleistocene, with clockwise rotations in Sicily and Calabria and counterclockwise rotations in the southern Apennines [Mattei *et al.*, 2007]. Paleomagnetic data also indicate that the measured rotations occurred at very high rates (10–20°/Ma) during the Pleistocene, mainly due to the fast southeastward migration of CSS [Faccenna *et al.*, 2014; Rosenbaum and Lister, 2004], and ceased at ~1–0.7 Ma [Mattei *et al.*, 2007]. Our results highlight instead that rotations through which the Calabrian Arc attained its arcuate shape did not cease during the Holocene but rather strongly decreased, reaching present-day values (1–2°/Ma) which are 1 order of magnitude lower than during the Pleistocene, in agreement with the remarkable slowing down of the rollback subduction processes since the middle Pleistocene [e.g., Faccenna *et al.*, 2007].

The southeastward migration of CSS requires the existence of lithospheric shear zones that accommodate the differential motions at its lateral borders. At the northern side, the region accounting for the differential motion shows a good spatial correspondence with a wider set of seismically active faults including the Pollino fault zone [Spina *et al.*, 2011] and the Amendolara ridge [Ferranti *et al.*, 2014]. Based on the regional pattern of *P* wave receiver functions, seismicity, and SKS anisotropy, Chiarabba *et al.* [2016] have suggested that these faults decouple the deformation across the region, from the one driven by the delamination of the southern Apennines to the one related to the retreat mechanism in the CSS fore arc. Our findings, coupled with these observations, support the idea that such a lithospheric-scale discontinuity is currently accommodating the southeastward migration of CSS, representing the shallow manifestation of the tearing process at the northern edge of the Ionian slab (Figure 3). Interestingly, this area is also characterized by strong attenuation and

low velocities in the  $P$  wave propagation supporting the presence of shallow asthenosphere due to a slab tear [Monna and Dahm, 2009].

Regarding the southern side, the location and kinematics of the lateral slab tear faults is largely debated [Rosenbaum *et al.*, 2008; Govers and Wortel, 2005; Argnani, 2014; Gallais *et al.*, 2013; Palano *et al.*, 2015a]. In our opinion, the “Ionian fault” [Polonia *et al.*, 2011] and the “Alfeo fault system” [Gutscher *et al.*, 2016] are the most likely among the proposed structures in the offshore (Figure 2), based on the evidence of active tectonics by recent seismic profiles and bathymetric surveys. We consider weaker candidates the Malta Escarpment, since it shows signs of active tectonics only along its northern segments [Argnani, 2014], and the set of N-S oriented structures located in between the Malta Escarpment and the Alfeo fault system, which have recently been interpreted as shallow lateral ramps of the accretionary wedge [Gutscher *et al.*, 2016]. The Ionian fault consists of an active NW-SE striking deformation zone bisecting the accretionary wedge in two lobes [Polonia *et al.*, 2011]. The kinematics of this fault is currently debated: some authors [e.g., Polonia *et al.*, 2016, and references therein] suggest that it behaves as a major dextral strike-slip fault along its entire length and others propose a more complicated kinematics with dextral and sinistral strike-slip features along its northwestern and southeastern sectors, respectively [Gutscher *et al.*, 2017]. The Alfeo fault system consists of a 140 km long, two-branched fault system located about 70 km east of the Sicilian coast (Figure 2) and characterized by transtensional (normal and right-lateral strike-slip) faulting. The surface toroidal pattern in the GPS-based velocity field in NE Sicily suggests that the southeastward motion of CSS is accommodated along the Aeolian-Tindari-Letojanni fault system (Figure 2). Such a fault system is considered as the inland continuation of the Ionian fault, therefore defining a 400 km long crustal shear zone with prevailing right-lateral kinematics, which elongates from the Aeolian Islands up to the Ionian Abyssal plain. Based on these considerations, we propose the Ionian fault and the inland segmented shear zone as the tear fault along which the differential motion of the two lobes is accommodated, with the eastern lobe advancing and the western one remaining relatively stationary. These observations are also consistent with the still active portion of subduction being confined beneath the Calabrian region, where a continuous slab is inferred by images from mantle tomography and the occurrence of deep earthquakes [Neri *et al.*, 2009; Giacomuzzi *et al.*, 2012; Calò *et al.*, 2013].

