The Ongoing Seismic Sequence at the Pollino Mountains, Italy

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INTRODUCTION

A sequence of thousands of small to moderate earthquakes has been occurring since spring 2010 in the Pollino Mountains area, southern Italy (Fig. 1), where a seismic gap was previously hypothesized by paleoseismological evidence associated with the lack of major earthquakes in historical catalogs (Michetti et al., 2000; Cinti et al., 2002). Seismic activity is in progress at the time of writing of this paper (December 2012) after quite a disturbing long-term acceleration of earthquake rate and strain release (Fig. 1b). The strongest earthquake (\(M_L\) 5.0 according to the Italian Seismological Instrumental and parametric Database [ISIDE], http://iside.rm.ingv.it; last accessed September 2013) was recorded on 25 October 2012 and produced damage in the epicentral area corresponding to a maximum intensity of 6 on the European Macroseismic Scale 1998 (EMS-98) in the localities of Mormanno, Campotenesi, and Piano Incoronata (Fig. 2; D’Amico and Scarfi, 2012). Because of this earthquake, more than a thousand people were evacuated from their homes and emergency actions have been carried out by the competent institutions. This earthquake with its effects, and the increasing number and intensity of events felt by the population in the preceding months, have further encouraged the attention and efforts of civil defense operators and scientific researchers toward this peculiar seismic crisis occurring in a presumed seismic-gap area. It should also be remarked that the Pollino area, lying at the northern edge of the Calabrian subduction zone (Fig. 1a), represents a highly deformed, very intricate sector of the subduction zone itself and the southern Apennines extensional domain. Previous studies have indicated this as a highly deformed zone including shallow dynamics associated with the activity of a Subduction–Transform Edge Propagator (STEP) fault (Neri et al., 2012; Presti et al., 2013).

Calabria and the southern Apennines are among the most seismically active regions of the entire Mediterranean area with their long record of destructive historical earthquakes of magnitude as large as 7 (Monaco and Tortorici, 2000; Galli and Bosi, 2003; Amoruso et al., 2006; Neri et al., 2006; Guidoboni et al., 2007; Galli et al., 2008; the locations of the \(M_6\)-\(5\) earthquakes reported in the CPT11 catalog are indicated by circles in Fig. 1a). In Calabria, the strongest earthquakes can be ascribed to an extensional regime with opening direction varying from east–west in central Calabria to northwest–southeast in southern Calabria and the Straits of Messina (see e.g., Neri et al., 2004, 2005). In the southern Apennines, major earthquakes are related to northeast–southwest extension (Billi et al., 2011; Presti et al., 2013). Between Calabria and the southern Apennines, the Pollino area has been affected only by moderate seismicity in the last centuries, as witnessed by historical and recent catalogs reporting earthquakes of maximum magnitude in the range 5.5–6, such as those, which occurred in 1693, 1708, and 1998 (see e.g., Galli et al., 2001; Arrigo et al., 2006; Rovida et al., 2011). On the other hand, paleoseismological investigations have identified in the southern Pollino area at least two surface-faulting events between the sixth and fifteenth centuries A.D. relatable to earthquakes of magnitude 6.5–7 (Michetti et al., 2000; Cinti et al., 2002; trench site locations are indicated in Fig. 2). This information has led the same investigators to propose the Pollino area as a seismic gap.

