Forearc extension and slow rollback of the Calabrian Arc from GPS measurements

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[1] Here we describe the horizontal velocities of continuous GPS stations in the Calabrian Arc (CA) and surrounding regions. The appropriate reference frame to evaluate the crustal motion of the CA is considered by assessing the internal deformation and the relative motion of the crustal blocks in the foreland of the Apennines-Ionian-Maghrebides subduction system. We propose that the motion of CA relative to the subducting Ionian lower plate is most properly assessed by minimizing the GPS velocities in Apulia. In this reference frame the significant ≈2 mm/yr southeastward motion of the stations on the Ionian flank of the CA shows that the arc is still moving towards the trench in agreement with the observations of active shortening in the Ioanian wedge. This southeastward migration is associated to 1.4 ± 0.3 mm/yr E-W extension of the forearc in northern Calabria, comparable with the seismic strain averaged in the last 500 years. The limited subaerial exposure decreases the resolution on locking of the subduction interface but the distribution and direction of crustal extension along the CA impose important constraints on geodynamic interpretations of the area. **Citation:** D'Agostino, N., E. D'Anastasio, A. Gervasi, I. Guerra, M. R. Nedimović, L. Seeber, and M. Steckler (2011), Forearc extension and slow rollback of the Calabrian Arc from GPS measurements, *Geophys. Res. Lett.*, *38*, L17304, doi:10.1029/2011GL048270.

1. Introduction

[2] The Calabrian Arc (CA) lies on the upper plate of the Tyrrhenian-Ionian subduction system (Figure 1). Here the Ionian lithosphere subducts beneath the CA and dips steeply at 75°–80° beneath the Tyrrhenian Sea down to a depth of 450–500 km [*Selvaggi and Chiarabba*, 1995]. Although there is a wide consensus that the Calabrian subduction evolved by the simultaneous retrograde motion of the subduction zone and opening of the Tyrrhenian back-arc basin [*Malinverno and Ryan*, 1986], large uncertainties still remain concerning the present-day activity and kinematics of the CA in terms of (1) the relationship between the upper crustal deformation and its deep structure and (2) the activity of the subduction zone. The subaerial part of the CA, more properly defined as the emergent, deforming part of the forearc [*Molin et al.*, 2004], presents a high rate of historical $M > 6$ destructive earthquakes and is currently assigned to the highest class of the Italian Seismic Hazard Zonation Map (http://zonesismiche.mi.ingv.it). Conversely, largely unclear and intensively debated [*Gutscher et al.*, 2006; *Mattei et al.*, 2007; *Serpelloni et al.*, 2010] is the active deformation and seismogenic potential of the Ionian wedge. As the subduction zones are the most important seismogenic and tsunamigenic sources in the Mediterranean Sea [*Lorito et al.*, 2008] the understanding of the contemporary kinematics of the CA and mode of seismic release has a large potential societal impact. Here we use a new GPS velocity field to (1) define the appropriate reference frame to evaluate the plate motion and regional kinematics of the subduction zone, and (2) assess the internal deformation of the northern part of the CA.

2. Tectonic Setting of the Calabrian Arc

[3] The evolution of the CA and its subduction zone in the last 15 Myr has been characterized by rollback of the Ionian lithosphere associated with opening of the Tyrrhenian back-arc basin [*Malinverno and Ryan*, 1986; *Patacca et al.*, 1990; *Faccenna et al.*, 2001]. Estimates of past trench positions in the Tyrrhenian Sea during the Neogene-Quaternary suggest that back-arc opening rates as high as 50–70 mm/yr have been much faster than the plate convergence during the same time interval. Deep seismicity is currently limited to a narrow (<200 km) and steeply NW-dipping Wadati-Benioff zone [*Selvaggi and Chiarabba*, 1995]. Recent seismological investigations [*Piana Agostinetti et al.*, 2009] show that the Moho in the northern CA lies at a depth of 35 km beneath the Sila Massif and gently dips westwards beneath the easternmost part of Calabria. The crustal velocity structure is here consistent with underplating of Ionian sediments scraped-off the subducting lithosphere. Underplating of Ionian sediments has also been invoked to explain the Quaternary uplift of the CA in the last 2 Myr [*Minelli and Faccenna*, 2010] documented by the widespread occurrence of flights of marine terraces [*Ferranti et al.*, 2006]. Outward migration of the arc in the last 2 Myr appear simultaneous with back-arc opening of the Marsili basin and frontal bulk deformation of the outer Ionian wedge [*Minelli and Faccenna*, 2010].

