

Analysis of recent seismic swarms in the Calabrian Arc

G. D. Chiappetta¹, A. Gervasi², M. Ponte¹, M. La Rocca¹

¹ *Università della Calabria, Rende, Italy;*

² *Istituto Nazionale di Geofisica e Vulcanologia, Rende, Italy.*

Introduction

Calabria is considered the Italian region with the highest seismic hazard (<https://emidius.mi.ingv.it/CPTI15-DBMI15/>, <http://storing.ingv.it/cfti/cfti5/>), mainly due to the numerous high intensity earthquakes (MCS>VIII) which occurred in historical times. Recent crustal seismicity, characterized by low-to-medium magnitude earthquakes ($M \leq 5$), is irregularly widespread throughout the region and surrounding seas. Some of the main active or presumed active tectonic structures in the Calabrian Arc are known, and many of them have considerable extents, up to tens of kilometers. Frequently, swarms of a few hundred low-magnitude events occur along minor structures, in areas where there isn't a comprehensive knowledge of the tectonic-structural context. The aim of this work is to study some of the seismic swarms that have occurred in the Calabrian Arc in the last 10 years. In fact, for some of them it has been possible to carry out very detailed analyses thanks to the quantity and quality of available data, despite the maximum magnitude observed is often quite low ($M < 4$). These analyses include absolute location, relative location, computation of the focal mechanism, estimation of the seismogenetic volume, and definition of the geometry of the fault along which the earthquakes of a given swarm occur.

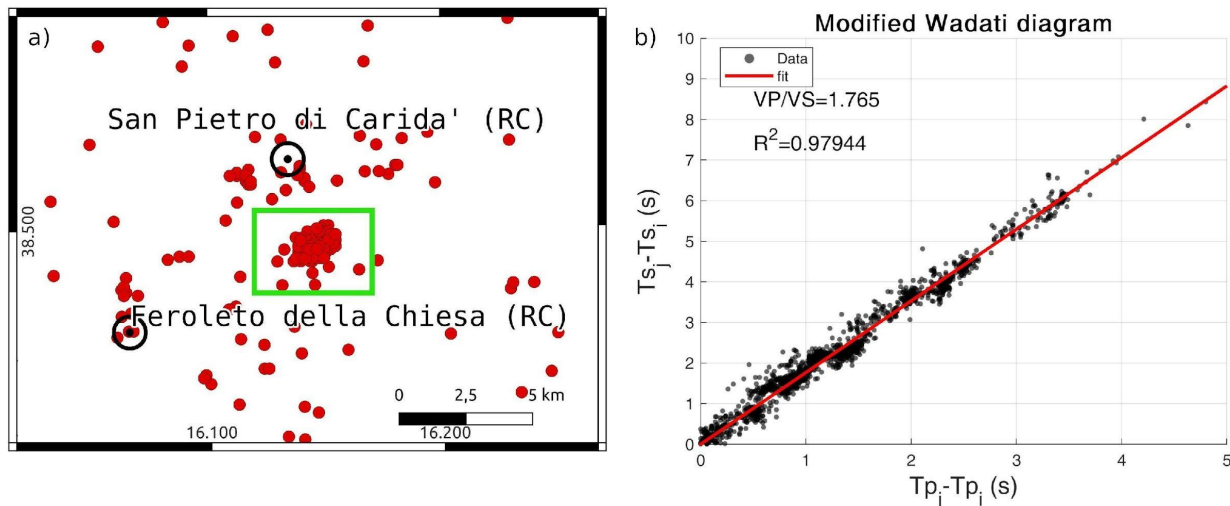


Figure 1. a) Epicenters of the initial selection of the earthquakes occurred recently in the Mesima valley area. b) Modified Wadati diagram computed to evaluate the quality of the picking and the V_p/V_s ratio.

