CONSTRAINTS ON THE SOURCE MECHANISM OF THE DAMAGING SEISMIC EVENT OF AUGUST 21, 2017, ON ISCHIA ISLAND (SOUTHERN ITALY)

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1) INTRODUCTION

Although in-depth investigations of moderate earthquakes are not generally warranted, a recent earthquake on Ischia, a small volcanic island located 33 km southwest of Naples (Southern Italy), is a worthwhile exception due to the striking discrepancy between the macroseismic intensity and the magnitude. On August 21, 2017, Ischia was struck by a seismic event of MD 4.0 that provoked significant shaking and severe damages (maximum intensity reached in Casamicciola village, ZR in Figure 1; Azzaro et al., 2017) including unfortunately 2 victims. The incongruity between damage and magnitude cannot be explained only by local site effects or especially vulnerable constructions, but may be influenced by particular characteristics of the seismic source. The first automatic hypocenter location at INGV was off-shore - at a standard crustal depth of 10 km - in the area between Ischia island and the Italian Peninsula. Relocation of the event confirmed a shallow hypocenter (ISIDe, 2016), in proximity of the maximum damage intensities observed. The calculated magnitudes of ML 3.6, Mw 3.8 and MD 4.0 seemed to be at odds with the high macroseismic intensity (hereafter reported as IEMS– the Intensity of the European Macroseismic Scale; EMS, 1998). While the coastal area of Marina di Casamicciola (MC in Figure 1) was less affected (IEMS 6), the upper part of Casamicciola Terme (CMRZ in Figure 1) showed the most severe earthquake damage (IEMS 7-8) and significant local variations, probably due to the diverse quality of construction (Azzaro et al., 2017). The complexity of the observed damage justified the assignment of IEMS 8 to the Red Zone (CMRZ in Fig. 1) of Casamicciola Terme (Azzaro et al., 2017).

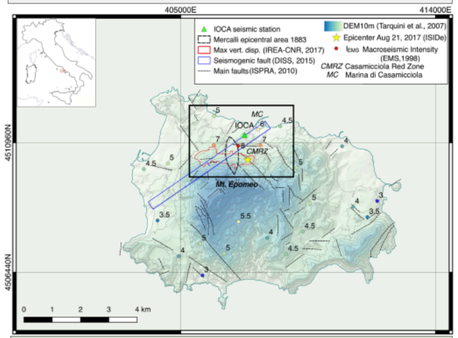

Figure 1: Map of Ischia Island, showing the epicenter of August 21, 2017 (yellow star), the seismic station IOCA (green triangle), the area of maximum deformation (red curve), the epicentral area of 1883 (rugby ball shaped area; Mercalli, 1884), the main faults (dashed black lines) and the position of the seismogenic source (blue rectangular area). Numbers indicate macroseismic intensity EMS values (after Azzaro et al., 2017).

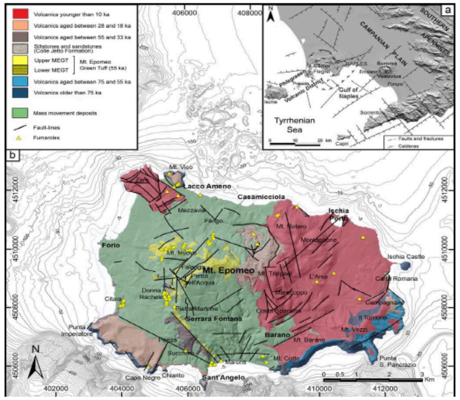

Fig. 2: (a) Location of the study area and structural sketch map of the Neapolitan volcanic complex. (b) geological setting of Ischia island (modified after Della Seta et al., 2012).