The structural and seismotectonic setting of the Pollino area is quite intricate and different views have been proposed by different authors (see, among others, Michetti et al., 2000; Catalano et al., 2004; Database of Individual Seismogenic Sources [DISS] Working Group, 2010; Spina et al., 2011). Although normal mechanisms on northwest-trending structures represent the most diffuse faulting style, diversely oriented structures

GEOLOGICAL SETTING

The Pollino Mountains are located in the northern section of the Calabrian accretionary wedge, which, since at least the Neogene, has been drifting southeastward onto the retreating Ionian subducting slab (Fig. 1a; Billi et al., 2006, 2007; Neri et al., 2012). During the rollback process, the northwestward-subducting slab has undergone a progressive reduction in its along-strike length up to the present size (Faccenna et al., 2011), which is about 150 km between the Straits of Messina and the Sila Massif (Fig. 1a; see also Neri et al., 2009; Billi et al., 2010). At the northern edge of the Calabrian subduction zone (Fig. 1a), the Pollino Mountains lie in a junction area between the subduction zone itself and the southern Apennines extensional domain. Previous studies have indicated this as a highly deformed zone including shallow dynamics associated with the activity of a Subduction–Transform Edge Propagator (STEP) fault (Neri et al., 2012; Presti et al., 2013).
and different mechanisms are also reported, such as left-lateral strike-slip kinematics in the west-northwest-trending Pollino fault zone (PFZ) on the southern side of the Massif (Van Dijk et al., 2000; Catalano et al., 2004; Spina et al., 2011; see Fig. 2).

The Database of Individual Seismogenic Sources (DISS Working Group, 2010) reports two normal-faulting sources in the Pollino area, an east-dipping north-northwest-trending one in the Mercure basin area (P in Fig. 2) and a west-dipping north-northwest-trending one located in the southern side of the Pollino Massif. We also show the traces of the main active faults reported by Michetti et al. (2000) and the Pollino fault zone (PFZ) proposed by Van Dijk et al. (2000) and more recently by other investigators (e.g., Spina et al., 2011). Following Michetti et al. (2000), MER and POL stand for Mercure and Pollino fault, respectively. Small squares indicate the three localities where the maximum macroseismic intensity was recorded for the magnitude 5.0 earthquake of 25 October 2012 (D’Amico and Scarfi, 2012). Circles show the trench sites (TS1 and TS2) where paleoseismological investigations identified faulting events relatable to earthquakes of magnitude 6.5—7, which occurred between the sixth and fifteenth centuries A.D. (Michetti et al., 2000; Cinti et al., 2002).

### SEISMIC DATA ANALYSIS AND RESULTS

The ongoing phase of Pollino earthquake activity started during spring 2010 and has consisted of more than 4000 earthquakes of maximum local magnitude 5.0 that have occurred with a fairly regular increase of number and energy since the
onset of activity to date (Fig. 1b). A frequency-versus-magnitude plot of the earthquakes reported in the ISIDE database for the Pollino area between 1 April 2010 and 5 December 2012 is shown in Figure 1c.

A map of the seismic stations used for the present analysis is given in Figure 3. We extracted from the INGV and University of Calabria databases the data of the earthquakes with local magnitude over 2.0 that occurred between 1 April 2010 and 5 December 2012 in the Pollino area (shadowed zone in Fig. 3). We then calculated hypocenter locations using the Simulps algorithm by Evans et al. (1994) and the 3D velocity structure of the study region by Orecchio et al. (2011). We selected for graphical presentation of results in Figure 4a,b all the earthquakes located with at least eight P and nine P + S readings, and rms < 0.7 s. For these events we estimated, following the procedures by Presti et al. (2008), horizontal and vertical average location errors of the order of 1.5 and 1.7 km, respectively. Next, we performed an analysis of focal mechanisms by applying the Cut-and-Paste (CAP) waveform inversion method by Zhu and Helmberger (1996) and selected the best-constrained solutions (i.e., those solutions with fault parameter errors less than 10°; see also D’Amico et al., 2010, 2011) that are shown in Figure 4c. Two spatial earthquake clusters can be detected in Figure 4a,b suggesting the presence of west-dipping north-northwest-trending sources. A circa 45° W-plunging elongated hypocenter cloud can be detected in Figure 4b for the western cluster. An apparently similar trend with higher dip, however, may be inferred from the same figure for the eastern cluster, although the smaller number of earthquakes and their discontinuous spatial distribution make the trend more doubtful in this case. The apparent north-northwest orientation of the two clusters matches well with the orientations of nodal planes from the focal mechanisms (Fig. 4c), which also indicate normal faulting.

