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2010-2014 SEISMIC ACTIVITY IMAGES THE ACTIVATED FAULT SYSTEM IN THE POLLINO AREA, AT THE APENNINES-CALABRIAN ARC BOUNDARY REGION

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Introduction. The main goal of this study is to increase the understanding of the physical mechanisms behind the ongoing seismic activity in the Pollino area and its influence on the seismic hazard of the Apennines-Calabrian arc boundary region.

The study area, near the Pollino massif, is located at the northernmost edge of the Calabrian Arc, which is the last oceanic subduction segment along the Africa-Eurasian plate. The subduction results from the sinking of the Ionian oceanic plate beneath the Calabrian Arc-Southern Tyrrhenian Sea and is part of the fragmented tectonic boundary between two macro-plates: Africa and Eurasia. The subduction geometry is well-documented by several seismological studies (i.e. Chiarabba *et al.*, 2005), and the lithospheric structure of the area is quietly well known (i.e. Totaro *et al.*, 2014; Piana Agostinetti and Amato, 2009)

Despite the slow N-S convergence between these major plates, the Southern Tyrrhenian Sea is a large basin characterized by E-W extensional tectonic. Since Late Miocene, the Calabrian Arc slab experienced rapid rollback, moving E to SE at a rate of 5-6 cm/yr, which is by far higher than the ~1-2 cm/yr rate of convergence between Africa and Europa (Faccenna *et al.*, 2004). However, during late Pleistocene, rollback and subduction have slowed and is likely proceeding at less than 1 cm/yr (D'Agostino and Selvaggi, 2004). Geodetic measurements show that the Pollino Range is subject to NE-SW anti-apenninic extension. In the region the strain rate field shows a continuous belt of extensional deformation that follows the ridge of the Southern Apennines and extends in the Pollino region. The extension rate appears to decrease from the Southern Apennines to the Calabria-Lucania border region (D'Agostino *et al.*, 2013). This finding indeed reveals that the Pollino region is deforming and accumulating tectonic strain which results in a complex system of normal active faults striking sub-parallel to the Apennines.

Two principal normal faults are present in the Italian Database of the Individual Seismogenic Sources DISS version 3.1.1 (DISS Working Group, 2010) in the Pollino area: the Pollino (P) fault and the "Rimendiello-Mormanno" (RM) fault system. The RM fault is an active seismogenic structure it strikes about NNW-SSE and dips toward NE; it has hosted in its northernmost part a M 5.0 earthquake on September 9, 1998. The P fault has similar strike but dips toward SW: it shows no recent seismicity and is hence one of the most prominent seismic gaps in the Italian historical seismic catalogue (Rovida *et al.*, 2011). Paleoseismic studies have shown that the P fault was active in the last ten thousand years and is capable to produce events with magnitude above 6.0. The DISS database reports as debated source also the Piana Perretti fault (Brozzetti *et al.*, 2009).

A detailed structural map of the area interested by the seismic sequence shows three fault systems (Brozzetti *et al.*, 2013) consisting of several aligned fault segments that have been active during the Late Pleistocene and are reasonably presently active. The first fault system strikes NW-SE and dips toward SW (including the Piana Perretti fault at the NE edge of the Mercure Basin), the second one has similar strike and NE dip, while the third one strikes about E-W.

Earthquakes reported in the historical catalogues for this area are not very strong. Few earthquakes with magnitude probably less than 6 affected the area, including the Mw=5.6

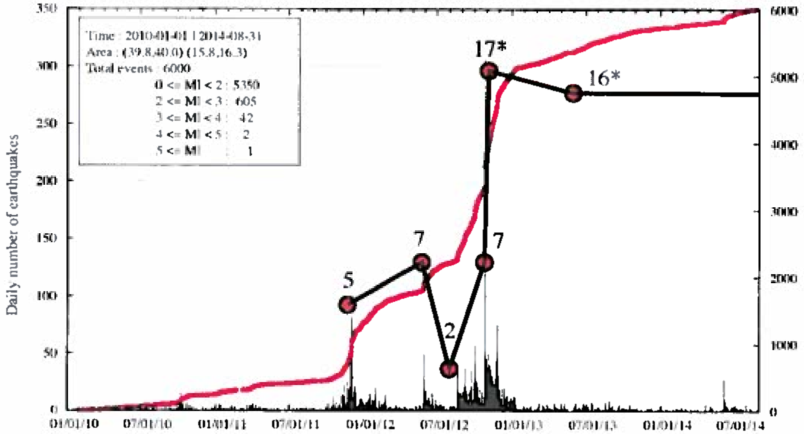

Fig. 1 – Daily number of earthquakes localized by the INGV monitoring survey in the Pollino region from January 2010 to August 2014 and the number of temporary stations deployed in the area. The * refers to the seismic array deployment.