2) GEOLOGICAL FRAMEWORK OF ISCHIA ISLAND

Ischia island is characterized by its volcanic activity, which started 150 ky (Della Seta et al., 2012) ago. Being mainly composed by volcanic rocks, epiclastic deposits and subordinate terrigenous sediments, Ischia's geology reflects the complex sequence of alternating constructive and destructive phases of the volcanic edifice (Della Seta et al., 2012). The main recent volcano-tectonic event was the resurgence of the caldera that took place after the explosive eruption (55ka BP) and deposition of the Mt. Epomeo Green Tuff (Acocella & Funiciello, 1999; Carlino, 2012). A maximum uplift of 900 m (Della Seta et al., 2012; Orsi et al., 1991) of the caldera floor is testified by the presence of marine sediments (siltstones and sandstones in Fig. 2-b) outcropping in the inner part of the island. The resurgent block which represents the central part of the island, has a polygonal shape and in its northern part (Mt. Epomeo in figure 1) is bordered by high angle inward-dipping faults (Acocella & Funiciello, 1999; Molin et al. 2003); its uplift seems to be connected to the intrusion of a magmatic body at shallow depths, 2 km below the surface. This mechanism seems to be responsible for the gravimetric and geothermic anomalies of the area (Carlino, 2012; Capuano et al., 2015). Cubellis and Luongo (1998) and Carlino et al. (2006) report that - due to the high geothermal gradient - the seismogenic volume capable to generate seismic events (brittle regime) is confined in the upper 2 - 2.5 km of the crust.

3) HYPOCENTRAL DETERMINATION

The configuration geometry of the Italian Seismic Monitoring Network is constrained by the shape of the Italian peninsula. In case of off-shore earthquakes, this leads often to large azimuthal gaps in the location process, introducing trade-offs among epicentral location, focal depth and origin time.

The first automatically calculated epicenter of the 2017 Ischia earthquake was located some kilometers off-shore at a standard depth of 10 km. It became quickly obvious that the off-shore location was in strong contradiction with the observed damage distributions at Ischia, which showed a certain pattern (Figure 1). This damage pattern, in fact, was narrow and concentric, slightly elongated in E-W direction (Azzaro et al., 2017), and suggested a very shallow hypocentral depth. A subsequent re-calculation established a hypocentral location that was much more compatible with the damage pattern, with a hypocenter at a depth of 1.7 km about 1 km SSW of the center of the small town Casamicciola (CMRZ in Figure 1). Any attempt to relocate the hypocenter by using arrival times, did not provide consistent and stable solution, due to the uncertainty about the local velocity model, as well as the inhomogeneity of the available seismic network (azimuthal gap). We therefore improve the hypocenter location by analyzing in detail the seismogram from station IOCA, concerning travel times, particle motions and azimuthal provenance of spectral energy.

The observed S-minus-P travel time difference of t_s-t_p=0.8s time can be used to estimate the hypocentral distance (d), using the simple relation:

$$d\,[km] = (t_s-t_p)\cdot v_p \cdot v_s/(v_p-v_s) = (t_s-t_p)\cdot c = 0.8\cdot c \qquad (1)$$

d depends particularly on the local geological situations of the volcanic island, where v_p and v_s are significantly lower than standard, and their ratio may differ from the classical value v_p/v_s = 1.73.

We derive the P-wave velocity from a 3D-model through tomographic inversion (Capuano et al., 2015). P-velocities of v_p = 1.5 km/s and 3.1 km/s are reported for the first two layers (0 - 900 m, 900 - 2500 m), respectively we assume thus a mean P-velocity of 2.3 km/s for the upper 2.5 km, c varies between 1.92 ≤ c ≤ 3.29 for 1.7 < v_p/v_s < 2.2, resulting in a hypocentral distance range between 1.53 km < d < 2.63 km. Compared to the location reported by ISIDe (2016) (yellow star in Figures 1 and 4), the epicentral distance with respect to station IOCA is very similar, while the backazimuth is rotated towards SW by 20°. As represented in Figure 4, the epicentral zone (purple) determined in this is study is (i) located at the northern rim of the red-encircled area that represents the 4 cm negative deformation (subsidence) found by satellite interferometry (IREA-CNR, 2017) and (ii) falls exactly in the rugby-shaped epicentral area as first outlined by Mercalli (1884).