[4] Active crustal deformation is documented by the intense historical seismicity generally associated with the active normal faults [*Tortorici et al.*, 1995; *Galli and Bosi*, 2003] which, following the trend of the arc, accommodate arc-perpendicular extension all along the CA. The distribution of historical seismicity and paleoseismological

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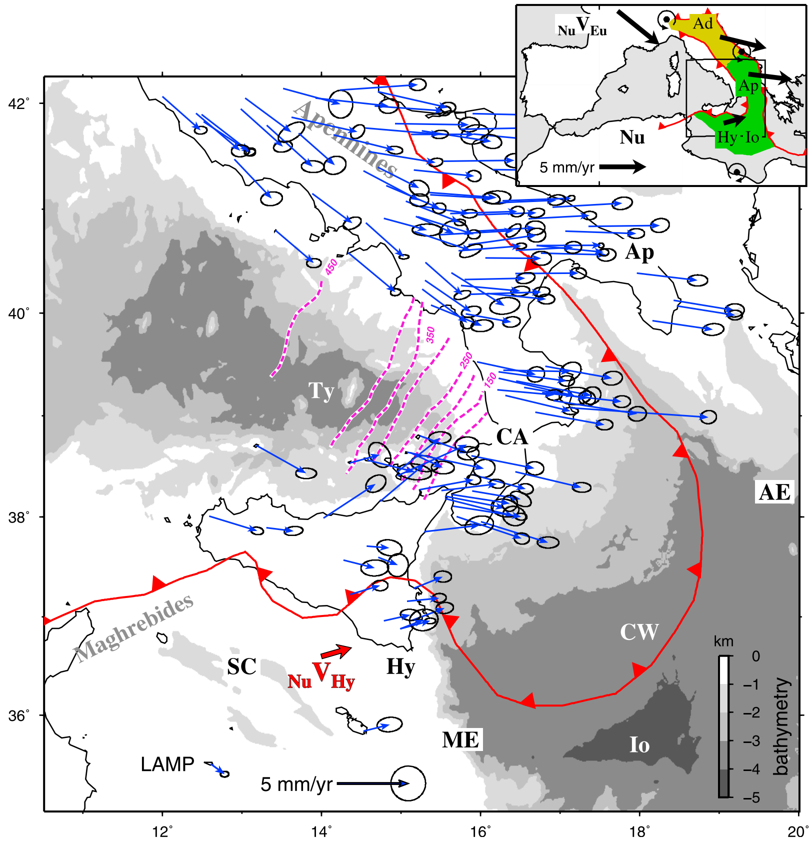

Figure 1. GPS velocities (error ellipses 95% CI) of the Calabrian Arc and surrounding regions in a Nubia reference frame. The red line is the outer limit of the Apennines-Ionian-Maghrebides subduction system. Pink dashed lines represent approximate isobaths of deep slab seismicity beneath the Tyrrhenian Sea. The red arrow shows the motion of the Hyblean region relative to Nubia. The inset shows a schematic map with Nubia-fix velocities calculated according to the slat model of *D'Agostino et al.* [2008]. Legend: Ap, Apulia; CA, Calabrian Arc; CW, Calabrian Wedge; Io, Ionian Sea; Hy, Hyblean; SC, Sicily Channel; Ty, Tyrrhenian Sea; Malta Escarpment; AE, Apulian Escarpment.

studies in northern Calabria shows that active deformation is distributed between two main fault systems trending approximately North-South: the Crati Valley [*Tortorici et al.*, 1995] and the Lakes fault system [*Galli and Bosi*, 2003]. More uncertain are the style of deformation and the tectonic activity of the Ionian wedge. Recent studies [*Gutscher et al.*, 2006; *Polonia et al.*, 2008] have documented recent deformation in the outermost portion of the Ionian accretionary wedge, suggestive of activity of the subduction zone. The occurrence of a large *M*8 subduction earthquake has been adopted by *Gutscher et al.* [2006] to explain the macroseismic and tsunami observations associated with the 1693 Catania earthquake [*Working Group CPTI*, 2004].