"Mercure" event in 1998 (Brozzetti *et al.*, 2009). The Parametric Catalogue of Italian earthquakes (CPTI11, Rovida *et al.*, 2011), shows very well the lack of strong earthquakes in the region: there is a clear evidence of large earthquakes in the Campania-Basilicata area (M~7.0) and several strong earthquakes in the Sila region and in the whole Calabrian territory. According to the seismic classification of the national territory, the area affected by the 2010-2014 seismic activity have a relatively higher probability to be shaken by a strong acceleration (Gruppo di Lavoro MPS, 2004). Most of the seismic events occurred in areas where the peak ground acceleration having 10% chance of being exceeded in next 50 years is between the values of 0.225 g and 0.275 g.

The 2010-2014 seismic activity and the temporary seismic networks. Between 2010 and 2014 the Italian Seismic Network (Amato and Mele, 2008) detected about 6000 earthquakes in the study area (Italian Seismological Instrumental and Parametric Data-Base ISIDE Working Group, 2010; ISIDe.rm.ingv.it; Fig. 1). The seismicity shows an unusual spatio-temporal pattern (Passarelli *et al.*, 2012): swarm like activity and mainshock-aftershock sequences coexist. In 2011 the earthquake rate has been variable, with increasing and decreasing phases and maximum magnitudes below M_L=4.0. On May 28, 2012, a shallow event with local magnitude M_L=4.3 struck about 5 km E of the previous swarm. The seismic activity remained concentrated in the M_L=4.3 source region until early August showing a mainshock-aftershock behaviour. At that time seismicity jumped back westward to the previous area, with several earthquakes of local magnitude larger than 3.0, culminating with a M_L=5.0 earthquake on October 25, 2012. The seismic rate remained high for some months, but magnitudes did not exceed 3.7. The seismic rate suddenly decreased at the beginning of 2013 and stayed quite low for the rest of the year up to June 2014 when a magnitude 4.0 occurred in the eastern cluster. The fault plane solutions identified by the Time Domain Moment Tensor (TDMT; http://cnt.rm.ingv.it/tdmt.html; Scognamiglio *et al.*, 2009) for the two major events are consistent with normal faults trending ~N20W and dipping at about 45°.

During these years several temporary seismic stations were deployed in the area (Fig. 2). After the increasing of seismic moment release in November 2011, the Centro Nazionale Terremoti of INGV, in collaboration with the Dipartimento di Fisica dell'Università della Calabria, improved the seismic monitoring network in the Pollino region in order to lower the detection threshold of the network and improve the hypocentral locations of small earthquakes. One permanent station of the Italian Seismic Network was installed to the south along the Tyrrhenian coast, 3 real time (UMTS transmission) temporary stations were deployed and 2 stand alone stations. At the end of May 2012, after the occurrence of the M_L=4.3 event, two other temporary stations transmitting in real time to the INGV monitoring room were deployed. At the end of July 2012 the first temporary stations were removed leaving only the two real time stations installed at the end of May 2012 (Amato *et al.*, 2012). Between the end of October and the beginning of November 2012, after the M_L=5.0 earthquake, an international research team by the INGV and the German Research Centre for Geoscience (GFZ) installed 15 seismic stations and an array to improve the detection capabilities of the INGV permanent network giving us the opportunity to refine the location of the earthquakes hypocenters.. Six stations costitute the small aperture seismic array (Govoni *et al.*, 2013)

