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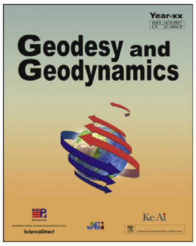

Geodynamics of the Calabrian Arc area (Italy) inferred from a dense GNSS network observations

Giuseppe Casula[*]

Istituto Nazionale di Geofisica e Vulcanologia (INGV), Sezione di Bologna, Via Donato Creti 12, I-40128, Bologna, Italy

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ABSTRACT

The tectonics and geodynamics of the Calabria region are presented in this study. These are inferred by precise computation of Global Navigation Satellite Systems (GNSS) permanent station velocities in a stable Eurasian reference framework. This allowed computation of the coordinates, variance and covariance matrixes, and horizontal and vertical velocities of the 36 permanent sites analyzed, together with the strain rates, and using different techniques. Interesting geodynamic phenomena are presented, including compressional, and deformational fields in the Tyrrhenian coastal sites of Calabria, extensional trends of the Ionian coastal sites, and sliding movement of the Crotone Basin. Conversely, on the northern Tyrrhenian side of the network near the Cilento Park area, the usual extensional tectonic perpendicular to the Apennine chain is observed. The large-scale pattern of the GNSS height velocities is shown, which is characterized by general interesting geodynamic vertical effects that appear to be due to geophysical movement and anthropic activity. Finally, the strain-rate fields computed through three different techniques are compared.

1. Introduction

At present, several institutions in Italy maintain Global Navigation Satellite Systems (GNSS) networks, to furnish potential users with precise positioning of sites in the field by simply operating a GNSS receiver with an antenna. For the Italian peninsula, there are hundreds of permanent GNSS sites that are operated daily by different institutions, such as government bodies, local and regional administrations, and private companies. In general, receiver-independent exchange format (RINEX), 30-s-rate GNSS data are made freely available to users through ftp or http servers. Some regional government bodies, including Liguria, Campania, Calabria,

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[*] Tel.: +39 051 4151415; fax: +39 051 4151499.
E-mail address: giuseppe.casula@ingv.it.
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Emilia Romagna, and Piemonte, provides users with the highest rate data (≤1 s), and transmit ambiguity corrections for real-time kinematic positioning.

These facilities can be valuable tools for geodynamical studies of high risk seismic areas [1] like the Calabria region in Italy. The Calabrian region is composed by Paleozoic aged crystalline rocks which gave rise to the Sila, Serre and Aspromonte massifs. Three groups of archaic rocks can be classified as follows: granitic, gneiss and mica-schists.

The group of the granitic rocks has developed particular along the Ionian coast giving rise to the zone of the Sila and Serre [2]. The group of gneiss rocks crop out mainly along the west part of the Sila massif, in the coastal chain coming from Paola to Cosenza, along the Maida and Chiaravalle plateaus to reach finally the Aspromonte massif together with the group of mica-schist, which can be defined as typical Aspromonte rock highly altered by metamorphic phenomena either in the aspect and structure.

The Mesozoic terrains of the secondary age constitutes practically one third of the southern mountains of Calabria region and are present in different shapes and aspects starting from Lagonegro village to Castrovillari and from Pazzano village to arrive at the Ionian sea.

Terrains of the tertiary age (Cenozoic) indeed, composed mainly by sedimentary rocks like clays and sandstone, have been originated by metamorphic strong phenomena and can be observed near Reggio Calabria Province, and in the mountains of Mosorrofa, Terreti and Ortì that reaches heights ranging from 700 to 1200 m above sea level, and are mainly composed by marine sediments [2].

The Calabria region is one of the highest seismic risk area of the world, in fact it is collocated along the zone of contact between Eurasia and Africa plates. For this reason it is practically compressed inside the big jaw constituted by these two plates. The earth crust of Calabria region is for this reason broken in big active normal seismogenetic faults dipping 10–15 km and long several km, and delineating graben styled structures.

The fault system of the Calabria region is represented in Fig. 1 with red lines, together with the earthquakes that historically occurred in this area with magnitude ≥6 which are represented with yellows dots. In particular, we can enumerate the following catastrophic events: the Valle of Crati earthquake of 1183, the Messina strait earthquake of 1908, the seismic sequence of the southern Calabria of 1783, the earthquakes of central Calabria occurred respectively in 1638 and 1905, the Cosentino area earthquakes of 1835, 1854, and 1870 [3,4].

This high magnitude seismicity makes the Calabria one of the Italian region more exposed to natural risks (quakes, tsunamis, and landslides), moreover it caused in the past more than 200.000 human casualties (1908) [5], high costs and damages.

From the geodynamical point of view the dominant mode of crustal deformation of the Calabrian area is represented by normal faulting with ESE-WNW extensional trend originated during the Middle Pleistocene.

A sliding movement of the Crotone Basin is present moving toward east, conversely along the Apenninic chain an extensional trend can be observed crossing the chain from west to east [6].

The area is then characterized by the slab of the Ionian sea that is submerged under the Arc in the ESE-WNW direction and is characterized by a subduction zone being located on the top of a narrow active Wadati-Benioff zone [6]. The tectonics that originated this area are in some way connected with the phenomena that originated the volcanic arc of the Aeolian Islands that is due to movement of the Earth's crust as a result of plate tectonics. The African continental shelf is in constant movement towards Europe. The resulting collision has created the volcanic arc of the Aeolian Islands.

More than 50% of the earthquakes that occurred in the Italian peninsula gave rise in Calabria along the active faults represented in red in Fig. 1. Many of these structures can potentially produce earthquakes of Magnitudes ≥7 (1638, 1783, 1905, 1908) [2–4].

As a supporting tool for the considerations written above, this study have gathered together daily GNSS RINEX 30-s daily data from the three public companies of RING (http://www.ring.gm) [7], EUREF (http://www.epncb.oma.be), and UNICAL, which are combined with the freely available ITALPOS (http://it.smartnet-eu.com)) Leica Geosystems data from this Italian private company network. These data are used to compute a dense and very accurate GNSS network of daily solutions over a 6-year time span, from the beginning of January 2008, to the end of December 2013 (see Table 1) [1,7].

