

**The 2017, Mw 3.9, Ischia Earthquake (Southern Italy): Source mechanism from the modelling of seismic, geodetic, and geological data and relation to the volcano resurgence mechanism**

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**Key Points:**

- The rupture complexity and source geometry of the 2017 Ischia earthquake (Italy) is investigated.
- The finite-fault model is implemented to invert the near-source velocity records.
- The results show that the rupture mechanism is thrust-strike (right lateral) slip and propagated north-west south-east direction.

**Abstract**

The moderate earthquake occurred at the volcanic island of Ischia, south-west of Naples (Italy) caused several buildings collapse, two victims, and several tens of injured people. This event generated a large amplitude ground shaking and long-lasting S-wave signal, longer than those expected for an earthquake. To investigate the event rupture complexity and its radiated wave field, we used finite-fault modeling to invert the near-source ( $< 1$  km epicentral distance), three-component velocity records of the accelerometric station (IOCA), and searched for the best-fit kinematic rupture parameters. This analysis showed that the rupture nucleated at about 600 m west of IOCA and 1.1 km depth, along a 1 km, NW-SE striking fault (thrust-strike slip with right-lateral component), with a rupture velocity 0.8 km/s. The retrieved rupture model coupled with multi-path reverberations effects related to a thin, low-velocity near-surface volcanic sedimentary layer, allowed us to explain the observed long ground motion duration and the large amplitudes recorded all over the island. The actual fault location, mechanism, and the spatial correlation between the simulated peak ground motion zone and the area where the maximum vertical displacement has been determined by DInSAR images suggest that the latter is associated with strong-shaking locally generated by land-slide phenomena caused by co-seismic slip. Our source model is consistent with the earthquake located near the border of the caldera resurgent block, which is likely still active, where mass rock creeps evolved into widespread collapses at NW of Monte Epomeo.

## 1 Introduction

On August 21, 2017, a moderate size earthquake,  $M_w$  3.9 (INGV bulletin), had struck the Casamicciola town in the northwestern sector of the Ischia island generating few casualties and damages in a limited area. Historical information reports that before the 19th century, the island was affected by various moderate magnitude events with relatively high macroseismic intensity (i.e.,  $IMCS > V$ ; Mercalli-Cancani-Siberg scale) (Figure 1). Then, in 1881 and 1883 two destructive events occurred in the same location of the 2017 event, the area of Lacco Ameno and Casamicciola, with more than a hundred of fatalities and widespread building collapses (Del Gaudio et al., 2019). The 1883 earthquake, with an estimated magnitude between 4.3 and 5.2, and a depth between 1 and 2 km (CPTI15, Luongo et al., 2006), reached a macroseismic intensity  $IMCS = X$  at the epicenter in the town of Casamicciola.

After the 2017 earthquake, several studies have been proposed with the aim to describe the earthquake source characteristics and its effects. De Novellis et al. (2018) investigated the 2017 earthquake mechanism by exploiting seismological, GPS and Sentinel-1 and COSMO-SkyMed differential interferometric synthetic aperture radar coseismic measurements. The 2017 mainshock and its five aftershocks have been located using the probabilistic location method of Lomax et al. (2000) using the available P- and S-phase pickings. To locate the mainshock only the P-wave arrivals at the three closest stations installed in the island have been used since the signal saturation prevents the accurate reading of the first S-arrival. A 3D velocity model built upon previous tomographic studies of the extended Neapolitan volcanic area has been used for the computation of theoretical arrival times. It should be noted that the first P-arrivals at coastal stations (distances larger than 10-20 km) are primarily head waves from the shallow

57 crustal discontinuities, among which, the main one is the interface separating the volcanic  
58 sediments and the limestone formation, whose morphology and depth is not known with  
59 accuracy and not included in 3D unified velocity model of D'Auria et al. (2008). This uncertainty  
60 on the velocity model may seriously affect the earthquake location and focal mechanism  
61 determination.

62 Braun et al. (2018) evaluated the 2017, Ischia earthquake location by combining the P-wave  
63 particle motion, rotated spectra, and S-minus-P time observed at IOCA station, yielding a  
64 hypocenter depth of 2 km and a location 0.5-1 km south-west of IOCA; leading to the same  
65 epicentral area of the 1883 devastating earthquake. The epicenter locations proposed by Braun  
66 et al. (2018) and De Novellis et al. (2018) are in good agreement, while their depth estimates  
67 differ of about 1 km.

68 Differently from location, several significantly discrepant solutions have been proposed for the  
69 focal mechanism of the Ischia mainshock; mainly derived from the inversion of P-wave  
70 polarities at local distances or moment tensor inversion at regional distances (De Novellis et al.,  
71 2018; Braun et al., 2018). A comprehensive review of the different published solutions is  
72 provided by Braun et al. (2018), who further applied the combined spectral and time domain  
73 method of Cesca et al. (2013) to determine the earthquake moment tensor. These authors  
74 provided a solution with both large negative isotropic and compensated linear vector dipole  
75 (CLVD) components, which led them to suggest the occurrence of a complex rupture process  
76 characterized by an initial shallow normal-faulting event that triggered a subsequent shallow  
77 underground collapse.

78 Based on the INGV hypocenter depth and focal mechanism solutions, De Novellis et al. (2018)  
 79 proposed that the 2017 Ischia earthquake mechanism has been generated by an E-W striking,  
 80 South dipping normal fault, with a hypocenter located at a depth of 800 m. In that study, the  
 81 joint inversion of DInSAR and GPS coseismic measurements led to estimate the origin of the slip  
 82 distribution in a main patch (maximum slip amplitude 14 cm) located at the center of the fault  
 83 plane at hypocentral depth (De Novellis et al., 2018). The strike of the fault has been found  
 84 roughly consistent with an apparent aftershock alignment along the E-W direction and with the  
 85 computed focal mechanism from regional seismic waveforms. However, the same authors  
 86 pointed out a main difference between the seismological and geodetic modelling solutions,  
 87 with an important strike-slip component of the first which is not present in the second one.

88 While the prompt availability of DInSar data allowed to rapidly provide estimates of source  
 89 location and mechanism for the Ischia earthquake, it is worth noting that DInSar data modelling  
 90 is based on the assumption that the detected ground displacement is primarily generated by  
 91 the co-seismic contribution of the causative earthquake fault. Recently, Albano et al. (2018)  
 92 revisited the DInSar data relevant to the Ischia event and investigated the possible contribution  
 93 of earthquake-induced landslides to the detected ground displacements. Based on the limit  
 94 equilibrium method, they estimated the spatial extent of the earthquake-induced landslides  
 95 and the associated probability of failure. The results of this study led the authors to conclude  
 96 that “the observed ground displacement field is the combination of both fault slip and surficial  
 97 sliding caused by the seismic shaking” (Albano et al., 2018).

98 The 2017, Ischia earthquake impact on buildings and structures of the island has been assessed  
 99 through a series of surveys conducted immediately after the event by the RELUIS-DPC team

(DPC, 2017) and INGV-ENEA team (Azzaro et al., 2017). Del Gaudio et al. (2019) reviewed the in-situ observations of the damage state of masonry and RC buildings in the epicentral area and matched them with the simulated damage scenarios built upon the data from the 15th national census of the population and dwellings (ISTAT) converted into vulnerability classes. The latter are expressed according to the classification of the European Macroseismic Scale (EMS-98). In evaluating the seismic damage scenarios, the intensity shake map of the 2017 Ischia event is reconstructed using an interpolation method based on QUEST macro-seismic survey data (Azzaro et al., 2017). The map shows an anisotropic distribution of intensities, with highest values in the SE and SW directions from the epicentral area, with the former having a more pronounced and extended lobe.

The present work has been primarily motivated by the availability of a high-quality strong-motion record in the near-source distance range (less than a 1 km epicentral distance) of the 2017, Ischia earthquake. Our refined modelling of the high-frequency signals (up to 3 Hz) brought new insight on both extended fault and rupture mechanism. Indeed, previous modelling of the IOCA waveform in De Novellis et al. (2018) and Braun et al. (2018), mainly concerned the low frequency band (0.1-2 Hz) and assumed a point-source earthquake approximation.

The anomalous duration (about 4 sec) of the large amplitude, velocity and displacement waveforms observed at IOCA station (Figure 2), as compared to the expected (about 1 sec) source duration of similar size events (Wells & Coppersmith, 1994), suggests a possible coupling effect of the very shallow earthquake rupture and wave propagation across the near-surface

sedimentary layers which could have contributed to amplify and extending the ground shaking duration and hence the event damaging effects.

We mainly adopted a two-step modelling procedure of the strong motion records assuming, first, a point-source mechanism, and then a finite-fault model where a forward modelling is combined with a non-linear inversion technique to retrieve the kinematic rupture model information (e.g., rupture length and orientation, slip distribution along the strike and average rupture velocity) and therefore it allows generating a synthetic shake map. In addition, the rupture model has been validated through the GPS data modelling and peak ground velocity prediction as converted from intensity contours.

The retrieved rupture model coupled with multi-path reverberations effects related to a thin, low velocity near-surface volcanic sedimentary layer, allows to explain the observed ground motion duration at IOCA and strong shaking amplitudes and intensities recorded all over the island. The joint interpretation of seismic, geodetic, and geological structural data point to an earthquake triggering process related to long-term volcano resurgence phenomena.