3. GPS Data and Processing

[5] Here we use data obtained from a nine-stations continuous GPS deployment in the northern CA in the frame of the NSF-funded Calabrian Arc Project. These stations, installed in cooperation with UNAVCO personnel, are operated by the Department of Physics of the Università della Calabria. This data set, combined with data from the RING (http://ring.gm.ingv.it) and other continuous GPS networks in the Mediterranean, Eurasian and African regions, has been analyzed using the GIPSY-OASIS II software package and the precise point positioning method [*Zumberge et al.*, 1997]. Carrier phase ambiguities have been successfully resolved across the entire network using an algorithm based on a fixed-point theorem that closely approximates a full-network resolution [*Blewitt*, 2008]. Satellite orbit and clock parameters, and daily coordinate transformation parameters into ITRF2005 were provided by the Jet Propulsion Laboratory (JPL). ITRF2005 positions were transformed into an Eurasia fixed reference frame by performing daily transformations into a frame that is defined by minimizing the horizontal velocities of 30 stations across the stable part of the Eurasian continent (away from areas affected by glacial isostatic adjustments). Common mode errors for this continental scale frame are further reduced by including an additional 60 stations as far away as Iceland, Eastern Eurasia, and Africa in a daily spatial (7 parameters) filter [*D'Anastasio et al.*, 2008]. We estimate velocities from the continuous GPS time-series using the CATS software package [*Williams*, 2003] accounting for annual and semi-annual constituents, and simultaneously estimating rate uncertainties given the assumption that the error model is dominated by white noise plus flicker noise. The Eulerian vector of the Nubia plate with respect to Eurasia is estimated using the horizontal velocities of 26 stations homogeneously distributed in the stable part of the plate

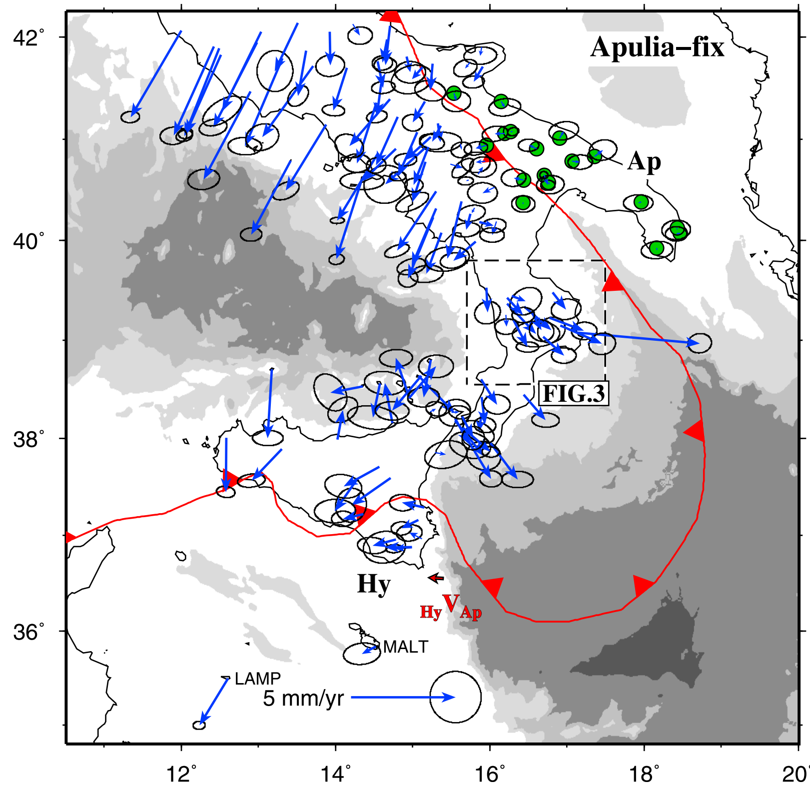

Figure 2. GPS velocity fields in the Apulian reference frame. The sites used to determine the relative Eulerian vector are marked with green circles. The red arrow shows the motion of the Hyblean region relative to Apulia.

(Figure S1 of the auxiliary material).[1] Station velocities and associated uncertainties, Eulerian vectors and their fit parameters are provided in the auxiliary material.