After robust data archiving using a suitably prepared Unix shell and the Fortran90 and C utilities, these data are processed using a distributed sessions approach [8–10]. They are then combined with other institution solutions and compensated, to obtain the station time series and velocities. Finally, different algorithms are applied to compute the pattern of the continuous strain-rate of the Calabrian area under study. Indications on the tectonics and geodynamics of this complex and interesting high-seismic-risk area are also provided.

2. Geodynamic setting of the Calabrian Arc

The Calabrian Arc is defined as the mountain chain belt lying under the eastern part of the Tyrrhenian Sea. It has a curved shape due to the compression acting between the Sicilian Maghrebides and the southern Apennines, the remote force for which is represented by the active north-eastern pushing of the African plate against the Eurasia plate. A peculiarity of this area is that the central part of the arc is dominated by the polymorphic Calabrian–Peloritanian mountain chain. This was generated by retro-arc tectonics that originated through the subduction of the Ionian Sea lithosphere under the continental crust of the Ionian area. In other words, the Calabro–Peloritanian domain is located on the upper part of a very narrow slab that is characterized by deep seismicity, which has been clearly delineated by the modern inversion of seismic tomography data [11,12, and references therein].

In this complex geodynamic context, there are two interesting aspects that need to be underlined, also when looking at the GNSS network solution in the Calabria region:

(a) Despite the very slow modern-day plate convergence rates observed by GNSS, subduction might still be active in the Calabrian Arc, whereby the subduction rate will

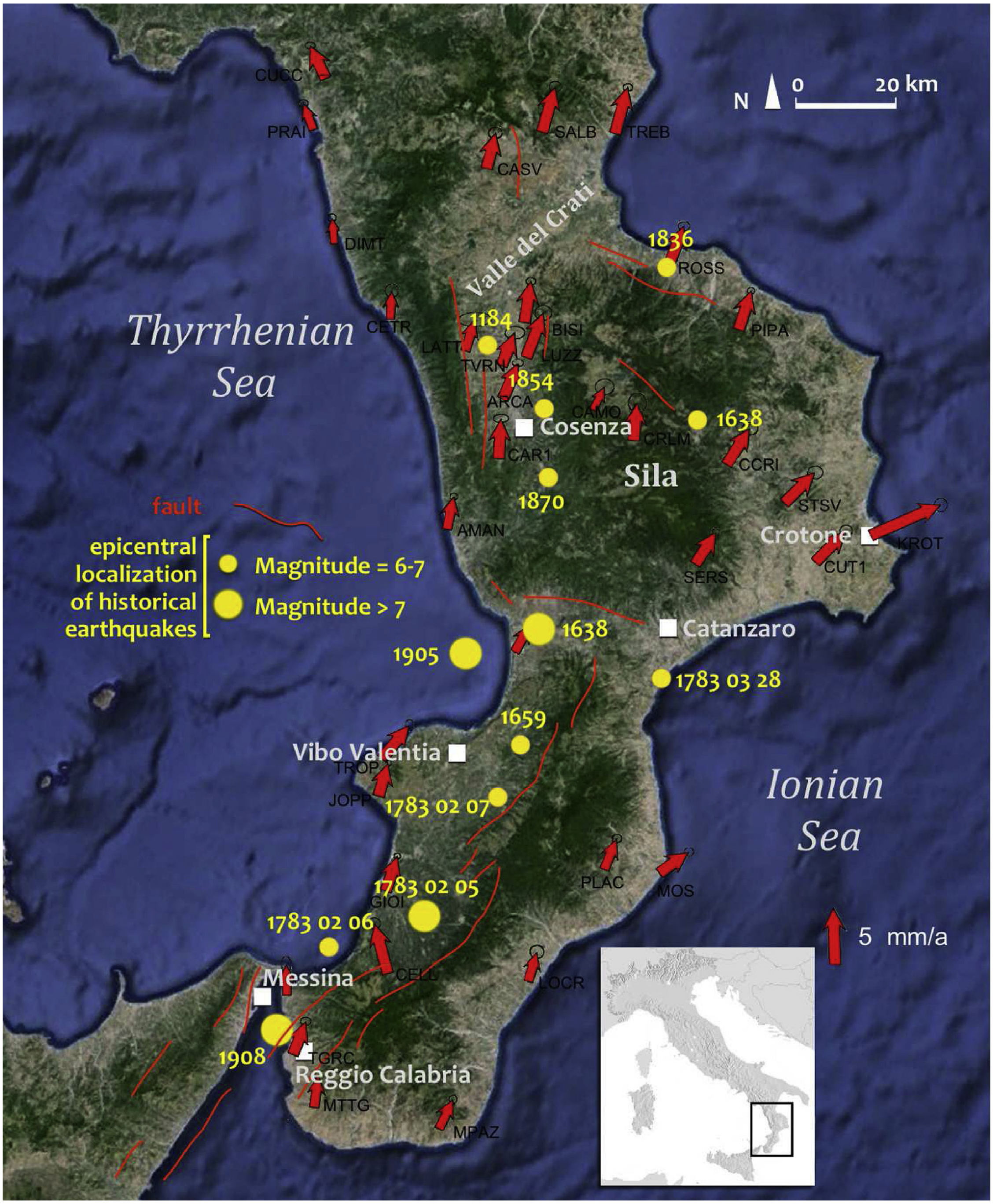

Fig. 1 – Residual intra-plate Eurasian GNSS velocities of the Calabrian sites of the network processed in this study (red arrows). The error ellipses (black circles) are at the 95% level of confidence (see Table 1). Main active faults and historical earthquakes (M > 6) occurred in the Calabrian region are represented respectively with red lines and yellows dots.

depend both on the convergence rate and the velocity of the subduction hinge [12]. Global Positioning System (GPS) sites in the Tyrrhenian part of the network shows anomalous eastern residual velocities that are directed toward the Ionian Sea. These suggests that the apparent still active crustal compression and outward motion of the Calabrian Arc is a result of the subduction motion, that demonstrates that the long-term slip still present in the subduction zone area is balanced by the shortening of the accretionary wedge [11,12, and references therein].