## **2 Geological and Volcanological Setting of Ischia Island**

Ischia belongs, together with volcanic islands of Procida and Vivara along a SW direction from the caldera of Campi Flegrei, to the Phlegraean volcanic district that was built since Pliocene as a result of the extensional deformation that involved the Tyrrhenian margin of Apennines chain and generated the graben of Campanian Plain (Gillot et al., 1982; Vezzoli, 1988).

Ischia is an active volcano that rises above the seafloor for over 1000 m (Bruno et al., 2002), whose natural hazard is connected to its magmatic system and the related interdependent

142 phenomena (Selva et al., 2019), as testified by the large number of eruptions occurred in  
143 historical times with the most recent of the 1302 AD (Vezzoli, 1988; Iacono, 1996).

144 Nowadays, the island is interested by an active hydrothermal system with widespread  
145 fumaroles and thermal springs (Chiodini et al., 2004; Di Napoli et al., 2011 and references  
146 therein) and seismic activity.

147 The oldest existing rocks on the Island of Ischia show an age of ca. 150 ky as evidenced by the  
148 K/Ar radiometric dating method (Vezzoli, 1988). By geological, volcanological, and petrological  
149 studies, in the last 55 k.y. of history, the volcanic system has been extensively restored (Civetta  
150 et al., 1991) as result of periods dominated by different differentiation processes related to the  
151 injection of new magmas (less differentiated) into a shallow reservoir (De Vita et al., 2010). The  
152 first period (55–33 k.y.; Gillot et al., 1982; Vezzoli, 1988) was dominated by the Monte Epomeo  
153 Green Tuff eruption that formed a volcanic caldera located at the center of the island. Since 33  
154 ka, the Ischia volcanic system experienced an asymmetric resurgence of the caldera floor due to  
155 the injections of new magma, forming the Monte Epomeo block (Orsi et al., 1991).

156 The complex volcano-tectonic framework of Ischia is related to the two regional fault systems  
157 with NE-SW- and NW-SE-trending, whose intersection controls the structure of the island  
158 (Acocella & Funiciello, 1999; De Vita et al., 2010) and it was responsible for shallow-depth  
159 magma emplacement and extrusion (Acocella et al., 2001) during the Pliocene-Quaternary  
160 extensional phases. The reactivation of regional faults and the newly generated fault activity,  
161 directly connected with volcano-tectonism, produced the resurgence of the irregularly  
162 octagonal shape block of Monte Epomeo (Orsi et al., 1991; Acocella & Funiciello, 1999). The



block displays an asymmetrical structure due to a variably and irregular growth that caused a tilt along an NE-SW trending horizontal axis and a larger uplift in the NW part of the caldera area. In this area, the deformation has been accommodated by inward-dipping, high-angle reverse faults, whose trends range between NE-SE to NW-SE through NS directions, especially at edges of the most uplifted block. Subsequently, gravitational instability phenomena produced late outward dipping normal faults, that cut the former tectonic features (Chiodini et al., 2004; De Vita et al., 2006). The area located to the E and SE of this block has been downthrow by several normal faults (N-S-, NE-SW-, and NW-SE-trending) through a series of differentially displaced blocks connected with the resurgent area of Monte Epomeo (De Vita et al., 2010).

Although several hypotheses have been proposed for the resurgence of Monte Epomeo block, the injection of new batches of magma towards shallow depths is the most accepted triggering mechanism by several authors (e.g., among others, Rittmann, 1930; Rittmann & Gottini, 1980; Orsi & Chiesa, 1988; Orsi et al., 1991; Luongo et al., 1995; Carlino et al., 2006).

The last 10 ky of the Ischia volcanic system was characterized by alternating periods of quiescence and periods of intense volcanism, especially at ca. 5.5 ky and over the past 2.9 ky (De vita et al., 2010). Structural and volcanological evidences show that the volcanism in this period was strongly influenced by the resurgence mechanism, which allowed new upward impulses of magma mainly in the eastern area of the island (Orsi et al., 1991; Marotta, 2001). In this sector, located outside the resurgent block, the magmatic activity produced local stress field likely capable of activating pre-existent regional faults developed in the extensional regime (De Vita et al., 2010). Since the volcanism at Ischia island was discontinuous in the last 33 ka,

185 the magma intrusion, as well as the caldera resurgence, is supposed irregular and intermittent  
186 through time (Orsi et al., 1991; Tibaldi & Vezzoli, 1997).

187 The resurgence of Monte Epomeo controlled, not only the volcanic activity, but probably the  
188 slope-instability that preceded and followed the emplacement of volcanic products as  
189 evidenced by geological data. In fact, in the past 5.5 ka, the volcanic eruptions coexisted with  
190 slope failures or mass movements that led to the development of terrigenous landslides  
191 deposit (De Vita et al., 2006; Selva et al., 2019).

### 192 **3 Data and Methodologies**

193 The 2017 Ischia earthquake has been well detected and recorded by INGV seismic stations on  
194 the island and on the Italian peninsula up to few hundreds' km far from the epicenter. Although  
195 at near-source distances few stations were operating, only the three-component accelerometer  
196 IOCA recorded the unsaturated and complete signal radiated from the earthquake. Two further  
197 INGV seismometer stations (velocity sensors, i.e., CAI and F09, Figure 1) show clear P-onsets,  
198 while the following seismic phases are clipped. Considering the event location reported by INGV  
199 network, IOCA is located at few hundred meters North of the epicenter; it measured peak  
200 amplitudes in acceleration (PGA) equal to 0.28 g (on both the EW and vertical components),  
201 velocity (PGV) of 18.14 cm/s, and displacement (PGD) of 2.32 cm.

202 To model this earthquake, we mainly performed a multi-steps strategy using various data and  
203 including different methods and the processing steps as it is presented in the following sections.

204 As a summary first, the three-component waveforms recorded at IOCA have been modelled to  
205 determine the rupture kinematic parameters of the 2017 Ischia earthquake using a two-step

modelling approach. In the first step, assuming a point-source approximation, the centroid location of the source and its focal mechanism have been constrained by modelling the low-pass filtered (up to 0.5 Hz), early P- and S-wave signals at IOCA station (about 2-seconds after the P-onset). In the second step, a signal time window of four seconds, which includes large amplitude reverberations appearing on the horizontal components and an extended frequency band (up to 3 Hz) have been used to retrieve the parameters of a finite-fault source model (linear rupture): rupture model (uni- or bi-lateral), length, velocity and slip amplitude along the line. Finally, to validate the retrieved rupture model, we compared the predicted and observed ground displacement model inferred from the GPS data, and matched the observed intensity map with synthetic generated peak ground velocity and acceleration.

### 3.1 Point-Source Approach

Assuming the point-source approximation, the source position and mechanism parameters, have been obtained by inverting the three-component strong motion records at the IOCA station in the time domain. To this purpose, the signals have been band-pass filtered (first order Butterworth filter) in the frequency band (0.05-0.5) Hz to be compliant with the point-source approximation, given the expected kilometric rupture size, depth and wave propagation velocity of shallow sedimentary layers.

For the waveform's inversion, we applied the unconstrained, nonlinear Powell's optimization algorithm (Powell, 1983; Tonel, 2020). This technique allows to retrieve the focal mechanism angles (strike, dip and slip) by optimizing a cost function built upon the criteria of both minimizing the Root-Mean Square Deviation (RMSD) and maximizing the Correlation Coefficient

227 (CC) parameter between observed waveform data ( $A^{obs}$ ) and calculated synthetics ( $A^{syn}$ ),  
 228 defined by:

$$RMSD = \sqrt{\frac{1}{N} \sum_{i=1}^N \|A_i^{obs} - A_i^{syn}\|^2} \quad (1)$$

$$CC = \frac{1}{N-1} \sum_{i=1}^N \left( \frac{\overline{A_i^{obs}} - \mu_{A^{obs}}}{\sigma_{A^{obs}}} \right) \left( \frac{A_i^{syn} - \mu_{A^{syn}}}{\sigma_{A^{syn}}} \right) \quad (2)$$

229 where  $N$  indicates total number of points in the discrete waves, and  $\mu$  and  $\sigma$  are the mean and  
 230 standard deviation of the signals, respectively.

231 The Powell's inversion method in an iterative procedure performs multi-dimensional  
 232 optimization to search for a local minimum in the model parameter space of a real-valued  
 233 function of observed and theoretical data computed from a given vector of model parameter  
 234 values. The search is initialized by setting a number of initial vectors of parameter values.  
 235 Typically, the initial search vectors are simply the normal parameter values aligned to each  
 236 model parameter axis. The algorithm establishes a model cost function of the actual model  
 237 parameter values  $Q_k$  by quadratic interpolation and then minimizes it  $Q_k$   
 238  $Q_k$  within a trust region with an iterative procedure.

239 Due to the expected strong non-linearity and not-uniqueness of the inverse problem solution,  
 240 the choice of the initial vector parameter for the Powell' inversion algorithm is relevant. For this  
 241 reason, we run the inversion using 11 different initial mechanisms (Figure 3c) which included  
 242 strike-slip, normal, thrust and reverse-oblique fault mechanisms, consistent with the observed  
 243 pattern of faults in the epicentral area (Acocella & Funiciello, 1999, 2006).