4. Kinematics of the Calabrian Arc

[6] In a Nubia-fix velocity field (Figure 1) we observe that (1) stations in the CA and in Apulia show eastward velocities at 3.5–4.5 mm/yr and (2) stations in the Hyblean region display northeastward residual velocities at 1–2 mm/yr. The hypothesis that the Ionian lithosphere (lower plate of the subduction system) is kinematically attached to the Nubia plate thus requires that the motion of the CA is accommodated by significant oblique convergence in the wedge [*D'Agostino and Selvaggi*, 2004; *Goes et al.*, 2004], and that 4–5 mm/yr of active deformation are taken up on the Apulian Escarpment to decouple the Apulian block from the Ionian lithosphere. Both predictions are not supported by geological observations either in the Calabrian wedge [*Gutscher et al.*, 2006; *Minelli and Faccenna*, 2010] or along the Apulian Escarpment [*Argnani*, 2009]. Systematic residual velocities in the Hyblean region also show that this area cannot be considered as part of the Nubia plate and that 1.7 ± 0.1 mm/yr of extension are taken up along the Sicily Channel between the islands of Malta and Lampedusa (Figure 2). These findings show that both the Apulian and Hyblean emerged forelands have significant residual velocities relative to the Nubia plate and it is therefore unlikely that a reference frame attached to Nubia is a valid realization of the subducting lower plate reference frame.

[7] An alternative kinematic scenario has been suggested, based on a limited number of continuous and survey-sites GPS measurements, by *D'Agostino et al.* [2008] who proposed that the Hyblean and Apulian forelands kinematically behave as a single microplate moving in such a way as to accommodate the Eu-Nu plate convergence (inset in Figure 1). Here we extend the analysis of *D'Agostino et al.* [2008] using a significantly larger number of continuous GPS stations (Figure 2). A least-square inversion of 17 GPS sites in Apulia and of 8 sites in the Hyblean region to fit distinct Eulerian poles to each region yields reduced χ^2_ν (chi-square normalized by the degree of freedom) of 1.3 and 1.5 and RMS values of 0.3/0.2 mm/yr (east/north) and 0.3/0.3 mm/yr for the Apulia and Hyblean fits respectively. This range of values is typical of intraplate settings and approximately within the average value of the uncertainties. A single Eulerian pole that fit simultaneously to the Hyblean and Apulian sites yields a χ^2_ν of 2.75 and RMS values of 0.4/0.2 (east/north) mm/yr.

[8] To test whether different microplate configurations provide a better kinematic description we use the *F* ratio test [*Stein and Gordon*, 1984]. This test verifies that the reduction in χ^2 derived from the use of a two-plate model instead of a single plate is statistically significant. If the null hypothesis is verified the decrease in χ^2 is consistent with the increasing number of model parameters at the given confidence level. The result of this test is not modified if velocity uncertainties are systematically over or underestimated. We first tested the significance of the χ^2 decrease

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2011gl048270. Other auxiliary material files are in the HTML.

from a solution with a single Apulian and Hyblean block to a solution where the two regions are divided in two blocks. Although the mean value of the Hyblean residuals (relative to Apulia) are only 0.8 and 0.2 mm/yr for the east and north components, respectively, the F statistics show that the decrease is significant at a confidence level larger than 99.9%. The improvement in fit resulting from the assumption of an Apulian microplate distinct from Hyblean thus exceeds that expected purely by chance because of the introduction of the three additional parameters associated with an additional Euler vector. The null hypothesis of an Hyblean block fixed to Nubia is also rejected with a confidence level larger than 99.9%.

[9] These findings suggest that the subaerial portions of the Apulian-Ionian-Hyblean foreland do not behave in a homogeneous kinematic way but are fragmented in different crustal blocks independent of the Nubia plate. At the current level of continuous GPS resolution the Apulian and Hyblean blocks cannot be regarded as belonging to the same microplate. If accommodated entirely along the Malta Escarpment, the relative motion between the Hyblean and Apulian blocks (red vector in Figure 2) results in <1 mm/yr of extension on this structure. On the other hand the limited relative velocity and the absence of clear recent deformation along the Apulian and southern part of the Malta escarpments [*Argnani*, 2009], show that the whole region moves in such a way as to accommodate relative Eu-Nu plate motion following the slat model proposed in *D'Agostino et al.* [2008] (inset in Figure 1). Following this reasoning we propose that the reference frame appropriate to evaluate the motion of the CA relative to the lower plate should be attached to those parts of the foreland most probably attached to the Ionian lithosphere, i.e. the Apulian block. The Apulia-fix GPS velocity field (Figure 2) shows a southeastward migration of the CA in agreement with the shortening directions observed in the most recently deformed part of the Ionian wedge [*Gutscher et al.*, 2006; *Minelli and Faccenna*, 2010]. These findings strongly suggest that the CA is migrating relative to Ionian lithosphere and approximately 2 mm/yr of convergence is absorbed in the Ionian wedge. The results in Figure 2 also show that the narrow CA now represents the sole segment along the Adriatic-Ionian-Maghrebides subduction system where the forearc is still migrating towards the lower plate (see the Sicily and Southern Apennines segments for comparison).