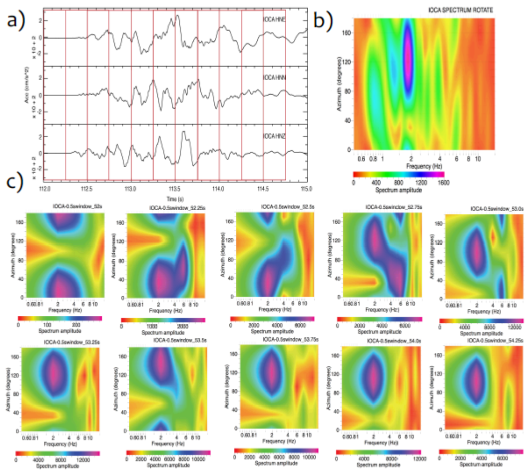

Fig. 3: (a) Accelerometric traces of the Ischia event recorded at IOCA; (b) Rotated spectrum of the 3 seconds selected trace (a); (c) temporal variations of the azimuthal distribution of spectral energy recorded.

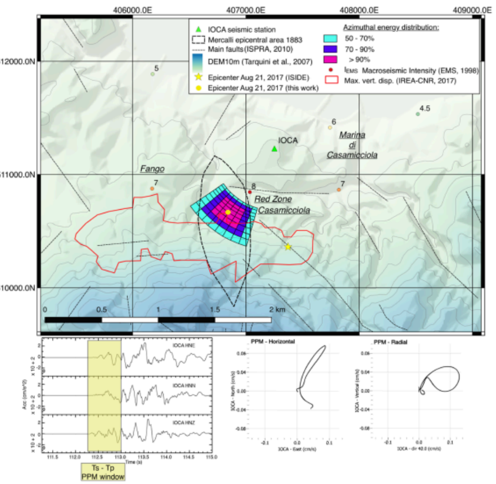

Figure 4: Azimuthal energy estimate of the M_D 4.0 Ischia epicenter of August 21, 2017, as derived in the present study. Below the 3-component accelerometric traces (left) and the particle motion (right).

4) SOURCE MECHANISM: DC and Full Moment Tensor solutions

A number of discrepant focal mechanism solutions have been proposed for the Ischia earthquake, based on time domain regional moment tensor inversion (Figure 5, from GdL-INGV, 2017). Following the method described in Cesca et al. (2013), we performed spectral and waveform based moment tensor inversions to determine the seismic source geometry, by assuming a pure double couple and a full moment tensor model and using the on-shore stations of the Italian Seismic Network (ISN) located at regional distances (Figure 5).

In comparison to former inversions (RCMT - Regional Centroid Moment Tensor by Pondrelli et al., 2006, Time Domain Moment Tensor - TDMT by Scognamiglio et al., 2009, and an approach by the Saint Louis University – SLU by Herrmann et al. 2011) all reported in Fig. 5, we use a greater number of seismic stations (up to 14 stations) in an effort to reduce the azimuthal gap (down to ~200°). Thanks to the improvement in stations' geometry and the fit of high frequency data we can better resolve the centroid depth and the moment tensor. We first invert for a double couple (DC), obtaining a M_w 3.9 normal fault with a best fit solution at a depth of 8 km. This solution is in good agreement with the one calculated by TDMT (Figure 5). We additionally perform a full moment tensor inversion, to assess the presence and robustness of isotropic and CLVD components. Comparative results of full MT and DC inversions (Figure 6) demonstrate a large improvement of spectral and waveform fit, when a very shallow MT solution is chosen, at a depth of 2 - 4 km. The best fitting MT solution, for a depth of 4 km, is characterized by a significant negative isotropic component of 36% (contraction), a negative CLVD of 26% and a normal faulting DC component of 38%. The seismic moment amounts to 2.30·1015 Nm, corresponding to a moment magnitude of Mw 4.1. The ~0.2 increase in Mw-magnitude, in comparison to the best DC solution and other reference solutions, can be mostly attributed to the non-DC term.