244 Among the tested initial mechanisms, we also considered the INGV (De Novellis et al. 2018)  
245 solution and three further mechanisms (Figure S1) resulted from the inversion of first-P- and S-  
246 wave polarities at CAI, F09 and IOCA stations and moment tensor inversion of the regional  
247 waveforms as well. To obtain these three initial mechanism solutions, we applied different  
248 methodologies relying on different pieces of information as explained below.

249 First, combining the information of S-wave polarization (IOCA) and P-wave polarities (IOCA, CAI,  
250 F09), we performed a non-linear inversion for studying the earthquake mechanism following  
251 Zollo & Bernard (1991). The posterior probability for the strike, dip and rake of the focal  
252 mechanism is computed using a Bayesian approach (Lancieri & Zollo, 2008), relying on  
253 observational data and a refined flat-layered velocity model retrieved in this work and  
254 described later (Figure S2).

255 Also, this analysis is used to constrain the depth and epicentral distance range of the source  
256 from station IOCA, consistent with the first P and S arrival time modelling. The origin time of the  
257 event has been constrained to the value provided by the INGV bulletin. This analysis gives an  
258 earthquake depth range of 300-800 m with epicentral distance of 400-800 m from IOCA.

259 Second, P-wave polarities provided by the Ischia island and Italian peninsula records are also  
260 inverted to find the double-couple fault-plane solution that best fits the observed first motions  
261 using FPFIT code (Reasenberg & Oppenheimer, 1985, Figure S3). The position of the seismic  
262 stations on the focal sphere is calculated using a gradient average model derived from a 1-D  
263 regional velocity structure (Scognamiglio et al., 2009), which allows to minimize the take-off  
264 angles of seismic P-wave rays by the depth of horizontal interfaces.

Finally, the moment tensor solution for the Ischia earthquake has been determined by the Time Domain Moment Tensor (TMDT) full waveform inversion (Dreger, 2003; Dreger & Helmberger, 1993). The complete, three-component broad-band displacement waveforms are inverted to estimate a point-source solution by fitting the synthetic seismograms to the observed data considering a regional velocity model (Herrmann et al., 2011). We used the broad-band velocity waveforms, filtered in a frequency band 0.05-0.1 Hz with a length of 120 seconds, recorded at 12 seismic stations within 150 km from the earthquake epicenter. We evaluated the source depth by finding iteratively the solution that yields the largest variance reduction (keeping the same observed data). The percentage of double couple component (fixing to zero the volumetric component in the TDMT algorithm) of the moment tensor solution is estimated, additionally, varying and testing different source depths with a sampling of 500 m (for more details, see supplementary material).

Given the small expected rupture length, it is important to determine the location of the earthquake rupture nucleation point with the highest possible level of accuracy. Indeed, the preliminary solution (considering a 1D-velocity model, Capuano et al., 2015 ) available from the probabilistic location method NNLOC (Lomax et al., 2000) and using the first P- and S-arrivals at inland stations at local and regional distances (maximum distance equal to 5.6 km) provided a relatively large error volume ellipsoid (axis lengths of 4 and 2 km, respectively) associated with a maximum likelihood epicentre located about 1 km south of station IOCA consistent with the solution given by (De Novellis et al., 2018).

As for the velocity model to be used for simulations, we adopted the 1D velocity model available from the literature and used by INGV to locate the earthquakes occurring at Ischia

287 island and in the more large Campi Flegrei area (Capuano et al., 2015). We further refined this  
288 4-layer velocity model (Figure S4), by subdividing the shallower 900m thick velocity layer in  
289 three further layers with variable thickness, P-velocity and  $V_p/V_s$ . In order to estimate the  $V_p$ ,  
290  $V_p/V_s$  and thickness of these shallow layers, we performed a grid-search analysis for the  
291 optimal values relying on waveforms that matched the average amplitude, frequency content  
292 and duration of the observed horizontal signals.

293 Based on the previous preliminary location, we explored the possible point-source earthquake  
294 position as nodes of three circular grids centred at station IOCA and having 600m, 900m and  
295 1200m radius respectively, for a total of 24 explored potential source locations (see Figure 3).  
296 After preliminary analyses and trial forward modelling, we fixed the depth of the source at 1.1  
297 km, moment magnitude  $M_w$  4 and an isosceles triangular source time function with total  
298 duration of 1 sec.

299 The synthetic seismograms for point- and line-source kinematic rupture models have been  
300 obtained computing numerical Green's functions in the 1D refined velocity model for the Ischia  
301 island using the code AXITRA (Coutant, 1990). AXITRA is based on the discrete wave number  
302 method (Bouchon & Aki, 1977). This method introduces a spatial periodicity of sources to  
303 discretize the radiated wave field, and it is based on the Fourier transform in the complex  
304 frequency domain to calculate the Green's functions.

305 For all the initial testing configurations including the 11 different source mechanisms and 24  
306 point-source locations in the circular grid around the IOCA station (Figure 3a/c), we run the  
307 Powell' inversion method to find the optimum location and mechanism of the rupture initiation

providing the minimum cost function value by fitting the observed and synthetic waveforms using a L2 minimum norm criterion. Figure 3 summarizes the results of the first step of our analysis. The best-fit point-source locations are obtained at circular grid nodes in W-NW sector within 600-1200 m epicentral distance from station IOCA, while the preferred focal mechanism solution is a N115° striking (conjugate plane, N227°) thrust fault with a significant right-lateral strike slip component. Figure 3b shows the comparison between the observed (black) and synthetic (red) waveforms for the best point source specified with number 1 in Figure 3a.

### 3.2 Finite-Fault Model

The obtained source position and mechanism parameters are taken as a reference model for the next step, which assumes an extended linear rupture to invert the whole 4-second duration waveforms in a higher frequency range. In this second modelling step, the preliminary information about the earthquake location, focal mechanism and velocity model inferred by the point-source analysis have been used as prior information to estimate the kinematic parameters of the linear rupture model.

It is worth to note that distinguishing between the nodal planes in the case of a point source is not possible, since the cost function values (RMSD or CC) are the same value for both fault planes. However, in the extended source model, the causative fault is possibly distinguished from the auxiliary plane as the associated seismograms and cost function values of each plane are made different by the rupture directivity. As for the line source geometry and orientation, since there is no prior information about the causative fault, both the fault plane solutions derived from the first step of the analysis have been tested in this second step of modelling.



329 The earthquake rupture is set as a line source with 1 km length (e.g. the expected rupture  
330 length for an earthquake of magnitude about 4 (Wells & Coppersmith, 1994)) discretized with  
331 four point sources, with a spacing of 250m along the line. The final number of sources  
332 composing the line and their relative spacing have been chosen after preliminary trials with  
333 different point-source spacing, considering the frequency range of the analysis (0.5-3Hz) and  
334 realistic values of rupture velocity to avoid the aliasing effect.

335 The slip-rate history at each of the radiating sources along the line is described by an isosceles  
336 triangular source-time function with equal duration of 1 second and varying amplitude, related  
337 to the point-source seismic moment.

338 We inverted the 0.5-3 Hz band-pass filtered horizontal velocity records at station IOCA using  
339 the Powell' method (and same cost functions as for the point-source step i.e., CC and RMSD) to  
340 search for the optimal distribution of the seismic moment for each of the considered point  
341 sources and uniform rupture velocity ( $v_r = \alpha v_s$ ). In addition, for each of the two fault planes of  
342 the previously retrieved point-source mechanism, the location of the point-source originating  
343 the rupture was evaluated in the inversion process by considering all sources as a possible  
344 rupture nucleation point.

345 For both fault planes of the source mechanism and all rupture models assuming the nucleation  
346 at each of the considered point-sources along the line, we run the Powell' inversion starting  
347 from 10 initial models with variable seismic moment distribution and average rupture velocity.  
348 All the resulting final 80 models (two lines x 4 point-source origin x 10 initial models) have been  
349 classified following their cost function values. By comparing only the best-fit cost function

(minimum RMSD and maximum CC among 10 initial models) for each point-source assumed as the initiation of the rupture, distinguishing between both nodal planes was not easy relying only on the RMSD values, as the difference between some categories were negligible and we faced a multi-minima problem. While the CC parameter played an important role to find the optimum model among all explored configurations as it is shown in Figure 4c. This figure represents the maximum CC for each point-source as the nucleation of the rupture.

To evaluate the cost function of the Powell' inversion method, we calculated the synthetic seismogram using the code AXITRA that has already been used for the first modelling step. During all simulation steps, the comparison between the observed and synthetic seismograms is done using a time window starting from the P-wave onset, which is picked manually for observed records and automatically for synthetic signals with theoretical arrival time estimated by TauP Toolkit (Crotwell, et al., 1999). To avoid any error in picking the P-arrival time, the alignment of observed and synthetic signals is also controlled by computing the signal cross correlation and shifting the signals accordingly when this value exceeded the threshold value of 0.2 seconds.

Therefore, among the 80 explored configurations along both nodal planes and assuming the CC parameter as a best cost function provided the best waveform misfit, the optimum line-source of this event is modelled as it is shown in Figure 4a.