(b) All of the sites of the Ionian part of the network show eastern movement, with the exception of the sites in the Crotone Basin. These are instead characterized by a greater eastern component of the residual velocity together with a negative vertical trend, which

Table 1 – The Calabrian sites and sites in neighboring regions used in this study.

Long.(°)	Lat.(°)	V_E (mm/a)	V_N (mm/a)	σV_E (mm/a)	σV_N (mm/a)	ρ	Site name	Network
16.70	40.65	1.2	4.4	0.3	0.3	−0.002	MATE	EUREF
16.64	39.60	1.7	4.0	0.5	0.4	−0.002	ROSS	ITALP
16.57	38.44	2.6	1.7	0.4	0.4	−0.003	MOST	ITALP
16.53	39.87	1.2	4.0	0.4	0.4	−0.002	TREB	ITALP
16.99	39.03	2.8	2.6	0.6	0.5	−0.002	CUT1	ITALP
16.29	39.51	0.7	3.6	0.4	0.3	−0.002	BISI	ITALP
16.24	38.24	0.8	2.5	0.6	0.6	−0.001	LOCR	ITALP
16.23	38.88	1.4	2.4	0.4	0.3	−0.003	LAME	ITALP
16.23	39.37	1.5	3.1	0.5	0.3	−0.002	ARCA	ITALP
16.20	39.81	0.9	3.1	0.6	0.5	−0.001	CASV	ITALP
16.08	39.12	0.7	2.8	0.3	0.3	−0.003	AMAN	ITALP
16.00	37.95	1.3	2.5	0.3	0.4	−0.003	MPAZ	ITALP
15.90	38.68	2.5	2.8	0.4	0.5	−0.002	TROP	ITALP
15.89	38.42	1.1	3.0	0.3	0.3	−0.004	GIOI	ITALP
15.82	39.68	−0.1	2.3	0.4	0.3	−0.003	DIMT	ITALP
15.78	39.90	−0.8	2.3	0.4	0.3	−0.002	PRAI	ITALP
15.65	38.11	1.2	2.8	0.5	0.4	−0.002	TGRC	ITALP
16.21	39.25	0.3	3.5	0.7	0.4	−0.002	CAR1	RING
15.89	38.26	−1.0	4.4	0.5	0.5	−0.001	CELL	RING
15.89	38.61	0.9	2.9	0.3	0.3	−0.004	JOPP	RING
16.82	39.49	1.2	3.4	0.3	0.3	−0.004	PIPA	RING
16.69	39.04	1.9	2.7	0.3	0.3	−0.004	SERS	RING
15.82	39.99	−1.3	2.9	0.4	0.3	−0.002	CUCC	RING
15.64	38.22	0.0	2.7	0.4	0.8	−0.001	VLSG	RING
16.44	38.45	1.2	2.6	0.4	0.4	−0.003	PLAC	RING
16.35	39.88	1.3	3.9	0.5	0.4	−0.001	SALB	RING
15.70	38.00	0.5	2.8	0.3	0.4	−0.003	MTTG	RING
16.45	39.34	1.1	2.0	0.8	0.7	−0.001	CAMO	UNICAL
16.78	39.23	2.1	3.1	0.7	0.6	−0.001	CCRI	UNICAL
15.95	39.53	0.2	2.5	0.7	0.6	−0.001	CETR	UNICAL
16.55	39.28	0.4	3.3	0.8	0.9	−0.001	CRLM	UNICAL
17.12	39.08	6.2	2.5	0.6	0.6	−0.001	KROT	UNICAL
16.14	39.46	0.9	2.7	0.5	0.6	−0.001	LATT	UNICAL
16.29	39.45	1.6	3.8	0.7	0.7	−0.000	LUZZ	UNICAL
16.23	39.43	1.2	2.8	0.9	0.6	−0.001	TVRN	UNICAL
16.91	39.15	2.7	2.6	0.7	0.6	−0.001	STSV	UNICAL

Long.(°) and Lat.(°) denote longitude and latitude of the sites; V_E and V_N denote east, north components of the intra-plate Eurasia velocities of the sites; σV_E and σV_N denote east and north components of the error ellipses (95% level of confidence); ρ denote correlation factor Rho.

demonstrates that there is an active sliding movement toward the Ionian Sea, as indicated also in Ref. [13].

3. GNSS observations and data processing

Here, the data were processed from 36 GNSS permanent stations in the Calabrian territory belonging to four different GNSS networks: UNICAL, the University of Calabria data that are made available to the scientific community for download (with a delay of 6 months) through the US Nonprofit University–Government Consortium (UNAVCO) (http://www.unavco.org); the Italian National Integrated GPS Network (Rete Integrata Nazionale GPS; RING) data of the National Institute of Geophysics and Volcanology (Istituto Nazionale di Geofisica e Vulcanologia; INGV) that are available at the corresponding http/ftp sites [7] (Table 1); the Italpos data of Leica Geosystems Italy that are available for INGV fellows also through the RING ftp site; and the Italian Space Agency permanent network data that are available at (http://geodaf.mt.asi.it). To better constrain the solutions here, the data from eight fiducial high-quality GNSS sites of the EUREF (European Network) were added: MATE, CAGL, NOT1, PADO, GENO, ZIMM, GRAZ, POTS and WTZR. These last are downloadable from the EUREF ftp site facility.

The Italpos and RING antenna–receiver pairs of the sites processed in this study were mainly GNSS instruments. Indeed, Leica GRX1200GGPRO with Leica AT504GGPRO GPS+GLONASS receiver–antenna pairs are mounted in such a way that these can be termed GNSS network data. The latest version of the GAMIT package (release 10.6 of June 2015) of the Massachusetts Institute of Technology (MIT) can process mixed GPS+GLONASS satellite data [14].

The UNICAL GNSS network was realized in collaboration with UNAVCO and was partially funded by the National Science Foundation, to provide an array of good quality nine permanent GNSS stations that cross the Calabrian region of Sila. All of these antennas were mounted on buildings, with the receiver–antenna pairs of the modern GPS+GLONASS Trimble and Topcon instruments [15].