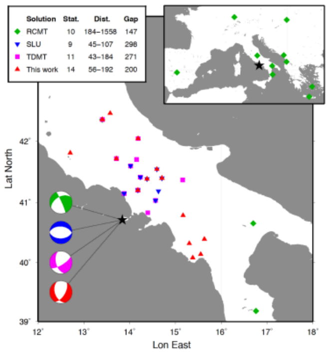

Fig. 5: Comparison of moment tensor solutions by: RCMT (green, best DC source), SLU (blue, best DC source), TDMT (purple, DC component of the best deviatoric MT) and this work (red, best DC source). The map show the stations used by different authors (different symbols, colors according to the focal spheres); with the upper right map inset showing stations at regional distances used by RCMT. The upper left inset lists the number of used stations, range of epicentral distances and azimuthal gap.

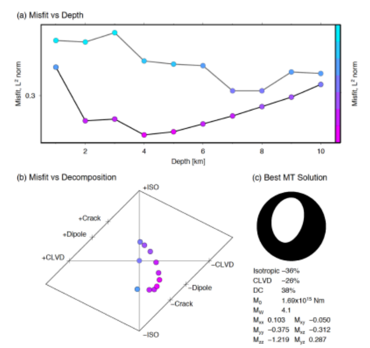

Fig. 6: DC and full MT solutions for the Ischia earthquake. (a) Comparison of amplitude spectra fit (L2 norm) for different source depths, assuming a DC (gray line) and full MT (black line) source model, the color bar denoting the misfit value. (b) Hudson plot representation of the source type for full MT and DC solutions at different source depths: best fitting solutions show a significant negative tensile component, a potential signature of a collapse process. (c) Best full MT solution and related source parameters.

5) Conclusions:

We use data from station IOCA to improve the epicentral location and depth of the August 21, 2017 Ischia earthquake and discuss the focal mechanisms, as a clear positive first motion onset (Figure 3a and Figure 4) is apparently in contrast with moment tensor solutions.

- P-phase particle motion, the evaluation of the rotated spectra, and ts-tp lead to a hypocentral depth of 2 km, in the same epicentral area as the devastating seismic event that struck Ischia in 1883.
- We model local waveforms and first motion onset at IOCA by using a 2-layered shallow structure after Capuano et al. (2015), assuming a shallow depth of 2 km. However, our best DC and MT solutions, as well as other proposed solutions (Figure 6), predict a negative onset, in contrast to observation. We could reproduce the positive onset for our best DC model and a shallower source depth (1 km or less). The 36% and 26% of negative isotropic component and negative CLVD components of full MT solution do not represent a pure closing tensile crack but a complex process, which could indicate the activation of a fault accompanied by a rapid subsidence.
- We suggest an hypothesis to explain the polarity mismatch, based on a model by Molin et al. (2003), who combine active reverse and normal faulting to explain the resurgence mechanism of Ischia caldera: seismic activity is triggered by reverse faults located at the northern periphery of the resurgent block, inducing the subsequent collapse of its outermost part and forming a parallel set of outward dipping high-angle normal faults in an innermost portion of the block for accommodation of the space created by the resurgence.

REFERENCES

Acocella, V., R. Funiciello, 1999. The interaction between regional and local tectonics during resurgent doming: The case of the island of Ischia, Italy. J. Volcanol. Geotherm. Res. 88, 109-123

Azzaro, R., S. Del Mese, G. Martini, S. Paolini, A. Screpanti, V. Verrubbi, and A. Tertulliani (2017). QUEST – Rilievo macrosismico per il terremoto dell'isola di Ischia del 21 agosto 2017. Rapp. Int. INGV. doi: 105281/zenodo.849091.

Braun T. , S. Cesca, D. Kühn, A. Martirosian-Janssen & T. Dahm: Anthropogenic seismicity in Italy and its relation to tectonics: State of the art and perspectives. Submitted to Anthropocene, 2017b.

Braun T., T. Dahm, F. Krüger and M. Ohrnberger (2016): Does Geothermal Exploitation Trigger Earthquakes in Tuscany? EOS 97 NO. 14, 15 July 2016, 20-24.

Capuano P., R. De Matteis, and G. Russo (2015). The structural setting of the Ischia Island Caldera (Italy): first evidence from seismic and gravity data. Bull. Volcanol. 77 (79). doi: 10.1007/s00445-015-0965-4.