The retrieved best-fit line-source model shows a bi-lateral (origin at the second point source from the north-western end) rupture propagation with a constant rupture velocity, 75% of the

average shear wave velocity within shallower first km layers. Figure 4b presents the comparison between the observed and synthetic waveforms inverted using finite dimension fault model.

## 4 Discussion

### *Fault mechanism and rupture model*

The 2017 Ischia earthquake has been recorded by the three-component accelerometric station IOCA located at a near-source epicentral distance ( $< 1$  km) showing a low-frequency, large amplitude ground shaking and long lasting (about 4 seconds) S- and surface-wave signal much longer than the expected source duration of similar size ( $M_w \sim 4$ ) events recorded worldwide (Wells & Coppersmith, 1994). This unusual amplification and time duration of the earthquake signal can be interpreted as the combined effect of a shallow propagating rupture and multi-path wave phenomena due to a low-velocity waveguide caused by the shallow trapping geological structures such as alluvial valleys, sedimentary basins or, as in this case, recent volcanic deposits (Foda et al., 1995; Di Giuseppe et al., 2017; Sbrana et al., 2009; Penta & Conforto, 1951). Using a trial and error modelling of the low-pass filtered IOCA record, we refined the initial INGV velocity model including a fine sub-structuring of the shallower layer, with a 80m thick very low P-velocity (400 m/s) layer, lying above a 400 m thick, high-velocity (1000 m/s) layer, which allows us to properly reproduce the clear signal reverberation, about 4-second long, in the ground velocity time series.

Although the near field waves are often ignored in the earthquake modelling to calculate the synthetic seismograms, similar to the work done by Legrand & Delouis (1999), we demonstrate that these near field signals provide important information to constrain the fault plane also if

391 only one station is available, both in the case of point source and finite extended source  
 392 models. Since the amplitudes of the near field waves with source to receiver distance ( $r$ ) decay  
 393 as  $1/r^2$ , a small change in distance implies a larger change in amplitude and then provides a  
 394 sharp restriction on the orientation of the fault (Legrand et al., 1999; Legrand & Delouis 1999).  
 395 Nevertheless, even considering the smallest considered frequency range for our modelling (0.5  
 396 Hz), the observation distance remains 2-3 times greater than the S-dominated signal.

397 The inversion of the 0.5 Hz low-pass filtered horizontal-velocity waveforms at IOCA, assuming a  
 398 point-source approximation of the earthquake rupture, indicates that it nucleated at an  
 399 approximate depth of 1 km, and at an epicentral distance of 600 meters west of the IOCA  
 400 station.

401 All the fault plane solutions for the 2017 Ischia earthquake, computed in this study with  
 402 different methodologies and observed data, are compatible with a thrust kinematics and are  
 403 consistent with the same tectonic regime (see supplemental material). In fact, according to the  
 404 P- and T-axes plunges, ranging between  $4^\circ$ - $32^\circ$  and  $47^\circ$ - $79^\circ$  respectively, the focal mechanism  
 405 solutions correspond to thrust or thrust-strike slip faulting (Zoback, 1992) with a rotation of  
 406 nodal planes according to the rake angle.

407 The total released seismic moment is estimated to be  $2.5 \times 10^{15} \text{ Nm}$  which corresponds to a  
 408 moment magnitude of  $M_w 4.2$ . If we consider an approximate rupture surface of  $1000 \times 1000 \text{ m}^2$   
 409 and a local rigidity  $\mu = 2.2 \text{ GPa}$ , this gives an average slip at the fault of  $1.1 \text{ m}$  and a static stress-

410 drop  $\Delta\sigma = 3.5 \text{ MPa}$ . The latter is computed using the average slip solution for shear crack under

411 a uniform stress drop ( $\Delta u = C \frac{\Delta\sigma}{\mu} W$ ,  $C=0.728$ ,  $W=1000\text{m}$ ) (Madariaga, 1977).

412 *Simulated shake map and observed macroseismic intensity field*

413 In order to check the consistency of the retrieved source model with the observed earthquake  
 414 impact in terms of ground motion intensity, we simulated the ground motion velocity wavefield  
 415 generated by the line-source model derived from the fitting of the waveforms at station IOCA.  
 416 3Hz low pass-filtered, synthetic velocity waveforms have been computed at a dense, regular  
 417 grid of virtual nodes covering the topographic surface of the island of Ischia. Figure 5 shows  
 418 that the computed PGV areal distribution has a main NW-SE elongation with predicted highest  
 419 values of 18-21 cm/sec possibly recorded in the proximity of the station.

420 To compare the predicted PGV map with the observed earthquake damage scenarios, we  
 421 converted the interpolated iso-contours of EMS-98 macroseismic intensity provided by Del  
 422 Gaudio et al. (2019) in PGV using the Faenza & Michelini (2010) empirical relationship (Figure  
 423 5). The synthetic and EMS-intensity derived PGV maps match well showing a similar areal  
 424 pattern, consistent co-located high observed values and decaying amplitude trend with  
 425 distance from the finite fault source region.

426 *Comparison of predicted vs observed GPS co-seismic displacement*

427 Comparing the GPS data with the co-seismic displacement fields obtained with the retrieved  
 428 source model of the 2017 Ischia earthquake, five stations (AQMO, FORI, MEPO, OSCM, SANT)  
 429 show the same vertical orientation of the computed displacement and other five stations

(AQMO, MEPO, OSCM, SANT, SERR) are consistent with the horizontal one (Figure 6) (see supplemental material). On the contrary, 2 stations are opposite or not coincident with vertical (ISC, SERR) and horizontal (FORI, ISCH) displacement. Despite the same orientation for the most of GPS data, the magnitude of the displacement seems to be less constrained at the single stations. It is worth noting that most of the GPS data show an error greater than their (vertical or horizontal) records and only 2 stations (MEPO and OSCM) display a considerable offset ( $> 10$  mm). In fact, the observations at MEPO and OSCM (co-located with the IOCA seismic station), confirm the validity of the horizontal direction of the modeled coseismic displacement. Moreover, interpolating its vertical component by the cubic spline algorithm, the maximum offset is located close to maximum movement evidenced by the DinSAR data with a comparable magnitude. Our coseismic modelling obtained following Okada (1992) confirms the maximum vertical and horizontal displacements equal to 34 mm and 24 mm, respectively, that are in good agreement with the 40 mm displacement detected during the 2017 Ischia earthquake by the DinSAR (De Novellis et al., 2018, Figure 3). The discrepancy of the average fault slip used in Okada modelling (0.13 m) with the slip as inferred from the kinematic rupture model (1 m) is related to the different fault area and local rigidity selected in the two models ( $A_1 = 2.30 \times 10^6 \text{ m}^2$  -  $\mu_1 = 7.02 \times 10^9 \text{ N/m}^2$ ;  $A_2 = 1.0 \times 10^6 \text{ m}^2$  -  $\mu_2 = 2.02 \times 10^9 \text{ N/m}^2$ , respectively). For more details on the ground displacement modeling, see supplementary material.

*Possible contribution of earthquake-induced landslides to the detected DinSar ground displacements*

In Figure 6b/c, we report the maximum displacement retrieved by our coseismic displacement modelling (vertical and horizontal components) and by DInSAR data (vertical component, De Novellis et al., 2018) which are included within the larger area of widespread land-sliding occurred during past historical earthquakes (Rapolla et al., 2010). Most of the strong historical earthquakes have occurred in the northern- northwestern- area of the island and near the village of Casamicciola and, as seismic induced effect, they have triggered slope instability and landslide phenomena as demonstrated by morphological surveys, historical reports and archeological evidences (Mele & Del Prete, 1998). The strongest earthquake occurred in 1883 ( $M = 6.9$ ) produced several landslides in the northwestern sector of Ischia causing a severe damage also with its secondary effects (Rapolla et al., 2010). Our coseismic displacement modelling predicts roughly the same maximum vertical displacement ( $\sim 40$  mm) and the same area (its spatial location and dimension), but opposite direction of movement as detected by DInSAR data (downward, De Novellis et al., 2018). So, our results point out that a combined effect of co-seismic maximum displacement with dynamic solicitation and soil compaction caused by low frequency surface wave propagation, can explain the high amplitude vertical displacement observed by DInSAR in the northwestern area of Ischia, where historical earthquake occurred and seismic-induced landslide susceptibility is particularly high.

#### *The 2017 earthquake mechanism and its relation to caldera resurgence mechanisms*

Large rock and debris landslides can be originated on Ischia island with different mechanism, extension, and temporal evolution (Selva et al., 2019). Large rock mass deformation can develop over a long-time period (100 years) producing mass rock creep (Chigira 1992) that,

accelerated by an external forcing such as earthquake or eruption, may originate landslides. As documented by Della Seta et al. (2012, 2015), the NW sector of Monte Epomeo is affected by an ongoing rock mass creep that originates a slope deformation over an area of about 1.6 km<sup>2</sup> and is controlled by the mechanical behaviour of the Green Tuff (Marmoni et al. 2017) involving about 190 million m<sup>3</sup> (Della Seta et al., 2015, Selva et al., 2019). The 2017 Ischia earthquake induced, as secondary effects, several landslides such as rock falls and shallow earth-slides (Nappi et al., 2018; GdL\_DST-CentroMS 2018) close to Casamicciola (Figure 1). Looking at our results, we argue that the 2017 Ischia earthquake triggered a downward rock mass movement in the NW sector of Monte Epomeo resurgent block and, acting as external force, accelerated the ongoing slope deformation consisting in a probably long-time creeping of rock mass in the area. So, under this hypothesis, the DInSAR data could have documented a downward movement that does not correspond to the direct co-seismic fault slip (upward), but rather to a combined effect of coseismic offset and slope instability as induced effect.