5. Crustal Deformation and Seismicity of Northern Calabria

[10] The GPS velocity field of northern CA (Figure 3a) in a local reference frame (site CETR) shows that relative motion across the ≈80 km spanned by the GPS array in northern Calabria is 1.4 ± 0.3 mm/yr. Only the site KROT shows a marked 4 mm/yr eastward acceleration relative to the rest of the network. Considering the absence of known clear active tectonic features able to accommodate the observed deformation, we believe that KROT velocity is not representative of the true crustal motion but more likely reflects local instability or gravity sliding towards the Ionian Sea, in agreement with the interpretation of seismic lines off-shore of Crotone by *Minelli and Faccenna* [2010]. The velocity of KROT will thus be excluded from the following calculations. A least-square minimization of the horizontal velocities to derive the best-fit homogeneous strain rate tensor yields an almost uniaxial extensional strain-rate of 18 ± 4 nstrain/yr directed at $N82E \pm 13°$. This deformation documents that the arc is not migrating rigidly but deforms internally extending in a direction markedly oblique to the local dip direction of the Ionian slab and to the direction of trenchward motion (Figures 1 and 2). The observed deformation is compatible with extension and strain accumulation distributed between the two main active fault systems: the Crati Valley and the Lakes faults.

[11] To compare the seismic release in the last 500 years with the geodetic strain accumulation rate we estimate the geodetic moment rate in the box of Figure 3 using the scalar version of the Kostrov's formula [*Kostrov*, 1974] $\dot{M}_{geod} = 2\mu AH\dot{\epsilon}_{\max}$ where $\dot{\epsilon}_{\max}$ is the largest absolute eigenvalue of the strain rate tensor (taken here as 18 ± 4 nstrain/yr), A is the considered area, H is the seismogenic thickness (taken here as 10 ± 2.5 km), and μ is the rigidity modulus (3.3×10^{10} N/m^2). The relation (1) furnishes an estimate of geodetic moment rate of $10.57_{6.53}^{17.01} \times 10^{16}$ Nm/yr. The upper and lower ranges in $\dot{M}_{geod}$ reflects the propagation of uncertainties in $\dot{\epsilon}_{\max}$ and in the thickness of the seismogenic layer H. Under the assumption that the geodetic moment rate distributes into earthquake sizes that follow a truncated Gutenberg-Richter distribution, the frequency of earthquakes of magnitude ≥M is [*Ward*, 1994]

$$N_{>}(M) = \left[\frac{1.5+b}{b}\right] \frac{\dot{M}_{geod}\left[10^{bM_{\max}} - 10^{bM}\right]}{10^{(1.5+b)M_{\max}+9.05}} \qquad (1)$$

Using the estimates of moment magnitude M_W given in the CPTI04 catalogue [*Working Group CPTI*, 2004], and assuming a b-value of −1.0 and $M_{\max}$ = 7.0 (maximum magnitude in the study area), we compare (Figure 3b) the seismically released deformation in the last 500 years, and the GPS-calibrated frequency distribution. This comparison shows a good agreement in the range $5.5 < M_W < 6.75$. The deficit of seismic release in the lower magnitude range may suggest the lack of catalogue completeness for $M_W < 5.5$ in the considered temporal window [*Working Group CPTI*, 2004], whereas the discrepancy in the highest magnitude classes is possibly affected by the limited statistical population (one $M_W \geq 6.75$ earthquake).

6. Discussion

[12] The most important finding of this work is the CA trenchward motion in the lower plate reference frame defined by the GPS sites in Apulia. This motion implies that shortening is still active in the Ionian wedge in agreement with the style and geometry of recent deformations. The trenchward motion of the CA relative to the deep Ionian Sea is accompanied by internal deformation of the subaerial part of the forearc resulting in ≈1 mm/yr of E-W extension in northern Calabria. This accumulation rate balances the seismic release in the last 500 years. Whether this balance is significant in the long-term is unclear. The lack of significant seismicity before 1500 A.D. (two $M_W \geq 6.0$ events in the CPTI04 catalogue) as compared to the last 500 years (six $M_W \geq 6.0$ events) may reflect the completeness of the earthquake catalogue but also a temporal clustering of seismic activity in the last centuries.

