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Short communication

# Crustal motion along the Calabro-Peloritano Arc as imaged by twelve years of measurements on a dense GPS network

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ABSTRACT

In this work, we show the results of 12 years of continuous and survey-mode GPS measurements carried out along the western part of the Calabro-Peloritano Arc, from 1996 until the more recent acquisitions in 2008. The results highlight that a NW–SE-oriented ~0.15 µstrain/yr extension across the Messina Strait and the Aeolian–Tindari–Letojanni fault system is active. Moreover, a N–S compressive strain-rate (~0.65 µstrain/yr) is acting across Vulcano and Lipari Islands coupled with an extensional strain-rate of ~0.15 µstrain/yr in the E–W direction. Finally, taking into account the observed horizontal velocity field, an analytical inversion was performed to obtain a reliable model of deformation of the investigated area. The main results are consistent both with focal mechanism solutions and the current structural setting of the investigated area.

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## 1. Introduction

On December 28 1908, a Mw = 7.1 earthquake struck the cities of Messina and Reggio Calabria (southern Italy) causing more than 100 000 casualties. Since that dramatic event, geologists and geophysicists have attempted to understand the complex tectonics of the Calabro-Peloritano Arc, with the aim of improving the knowledge on the current geodynamic setting of this area and in particular on the rate and the shape of inter-seismic loading of active faults cutting the area. Notwithstanding geodetic studies of this area began as early as the 1970s, knowledge of the crustal deformation pattern is still far from satisfactory since all published data have a limited areal coverage (*e.g.* Anzidei et al., 1998; Bonaccorso, 2002) or poor spatial densities (*e.g.* Hollenstein et al., 2003; D'Agostino and Selvaggi, 2004; Serpelloni et al., 2005).

In this work, in order to obtain a detailed spatial resolution of the ongoing crustal motion, we analyzed periodical and continuous GPS data collected between 1996.00 and 2008.21 on three geodetic networks installed in the Peloritani Mts., on the Aeolian Islands and across the Messina Strait (Fig. 1a,b). In the following, we present and discuss the main results, in terms of i) velocity field (computed in an Eurasian reference frame) and ii) strain-rate field of the investigated area. Finally, we apply different approaches (*i.e.* vectorial decomposition of velocities measured across the faults; analytical inversion of velocity field) to our results, in order to verify their coherence with geological evidences and models proposed in literature. In particular, we have found that the observed deformation pattern is influenced by local tectonics, although the NNW–SSE regional compression related to the Nubia–Eurasia interaction is the main "engine" of the kinematic of this area.

## 2. Background setting

The present-day tectonic framework of northern Sicily and southern Calabria is the result of the geodynamic processes due to the Neogene–Quaternary convergence between Nubia and Eurasia (*e.g.* Barberi et al., 1973; Patacca et al., 1990) and to the subduction and rollback of the Ionian plate underneath the Calabria and the Tyrrhenian Sea (*e.g.* Malinverno and Ryan, 1986; Gueguen et al., 1998; Faccenna et al., 2001; Gvirtzman and Nur, 2001). The tectonic setting of this area is dominated by two main systems: the "Messina Strait" (hereinafter MS) and the Aeolian–Tindari–Letojanni fault system (hereinafter ATL; Fig. 1a,b). The former, developed in north-eastern Sicily and southern Calabria, describes a continuous extensional belt cutting at high-angle the front of the Calabro-Peloritano Arc (Tortorici et al., 1995). It is characterized by faults with steeply inclined surfaces (dip ≥ 70°) and showing prevailing dip–slip movements.