As evidenced by the calculated normal fault plane solution (De Novellis et al., 2018; Nappi et al., 2018), several authors (Trasatti et al., 2019; De Novellis et al., 2018) suggested that 2017 Ischia earthquake is consistent with a deflationary mechanism due to magma degassing from a cooling magma body. A slow subsidence has been supposed active and continuous at Ischia for the last centuries as recently recorded by GPS and DInSAR data (De Martino et al., 2011; Manzo et al., 2006; Castaldo et al., 2017). Nevertheless, the source modelling of 2017 Ischia earthquake retrieved in this study seems to be not consistent with a deflationary/subsidence mechanism. In fact, the earthquake location, the fault geometry, the kinematics, and the surface coseismic displacement suggest that the earthquake activated a reverse dipping-inward



493 fault according to a resurgence mechanism of Monte Epomeo block. Although proving that the  
494 caldera resurgence is still active or not at Ischia is beyond the scope of this work, we think that  
495 it cannot be completely excluded as evidenced by our results. Several reasons can be brought  
496 to support our hypothesis:

497 1. Ischia magmatic system is still active and recent volcanic activity of the island was  
498 strongly influenced by the resurgence mechanism whose rest is not fully proved

499 2. Structural and volcanological evidences show that the caldera resurgence was  
500 discontinuous, episodic, and asymmetrical (i.e. restricted): it was accommodated by reverse  
501 dipping-inward fault system mostly at the NW-border of Monte Epomeo block.

502 3. The extensional regional stress field, as evidenced by GPS and DInSAR measurements, is  
503 not in contrast with a local stress field of the resurgence block, that in the NW sector of the  
504 island may locally allow the asymmetrical uplift of the Monte Epomeo, as proved by the  
505 volcanic activity of the last 33 ka

506 4. The subsidence of the Ischia island should be widespread and favoured by a normal  
507 outward-dipping fault system like those mapped and surveyed at the borders of Monte  
508 Epomeo, not only concentrated at its NW- sector. On the contrary, the 2017 Ischia earthquake  
509 is modelled by an inward dipping normal fault, despite the existence of a fault system with  
510 opposite dip and the presence of N-, NE-dipping coseismic fractures, as pointed out by some  
511 authors (Nappi et al., 2018).

512 5. Ischia is a complex active volcanic system in which different mechanisms (volcanism,  
513 earthquake, and slope instability) may occur with different temporal evolution and spatial

extent. Their interactions may produce different local stress field and surface deformations that can be misinterpreted when GPS or DInSAR data are measured.

Our source model is therefore compatible with a shallow earthquake located near the border of caldera resurgent block (probably still active) where mass rock creep evolved into widespread collapses, recorded by Dinsar data, at NW of Monte Epomeo. In addition, this retrieved model well fits a possible natural hazard scenario proposed for the Ischia volcano (Selva et al., 2019).

## 5 Conclusions

The analysis and modelling of seismic, geodetic, and structural geological data related to the 2017 M 4.2 (the magnitude determined in this study) Ischia earthquake allows to draw the following summary conclusions:

- The earthquake rupture nucleated at an approximate depth of 1 km, and at an epicentral distance of 600 meters west of the IOCA station along a NW-SE, 1 km long, rupturing plane (e.g. the NW-SE trending plane of the point-source mechanism solution). The rupture propagated bi-laterally at an approximately constant rupture velocity of 650 m/s, (60% of the average shear wave velocity within the first km layer). Assuming an approximate rupture surface of  $1000 \times 1000 m^2$  and a local rigidity  $\mu = 2.2 GPa$ , this gives an average slip at the fault of 1.1 m and a static stress-drop  $\Delta \sigma = 3.5 MPa$ .
- All our fault plane solutions for the 2017 Ischia earthquake are consistent with a thrust kinematics and the same tectonic regime. The P- and T-axes plunges range between 4°-32° and 47°-79° respectively, with the focal mechanism solutions corresponding to

thrust or thrust-strike slip faulting (Zoback, 1992) with a rotation of nodal planes according to the rake angle.

- The computed PGV areal distribution has a main NW-SE elongation with predicted highest values of 18-21 cm/sec possibly recorded in the proximity of the station. This pattern well matches the observed earthquake damage scenarios, as reproduced by iso-contours of EMS-98 macroseismic intensity converted in in PGV. The synthetic and EMS-intensity derived PGV maps show a similar areal pattern, consistent co-located high observed values and decaying amplitude trend with distance from the finite fault source region.
- The comparison of the GPS data with the co-seismic displacement field obtained with the retrieved source model of the 2017 Ischia earthquake shows a good consistency with vertical and horizontal orientation of the computed displacement while the absolute amplitude is less constrained. Our coseismic modelling confirms the maximum vertical and horizontal displacements equal to 34 mm and 24 mm, are in good agreement with the DinSAR detected 40 mm displacement.
- Our coseismic displacement modelling predicts the same area, a similar amplitude but opposite movement direction with respect to the one derived by DInSAR data. We hypothesize that a combined effect of co-seismic maximum displacement with dynamic wave solicitation/soil compaction can explain the observed displacement by DInSAR in the northwestern area of Ischia, where historical earthquake occurred, and seismic-induced landslide susceptibility is particularly high.

- The source modelling of 2017 Ischia earthquake, that has been retrieved in this study, seems to be not consistent with a deflationary/subsidence mechanism but rather with a resurgence mechanism of the Mt. Epomeo through an activated reverse dipping-inward fault.