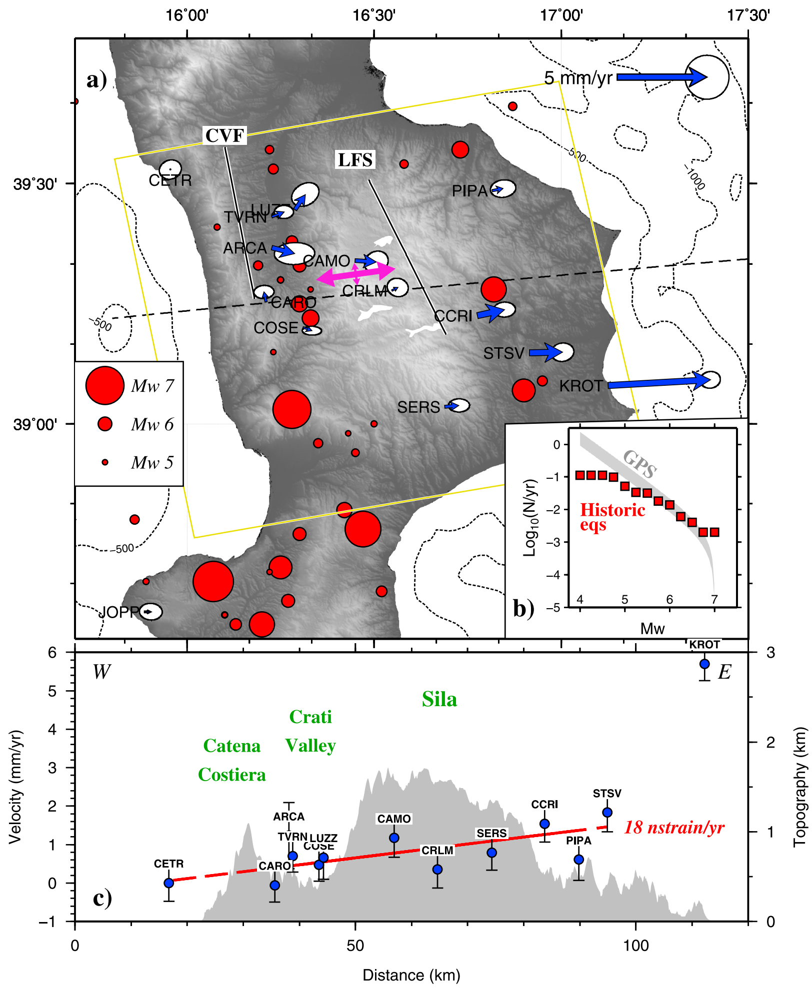

Figure 3. (a) GPS velocities (relative to site CETR) in Northern Calabria. The double divergent arrows are the principal axes of the strain rate tensor calculated using the GPS stations (excluding site KROT, supposed to be affected by local site instability) contained within the box (yellow dashed line). The value of the most extensional strain rate axes is 18 ± 4 nstrain/yr. Red circles are $M > 5$ earthquakes from the CPTI04 catalogue in the interval 1500 A.D.-present. Legend: CVF, Crati Valley Fault System; LFS, Lakes Fault System. (b) Cumulative magnitude-frequencies of CPTI04 seismicity from 1500 A.D. to the present (red squares) extracted from the yellow box in Figure 3a. The gray region represents the range of frequencies obtained from a truncated GR relationship assumed to respect the GPS−derived moment rate (see text for details). (c) GPS velocity profile across Northern Calabria. The error bars represent two standard deviations on either side of the plotted point. Excluding KROT the rest of the sites define a linearly distributed 18 nstrain/yr deformation across Northern Calabria.

[13] More obscure is the style of deformation and seismogenic potential in the Ionian wedge. The limited extent of the GPS network limits the resolution capability to detect locking of the subduction interface, especially if the coupled zone extends principally offshore (see also *Serpelloni et al.* [2010] for the southern part of the CA). An important constraint to the geodynamic interpretation of the CA is, however, that the process responsible for the active deformation does not determine measurable shortening in the subaerial part of the CA and that the direction of extensional strain is oblique to the motion of the arc relative to the lower plate.

