Govoni, A., Passarelli, L., Braun, T., Maccaferri, F., Moretti, M., Lucente, F. P., Rivalta, E., Cesca, S., Hainzl, S., Woith, H., De Gori, P., Dahm, T., Chiarabba, C., Margheriti, L. (2013): Investigating the origin of seismic swarms. - *Eos, Transactions American Geophysical Union*, *94*, 41, pp. 361—362.

DOI: http://doi.org/10.1002/2013EO41

EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 94 NUMBER 41
8 October 2013
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Investigating the Origin of Seismic Swarms

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According to the U.S. Geological Survey's Earthquake Hazards Program, a seismic swarm is "a localized surge of earthquakes, with no one shock being conspicuously larger than all other shocks of the swarm. They might occur in a variety of geologic environments and are not known to be indicative of any change in the long-term seismic risk of the region in which they occur" (http://vulcan.wr.usgs.gov/Glossary/Seismicity/description_earthquakes.html).

The definition reveals how little is actually known about seismic swarms. For example, could certain seismic settings be more prone to swarms? Could a fault zone prone to large energetic earthquakes release part of its stress through seismic swarms? Do swarms keep hazards in balance, or could their onset increase hazards?

To gain insight into the nature of seismic swarms in nonvolcanic areas and to better understand their influence on seismic hazards, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and the German Research Centre for Geoscience (GFZ) began a combined research project within the framework of the Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation (NERA; see http://www.nera-eu.org/). The project focused on monitoring swarm activity occurring in the Pollino range in Southern Apennines, Italy.

Seismic Swarms in Southern Italy

During the end of October and the beginning of November 2012 the international research team installed 13 seismic stations in the Pollino range to improve the detection capabilities of the INGV permanent network (Figure 1a); 3 of the 13 are equipped with broadband sensors from the European Union's Cold Cases in Magma Propagation—Physics of Magma Propagation: A Multi-Methodological Investigation project (CCMP-POMPEI; http://www.gfz-potsdam.de/en/research/nachwuchsgruppen/erc-starting-grants-eu/ccmp-pompei/), and 6 were deployed as a small-aperture seismic array.

The Pollino range is located at the northernmost edge of the Calabrian Arc, the last oceanic subduction segment along the Nubian-Eurasian plate. Geodetic measurements show that the area is subject to northeast-southwest extension, which results in a complex system of normal faults striking nearly parallel to the Apennines. Two

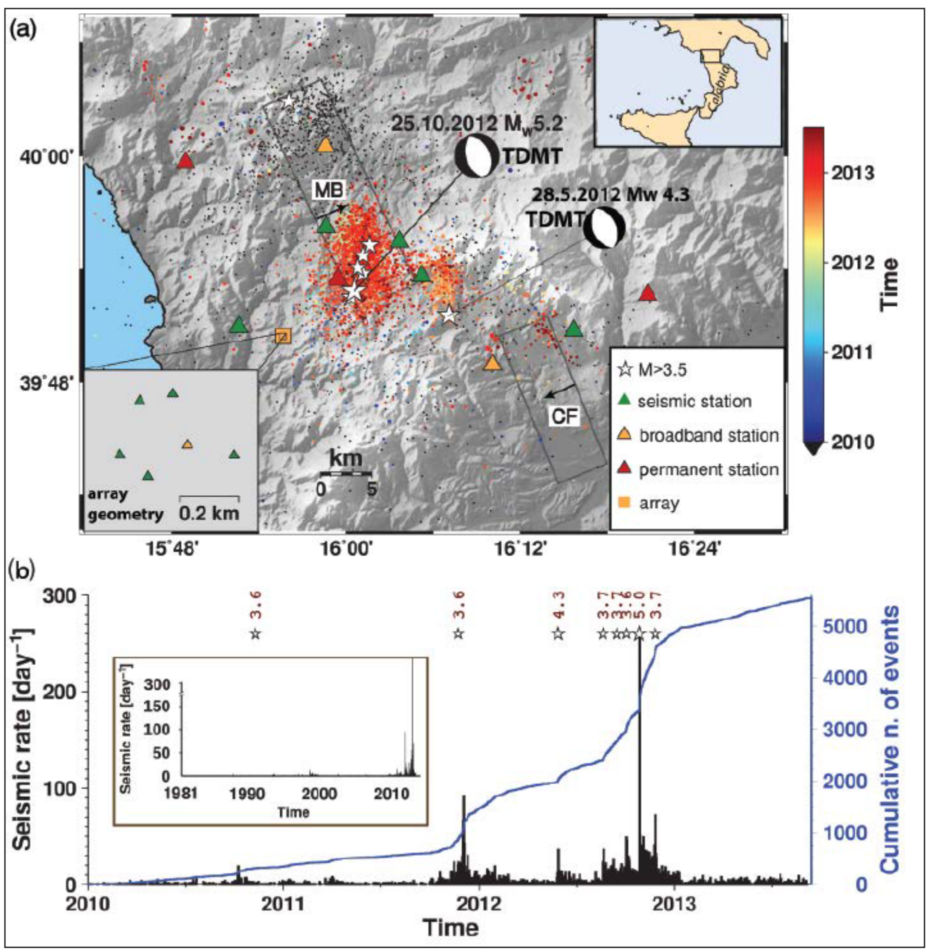

Fig. 1. (a) Map of seismic stations and seismicity of the Pollino range. The boxes are the surface projection main faults (MB stands for Mercure Basin fault; CF stands for Castrovillari fault), and arrows indicate their dip. TDMT stands for time domain moment tensor. (b) Daily rate of events since 2010 (since 1981 in the inset) and cumulative number of events.