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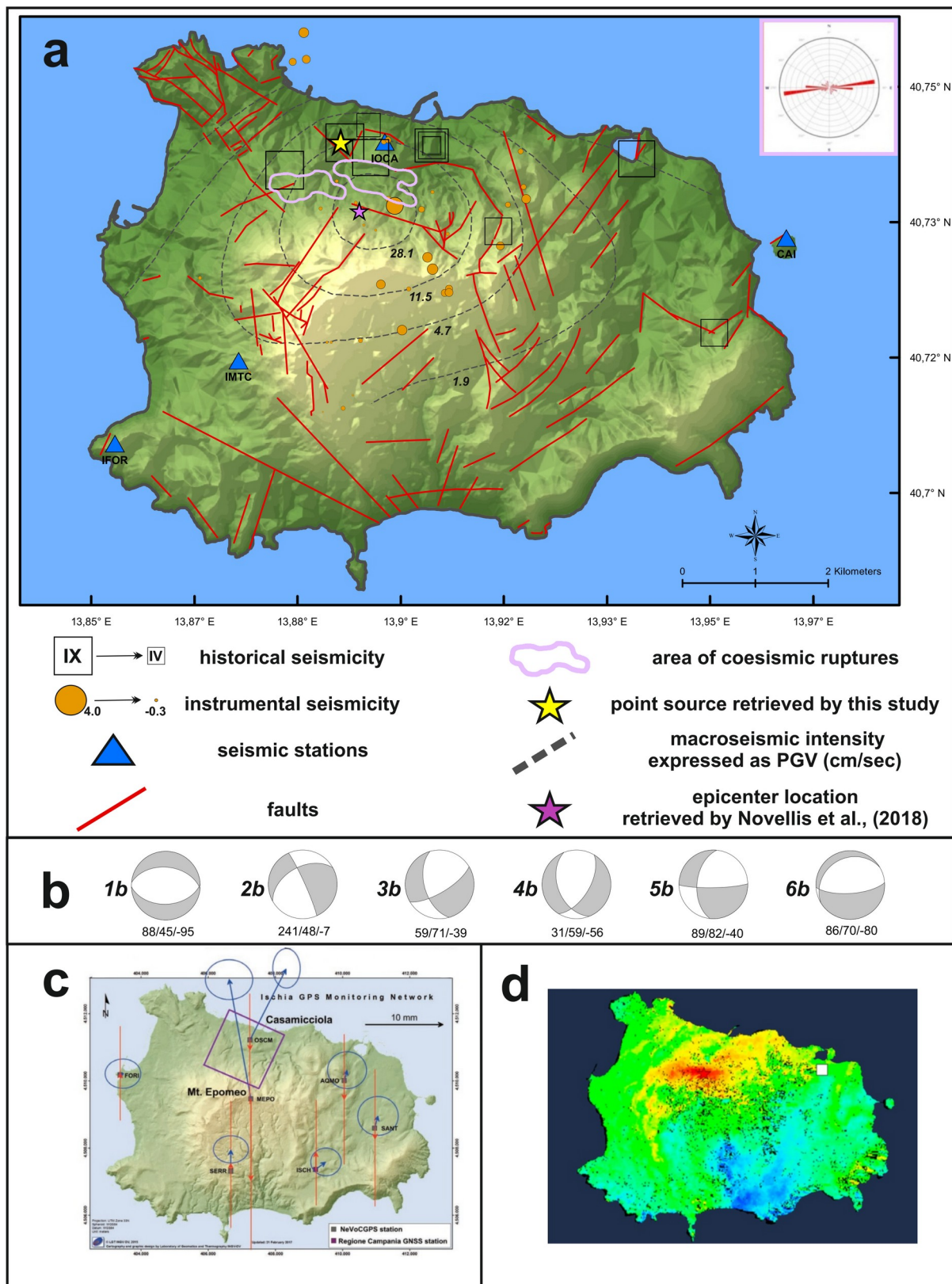
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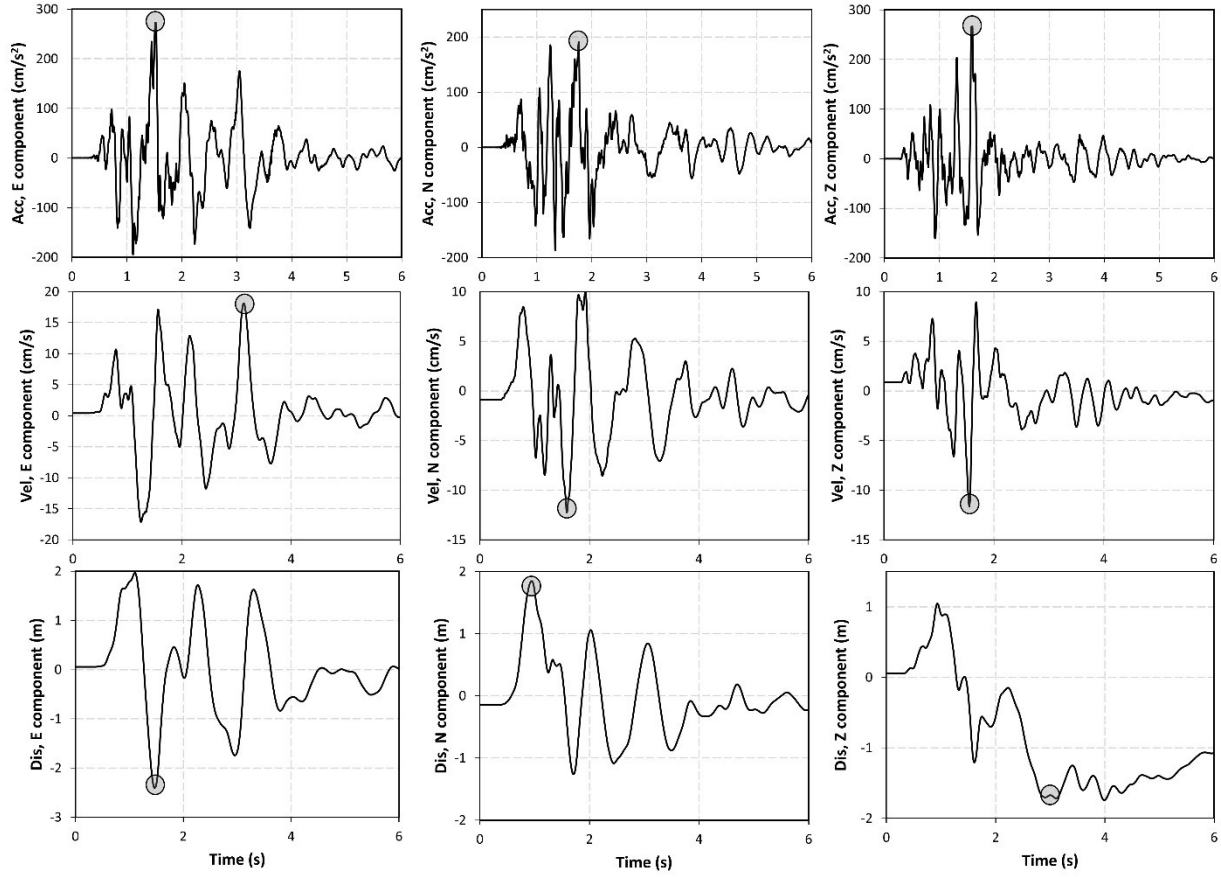
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**Figure 1.** (a) Map of the Ischia island with main structural lineaments (redrawn from De Vita

et al., 2010). Historical (Rovida et al., 2019) and instrumental seismicity (Osservatorio Vesuviano seismic bulletin, earthquake data time span is 2000-2020) is reported with epicenter locations of 2017 Ischia earthquake derived by De Novellis et al. (2018) (violet star) and by this study through the point source modelling (yellow star). Location of the coseismic geological effects of 2017 Ischia earthquake are reported with pink lines with rose diagram indicating the main directions of mapped ruptures (top left). Blue triangles correspond to seismic stations operating on the island. The 10-m-resolution DEM (Tarquini et al., 2007) is represented in the figure. **(b)** Focal mechanism solutions of the 2017 Ischia earthquake computed by different methods from recent works. Keys: 1b=Regional moment tensor by the Saint Louis University, SLU, Herrmann et al. (2011) ([http://www.eas.slu.edu/eqc/eqc\\_mt/MECH.IT/](http://www.eas.slu.edu/eqc/eqc_mt/MECH.IT/)); 2b= Regional Centroid Moment Tensor, RCMT, Pondrelli et al. (2006) (<http://rcmt2.bo.ingv.it/>); 3b= Time Domain Moment Tensor, TDMT, Scognamiglio et al. (2009) (<http://terremoti.ingv.it/tdmt>); 4b=Spectral- and waveform-based moment tensor inversions, Cesca et al. (2013) (Braun et al., 2018); 5b=Inversion of focal mechanism by using the P-wave polarities (De Novellis et al., 2018); 6b=Focal mechanism derived by the jointly inversion of t DInSAR displacement and GPS measurements (De Novellis et al., 2018). **(c)** Map of the coseismic displacement field of the Ischia GPS network with horizontal (blue arrows) and vertical (red arrows) components, from Devoti et al. (2018). The source location obtained from the inversion of GPS data (Devoti et al., 2018) is shown with purple box. **(d)** DInSAR displacement maps computed by CSK images acquired from descending orbits on 19–23 August 2017, from De Novellis et al. (2018).





**Figure 2.** 3-components acceleration waveforms recorded by IOCA station are presented on top-row panels. The middle- and bottom-row panels are velocity and displacement respectively calculated from integration. Circles show the maximum amplitude of each waveform.

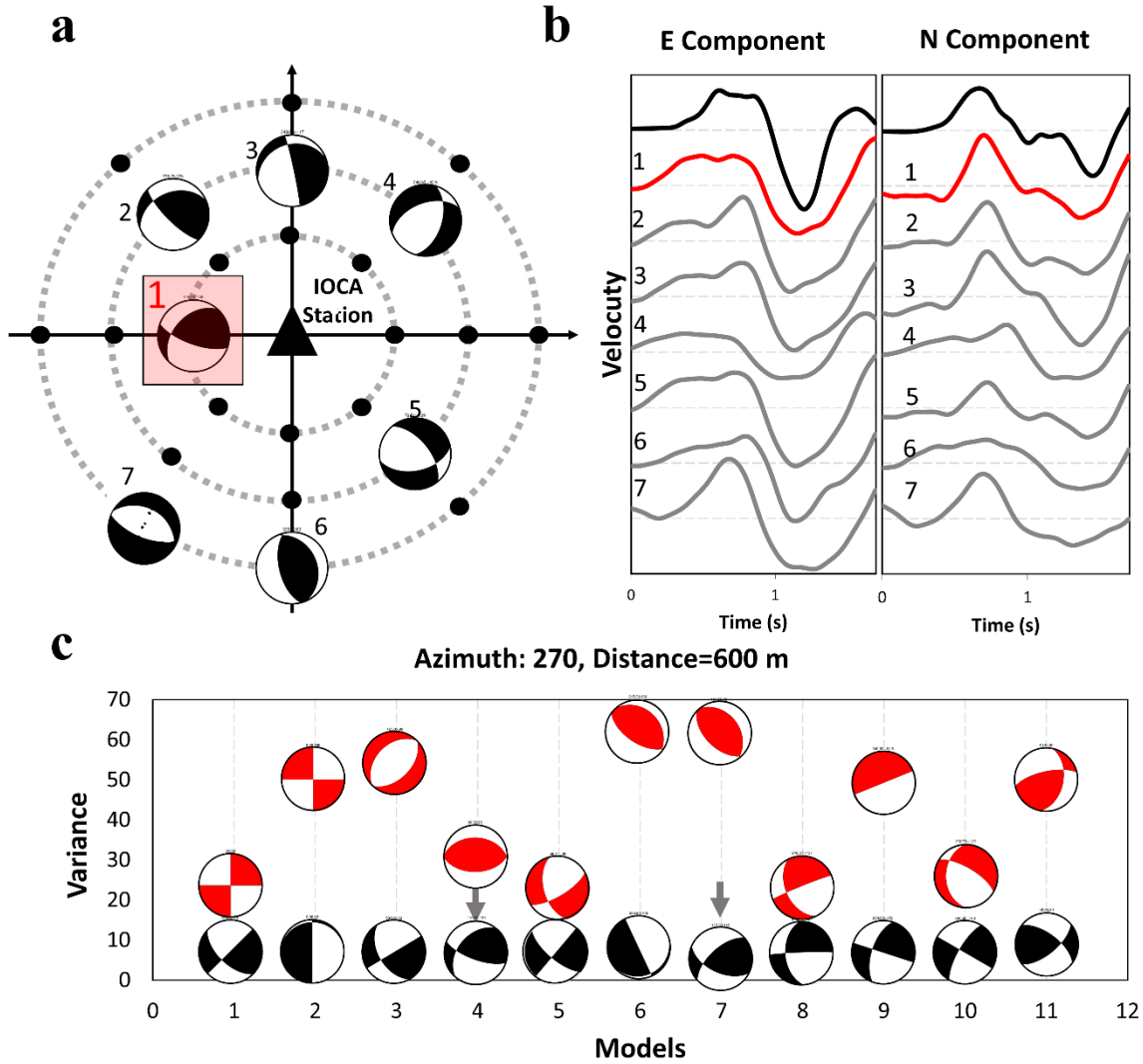
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**Figure 3. (a)** Schematic map of the point source locations in a circular grid around IOCA used in the first step of the inversion of the complete, three-component waveforms in a time domain. Final focal mechanism of some point-sources is shown as an example. **(b)** Comparison between the observed horizontal velocity waveforms (black) with the synthetic waveforms of the best point source (red) indicated with number 1 in panel a. The gray lines represent the synthetic seismograms for the other numbered locations (from 2 to 7) in panel a. All signals have been aligned from the P-onset and band-pass filtered in the frequency range of (0.05-0.5) Hz. **(c)** This