The GAMIT/GLOBK package (version 10.6) was used to process the GNSS data. This package is a complete collection of programs and utilities written in Fortran90, C and UNIX shells for the analysis of GNSS data that is mainly suitable for Earth crust deformation studies. The software was developed mainly by the Department of Earth, Atmospheric, and Planetary Sciences of the MIT, the Scripps Institution of Oceanography, and Harvard University, with economic support from the National Science Foundation [14]. The package itself is based on a distributed sessions approach [8–10]. For this reason, a multistep procedure strategy was adopted here, starting from the Hatanaka [16] format for the raw data archive of the Calabria network. This was suitably built using UNIX shell procedures (i.e., BASH, CSH) and C and Fortran90 programs.

The whole dataset was divided into three clusters of about 18 stations (12 Calabrian, plus the eight fiducial sites). This allowed a second step to be performed, as a robust combination of the solutions (i.e., quasi-observations) and the Scripps Orbital and Permanent Array Center (SOPAC) solutions downloaded from SOPAC ftp site facility (http://garner.ucsd.edu).

As for standard GNSS data processing, the analysis started from the sub-metric precision-level coordinates that can be estimated a priori using the precise point positioning tool (SH_RX2APR) of the GAMIT package, or extracted by coordinates files of the SOPAC or EUREF facilities. This was to improve the coordinate precision at the sub-centimeter level at the end of the processing, when a global least-squares parameters adjustment was carried out for the coordinates, variance and covariance matrixes, and ambiguities of the whole processed network. GAMIT computes single, double and triple difference observables to correct for outliers and bias, using an automatic cleaning program called AUTCLN.

The set-up of the processing is available on-line as SESTBL, files at the SOPAC facility for standard regional clustering, to standardize all the bias modeling during the processing. In particular, standard Earth orientation parameters were adopted, as taken from previously described facilities, precise orbits, absolute antenna phase corrections, and the FES2004 oceanic model. The data and metadata are made available to users to take into account antenna offsets due to instrumental and internal firmware upgrading [17].

The final solutions (h-file) were generated that contain the coordinates, variance and covariance matrixes, and ambiguities, together with the optionally estimated orbital parameters.

In general, like in the case of this study, the estimation of orbital parameters was unnecessary owing to the fact that the scale of the network analyzed is little.

These were based on a multi-step procedure performed using the main GPSEST (Global Parameters Estimator) program of GAMIT. The percentage of ambiguity resolved in a normal run was over 90%.

For the sake of convenience, only the sites available with a data span of at least 3 years of daily continuous observations were selected for the final compensation. This allowed removal of the colored noise that generally affects GNSS permanent site time series, such as the periodicity that ranged from 12 h to 24 h up to 6 months–12 months due to unwanted atmospheric effects, orbital periodicity, water ground tables effects, and others.

The robust definition of the IGS08 reference frame was used, as published by EUREF for about 100 fiducial sites with appropriate coordinates and velocities, to register the combined observations in the IGS08 reference frame [18–20]. The time series of continuous GPS site positions were computed for every permanent GNSS station analyzed, so as to estimate the error sources of the GNSS data, such as the colored noise that in general affects these types of observation. This was achieved with the aid of the MATLAB tools written by Tom Herring [21]. Also for comparison of the results obtained, the Create and Analyze Time Series (CATS) package of Simon Williams [22] was applied. In this way, the permanent station offsets due to instrumental changes or other unwanted errors like annual and semi-annual periodicities, normal modes, and so on were estimated and corrected for.

Site-by-site suitable Markov a-priori North East Up (MAR_NEU) condition parameters were estimated for the network adjustment with GLOBK, using the weighted root-mean-square of the robust fit performed, as described previously [10,17]. During the solutions of the h-files combination, each daily solution was weighted using the root mean square computed for repeatability. This procedure allowed removal of the colored noise that generally affects GNSS permanent stations observations.

A robust computation of vertical velocities was performed using robust fit estimator of TSVIEW tool of MATLAB package written by Tom Herring [14,21], by taking into account annual, semi-annual periodicities together with offset, outliers corrections and when necessary exponential decay seismic transients. The resulting vertical velocity field was processed with GMT graphical package in order to produce the vertical velocity pattern map shown in Fig. 2.

After subtraction of the rigid rotation of Eurasia, as published by Altamimi [23], or after estimation of a relative rotation pole solution, the intra-plate Eurasian residual velocities were computed using GLOBK 10.6 [24]. The final results of the processing are shown in Figs. 1 and 2, as the intra-plate Eurasian residual velocities, and as the general trend obtained by interpolation of the GNSS heights estimated in this study, respectively.

4. Results and discussion

4.1. *Strain rate estimation strategy*

While the station velocity diagrams demonstrate the relative motions among the stations, the strain-rate maps show the in-situ strain concentration rates, which are proportional to the local stress concentration rates, and possibly to the seismic hazard potentials [25, and references therein]. The strain rates were derived using the input of the velocities estimated through the above-described multi-step processing procedure.

Three different techniques were applied to compute the strain rate in the Calabria region using the a-priori values of the intra-plate velocities of the previously processed GNSS network data. First, ANALYZE_STRAIN of the Quasi–Observation Combination Analysis (property of the Jet Propulsion Laboratory of the National American Space Agency) (http://qoca.jpl.nasa.gov/tutor_base.html) was applied, and based on the least-squares adjustment (Fig. 3). These preliminary data were useful to estimate the main deformational regimes of the studied area, together with the order of greatness of the principal strain-rate axes.

To produce the strain values shown in Fig. 3, ANALYZE_STRAIN was set-up for a least-squares approach, to estimate the strain rates at given grid points. These are represented here as dilatation and maximum shear rates, starting from the velocity values comprised within a predefined distance from each grid point.

The radius of influence was set at 20 km. The software uses a Gaussian weighting scheme with a 5-km Gaussian interval width around each grid point. This is implemented to make the weights increase as the distances to the GNSS stations approach the grid points where the strain rates are calculated [26–28]. The strain tensor principal axes obtained after this operation are shown in Fig. 3.

