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Seismological and structural constraints on the 2011–2013, M_{max} 4.6 seismic sequence at the south-eastern edge of the Calabrian arc (North-eastern Sicily, Italy)

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ABSTRACT

Between June 2011 and September 2013, the Nebrodi Mountains region was affected by a seismic swarm consisting of > 2700 events with local magnitude $1.3 \leq M_L \leq 4.6$ and located in the 5–9 km depth interval. The seismic swarm defines a seismogenetic volume elongated along the E-W direction and encompasses the NW-SE-oriented tectonic boundary between the Calabrian arc (north-eastward) and the Sicilide units (south-westward). By exploring the recent tectonic deformation and the seismic behavior of the region, this study aims at providing additional constraints on the seismogenetic faults at the southern termination of the Calabrian arc. Waveform similarities analysis allowed observing that ~45% of the whole dataset can be grouped into six different families of seismic events. Earthquake multiplet families are mainly located in the eastern part of the seismogenetic volume. We suggest that such a feature is responsive to the lateral lithological variations as highlighted by geology (at the surface) and P-wave seismic tomography (at depth of 10 km). Stress tensor inversions performed on FPSs indicate that the investigated region is currently subject to a nearly biaxial stress state in an extensional regime, such that crustal stretching occurs along both NW-SE and NE-SW directions. Accordingly, mesoscale fault geometries and kinematics analyses evidence that a younger normal faulting stress regime led to a tectonic negative inversion by replacing the pre-existing strike-slip one. Based on our results and findings reported in recent literature, we refer such a crustal stretching to mantle upwelling process (as evidenced by diffuse mantle-derived gas emissions) coupled with a tectonic uplift involving north-eastern Sicily since Middle Pleistocene. Moreover, seismic swarms striking the region would be related to the migration of mantle and sub-crustal fluids toward the surface along the complex network of tectonic structures cutting the crust and acting as pathways.

1. Introduction

North-eastern Sicily, located at the southern termination of the Calabrian arc (Fig. 1), is characterized by the occurrence of temporally protracted seismic swarms. These swarms comprise small-to-moderate earthquakes and often involve shallow crustal volumes, exhibiting normal faulting features and appearing related to pore pressure transients by mantle fluid flows (e.g. Scarfì et al., 2005; Giammanco et al., 2008; Camarda et al., 2016). Here, we focus on a seismic swarm that began in June 2011 and lasted until September 2013, cumulating > 2500 events with local magnitude $1.3 \leq M_L \leq 4.6$. The north-eastern off-shore area was struck by a $M_L = 5.6$ earthquake in April 1978 while the $M_L = 4.6$ earthquake represents the largest earthquake striking the area in the instrumental age (Rovida et al., 2011). Moreover, in historical times, such area has experienced the occurrence of two destructive earthquakes in 1613 and in 1739 (Rovida et al., 2011), whose seismogenetic sources are still debated. In this regards, the main challenge of this study is to explore the recent tectonic deformation stages and the seismic behavior of the study area by comparing structural data from field geology with the high-resolution spatial distribution and kinematics of the whole seismic swarm, in order to provide additional constraints on the seismogenetic faults that bound the southern termination of the Calabrian arc. The seismic events data have been collected by the INGV permanent seismic network that, since 29 June 2011, has been integrated with a mobile network consisting of 3 stations (see Cammarata et al., 2014 for additional details). In the same area, recent studies have outlined an updated morphotectonic setting of the region, highlighting a dominant NE-SW-oriented crustal stretching pattern,