770 plot shows the output of the Powell inversion method for the best point source (number 1 in  
771 panel (a). The black and green beach-balls refer to the initial and final models, respectively.

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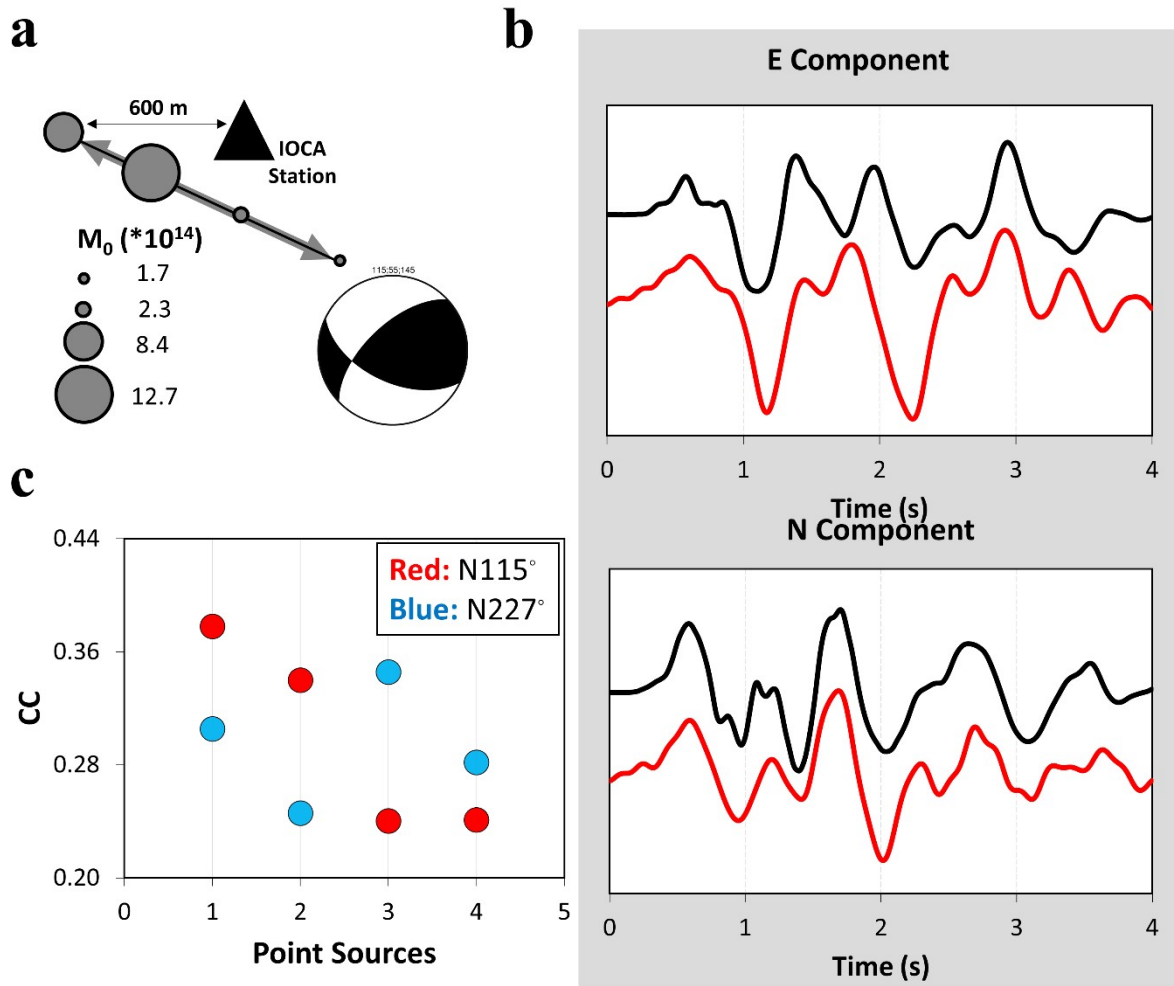
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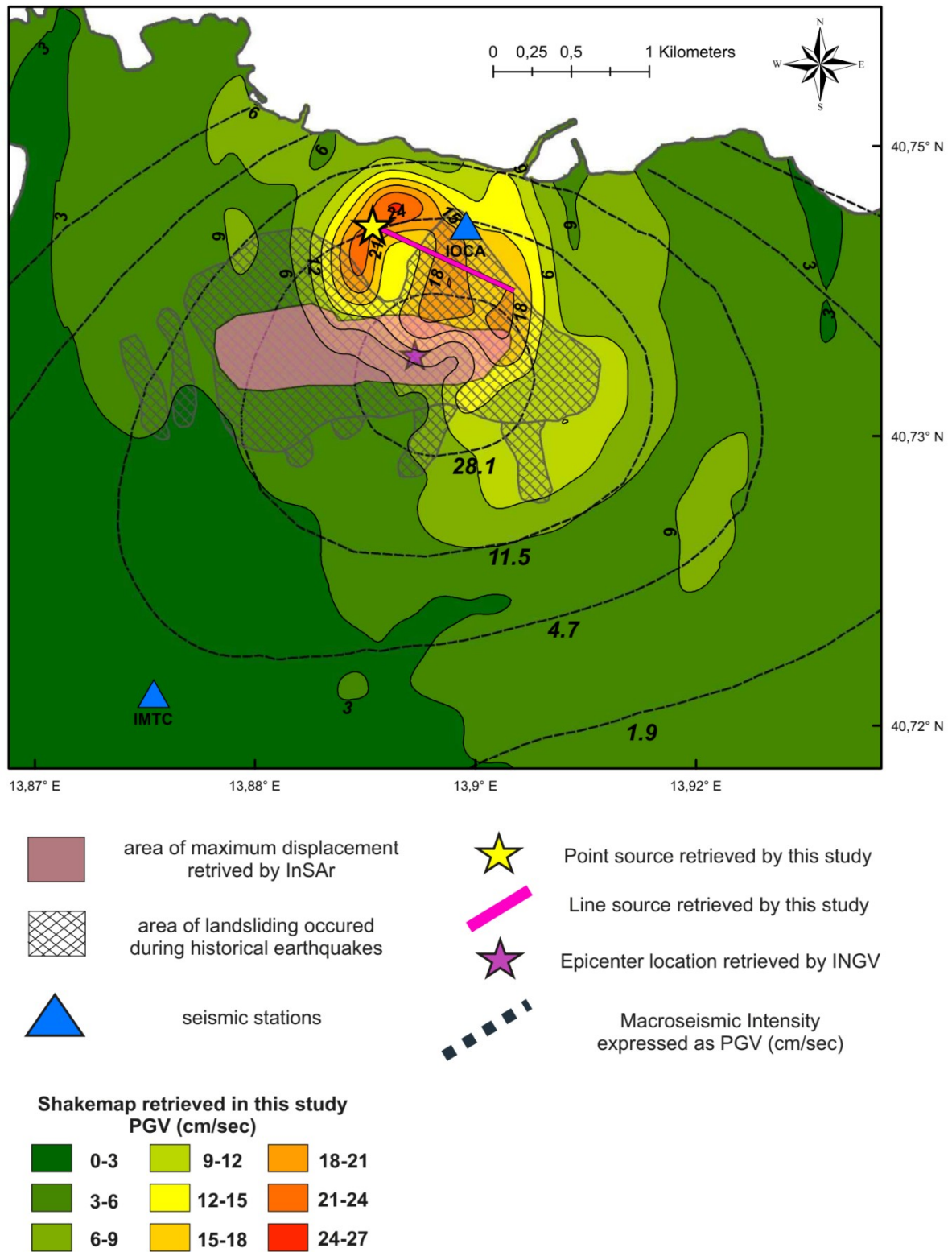
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**Figure 4.** (a) The best line-source geometry and orientation (1 km length discretized with four point-sources) with respect to the station IOCA. (b) Comparison between the observed and synthetic horizontal velocity waveforms, black and red lines, respectively. Both signals have been band-pass filtered in the frequency range of (0.05-3) Hz and aligned from the P-onset. (c) Maximum of CC parameter for each point sources assumed as a nucleation of the rupture. Different colors refer to different nodal planes as written in the legend.