By A. Govoni, L. Passarelli, T. Braun, F. Maccaferri, M. Moretti, F. Pio Lucente, E. Rivalta, S. Cesca, S. Hainzl, H. Woith, P. De Gori, T. Dahm, C. Chiarabba, and L. Margheriti

principal normal faults are known in the area: the Mercure Basin fault (MB) and the Castrovillari fault (CF), located in the northernmost and southernmost parts of the range, respectively (boxes in Figure 1a) [*Basili et al.*, 2008]. The MB is an active seismogenic structure, having probably hosted in its northernmost part an earthquake with a body wave mag-nitude (m_b) of 5.0 on 9 September 1998, whereas the CF shows no recent seismicity and is hence one of the most prominent seismic gaps in the Italian historical seismic catalog [*Rovida et al.,* 2011]. However, paleoseismic studies show that the CF was active in the last 10,000 years and is capable of producing events with magnitudes greater than 6.

Since the beginning of 2010, the Pollino area has been affected by an intense seismic swarm: the Italian Seismic Network detected more than 5000 earthquakes in the area (Italian Seismological Instrumental and Parametric Data-Base (ISIDe); http://iside.rm.ingv.it; Figure 1a). The earthquake rate has been variable, with increasing and decreasing phases. Most of the cycles of activity do not appear to follow a pure Omori-type decay, where the aftershock frequency decreases with the reciprocal of time after the main shock: They feature a gradual increase, as opposed to a sharp onset, followed by a gradual decrease to a few events per day (Figure 1b), which is characteristic of swarm-like behavior [*Mogi,* 1963]. All of these earthquakes have hypocentral depths between 0 and 10 kilometers, and most of the activity is concentrated between 5 and 10 kilometers. No other large regional earthquakes have been recorded just before or during the 3 years of seismic activity.

At the end of May 2012, the seismic activity moved suddenly eastward. A shallow event with local magnitude (M_L) of 4.3 struck on 28 May, about 5 kilometers east of the previous swarm. The daily rate of events following this earthquake appears more similar to an Omori-type sequence. The activity remained concentrated in the $M_L = 4.3$ source region until early August and then jumped back westward to the previous area, where it once again followed a non-Omori-type behavior. An increase of seismic activity was observed in that western location by the end of August, culminating with an $M_L = 5.0$ earthquake on 25 October 2012. The seismic rate remained high for some months, but aftershock magnitudes did not exceed magnitude 3.7. The seismic rate then suddenly decreased at the beginning of 2013 (Figure 1b).

Identifying Active Faults

The geometry depicted by the seismicity hypocenters [*Amato et al.,* 2012] helps in identifying the faults activated by the swarm. This, together with the fault plane solutions identified by analysis of seismic waveforms (in Figure 1a, the beach ball diagrams, which are derived from the time domain moment tensors), is consistent with normal faults trending about N20°W and dipping at about 45° to the southwest.

As of now, no inferences can be made on the relationship between the three clusters of swarms, but hypocentral distribution and focal mechanisms suggest that they are characterized by similar geometry and kinematics. By comparing these data with the MB and CF fault plane boxes in Figure 1a, it can be readily seen that the geometry suggested by the seismic swarms does not match the geometry of MB and CF. Only the strike of MB is mirrored by the trend of the recent seismicity, but MB is northeast dipping, whereas the seismicity of the swarm depicts two small planes dipping to the southwest. More to the south, the CF source has a comparable strike (N20°W) and a southwestern dip but is not intersected by 2010–2013 seismic swarms.

These results suggest that the swarm is not occurring on the main faults of the region. The relation between the faults activated by the swarm and MB and CF faults is not yet clear.

The *b* value for the seismic swarm, which is an indicator of the proportion of small to large earthquakes, was also evaluated [*Passarelli et al.,* 2012]. The values range between 1 and 1.4, with a decreasing trend from 2010 until the second half of 2011. Just after June 2011 the *b* value sharply jumped to 1.4, and several oscillations in the value occurred during the higher seismic activity at the end of 2012, patterns that continue to the present. These relatively high *b* values might suggest low confining stress, the presence of fluids, and/or the presence of highly fractured rocks in the fault areas.

Determining Seismic Hazard

Further research will hopefully yield a better understanding of the origin of the ongoing seismic activity in the Pollino area and its possible relation to changes related to the presence of fluids and their pore pressures. For this purpose, researchers will refine the velocity model of the area and precisely map all events of the swarm using array techniques and wave polarization analysis. Fluid-fault interaction studies and statistical and physical modeling of the area may also increase understanding of the physical mechanisms behind the seismic swarm and its influence on the quite high seismic hazard of the region.

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—Aladino Govoni, Centro Nazionale Terremoti, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy, and Centro Ricerche Sismologiche, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Udine, Italy; email: aladino.govoni@ingv.it; Luigi Passarelli, Physics of Earthquakes and Volcanoes Section, German Research Centre for Geoscience (GFZ), Potsdam, Germany; Thomas Braun, Sezione Roma 1, INGV, Arezzo, Italy; Francesco Maccaferri, Physics of Earthquakes and Volcanoes Section, GFZ; Milena Moretti and Francesco Pio Lucente, Centro Nazionale Terremoti, INGV; Eleonora Rivalta, Physics of Earthquakes and Volcanoes Section, GFZ; Simone Cesca, Institute of Earth and Environmental Science, University of Potsdam, Potsdam, Germany, and Physics of Earthquakes and Volcanoes Section, GFZ; Sebastian Hainzl and Heiko Woith, Physics of Earthquakes and Volcanoes Section, GFZ; Pasquale De Gori, Centro Nazionale Terremoti, INGV; Torsten Dahm, Physics of Earthquakes and Volcanoes Section, GFZ; and Claudio Chiarabba and Lucia Margheriti, Centro Nazionale Terremoti, INGV