Data and methods

The analysis of the seismic catalog allowed to select some swarms consisting of hundreds of earthquakes located in epicentral areas of few km^2 which occurred within a few weeks or a few months. All available data, i.e., seismograms recorded by the regional seismic network of the University of Calabria (www.sismocal.org) and by the national seismic network (www.ingv.it, www.eida.ingv.it), were used to analyze the selected events. The most important seismic swarms in terms of the number of events include Catanzaro (2022), Umbriatico (2022), Aspromonte (2020), Amantea (offshore, 2020), Cirò (2020), Albi (2020), Gulf of Policastro (2019), Mesima valley (2019), Bagnara Calabria (offshore, 2018), and others. The epicentral area of the various swarms did not allow analysis with the same resolution, mainly because in some cases (e.g., offshore sequences) the configuration of the seismic network is not appropriate and the location is affected by high azimuthal gap. To accurately locate the earthquakes of each swarm, the manual P- and S-wave picking has been performed for all selected events, and the location has been computed using the software Hyposat (Schweitzer, 2001) and a 1D velocity model. Furthermore, the focal mechanism has been computed for as many events as possible using one or more of the following software: FocMec (Snook, 1989), HybridMT (Kwiatek, 2016), and gCAP (Zhu & Ben-Zion, 2013). FocMec is based on P-wave and (possibly) S-wave polarity, while HybridMT is based on polarity and amplitude of the first P-wave pulse, so these two methods are the most suitable for small magnitude earthquakes ($M < 3$). On the other hand, gCAP is better for medium to high magnitude earthquakes because it is based on the comparison of observed and theoretical seismograms. Using different software gives a strong constraint about the result and increases its reliability. Relative location was also performed for the analyzed swarms following the method proposed by Got et al. (1994). This analysis allows for a more accurate location of the events of a swarm respect to a reference event and it is based on the differences in arrival times observed at the various stations considered. Furthermore, the relative location result allows to compute an approximate but realistic estimation of the seismogenetic volume that generated the swarm, and in the most

favorable cases it also allows to obtain the direction and inclination of the fault plane through the hypocenters interpolation. The study of the distribution of the hypocenters and the estimation of the volume has been carried out with Matlab.