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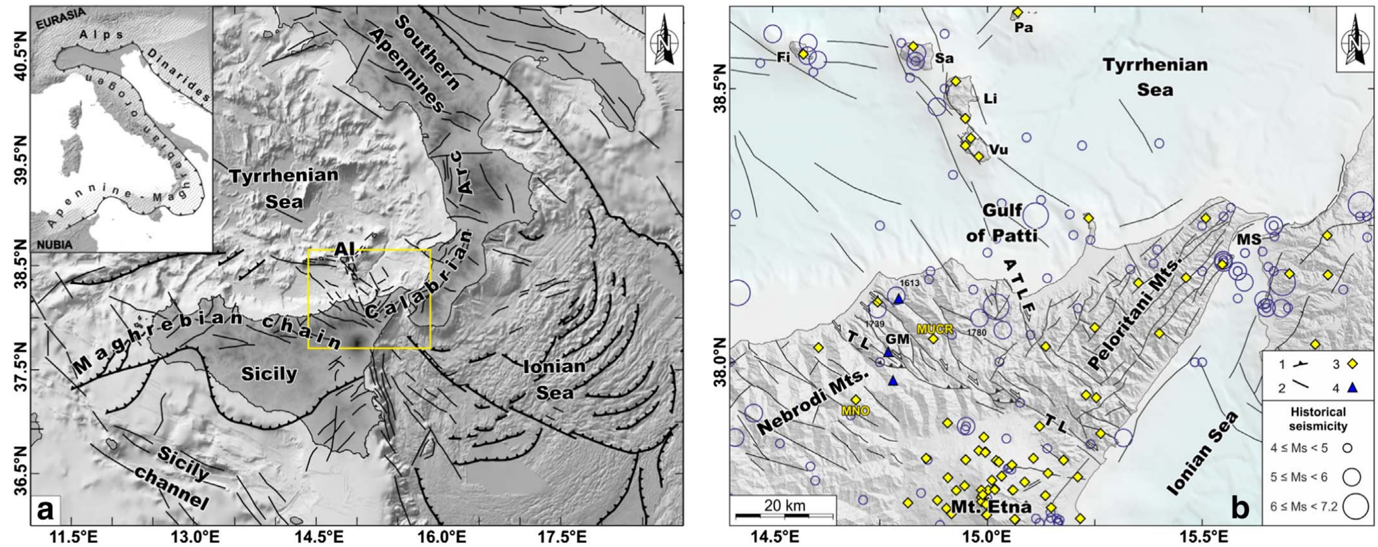

Fig. 1. a) Simplified tectonic map of Sicily and surrounding areas. The yellow box indicates the area reported on panel b. The Maghrebian Chain and the Calabro Peloritanian Arc are parts of the Apennine-Maghrebian orogen (see inset), a large-scale fold-and-thrust belt formed during the Neogene-Quaternary convergence between Nubia and Eurasia plates. b) Simplified tectonic map of north-east Sicily. Epicentres of earthquakes occurring in the study region since 1000 CE are reported as blue circles (see legend in the bottom right corner). Data are from the CPTI catalogue (Rovida et al., 2011); magnitude completeness of the catalogue was 6.4, 5.8, 4.9 and 4.3 since 1300, 1530, 1700 and 1895, respectively. The location of the two seismic stations (MUCR; MNO), whose recorded data have been used for cross-correlation analyses, are also reported. Abbreviations are: GM, Galati Mamertino; Ta, Taormina; MS, Messina Strait; ATLF, Aeolian-Tindari-Letojanni Fault System; TL, Taormina Line. On legend: (1) Major reverse faults, (2) oblique and dip-slip faults, (3) continuous and (4) mobile seismic stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

inferred by several NW-SE oriented, SW-dipping rejuvenated normal faults (Pavano et al., 2015). In order to recognise possible spatial clusters and to better set the 2011 seismic swarm in such an updated tectonic frame of north-eastern Sicily, we computed 45 fault plane solutions and analyzed the spatial pattern of seismicity, achieved by applying the double-difference relocation technique for 130 events by using the HypoDD algorithm (Waldhauser and Ellsworth, 2000). This latter produces more accurate locations than the standard absolute procedures, especially for spatially well-clustered seismic events (e.g. Lippitsch et al., 2005; Alparone and Gambino, 2003; Gambino et al., 2012).