In GPS and paleomagnetic studies, toroidal patterns like those observed here are traditionally attributed to local crustal flow or to rigid block rotations due to ambient tectonic forces [i.e., Kreemer *et al.*, 2004; Holt, 2000; Liu *et al.*, 2014]. Some authors have made the alternative hypothesis that mantle flow at slab edges caused by slab rollback migration can have a role in driving the surface deformation from below [i.e., Faccenna *et al.*, 2006; Jolivet *et al.*, 2009; Faccenna and Becker, 2010; Pérouse *et al.*, 2012; Chen *et al.*, 2016]. Toroidal mantle flows at slab edges should be strong and well coupled to the upper plate in order to cause a vertically coherent deformation pattern up to the surface [e.g., Jadamec and Billen, 2010]. By means of 3-D thermomechanical modeling, Sternai *et al.* [2014] recently demonstrated that subhorizontal mantle return flow originated by rollback subduction, and slab tearing is able to produce tectonically significant shear stresses at the base of the lithosphere and crust, actively driving surface deformation and kinematics, especially in hot and thinned domains like back arcs. Based on a dense GPS velocity solution, Pérouse *et al.* [2012] suggest that the toroidal crustal pattern at the northwestern edge of the Hellenic subduction zone could represent the surface expression of a slab tear driven by toroidal mantle return flow. In the CSS, the GPS-derived present-day kinematics and paleomagnetic data consistently show continuous (from late Pliocene to present) crustal deformation in terms of opposite toroidal patterns around the two slab hinges, while at depth the asthenospheric flow field inferred from SKS anisotropy [Baccheschi *et al.*, 2011] apparently reveals an asymmetry. Toroidal mantle stirring is visible only at the southern slab edge (Figures 3 and S3 in the supporting information), where the flow field pattern is consistent with the surface deformation, suggesting that the asthenosphere could be coupled strongly enough to the plate. At the northern slab edge, instead, SKS fast directions are trench parallel [Baccheschi *et al.*, 2011] and do not correlate with surface rotations. A plausible explanation for this discrepancy is related to the more recent development of the slab tearing at the northern edge and the consequent reorganization of the mantle return flow. According to the reconstruction of the Calabrian subduction history proposed in the multidisciplinary study by Faccenna *et al.* [2007], the southern slab tear opened earlier (at around 10–8 Ma), while the northern one likely formed only after the cessation of the southern Apennines main thrusting phase (at around 1 Ma) [Patacca *et al.*, 1990]. As a consequence, mantle material inflow across the southern slab tear started early enough to establish a continuous and

long-lived circulation that could efficiently orient the anisotropic fabric along mantle flow trajectories. Conversely, time elapsed since the opening of the northern tear is still too short to achieve a mature mantle circulation (uniform motion for a prolonged time) able to reset the mantle fabric.

## 5. Conclusions

The extensive GPS data set analyzed in this study provides, for the first time, clear evidence of the surface imprint of toroidal mantle circulation at both sides of the retreating Ionian slab. We infer a counterclockwise rotation rate of  $\sim 1.29^\circ/\text{Ma}$  for the northern slab edge with a pole located in the Sibari Gulf and a clockwise rotation rate of  $\sim 1.74^\circ/\text{Ma}$  at the southern slab edge with a pole located close to the NE Sicily coastal area.

The present-day opposite direction, small-scale rotations are consistent with paleomagnetic observations. This indicates that processes through which the Calabrian Arc attained its arcuate shape did not cease during the Holocene, but rather decreased in intensity.

Rotations occur along active lithospheric tears that are currently accommodating the southeastward migration of the CSS. We suggest that the present-day lithospheric tear fault cutting the northern slab edge is represented by a complex left-lateral shear zone that includes the Pollino fault and the Amendolara ridge. A shear zone characterized by right-lateral kinematics, including the Aeolian-Tindari-Letojanni fault system and the Ionian fault, borders the southern slab edge.

While at the surface present-day kinematics and paleomagnetic data coherently point to opposite toroidal patterns at the two slab edges, suggesting continuous crustal deformation from the late Pliocene to present, at depth the mantle seems to flow unevenly. From seismic anisotropy, a toroidal pattern of subsurface return flow appears only at the southern slab edge, while at the northern end SKS fast directions are trench parallel. A possible cause for this asymmetric coupling of the upper plate deformation with underlying mantle flow is the immature stage of the northern slab tear.

Evidences like the asymmetric coupling observed in this study can be used in the context of numerical modeling at a regional scale [e.g., *Jadamec and Billen*, 2010; *Faccenna and Becker*, 2010; *Sternai et al.*, 2014] to assess how model results can be translated to nature, by testing the influence of different assumptions (i.e., mantle rheology, slab geometry, and prescribed mechanical boundary conditions at the surface) on plate motions and flows occurring in the underlying mantle.

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