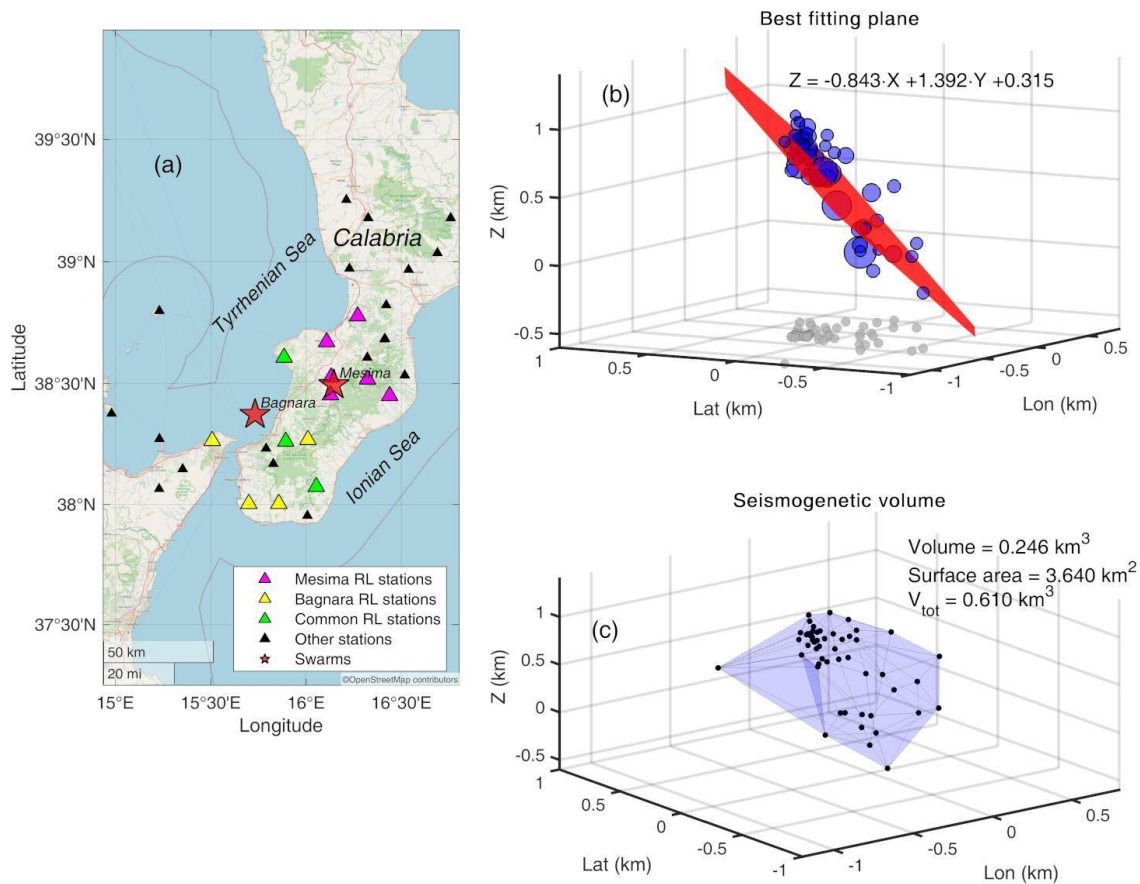


Figure 2. a) Seismic stations used for the analysis of the Mesima valley and Bagnara Calabria swarm, RL indicates the stations used for relative location. b) 3D representation of the hypocenters obtained from relative location and their fit with a plane. c) Computation of the seismogenetic volume based on the distribution of hypocenters.

Results

This paper describes the results of the analyses performed for two swarms: the Mesima valley swarm (2019) and the Bagnara Calabria swarm (offshore, 2018). The Mesima valley swarm occurred from April to May, with a main event of magnitude 3.6 which happened on May 26, 2019 at 23:31 UTC (lat. 38.492°, lon 16.145°, depth 19.45 km), followed by more than a hundred of lower magnitude events. Subsequently, many other events likely related to the same seismogenetic structure occurred sparsely over the following months and also in 2020. The starting dataset consists of about 300 earthquakes, selected in a circular area with radius 10 km around the mainshock epicenter. These events were located with high accuracy using all available data, and 172 of them have epicenters within an area of 2x2 km² (Fig. 1a) and depths between 17 and 20 km. Most of these earthquakes were located with an azimuthal gap of about 100 degrees due to the good distribution of seismic stations around the epicenter area (Fig. 2a). To assess the quality of the picking, the modified Wadati diagram (Chatelain, 1978) has been computed, from which a

mean value of V_p/V_s equal to 1.76 is obtained for the area (Fig. 1b). The focal mechanism has been computed for the 7 strongest earthquakes ($2.6 \leq M \leq 3.6$), obtaining in all cases normal kinematics with P axis approximately vertical and T axis oriented NW-SE (Fig. 3a). These mechanisms, as a whole, can be described by a single solution defined by strike = 239° , dip = 56° , rake = -93° (or strike = 64° , dip = 34° , rake = -85° considering the other nodal plane), computed according to the method of Michael (1984). Relative location has been computed on 54 events using the arrival times at the stations shown in Figure 2a, using the event occurred on July 2, 2020 at 10:15 UTC (lat 38.494° , lon 16.147° , depth 18.6 km, $M=2.2$) as a reference. The distribution of the hypocenters shows a strong orientation in space, and allowed us to identify a plane with strike equal to 58° and dip equal to 59° toward southeast (Fig. 2b), which is compatible with one of the nodal planes provided by the focal mechanism. The seismogenetic volume has been computed from the polyhedron enveloping the hypocenters, then its size has been increased by an amount computed by assuming a thickness Δl equal to 0.1 km surrounding the polyhedron to account for the finite extent of the faults associated with single events. The result of this procedure gives a volume of 0.6 km^3 for the Mesima swarm (Fig. 2c). Assimilating the distribution of hypocenters to a flat surface, the size of the corresponding portion of the fault is $1.0 \times 1.8 \text{ km}^2$. These values are much larger than the extent of the source of the mainshock, which has a radius of about 0.4 km if we assume a circular geometry with uniform dislocation and stress drop of 3 Mpa.