Furthermore, in the area affected by the 2011 seismic swarm, a mesoscale structural field analysis has been carried out. This investigation enables recognising different Riedel shear fault patterns, aiming at how the disposition and mechanical properties of pre-existing fracture has influenced the distribution of mesoscale fault planes kinematics. As a whole, the relocated seismicity, together with both the resulting focal mechanisms and the mesoscale structural analysis data, have been compared with the mapped faults of the region, seeking both to test their mutual compatibility and establish the consistency with the available morphostructural data and the present stress field. As a whole, these results lead to an improvement of the current crustal deformation pattern of the investigated region.

2. Tectonic and seismotectonic setting

Since the Cretaceous, the geodynamic processes of the Mediterranean region have been dominated by the still active Nubia-Eurasia plates convergence (see inset in Fig. 1), which has controlled the distribution of the synorogenic tectonic domains (Malinverno and Ryan, 1986; Anderson and Jackson, 1987; Dewey et al., 1989; Doglioni, 1993; Jolivet et al., 1998). In such a geodynamic frame, north-eastern Sicily represents the southern edge of the Calabrian arc (Scandone, 1979; Amodio-Morelli et al., 1976), the orocline (upper plate) related to the Ionian subduction region and connecting the southern NW-SE trending Apennines and the E-W oriented Maghrebian collisional belts (Fig. 1). The geological backbone of north-eastern Sicily consists of imbricated Hercynian crystalline units, represented by low-grade to high-grade metamorphic rocks, with their Mesozoic sedimentary covers (Lentini et al., 2000; Catalano et al., 2017a). These tectono-metamorphic nappes, as a whole, overlie the accretionary wedge terrains of the Sicilide Units, along an Oligo-Miocene regional thrust, which is now exposed in the Nebrodi Mountains, along a NW-SE oriented alignment, known as the Taormina Line (Fig. 1; Amodio-Morelli et al., 1976; Ghisetti et al., 1991; Ghisetti and Vezzani, 1982; Lentini et al., 2000).

From the Late Miocene, due to the roll-back of the Ionian subducting slab, the Calabrian arc (Malinverno and Ryan, 1986; Patacca et al., 1990) experienced a rapid SE-ward migration, at rates up to 5–8 cm/yr, until the Early Pleistocene, and of ~1 cm/yr, during the Middle-Late Pleistocene (Westaway, 1993; Wortel and Spakman, 2000; Faccenna et al., 2001; Goes et al., 2004). The Calabrian arc migration was accommodated by the development of high-angle left-stepping right-lateral shear zones that superimposed on the previous thrust features, along its south-western end (see Chiarabba and Palano, 2017 and references therein for an overview). Along this transcurrent tectonic boundary the sharp lateral juxtaposition of the Maghrebian accretionary wedge, to the south-west, and the European crust, to the north-east, occurs.

Since the Middle Pleistocene (~600 ky), the entire north-eastern Sicily region has undergone an almost uniform and huge tectonic uplift (~1.1 mm/yr; Catalano and Cinque, 1995; Catalano and Di Stefano, 1997), coeval with the fragmentation of the southern termination of the Calabrian arc (Catalano et al., 2011; Pavano et al., 2012, 2015, 2016). Relative vertical motions between north-eastern Sicily and the adjacent Sicily collision belt reactivated the southern boundary of the Calabrian arc, where the negative tectonic inversion of discrete segments of the Plio-Pleistocene NW-SE oriented dextral shear zones occurred (Pavano et al., 2015). The rejuvenated fault planes are distributed in the surroundings of Galati Mamertino (Fig. 1), where they frequently show sharp basal, up to 5 m-high, fresh bedrock scarps (Pavano et al., 2015), governing the geomorphic features of the landscape (e.g. relief and drainage system) of the area (Pavano, 2013). The inversion of the kinematic data measured on these main fault segments points to a NE-SW extension, which is coherent with geodetic (Palano et al., 2015) and seismological observations (ISIDe Working Group, 2010; Scarfì et al., 2013). This recent deformation has prominent morphological