The latter, developed between northern Sicily and the southernmost part of the Aeolian Archipelago, is generally characterized by steeply inclined scarps (dip ≥ 60°) that mostly dip eastward. Structural studies carried out along the Lipari–Vulcano complex revealed how this fault system is arranged with an en-echelon configuration

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along two main branches, N160°E-oriented, bordering the western and the eastern flanks of Vulcano and is characterized by prevailing right-lateral strike–slip movements (*e.g.* Barberi et al., 1994; Ventura, 1994; De Astis et al., 2003). In the northern margin of Sicily, the fault system is characterized by an early kinematics as a right-lateral fault during Pliocene age, followed by dominant normal mechanism in Quaternary age (*e.g.* Ghisetti and Vezzani, 1982). Since 1983, more than 2500 crustal earthquakes with $M_{\max} = 4.4$ have been recorded in the investigated area (ftp://ftp.ingv.it/pro/bollet). In the southern Tyrrhenian Sea, the depth distribution of earthquakes, as deep as 600 km, fairly well depicts a subvertical slab extending from Calabria to the southern Tyrrhenian Sea (Selvaggi and Chiarabba, 1995). Seismicity occurring along the slab shows focal mechanisms with pervasive down–dip compression at all depths beneath 100 km, while seismicity occurring at shallow depth has normal faulting focal mechanisms evidencing a general extension of the area (Selvaggi, 2001; Neri et al., 2005). Deep and intermediate earthquakes abruptly terminate westward beneath northern Sicily and the Aeolian Archipelago, whereas shallower seismicity (depth range 0–25 km) has a clear NNW–SSE trend matching well with the ATL (Neri et al., 2005). Focal mechanisms computed for this area reveal normal faulting coupled with dextral transcurrence. Westward of the ATL, the seismic events mostly occur in the upper 30 km of the crust, showing a spatial distribution along an E–W trend and having focal mechanisms with NNW–SSE and NW–SE compressive axes (Fig. 1a; Frepoli and Amato, 2000; Neri et al., 2003, 2005; Pondrelli et al., 2006) in agreement with a NW–SE compression inferred by large-scale GPS networks (Hollenstein et al., 2003; Serpelloni et al., 2005; Ferranti et al., 2008a) and with the main NNW–SSE plate convergence predicted for this area by large-scale crustal motion models (Sella et al., 2002; Nocquet and Calais, 2004). Despite the absence of any active fault mapped here (Valensise and Pantosti, 2001), the focal mechanisms distribution indicates that thrust or reverse faults could be activated offshore from the northern Sicily coast in future.

All these features clearly show that two main crustal domains along the Calabro-Peloritano Arc can be recognized: a contractional domain in the north-western sicilian offshore and an extensional domain in north-eastern Sicily and southern Calabria. The transition between the two domains seems to occur along the ATL fault system.

## 3. Geodetic network and data processing

GPS monitoring of the ground deformations of Peloritani–Nebrodi area (Fig. 1b) started in late 1995, when a geodetic network was set up. The network, surveyed for the first time in October 1996, consisted of 7 benchmarks and has been successively expanded to reach the current configuration of 12 benchmarks. In late 2000, a geodetic network of 13 benchmarks was established across the Messina Strait and was surveyed for the first time in February 2001 (Mattia et al., 2006). In the framework of the Italian National GPS Network RING (http://ring.gm.ingv.it/), since early 2005, the “Istituto Nazionale di Geofisica e Vulcanologia” has installed 5 CGPS stations thereby improving the spatial detail of the entire north-eastern Sicily and southern Calabria areas (Table 1). All non-permanent and CGPS data collected between 1996.00 and 2008.21, together with 9 continuously operating IGS stations (AJAC, CAGL, GRAS, GRAZ, LAMP, MATE, MEDI, NOT1 and NOTO), were analysed using the GAMIT/GLOBK software (Herring et al., 2006a,b) with IGS precise ephemerides and Earth orientation parameters (http://www.iers.org) to produce loosely constrained daily solutions. By using the GLOBK Kalman filter, these solutions were combined, on a daily basis, with global solutions (IGS1, IGS2, IGS3, IGS4 and EURA) provided by the SOPAC (ftp://garner.ucsd.edu/pub/hfiles) and local solutions of data collected on the Aeolian Archipelago and analyzed in Mattia et al. (2008a), in order to create a daily unconstrained combined network solution. By using the GLORG module of GLOBK (Herring et al., 2006b) the solutions were transformed into the ITRF2005 reference frame and then rotated into a fixed Eurasian frame (Altamimi et al., 2007).