The Bagnara Calabria swarm occurred from September to November 2018, with a main event of magnitude $M=4.0$ which happened on September 28 at 05:24 UTC (lat 38.375° , lon 15.731° , depth 18.5 km). The swarm includes about a hundred earthquakes, and most of them, about 80, had magnitudes lower than 2. The absolute location results of 98 events show a distribution elongated in the EW direction, a depth range of 15 to 20 km, and an average V_p/V_s ratio of 1.8, this latter estimated from the modified Wadati diagram. Since this is an offshore sequence, for most of these earthquakes the azimuthal gap is wider than that of the previous study case, and it is generally comprised between 120° and 150° , with values greater than 180° for the smaller earthquakes. The focal mechanism has been computed for the 4 strongest earthquakes, with magnitude ranging from 3 to 4. All the solutions show a normal kinematics, with P axis approximately vertical and T axis varying from N-S to NW-SE (Fig. 3b). The Kagan angle (Kagan, 2007), computed among the mechanisms of the 3 smaller magnitude earthquakes and the mainshock, gives values between 24° and 33° , indicating rather similar solutions. This analysis strengthened the reliability of the results obtained, despite the difficulties in calculating the focal mechanism mainly related to the high azimuthal gap. Relative location has been performed on the 37 events for which it was possible to pick the P-wave arrival time to at least 5 of the stations in Figure 2a, with an uncertainty lower than one hundredth of a second. The distribution of the hypocenters with respect to the mainshock (chosen as the reference event) does not show any planar distribution so it wasn't possible to fit them in order to constrain one of the solutions obtained from the focal mechanism. Anyway, this analysis confirms the EW trend of the epicenters already observed, and allows us to estimate a seismogenetic volume of 1.1 km^3 , computed as the previous case. The distribution of hypocenters indicates an extent of 2 km which is, again, much greater than the size of the fault that generated the strongest event of the swarm. For all swarms analyzed in this paper, the result

of relative location indicates a much smaller volume than that obtained from absolute location. Nevertheless, the extent of the distribution of the hypocenters is significantly larger than the length of the rupture estimated from the magnitude of the strongest event of the swarm.

Conclusions

Detailed analysis of seismic swarms is very important in areas where strong earthquakes have not occurred for many decades. In fact, seismic swarms may allow the identification of active faults whose existence and seismogenetic potential are unknown. Therefore, the study of seismic swarms is very useful to identify active seismogenetic sources, especially when they do not have a correspondence with known tectonic structures. This is especially true for swarms occurring at depth greater than 10 km and/or with epicenter in the sea, for which it is often impossible to associate them with faults whose traces can be seen on the surface. It is worth to note that in Calabria the reference seismic hazard in coastal areas may be underestimated because of the lack of strong earthquakes occurred in the last century. The relative location of many tens of hypocenters allows to identify the geometry of the source and to estimate its volume. In cases where the distribution of hypocenters is characterized by a very anisotropic shape, it is also possible to estimate direction and inclination of the portion of the fault that generated the swarm. The distribution of the hypocenters in a seismogenetic volume much greater than the extent of the mainshock rupture suggests that many events occur on different sectors of the same fault. These sectors may not overlap themselves or may not be contiguous. Conversely, this feature can also suggest that many events occur on different faults distributed in a highly fractured crustal volume. Finally, the kinematics of the events gives very important information about the active stress field in the volume surrounding the source.