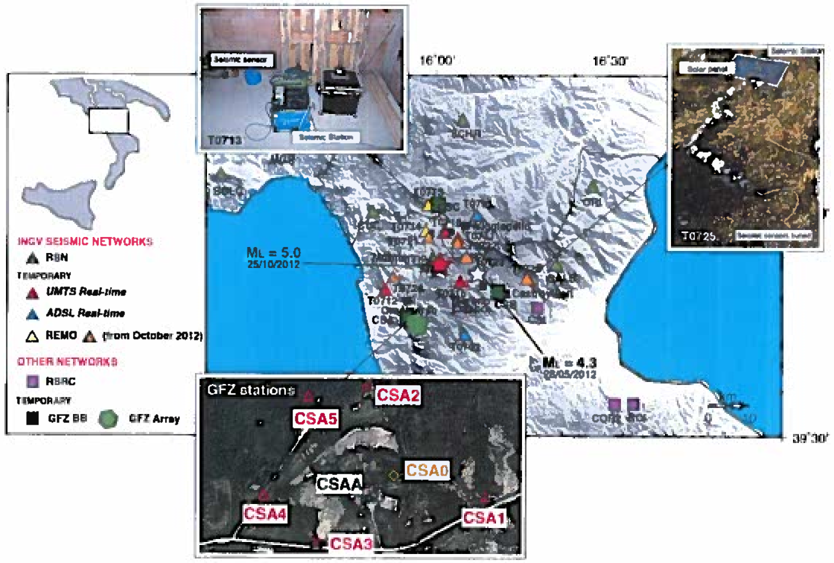

Fig. 2 – Seismic network running in the Pollino region during the seismic sequence. The different symbols for the different stations are explained in the legend; the stars are the epicenters of the two mainshocks. Inset pictures show the seismic stations and the geometry of the GFZ array.

The activated fault system. A combined dataset, including three-component seismic waveforms recorded by both permanent and temporary stations, has been analyzed in order to obtain appropriate 1D and 3D velocity models for earthquakes location in the study area. We produced refined locations by means of Hypoellipse (Lahr, 1989) for events recorded from October 2011 to March 2013 using waveforms of temporary stations installed during the seismic sequence. In order to compute the final 1D velocity model we apply the inversion scheme introduced by Kissling *et al.* (1994) and implemented in the code VELEST to an optimal sample of seismicity, representative of the seismogenic volume. We plot in figure 3 only events with small location errors (smaller tha 1km).

Refined earthquakes locations allowed us to infer the geometry of the faults relative to the two strongest shocks and to image the entire activated fault system. The seismicity is mainly

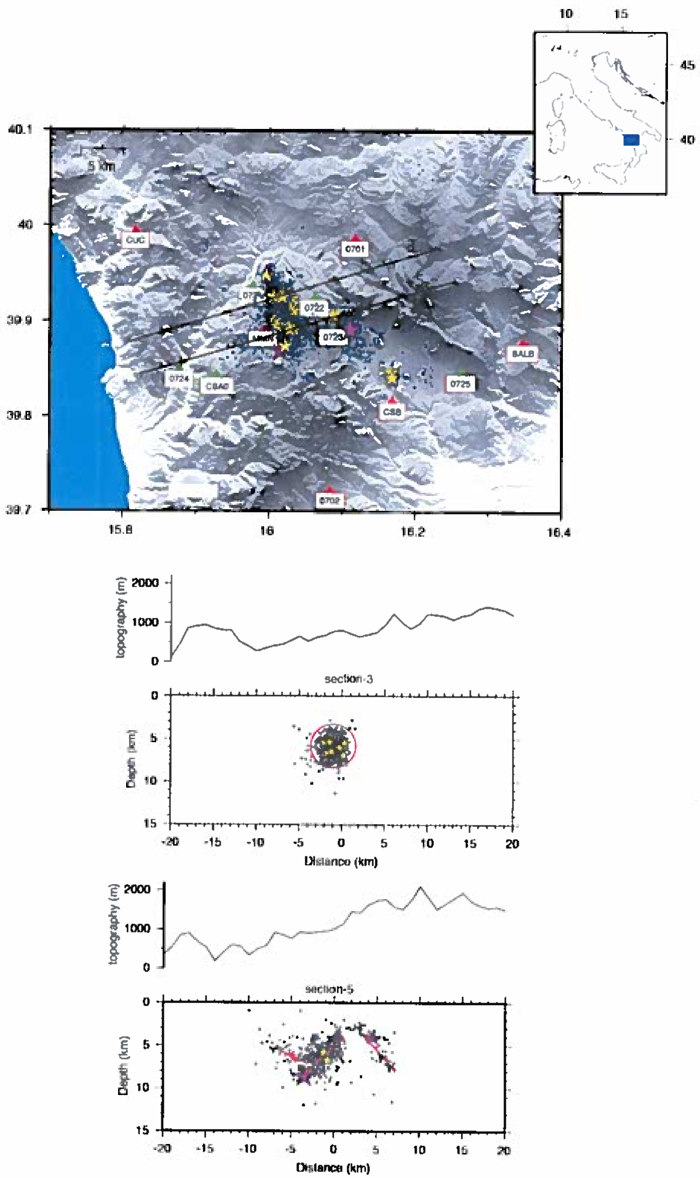

Fig. 3 – Refined locations of the seismicity recorded by permanent and temporary seismic stations from October 2011 to March 2013. The Top Image shows a map of the epicenters. We identify two main clusters: the first one to the W which include the M_L=5.0 event and the second one to the E where the M_L=4.3 occurred. The hypocenters, in section 3, depict a ball-shaped seismogenic volume. The hypocenters, in section 5, depict three seismogenic faults.

distributed in two clusters: a larger one to the W below Mormanno (MMN station) where the M_L=5.0 event occurred, and a smaller one to the E, closer to Castrovillari town, where the M_L=4.3 event occurred. In the map of Fig. 3 these two larger events are represented by the purple stars and earthquakes with magnitude larger than 3.5 are the yellow stars.