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**Figure 5.** Northern sector of the simulated shake-map calculated for the final rupture model of the 2017 Ischia earthquake together with area of maximum vertical displacement (pink color) from DInSAR data and area of landslides induced by historical earthquakes (reticulate). Macroseismic intensity data, derived from Del Gaudio et al. (2019) and converted in PGV data, are displayed. Line source location derived in this study and epicenter from De Novellis et al. (2018) of the earthquake with IOCA seismic station (blue triangle) are shown.

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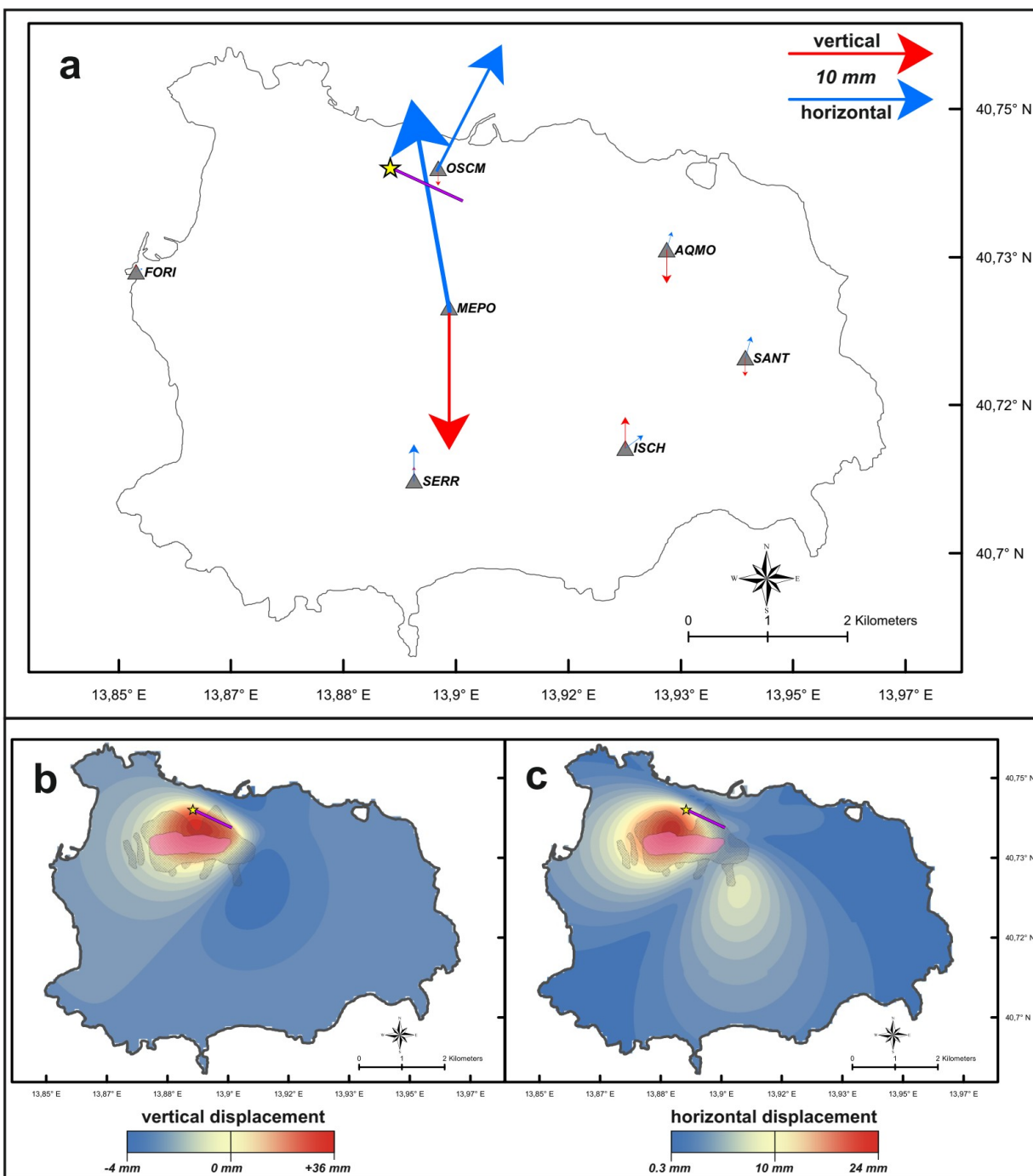
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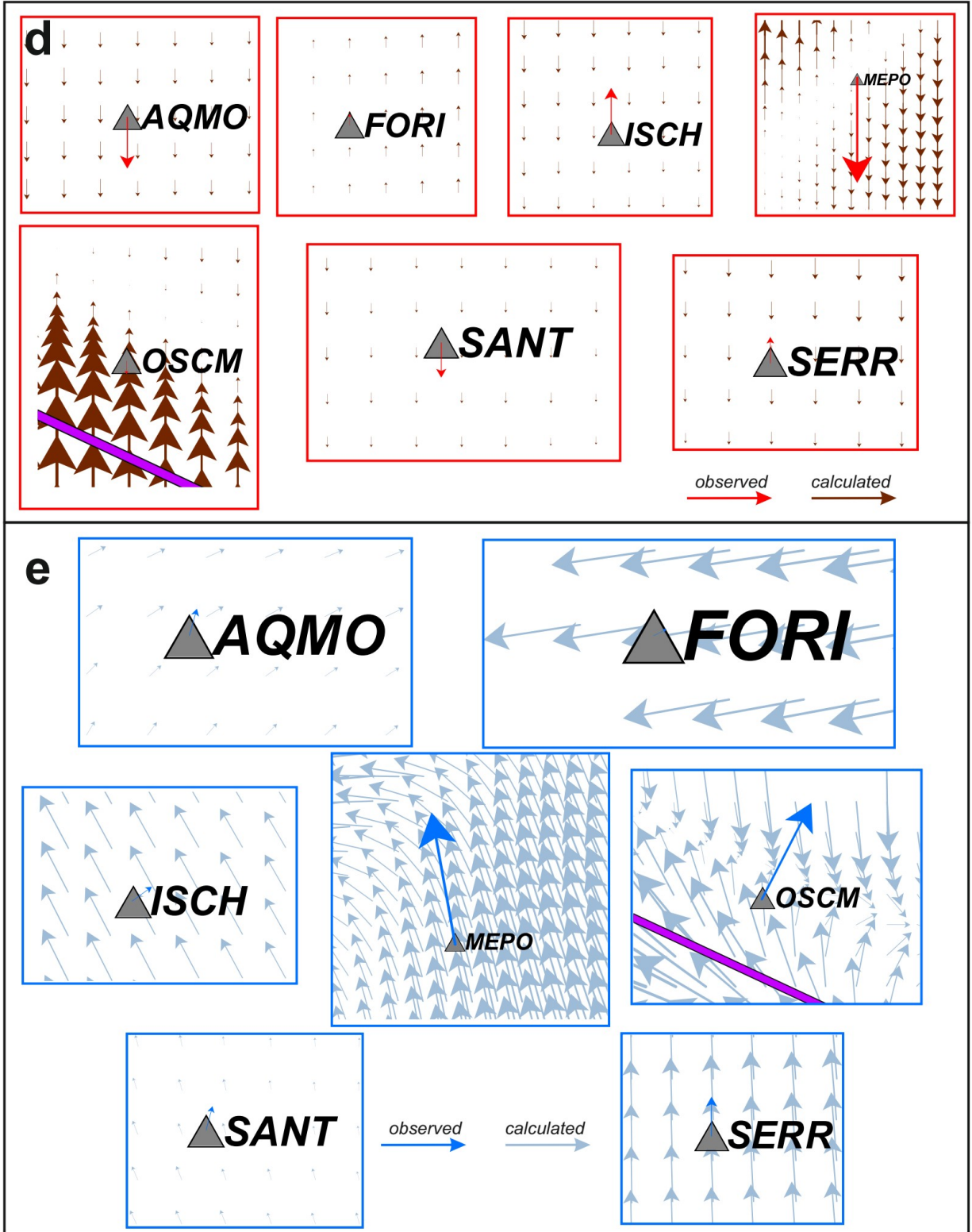
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**Figure 6.** (a) GPS measurements and network employed on the Ischia island to detect the coseismic displacement of the 2017 earthquake. Vertical (red arrows) and horizontal (blue

arrows) components, displayed in the figure, are derived from Devoti et al. (2018). Vertical **(b)** and **(c)** horizontal coseismic surface displacement, calculated with Okada (1992) by using the earthquake source model retrieved in this work, are shown. In figure, maximum coseismic displacement evidenced by DInSAR data (pink area) and area of landsliding occurred during historical earthquakes (grey area) are reported. In **(d)** and **(e)** a comparison between GPS data and coseismic surface displacement, as modelled in this study, is displayed for each GPS station. Both vertical **(d)** and horizontal **(e)** components of field displacement are calculated.