[14] In our view these features can be explained by two alternative geodynamic scenarios. (1) A still active retrograde motion (rollback) of the Ionian lithosphere (although at a much slower rate relative to Plio-Pleistocene averages). (2) Gravitational southeastward flow of the entire CA under the effects of the difference in potential energy between the crest of the CA (≈1000 m above sea level) and the bottom of the Ionian Sea (≈−4000 m below sea level). Following the rollback hypothesis the ≈1 mm/yr extension observed across the Crati Valley and the Sila Massif could be interpreted as the present-day rate of back-arc opening. On the other hand the attribution of the observed extension to back-arc opening is not easily reconciled with (1) the obliquity between the direction of trenchward motion and the axis of maximum extension (Figures 2 and 3), and (2) the underlying presence of the shallow NW-dipping rigid Ionian lithosphere, ahead of the steepening of the slab beneath the Tyrrhenian Sea in correspondence with the Crati Valley. The second hypothesis (Ionian-ward gravitational motion of the CA) may alternatively explain the observed extension as the effect of

gravitational flow of the CA above the rigid Ionian lithosphere without any contribution from active retrograde motion of the underlying subduction zone. Migrating episodes of extension between the back-arc and the forearc, driven by rollback and trenchward gravitational flow respectively, may be a more general characteristics of the upper plate deformation in subduction zones where trench retreat velocity undergoes episodic pulses of acceleration [*Guillaume et al.*, 2010].

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References

Argnani, A. (2009), Evolution of the southern Tyrrhenian slab tear and active tectonics along the western edge of the Tyrrhenian subducted slab, *Geol. Soc. Spec. Publ.*, *311*, 193–212, doi:10.1144/SP311.7.

Blewitt, G. (2008), Fixed point theorems of GPS carrier phase ambiguity resolution and their application to massive network processing: Ambizap, *J. Geophys. Res.*, *113*, B12410, doi:10.1029/2008JB005736.

D'Agostino, N., and G. Selvaggi (2004), Crustal motion along the Eurasia-Nubia plate boundary in the Calabrian Arc and Sicily and active extension in the Messina Straits from GPS measurements, *J. Geophys. Res.*, *109*, B11402, doi:10.1029/2004JB002998.

D'Agostino, N., A. Avallone, D. Cheloni, E. D'Anastasio, S. Mantenuto, and G. Selvaggi (2008), Active tectonics of the Adriatic region from GPS and earthquake slip vectors, *J. Geophys. Res.*, *113*, B12413, doi:10.1029/2008JB005860.

D'Anastasio, E., N. D'Agostino, A. Avallone, and G. Blewitt (2008), Present-day kinematics of the central Mediterranean plate boundary region from large GPS network analysis using the Ambizap algorithm, *Eos Trans. AGU*, *89*(53), Fall Meet. Suppl., Abstract G21A-0673.

Faccenna, C., T. W. Becker, F. P. Lucente, L. Jolivet, and F. Rossetti (2001), History of subduction and back-arc extension in the central Mediterranean, *Geophys. J. Int.*, *145*, 809–820, doi:10.1046/j.0956-540x.2001.01435.x.

Ferranti, L., et al. (2006), Markers of the last interglacial sea-level high stand along the coast of Italy: Tectonic implications, *Quat. Int.*, *145–146*, 30–54, doi:10.1016/j.quaint.2005.07.009.

Galli, P., and V. Bosi (2003), Catastrophic 1638 earthquakes in Calabria (southern Italy): New insights from paleoseismological investigation, *J. Geophys. Res.*, *108*(B1), 2004, doi:10.1029/2001JB001713.

Goes, S., D. Giardini, S. Jenny, C. Hollenstein, H-G. Kahle, and A. Geiger (2004), A recent tectonic reorganization in the south-central Mediterranean, *Earth Planet. Sci. Lett.*, *225*, 335–345, doi:10.1016/j.epsl.2004.07.038.

Guillaume, B., F. Funiciello, C. Faccenna, J. Martinod, and V. Olivetti (2010), Spreading pulses of the Tyrrhenian Sea during the narrowing of the Calabrian slab, *Geology*, *38*(9), 819–822, doi:10.1130/G31038.1.

Gutscher, M. A., J. Roger, M. A. Baptista, J. M. Miranda, and S. Tinti (2006), Source of the 1693 Catania earthquake and tsunami (southern Italy): New evidence from tsunami modeling of a locked subduction fault plane, *Geophys. Res. Lett.*, *33*, L08309, doi:10.1029/2005GL025442.