The swarm like activity, of November 2011-May 2012 and again August 2012-November 2012, seems to be concentrated mainly in the northwestern part of the activated fault system and occurred on a diffuse crustal volume more than on fault planes (see sections in Fig. 3). The western cluster is active since the end of 2011: in its northern portion (section 3) hypocenters are localized in a ball-shaped volume, while in the southern part (section 5) hypocenters define a SW-dipping fault plane. The plane was imaged by the seismicity also in the period before the M_L=5.0 event. In the section 5 it is also visible an antithetic fault plane to the W. Even if the eastern cluster has a lower number of refined locations, nevertheless the hypocenters define a NE-dipping plane, which seems related to the occurrence of the M_L=4.3 event of May 2012.

Conclusion. The geometry depicted by the seismicity and shown in Fig. 3 images the activated fault system: i) it affects the shallower 10 km of the crust; ii) it is constituted by at least three faults shorter than 10 km; iii) it strikes about NW-SE. The dip of the fault of the M_L=5.0 event is toward SW while the two other smaller faults dip toward NE. A similar geometry of the main fault has been pointed out Totaro *et al.* (2013), although with lower resolution

Comparing our results with the seismogenic sources reported in the DISS we find that the activated fault system is placed between the two major faults reported in this Database. The geometry of the "Rimendiello-Mormanno" fault system, constrained by geological data, is roughly consistent with the trend of the recent seismicity, but its dip is to the NE. The "Pollino" source (Castrovillari Fault, according to Cinti *et al.*, 1997) has a comparable trend (N20W) and a western dip, as the 2010-2012 seismicity, but its northern edge corresponds with the southernmost epicenters. Lastly, the fault systems described by Brozzetti *et al.* (2013), in the detailed structural map, shows several faults that could be connected to the faults depicted by the seismicity at depth.

The scientific developments of this work will aim at a better understanding of the origin of the ongoing seismic activity in the Pollino area. Furthermore we are analyzing thousand of seismograms looking for anisotropic parameters, by means of Anisomat code (Piccinini *et al.*, 2013); and tomographic vp and vp/vs models, by means of Simulps14q code (Haslinger, 1998) to gain a better understanding of the ongoing seismic activity and to yield a better correlation between the fault structures at the surface and at depth.

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I TERREMOTI OLOCENICI DELLA FAGLIA DI CITTANOVA (CALABRIA MERIDIONALE): NUOVI DATI PALEOSISMOLOGICI

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Introduzione. L'Arco Calabro, nel suo settore tirrenico, è stato l'area sorgente dei più energetici e catastrofici terremoti della storia sismica italiana. A partire dal diciassettesimo secolo, separati a volte da pochi anni o tutt'al più da qualche decennio, quasi venti eventi con Mw ≥ 6 si sono succeduti tra la foce del Crati a nord e lo Stretto di Messina a sud. Di questi, dieci sono stati parametrizzati con Mw ≥ 6.5 nei cataloghi sismici, cinque dei quali con Mw ≥ 6.9 (Fig. 1). Prima di questa micidiale sequenza, responsabile di oltre duecentomila morti e della distruzione di centinaia di località, gli eventi sismici presenti in catalogo o rintracciati da recenti studi specialistici sono pochissimi e caratterizzati da una documentazione generalmente povera e non conclusiva. L'unico per il quale si abbia contezza di danni molto gravi ed estesi è quello del 1184, avvenuto tra la valle del Crati e quella del Sinni, ma con fonti così scarne ed elusive che non ne hanno permesso una valida parametrizzazione.

Non è chiaro se questa distribuzione temporale dei terremoti in Calabria sia dovuta ad un reale silenzio delle principali sorgenti sismogenetiche prima del seicento o, viceversa, ad un silenzio delle fonti, dovuto - per esempio - alla generale marginalità ed isolamento storico-culturale della regione nel corso del medioevo e dell'epoca moderna, oltre che all'effettiva perdita di migliaia di documenti nelle catastrofi sismiche degli ultimi secoli (Scionti *et al.*, 2006). Probabilmente, ad entrambe le cose.