## 4. Data analyses

### 4.1. GPS velocity field

GPS velocity field in the Eurasian reference frame for the investigated area is reported in Fig. 1b. Velocities observed at CGPS stations have been determined from data spanning ~2.5 years (MMME, MILA, MRSU and MESS). As postulated by some authors (Blewitt and Lavallee, 2002) and as testified by the spatial consistency of the velocity field and the similarity in velocities from nearby GPS sites with longer observation intervals (*e.g.* PACE, MM01 and MM04; Fig. 1d), this limited time span can be considered sufficient for considerations on tectonic aspects. A striking aspect of the ground deformation pattern is a marked decrease of velocity values from northern Sicily to the Aeolian Islands, highlighting how part of the NNW–SSE regional compression is localized within a ~15 km-wide zone with the buttressing of Vulcano and Lipari islands. In particular, as shown along a roughly N–S profile (Fig. 1b), the velocity values pass from ~7.5 mm/yr in the northern part of Sicily (*e.g.* CALA, MONT, TIND) to ~10.5 mm/yr in the southern part of Vulcano Island (*e.g.* VSAR, VSER and VMOL; Fig. 1c), to ~5.4 mm/yr in the central part of Lipari Island (*e.g.* LMAZ and LROS), to ~2.9 mm/yr on Stromboli Island (*e.g.* SPLN and STDF). In addition, in northern Sicily and southern Calabria, going from west toward east the velocity field is characterized by a progressive rotation from an azimuth of ~N15°W to an azimuth of ~N15°E. This aspect is coupled with a slight decrease of velocity values in an eastward direction. Along the Vulcano–Lipari–Stromboli axis, the velocity field is characterized by a rotation from an azimuth of ~N10°W on Vulcano and Lipari islands to an azimuth of ~N12°E on Stromboli Island. It is noteworthy that the velocities of the Vulcano (with the exception of VCRA), Lipari and Stromboli islands can be considered unaffected by volcanic effects (Mattia et al., 2008a, b), while the velocities of Panarea Island may certainly be biased by local effects due to fractures and geothermal effects (D'Agostino and Selvaggi, 2004; Esposito, 2007). For these reasons, the velocities of the stations PANA and LI3D (Panarea and Lisca Bianca Islands) haven't been considered in the profile reported in Fig. 1e.

### 4.2. Strain-rate field

Taking into account the network geometry and the estimated velocity at each site, we calculated the horizontal strain-rate field, applying the method of Haines and Holt (1993). Following this method, we adopted a spherical geometry, expressed in terms of a rotation function $W(r)$ by using a bi-cubic Bessel interpolation on a curvilinear grid (Haines et al., 1998) with a variable spacing of knots. The estimated strain-rate distributions are shown in Fig. 2a,b,c as principal axes, dilatation, and maximum shear. The principal axes of strain-rate clearly detect an area of prevailing N–S shortening (about 0.65 µstrain/yr), coupled with an E–W extension (about 0.15 µstrain/yr) between Vulcano and Lipari islands. In addition, a NNE–SSW shortening of about 0.1 µstrain/yr can be recognized between Stromboli and Lipari islands. Across the Nebrodi–Peloritani and the Messina Strait areas the strain-rate pattern is extensional, showing maximum values (about 0.15 µstrain/yr) along the MS fault system (with principal axes mostly NW–SE–oriented) and the ATL fault (with principal axes NW–SE-oriented). This pattern is confirmed by the dilatation strain-rate distribution (Fig. 2b). Regarding the maximum shear strain-rate, the greatest values (about 0.75 µstrain/yr) are detected between Vulcano and Lipari islands, and lower values are distributed over the whole investigated area (Fig. 2c).

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