In particular, the subnetwork strategy was used, where the Calabrian network was divided into five subnetworks, and for each of these, the values of the main strain-rate tensor axis were computed, with the data from this last computation shown in Fig. 3. In this way, five types of deformation trends can easily be recognized. These start from the extensional regime parallel to the Messina straits in the southern part of the network, and pass on to the small compressional trend near the Tyrrhenian coast, which arises as the solution shows a little clock-wise rotation of the residual velocities (see Fig. 1). Evidence of the eastern sliding drift of the Crotone Basin is present in the central-eastern side of the network analyzed. For the northern part of the network, there was the usual extensional trend normal to the Apennine chain in the direction from west to east.

The errors here are not shown in Figs. 3 to 5 for simplicity. However, the variance propagation for all of the methods applied gives an uncertainty of near 10% of the maxima of the strain-rate tensor measured (10^{-8}/a). In other words, the strain values were significant if they overcame the threshold of 0.01 μstrain/a.

In the second step, a Fortran90 subroutine was applied, which was written following the theory published in Ref. [25]. Like most previous methods, this method interpolates the strain rates using discrete GNSS measurements. However, like other previous methods, this approach is useful to model strain rates as a function interpolated over a regular grid into which the whole network is divided. At each node of the grid, a uniform strain-rate field was assumed, and a least-squares inversion was performed over the station velocity solutions and their covariance to solve for six parameters: the velocity component, the rotation rate, and the strain-rate components. Other useful components of the strain-rate tensor, like the main shear strain rate, and the dilatation rate can be computed in a second step as the linear combination of the strain-rate components. The results of this computation are shown in Fig. 4, where the more comprehensible continuous strain-rate pattern is shown to be in good agreement with the values shown in Fig. 3 for both the direction and the intensity.

As the final computation, the software written by Hackl et al. [29] was used, as rearranged for the Calabrian network and based on the spline in tension method [30] and the Generic Mapping Tools graphical package [31]. The interested reader can read also references [28,32,33], where these different approaches are used.

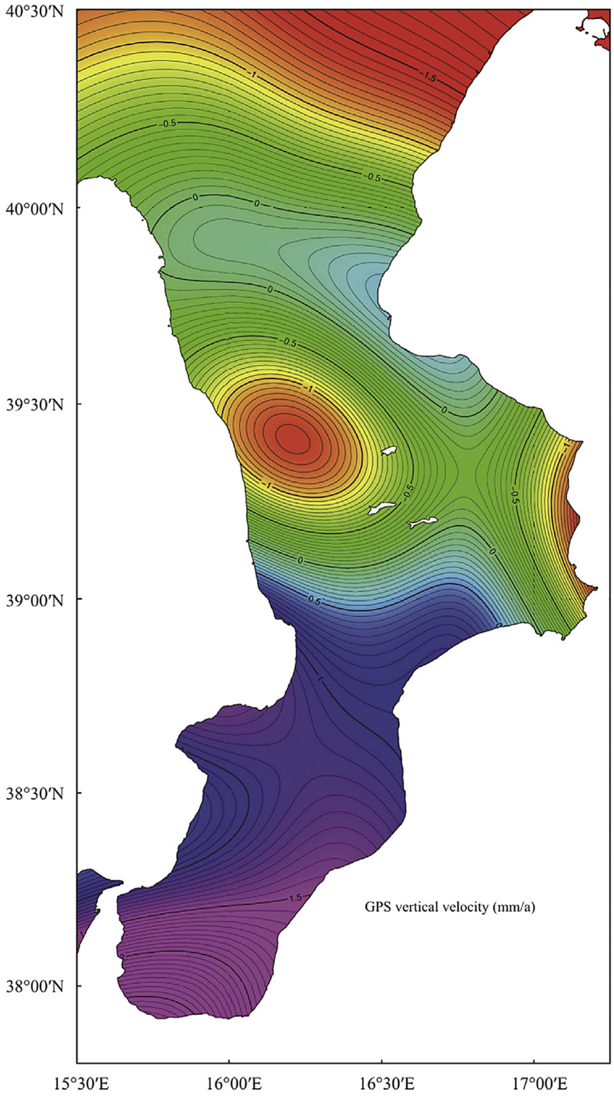

Fig. 2 – Large-scale GPS height variations estimated in this study, after the network compensation performed with GLOBK 10.6.

As for the algorithm presented in Refs. [25], an interpolation of the horizontal component of the velocity field was performed at the beginning of this algorithm. This used the method of Wessel and Bercovici on a regular grid of 0.05° or as a scale chosen by the user, using the method presented in Refs. [29,30]. The interpolated velocity field was partially derived to compute the interpolated velocity gradient. Then all of the components of the tensor strain-rate gradient were computed as a linear combination of the gradient component, or using the estimated eigenvalues and eigenvectors of the tensor itself. The result of this last computation is shown in Fig. 5, where the pattern of the horizontal components of the tensor strain rate is shown. The strain rate ranged between ±0.1 μstrain/a (i.e., ±1 × 10^{-7}/a). This level of strain is characteristic of the Italian region, with the highest level of crustal stress indeed in this area (Calabria), where the highest magnitude earthquakes have occurred in the past.