An analysis of the crustal seismicity, which occurred in the wider area of northern Calabria and southern Apennines was then performed and the results are presented in Figure 5. In this case, a larger investigation time window (1 January 1997 to 5 December 2012) has been adopted. Figure 5a shows the cumulative seismic strain released over this wider area and
Figure 5. Results from the analysis of the crustal seismicity (depth less than 30 km) occurred in the wider area of northern Calabria and southern Apennines between 1 January 1997 and 5 December 2012. Hypocenters were relocated in the 3D tomographic velocity model obtained by Orecchio et al. (2011). (a) Cumulative seismic strain release over the whole area and time window with indication of the Pollino sequence period (Psp). (b) Earthquake epicenter map plotted over the $V_p$ tomographic plate at 10 km depth (tomography by Orecchio et al., 2011). The white curve marks the transition between the low-$V_p$ domain of the southern Apennines and the high-$V_p$ domain of the Calabrian Arc. (c) Map of the waveform inversion focal mechanisms estimated in the present study (yellow background) or taken from the literature (TDMT database; Presti et al., 2013). In addition to the focal mechanisms available for the 1 January 1997–5 December 2012 time window, the map also includes five good-quality solutions (indicated by arrows) available for the previous period, i.e., since 1980. Different colors in the legend mark different types of mechanisms according to the standard definitions of normal faulting (NF), normal faulting with minor strike-slip component (NS), strike-slip (SS), or unknown stress regime (U; Zoback, 1992). The beach-ball size is proportional to the earthquake magnitudes that range between 1.9 and 5.2. The two gray belts mark the two main faulting domains, i.e., the normal-faulting domain of the southern Apennines including the Pollino Mountains, and the left-lateral transtensional domain of northeastern Sila and Ionian coast. CV is the focal mechanism available for the Crati valley, whereas SM1, SM2, and SM3 are those available for the Sila Massif area. (d) Polar plots of the P and T axes and strikes of nodal planes (red rose diagram) for the earthquakes of section (c) located in the two selected areas of Pollino and northeastern Sila–Ionian coast, respectively. Squares and stars indicate earthquakes of magnitude less than 4.0 and in the range 4.0–5.2, respectively.
larger time window, and highlights the contribution by the Pollino sequence to seismic strain released in the last 15 years on a regional scale. Figure 5b displays the epicenters of the earthquakes of local magnitude over 2.0, occurred at depths shallower than 30 km during 1 January 1997–5 December 2012. These earthquakes have been relocated in the present work by using the 3D tomographic model by Orecchio et al. (2011). The epicenters are plotted over the tomographic results at 10 km depth. A south-southeast-trending epicenter cloud runs along the southern Apennines and covers also the Pollino area (Fig. 5b). This cloud is interrupted, toward south, at the latitude of the southern Pollino Mountains and Sibari Plain. In this area, with a white thick curve (Fig. 5b), we mark the transition between two different seismic-velocity domains evidenced by tomography: (1) the low-$V_p$ domain of the southern Apennines and (2) the high-$V_p$ one of the Calabrian Arc. To the south of the transitional white curve, the epicenter cloud reappears and shows separation in two branches. The major branch continues south-southeastward in the Crati valley and in the western Sila Massif, whereas the other one trends circa east-southeast and follows the eastern Sibari Plain, the northeastern Sila Massif and the nearby Ionian coast of Calabria (Fig. 5b). A shift can also be noted in Figure 5b between the southern Apennines epicenter cloud with its southern edge in the Pollino Mountains and the cloud reappearing south of the discussed transition zone. Figure 5c reports the best-quality focal mechanisms available in the same area of Figure 5b for the 1 January 1997–5 December 2012 time interval, with the addition of five good-quality solutions available for the previous period (these latter solutions are indicated by arrows). Figure 5b,c include the earthquakes of the 2010–2012 Pollino sequence reported in Figure 4a,c, and confirm that the Pollino earthquakes occurred along north-northwest-striking normal-fault surfaces in response to a perpendicular extension (Fig. 5d). To the south, the only focal mechanism available for the Crati valley (CV solution in Fig. 5c) indicates a similar regime but slightly rotated, with north-striking normal-fault surfaces responding to an east–west-oriented extension. Further extensional focal mechanisms are located in the middle of the Sila Massif (SM1, SM2, and SM3 in Fig. 5c). Toward the east, the seismotectonic regime of the northeast Sila and Ionian coastal area is rather different and more complex, principally with N120°-striking fault surfaces affected by left-lateral, strike- and oblique-slip movements (Fig. 5c,d). According to these data, the two branches of the epicenter cloud detected south of the transition zone (white thick curve in Fig. 5b) correspond to significantly different seismotectonic regimes, i.e., normal faulting in the south-southeast-trending branch of the Crati valley and western Sila area, and left-lateral transtensional faulting in the east-southeast-trending branch of the northeast Sila–Calabrian Ionian coast (Fig. 5c,d).