Kostrov, V. V. (1974), Seismic moment and energy of earthquakes, and seismic flow of rock, *Phys. Solid Earth*, *1*, 23–44.

Lorito, S., M. M. Tiberti, R. Basili, A. Piatanesi, and G. Valensise (2008), Earthquake-generated tsunamis in the Mediterranean Sea: Scenarios of potential threats to southern Italy, *J. Geophys. Res.*, *113*, B01301, doi:10.1029/2007JB004943.

Malinverno, A., and W. B. F. Ryan (1986), Extension on the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere, *Tectonics*, *5*, 227–245, doi:10.1029/TC005i002p00227.

Mattei, M., F. Cifelli, and N. D'Agostino (2007), The evolution of the Calabrian Arc: Evidence from paleomagnetic and GPS observations, *Earth Planet. Sci. Lett.*, *263*, 259–274, doi:10.1016/j.epsl.2007.08.034.

Minelli, L., and C. Faccenna (2010), Evolution of the Calabrian accretionary wedge (central Mediterranean), *Tectonics*, *29*, TC4004, doi:10.1029/2009TC002562.

Molin, P., F. Pazzaglia, and F. Dramis (2004), Geomorphic expression of active tectonics in a rapidly-deforming arc, Sila Massif, Calabria, southern Italy, *Am. J. Sci.*, *304*, 559–589.

Patacca, E., R. Sartori, and P. Scandone (1990), Tyrrhenian basin and Apenninic arcs: Kinematic relations since late tortonian times, *Mem. Geol. Soc. Ital.*, *45*, 425–451.

Piana Agostinetti, N., M. S. Steckler, and F. P. Lucente (2009), Imaging the subducted slab under the Calabrian Arc, Italy, from receiver function analysis, *Lithosphere*, *1*, 131–138, doi:10.1130/L49.1.

Polonia, A., L. Torelli, R. Capozzi, F. Riminucci, A. Artori, R. Ramella, and Calarc Group (2008), African-Eurasian plate boundary in the Ionian Sea: Shortening and strike slip deformation in the outer Calabrian Arc accretionary wedge, paper presented at 27th National Congress, Gruppo Naz. di Geofis. della Terra Solida, Trieste, Italy.

Selvaggi, G., and C. Chiarabba (1995), Seismicity and P-velocity image of the southern Tyrrhenian subduction zone, *Geophys. J. Int.*, *121*, 818–826, doi:10.1111/j.1365-246X.1995.tb06441.x.

Serpelloni, E., R. Bürgmann, M. Anzidei, P. Baldi, B. Mastrolembo Ventura, and E. Boschi (2010), Strain accumulation across the Messina Straits and kinematics of Sicily and Calabria from GPS data and dislocation modeling, *Earth Planet. Sci. Lett.*, *298*, 347–360, doi:10.1016/j.epsl.2010.08.005.

Stein, S., and R. Gordon (1984), Statistical tests of additional plate boundaries from plate motion inversions, *Earth Planet. Sci. Lett.*, *69*, 401–412.

Tortorici, L., C. Monaco, C. Tansi, and O. Cocina (1995), Recent and active tectonics in the Calabrian Arc (southern Italy). *Tectonophysics*, *243*, 37–55.

Ward, S. N. (1994), A multidisciplinary approach to seismic hazard in southern California, *Bull. Seismol. Soc. Am.*, *84*, 1293–1309.

Wessel, P., and W. H. F. Smith (1998), New, improved version of Generic Mapping Tools released, *Eos Trans. AGU*, *79*(47), 579.

Williams, S. D. P. (2003), The effect of coloured noise on the uncertainties of rates estimated from geodetic time series, *J. Geod.*, *76*, 483–494.

Working Group CPTI (2004), *Catalogo Parametrico dei Terremoti Italiani, version 2004 (CPTI04)*, Ist. Naz. Geofis. e Vulcanol., Bologna, Italy. (Available at http://emidius.mi.ingv.it/CPTI.)

Zumberge, J. F., M. B. Heflin, D. C. Jefferson, M. M. Watkins, and F. H. Webb (1997), Precise point positioning for the efficient and robust analysis of GPS data from large networks, *J. Geophys. Res.*, *102*, 5005–5017.

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