In ogni caso, la risoluzione di questo problema, attualmente impossibile da un punto di vista meramente storiografico - attesa anche la distruzione dei registri delle cancellerie angioine e aragonesi e di molti altri documenti archivistici nei bombardamenti a Napoli nel 1943 - può essere affrontata precipuamente per via geologica, invero approfondendo le conoscenze sull'evoluzione tettonico-stratigrafica tardo quaternaria dei depositi e delle forme distribuiti lungo tutta la fascia sismogenetica dell'Arco Calabro in prospettiva di studi di carattere paleosismologico attraverso le strutture indiziate di movimenti recenti.

Da questo punto di vista, negli ultimi anni, grazie all'impegno di molti gruppi di ricerca, la fascia costiera tirrenica della Calabria meridionale, anche nel tratto di offshore, è stata ripetutamente oggetto di studi finalizzati all'inquadramento crono-stratigrafico delle successioni di terrazzi marini, del loro sollevamento e delle loro eventuali deformazioni (p.e.: Dumas *et al.*, 1982, 1987, 1999, 2005; Miyauchi *et al.*, 1994; Balescu *et al.*, 1997; Pirazzoli *et al.*, 1997; Catalano *et al.*, 2003; Dumas e Raffy, 2004; Tortorici *et al.*, 2002, 2003; Antonioli *et al.*, 2006; Cucci e Tertulliani, 2006; Ferranti *et al.*, 2007, 2008; Bianca *et al.*, 2011; Pepe *et al.*, 2013; Spampinato *et al.*, 2014). I diversi studi sono giunti a importanti conclusioni, a volte anche in contrasto tra loro, sia nell'attribuzione dei singoli terrazzi ai rispettivi stadi isotopici marini e quindi ai ratei di sollevamento degli stessi, che all'esistenza e all'attività di faglie al margine o trasversali ai terrazzi [se ne veda la sistematica revisione e confutazione in Dumas (2008)], alle quali sono stati talvolta associati terremoti noti (p.e., un aftershock della sequenza iniziata il 5 febbraio 1783 o l'evento di Mw > 7 del 1905) o anche sconosciuti. In quest'ultimo caso, l'esistenza dei paleoterremoti e la loro scansione temporale è stata inferita dagli autori sulla base del presunto e ripetuto sollevamento cosismico di linee di costa oloceniche, ubicate nel blocco di letto di faglie normali, e datate tramite analisi al carbonio 14 di *markers* biologici. Tuttavia, oltre a quanto già stigmatizzato in Dumas (2008), considerando che in una faglia distensiva circa l'80% dello scorrimento viene aggiustato dallo sprofondamento del blocco di tetto, il sollevamento cosismico da 0.5 m a 2 m del blocco di letto riportato dagli autori per ciascun evento non sembra consistente con un evento di fagliazione normale associabile a strutture di lunghezza tipicamente tra 20 e 30 km.

D'altra parte, nella fascia più interna, ovvero nell'area epicentrale dei terremoti più distruttivi del sei-settecento, le conoscenze sull'evoluzione stratigrafica e tettonica pleistocenica dei depositi marini e continentali coinvolti nei processi deformativi restano limitate a pochi lavori, quasi mai supportati da vincoli cronologici numerici. Ciò non ha impedito, nel corso degli ultimi due decenni, di condurre alcuni studi paleosismologici sia nella Calabria settentrionale che in quella meridionale. Questi hanno permesso di individuare diverse evidenze di fagliazione di superficie riconducibili ad altrettanti eventi cosismici sia su strutture note in bibliografia che su faglie precedentemente sconosciute. Partendo da nord (Fig. 1), le prime sono la faglia del Monte Pollino (1 in Fig. 1: Michetti *et al.*, 1997; Cinti *et al.*, 1997, 2002), di Rossano (3 in Fig. 1: Galli *et al.*, 2010), delle Serre (8 in Fig. 1: Galli *et al.*, 2007) e di Cittanova (9 in Fig. 1: Galli e Bosi, 2002), mentre le seconde si riferiscono al sistema di faglie dei Laghi (5 in Fig. 1: Galli e Bosi, 2003; Galli *et al.*, 2007). I paleoterremoti associabili alle numerose fagliazioni individuate sono stati parametrizzati e compendiati nel Catalogo dei Paleoterremoti italiani (Galli *et al.*, 2008).

In alcuni casi, questi studi hanno consentito di associare alcuni terremoti di epoca storica - già presenti e parametrizzati nelle compilazioni sismiche - alle rispettive faglie, come nel caso degli eventi del 5 e 7 febbraio 1783 (faglia di Cittanova e delle Serre, rispettivamente), dell'8