**DISCUSSION**

Hypocenter locations and focal mechanisms of the 2010 to date Pollino seismicity (Fig. 4) suggest that this activity can be ascribed to normal faulting on north-northwest-trending west-southwest-dipping dislocation surfaces consistent with the general seismotectonic frame of the southern Apennines (Fig. 1a; e.g., Frepoli et al., 2011). Also, the analysis of crustal seismicity in the wider area of northern Calabria and the southern Apennines over a larger time interval of circa 15 years (Fig. 5) shows a well-defined south-southeast-trending belt of normal-faulting earthquakes running along the southern Apennines and interrupted to the south at the latitude of the southern Pollino Mountains and Sibari plain. A rather different seismotectonic regime is detected just south, in the area of northeastern Sila and the nearby Ionian coast of Calabria (Fig. 5). Here, N120°-striking fault surfaces affected by left-lateral, strike- and oblique-slip movements are evidenced by our focal mechanisms (Fig. 5c,d) and by geologic data available from the literature (Fig. 2). This change corresponds to the horizontal variation of the seismic velocity structure shown in Figure 5b. All these data lead us to locate the transitional area between the domains of the southern Apennines (north) and the Calabrian Arc (south) roughly at the latitude of the white thick curve shown in Figure 5b. It should be remarked that south of the Pollino Mountains, the geodynamic setting is very intricate and is complicated by the lateral edge of the Calabrian subduction zone (Faccenna et al., 2011; Neri et al., 2012). Since at least Neogene time, the Calabrian accretionary wedge has drifted southeastwards onto the retreating Ionian slab (Fig. 1a; see, among others, Faccenna et al., 2004). Several studies have pointed out how the drifting mechanism has also been made possible by the presence of northwest-striking strike-slip faults across Calabria, some of these faults being active until recent times and also in the present (e.g., Van Dijk et al., 2000; Speranza et al., 2011; Neri et al., 2012). In some instances, these faults have presumably constituted the shallow expression of the dynamics occurring at the lateral edge of the Ionian slab (e.g., Govers and Wortel, 2005). One of these strike-slip fault systems probably occurs south of the Pollino Mountains (Figs. 1a and 2) and appears to be seismically active at least in its eastern Ionian section including the Sibari plain, northeastern Sila, and the nearby Ionian coast (Fig. 5). This strike-slip domain, which is complicated by the rapid uplift of the Sila Massif and surrounding areas (Faccenna et al., 2011), separates the southern Apennines from most of Calabria, where the extensional tectonics is probably driven by backarc mechanisms. The data presented in Figures 4 and 5 give new support to this geodynamic scheme, improve its accuracy in correspondence with the northern edge of the Calabrian subduction zone, and allow us to interpret the 2010 to date Pollino activity as seismic deformation occurring inside the southern Apennines seismotectonic domain, specifically at its southern tip (Fig. 6).