Carlino, S. (2012). The process of resurgence for Ischia Island (southern Italy) since 55 ka: the laccolith model and implications for eruptions forecasting. Bull. Volcanol. 74 (5), 947-961.

Carlino, S., E. Cubellis, G. Luongo, and F. Obrizzo (2006). On the mechanics of caldera resurgence of Ischia Island (southern Italy). In: C. Troise, G. De Natale, C.R.J. Kilburn (eds.), Mechanism of activity and unrest of large calderas. Geological Society Special Publications, 269, London, 181-193.

Carlino, S., E. Cubellis, and A. Marturano (2010). The catastrophic 1883 earthquake at the island of Ischia (southern Italy): macroseismic data and the role of geological conditions. Nat. Hazards 52: 231-247. doi: 10.1007/s11069-009-9367-2.

Cesca, S., A. Rohr, and T. Dahm (2013). Discrimination of induced seismicity by full moment tensor inversion and decomposition, J. Seismol. doi: 10.1007/s10950-012-9305-8.

Cubellis, E., and G. Luongo (1998). Il terremoto del 28 luglio 1883. Campo macrosismico e studio della sorgente. In: "Il terremoto del 28 luglio 1883 a Casamicciola nell'isola d'Ischia". Servizio Sismico Nazionale, Istituto Poligrafico e Zecca dello Stato, 101-110.

Della Seta M., C. Esposito, G.M. Marmoni, S. Martino, A. Paciello, C. Perinelli, and G. Sottili, (2012): Geological constraints for a conceptional evolutionary model of the slope deformations affecting Mt. Nuovo at Ischia (Italy). Ital. J. Eng. Geol. Environm., 2, 15-28. doi:10.4408/IJEGE.2015-02.O-04.

GdL-INGV (2017). Rapporto di sintesi preliminare sul terremoto dell'isola di Ischia (Casamicciola) M4.0 del 21 agosto 2017 (6 settembre 2017). *Gruppo di lavoro sul terremoto dell'isola di Ischia, INGV*. doi: 10.5281/zenodo.886045.

Guidoboni, E., G. Ferrari, D. Mariotti, A. Comastri, G. Tarabusi, and G. Valensise (2007). Catalogue of Strong Earthquakes in Italy (461 B.C. - 1997) and Mediterranean Area (760 B.C.-1500). SGA Bologna. http://storing.ingv.it/cfti4med/

Herrmann, R.B., L. Malagnini, and I. Munafò (2011). Regional moment tensors of the 2009 L'Aquila earthquake sequence. Bull. Seism. Soc. Am., 101, 975-993. doi: 10.1785/0120100184.

ISIDe (2016) - *ISIDe working group (2016) version 1.0, DOI: 10.13127/ISIDe'.* http://iside.rm.ingv.it/iside/standard/index.jsp

Mercalli, G. (1884). L'isola d'Ischia ed il terremoto del 28 luglio 1883. Mem. Reg. Ist. Lombardo Scienze e Lettere, 3 (6), 99-154.

Molin, P., V. Acocella, and R. Funiciello (2003). Structural, seismic and hydrothermal features at the border of an active intermittent resurgent block: Ischia Island (Italy). J. Volcanol. Geotherm. Res. 121, 65-81.

Orsi, G., G. Gallo, and A. Zanchi (1991). Simple shearing block resurgence in caldera depressions. A model from Pantelleria and Ischia. J. Volcanol. Geoth. Res., 47, 1-11.

Pondrelli, S., S. Salimbeni, G. Ekström, A. Morelli, P. Gasperini, and G. Vannucci (2006). The Italian CMT dataset from 1977 to the present. *Phys. Earth Planet. Int.*, **159** (3-4), 286-303, doi: 10.1016/j.pepi.2006.07.008

Scognamiglio, L., E. Tinti, and A. Michelini (2009). Real-time determination of seismic moment tensor for the Italian region. Bull. Seismol. Soc. Am., **99** (4), 2223-2242.