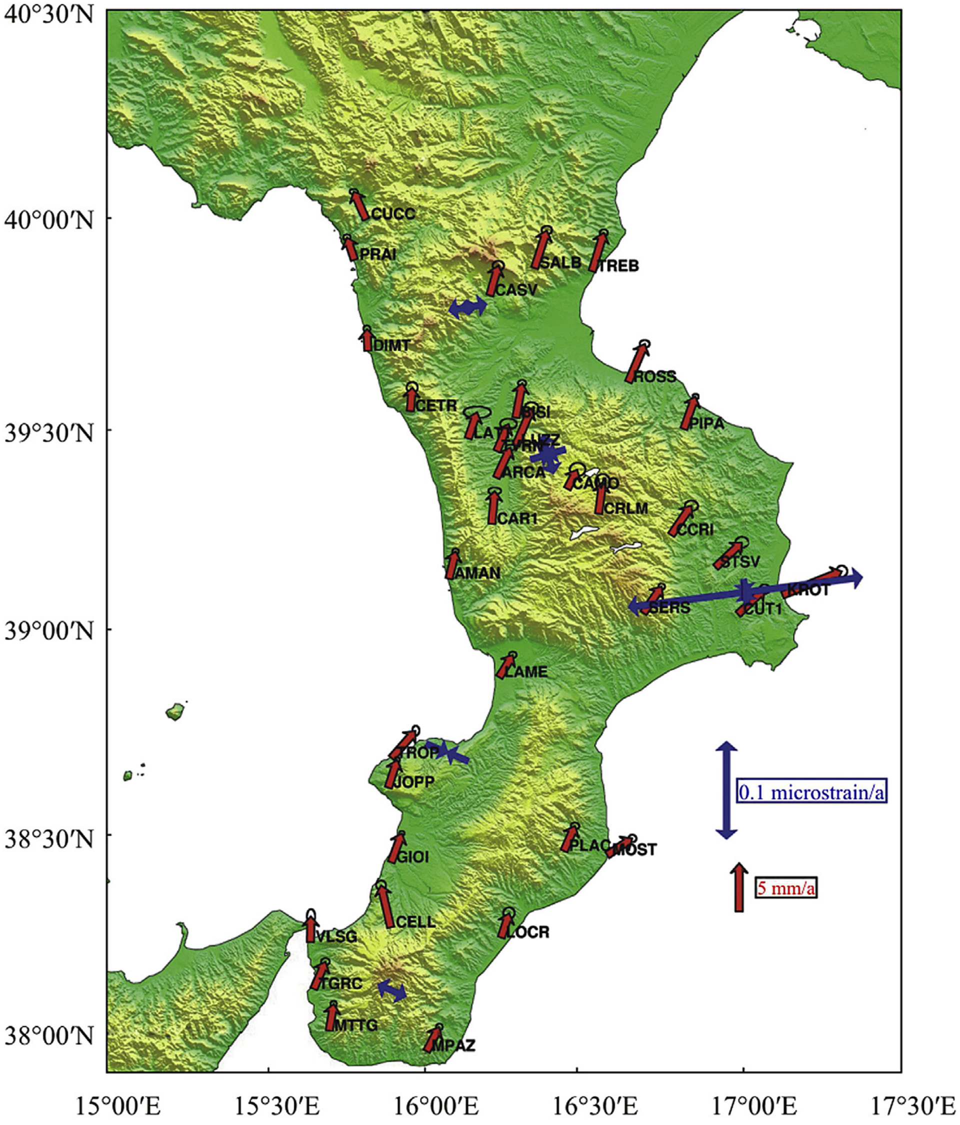

Fig. 3 – Residual Calabrian intra-plate velocities computed in this study (red arrows). Superimposed in blue on the principal axes of the strain-rate tensor computed using the ANALYZE_STRAIN tool of the Quasi–Observation Combination Analysis package [26].

Even if the study of crustal strain-rate patterns does not represent a necessary or sufficient condition for prediction of the seismicity, it can give useful indications. It is also characterized by analogies with the maps of seismic risk. For this task in general, complete knowledge of the geology of an area is not necessary if the approach implemented is followed specifically for application to the discrete measurements of the GNSS network [29,30].

4.2. *Geodynamics and discussion*

As previously described in this work a multi-step network solution strategy based on the distributed sessions approach has been applied to a dense high quality GNSS network in Calabria region. The intra-plate Eurasian velocities have been used as input for different software for the strain rate estimation (Figs. 1–5).

The results of the former processing gives useful indications aimed to account for some evident active geodynamical phenomena of the Calabrian area. In particular, the following indications are provided by intra-plate velocities and strain rate patterns computed in this study:

(a) As pointed out also by other authors, the geodynamics of the Calabria region is mainly characterized by the extensional trend along an axis E–W crossing the Calabrian peninsula. In fact in Figs. 1, 3–5 along the Sila transect of the nine UNICAL GNSS permanent stations, an extensional trend of about 3×10^{-8}/a is evident.

(b) In the southern and northern part of the network, the residual intra-plate velocities and strain rate pattern shows an extensional tectonic along an axis ESE-WNW proved by the fact that the east component of the