Deeper investigation of the space–time evolution of the Pollino activity is going to be undertaken by this same team, profiting of new data that are starting to come from in situ recording stations managed by different institutions. This will allow for the production of a larger location and mechanism database of the ongoing sequence and, consequently, to better
The ongoing phase of earthquake tectons (see Fig. 4) and in a wider area including the southern Apennines and Calabria (Fig. 5). The ongoing phase of earthquake activity in the Pollino Mountains is interpreted as seismic deformation occurring inside the southern Apennines extensional domain, specifically at its southern tip. South of Pollino, a left-lateral transtensional east-southeast-trending fault zone (closely corresponding to interruption of the seismic belt and transition between low- and high-VP crustal domains; white curve in Fig. 5b) probably represents a shallow response to deeper dynamics occurring at the northern edge of the Calabrian subduction zone. The southeastward-retreating Ionian subducting slab and backarc mechanisms and/or the collapse induced by the general uplift of Calabria should drive the scientific community and the responsible institutions to carry out greater monitoring and investigational efforts in the Pollino area both for scientific and social reasons.

Figure 6. Sketch view of the main deformation processes detected by the analysis of crustal seismicity in the Pollino Mountains (see Fig. 4) and in a wider area including the southern Apennines and Calabria (Fig. 5). The ongoing phase of earthquake activity in the Pollino Mountains is interpreted as seismic deformation occurring inside the southern Apennines extensional domain, specifically at its southern tip. South of Pollino, a left-lateral transtensional east-southeast-trending fault zone (closely corresponding to interruption of the seismic belt and transition between low- and high-VP crustal domains; white curve in Fig. 5b) probably represents a shallow response to deeper dynamics occurring at the northern edge of the Calabrian subduction zone. The southeastward-retreating Ionian subducting slab and backarc mechanisms and/or the collapse induced by the general uplift of Calabria would be the engine of the seismogenic extensional processes in western Calabria.

characterize the sequence itself. With this additional effort, we should also be able to better investigate the increasing rate and strain-release patterns observed since the beginning of the sequence. This feature, at a very early inspection, looks similar to some documented examples of microfracture temporal patterns preceding failures of rock samples subjected to progressive stress loading in laboratory experiments (see e.g., Meredith et al., 1990; Sammonds et al., 1992; Ponomarev et al., 1997; Zang et al., 1998; Lei et al., 2004; Benson et al., 2010). Also, comparisons with real patterns observed in other regions are being attempted. As regard to possible forthcoming major failures in the Pollino area, it should be considered that the limited and partly contrasting information locally available on fault location and geometry (see e.g., Michetti et al., 2000; DISS Working Group, 2010) does not allow us to assume the continuity or structural link of the activated dislocation surfaces with other structures. Therefore, any hypotheses of a major seismogenic fault close to rupture are not properly founded. It can, however, be noted that the sharp geodynamic change attested by detection of a west-northwest-striking strike-slip domain and tomographic structure variation at the southern edge of the Pollino Mountains may, plausibly, cause mechanical disconnection between the north-northwest-trending normal-faulting seismogenic structures located north and south of the discussed strike-slip domain, respectively (Figs. 5 and 6). Moreover, the occurred activation of local shallow structures trending north-northwest—south-southeast in the Pollino area does not necessarily imply that major stress is loading on a fault comprising the activated structures or parallel to them, for example, other nearby and diversely oriented ones could be involved in the forthcoming phases of activity (as also indicated by laboratory experiments; see e.g., Lockner et al., 1991; Lei et al., 2004). In any case, the information currently available should drive the scientific community and the responsible institutions to carry out greater monitoring and investigational efforts in the Pollino area both for scientific and social reasons.

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REFERENCES