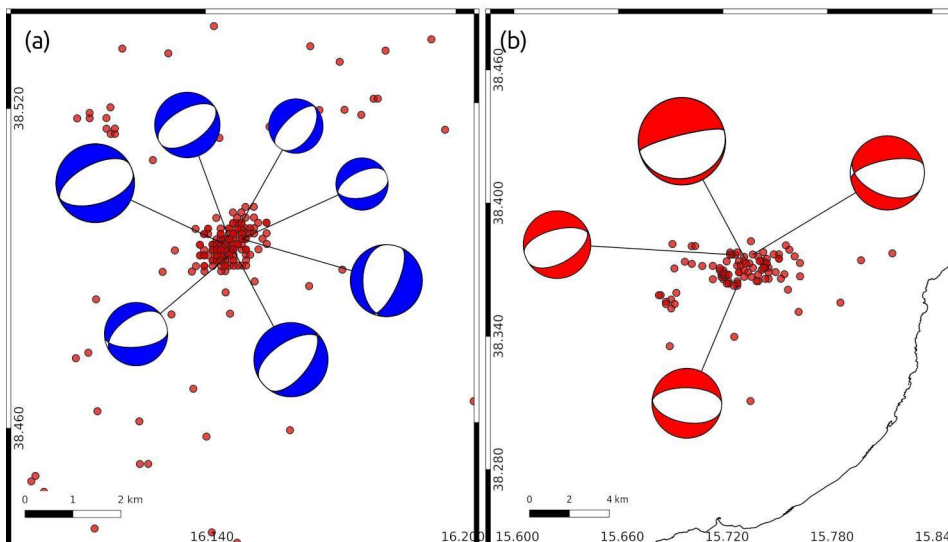


Figure 3. Focal mechanisms of (a) 7 Mesima valley swarm earthquakes and (b) 4 Bagnara Calabria swarm earthquakes.

References

- Chatelain, J.; 1978: Étude fine de la sismicité en zone de collision continentale à l'aide d'un réseau de stations portables: la région Hindu-Kush-Pamir, Ph.D. thesis, Université Paul Sabatier, Toulouse.
- Got J.L., Frechet J. and Klein F.W.; 1994: Deep fault plane geometry inferred from multiplet relative relocation beneath the south flank of Kilauea. *J. Geophys. Res.*, 99, 15375-15386, <https://doi.org/10.1029/94JB00577>.
- Kagan, Y. Y.; 2007: Simplified algorithms for calculating double-couple rotation. *Geophys. J. Int.*, 171, 411-418, <https://doi.org/10.1111/j.1365-246X.2007.03538.x>.
- Kwiatek G., P. Martínez-Garzón and M. Bohnhoff; 2016: HybridMT: A MATLAB/Shell Environment Package for Seismic Moment Tensor Inversion and Refinement. *Seismological Research Letters*, 87 (4), 964–976 <https://doi.org/10.1785/0220150251>.
- Michael, A.J., 1984: Determination of stress from slip data: Faults and folds. *J. Geophys. Res.*, 89, 11517-11526, <https://doi.org/10.1029/JB089iB13p11517>.
- Schweitzer J.; 2001: HYPOSAT - An Enhanced Routine to Locate Seismic Events. *Pure Appl. Geophys.* 158, 277-289, <https://doi.org/10.1007/PL00001160>.
- Snoke, J. A.; 1989: Earthquake Mechanisms. In: James D. E., *Encyclopedia of Geophysics*. New York: Van Nostrand Reinhold Company, pp. 239-245.
- Zhu L. and Ben-Zion Y.; 2013: Parametrization of general seismic potency and moment tensors for source inversion of seismic waveform data. *Geophys. J. Int.* 194, 839–843, <https://doi.org/10.1093/gji/ggt137>.

Corresponding author: G.D. Chiappetta, giuseppe.chiappetta@unical.it