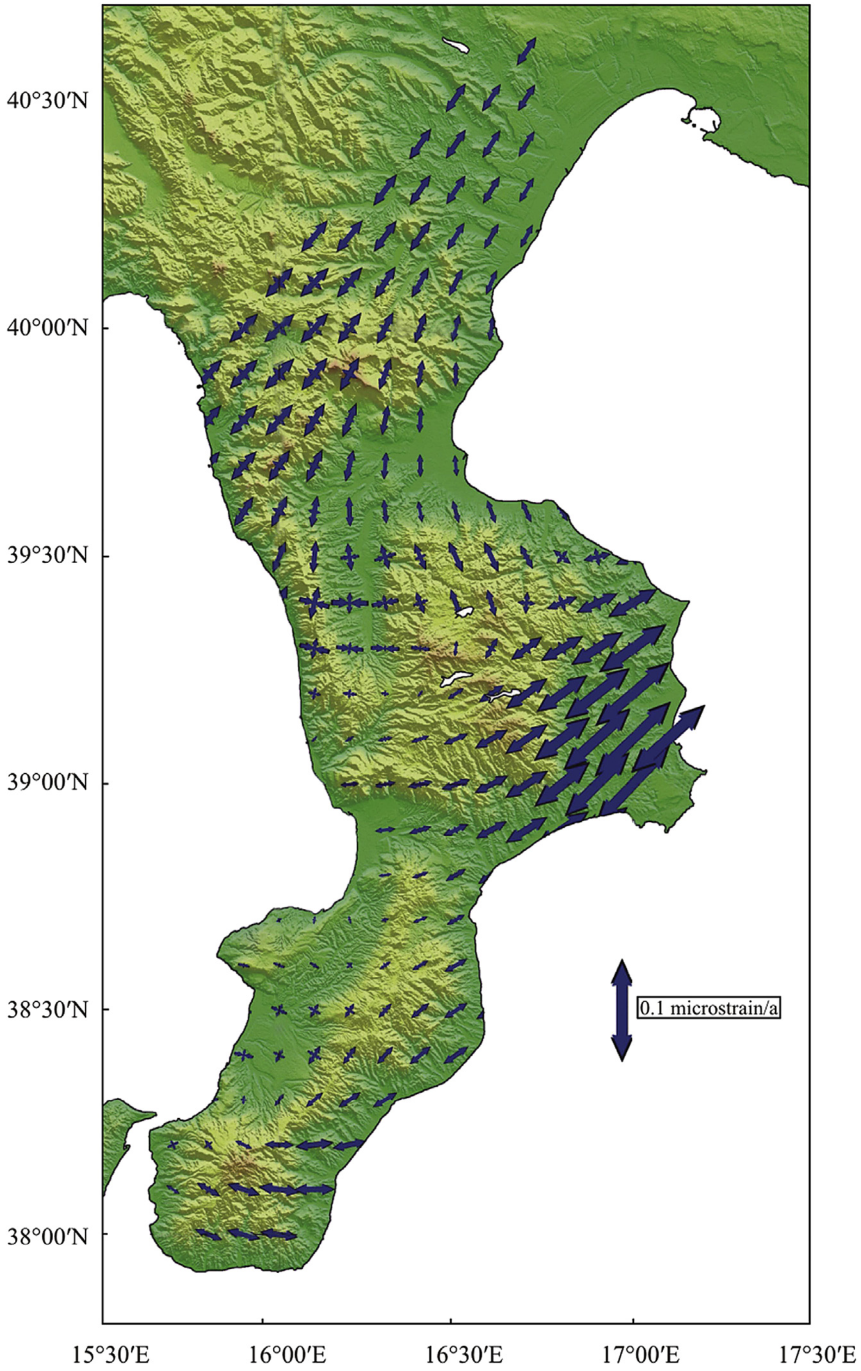

Fig. 4 – Horizontal principal strain-rate axes computed with the technique of extended least squares, using the input of the residual velocities of the GNSS network processed in this study [25].

permanent GNSS stations are positive in the Ionic coast and negative in the Tyrrhenian ones (Figs. 1, 2 and 6).

(c) Along the Messina strait an extensional tectonic can be appreciated following the considerations of (b). In fact the main seismogenetic structures of the Calabria region are grabens divided by normal faults.

(d) Despite the very slow modern-day plate convergence rates observed by GNSS, subduction might still be active in the Calabrian Arc (Figs. 1–3). These suggests active crustal compression and outward motion of the Calabrian Arc as a result of the still-active subduction [11,12,13 and references therein].

(e) A little compressional trend can be observed in our solutions in the central Tyrrhenian area of the analyzed network proved by the fact that in this area the east component of the residual velocities are positive (clockwise rotated, Fig. 6), for this reason a compressional

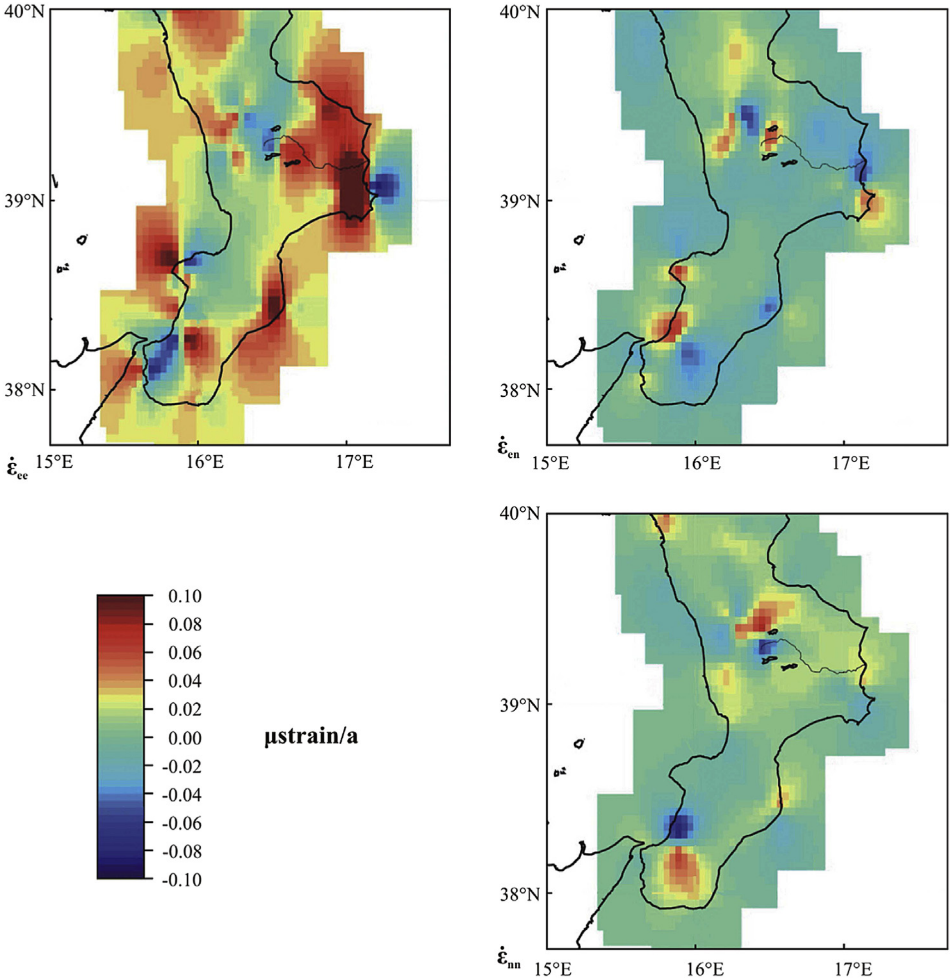

Fig. 5 – Pattern of the strain-rate tensor horizontal components computed with the method of Hackl et al. [29] for the Calabria region.

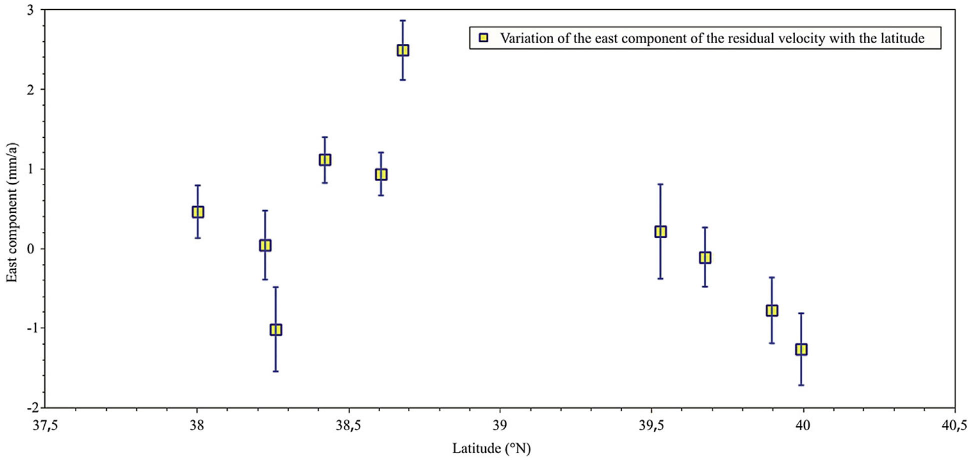

Fig. 6 – Values of the east components of the residual intra-plate velocity of the permanent GNSS stations of the Tyrrhenian coast of Calabria processed in this study. The east component is positive and reaches its maximum value in the central part of the network. This effect testifies to the presence of a compressional trend, as shown in Figs. 3 and 4. Closer to the Messina Strait and to Cilento Park, the east components of the velocity are characterized by negative values (i.e., extension).

strain rate of about 0.02–3 × 10^{-6}/a can be observed (Figs. 4 and 5).

(f) All of the sites of the Ionian part of the network show positive eastern wise movement, testifying the opening of the Ionian sea, with the exception of the sites in the Crotone Basin which are characterized by a greater (>3 mm/a) eastern component of the intra-plate velocities together with a negative vertical trend, which demonstrates the presence of a body slowly sliding toward the Ionian Sea, as indicated also by other authors [13,33].

Concerning the vertical velocities two important consideration can be done as inferred by the results of our GNSS network results; (i) As pointed out before the sliding movement of the Crotone Basin seems to be active, as indicated in the reference [13], and this is testified also by the general negative trend (−1 mm/a) of the heights in this area (see Fig. 2); (ii) A subsidence phenomena (−0.5 mm/a) probably due to anthropic activities like water pumping for industrial purposes, seems to be active in Sibari plane, see also reference [34].

5. Conclusions

A dense GNSS network of about 36 permanent sites in the Calabria region, plus some other GNSS sites in Italy, was analyzed in this study using the GAMIT/GLOBK 10.6 software package [14,24]. Following the distributed sessions approach, it was possible to perform a robust combination of these solutions with those of the SOPAC facility and regional cluster modeling [8,9,10, and references therein].

The intra-plate Eurasian residual velocities were computed for all of the sites analyzed. These were supported by using several fiducial sites, where their coordinates and velocities were obtained from the EUREF facility [19,20] using the definition of absolute Euler pole given for Eurasia by Altamimi [23], or eventually by estimation of a local pole using GLOBK 10.6. Residual velocities were useful as the input for the computation of regular-grid-interpolated strain-rate patterns. These give information about the active tectonics present in this region, which can be used to try to solve the debate that remains open. For example, whether the Crotone Basin is sliding, whether there is still subduction near the slab in the Ionian area of the network, or whether full compressional or extensional regimes are still active for the Tyrrhenian side of the region [13,33]. A general vertical velocity trend was estimated starting from the ellipsoid GNSS Calabria network heights, and using Generic Mapping Tools subroutines and the powerful approach of spline in tension [29–31].

Table 1 provides the intra-plate velocities, in order to be available to others for other studies or for computation of models. Optional solution-independent exchange (SINEX) daily network solutions can be made available to the scientific community.

The crustal strain tensor was estimated using the GNSS network discrete intraplate velocity values, through three different approaches that obtained good agreement between the corresponding data. The uncertainties of the values of the strain rate are at a level of 10% of the maximum strain values, and for this reason, no significant results were obtained in the areas where the strain tensor was less than 10^{-8}/a (i.e., 0.01 μstrain/a).

Finally, this study also shows that the new version of GAMIT/GLOBK 10.6 can be used to estimate coordinates, variance and covariance matrixes, and velocities that are in agreement with the solutions given by the EUREF facility [19,20].

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Dr Giuseppe Casula was born in Genova on March 17, 1964. He took a degree in Applied Physics addressed to Geophysics at University of Bologna on July 20, 1990 by discussing his thesis titled "Using the LaCoste-Romberg gravimeter D-149 in Geophysics". Since October 1990 to December 1992, he worked as scholarship owner to carry out researches in the field of: "Seismic wave propagation on elastic media" at OGS (Osservatorio di Oceanografia e Geofisica Sperimentale) of Trieste Italy. Since January 1992 up to January 1996 he worked at INGV as scholarship owner to carry out researches in the field of Seismology, in particular Gravimetry and Geodesy. In February 1996 up to December 1998 he was employed as non-permanent researcher at INGV (National Institute of Geophysics and Volcanology) working on Geodesy, GPS (Global Positioning System), and Gravimetry. In January 1999 he was employed as permanent researcher at INGV where he worked up to July 2003 developing researches in the above mentioned research themes. Since August 2003 Dr Giuseppe Casula took a permanent position of Senior Technologist at INGV, presently he is working at INGV Unit of Bologna in the fields of Geodesy, GNSS (Global Navigation Satellite Systems), computation of the strain rate from GPS data, Terrestrial Laser Scanning applied to cultural heritage.