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The Casamicciola fault system (Ischia Island, Campania region, Italy): mapping the surface trace of the 1883 and 2017 earthquake source from UAV LiDAR images and 2-D ERT profiles

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ABSTRACT

We present a high-resolution topographic map at 1:5000 scale of the northern slope of Mt Epomeo (Ischia Island, Italy), where the active Casamicciola fault system is exposed, and where coseismic surface ruptures associated with the 21 August 2017 earthquake (Md 4.0) were documented. This fault system is also considered the likely source of the destructive 28 July 1883 earthquake (Io = XI MCS), which caused extensive damage and approximately 2300 fatalities. The fault mapping was conducted by integrating UAV-based LiDAR-derived topography with extensive field investigations, 2-D Deep Electrical Resistivity Tomography, and seismic ambient noise measurements. Despite logistical challenges due to urban density, vegetation cover, and rugged terrain, fault scarps were identified and mapped in detail within the Casamicciola Holocene Graben. The map reveals a nested graben structure defined by two principal faults (Monte Cito and Sentinella) and two subsidiary ones (Purgatorio and Nizzola). Improved understanding of fault geometry is essential for seismic source characterisation and surface faulting hazard assessment in this densely populated, high-tourism region.

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Volcano-tectonic earthquake; capable faults system; electrical resistivity tomography; seismic noise; lidar DTMs

1. Introduction

In this paper we provide a detailed topographic map of the northern slope of Mt Epomeo (Ischia Island) at the 1:5000 scale (Main Map), gathered through high-resolution and high-accuracy DTMs generated by drone-based LiDAR systems. We include the fault scarps, identified through extensive field investigations and geophysical surveys within the Casamicciola Holocene Graben (CHG).

Ischia Island represents the subaerial portion of a volcanic complex active since at least 150 ka (Vezzoli, 1988), located on the northwest side of the Gulf of Naples, belonging to the Campanian volcanic province (Figure 1). The volcanic activity was dominated by the caldera-forming Green Tuff eruption 55 ka, which was followed by block resurgence within the caldera since at least 30 ka. This latter was associated to an overall asymmetric uplift of ca. 900 m, finally forming Mt. Epomeo (787 m a.s.l.), with a maximum displacement on the N flank linked to an E – W normal fault system (De Vita et al., 2010; Nappi et al., 2010; Orsi et al., 1991; Tibaldi & Vezzoli, 1998; Vezzoli, 1988). The last volcanic period of volcanic activity started 10 ka, with eruptions in the eastern sector of the island, including the most recent eruption of Arso in A.D. 1302 (De Vita et al., 2010).

Evidence of intense seismic activity on Ischia dates back to prehistorical times (Covelli, 1828; Mercalli, 1884a, 1884b; Johnston-Lavis, 1885; Baratta, 1901), and the entire Island is characterized by high seismic hazard (Alessio et al., 1996; Cubellis & Luongo, 1998). Despite the relatively small magnitude of volcano-tectonic events, their shallow hypocentral depth (1-2 km) is responsible for the severe damage concentrated in a relatively small epicentral area. Local stratigraphic and geomorphic setting can locally increase ground motion amplitude, due to the occurrence of site amplification effects (e.g. Nardone et al., 2023), that may increase the potential damage. Moreover, seismic risk is exacerbated due to the high exposure during summer months, with up to 1 million of people per day visiting the Island.

In the last three centuries the most relevant earthquakes, with very strong impact, occurred in 1796,

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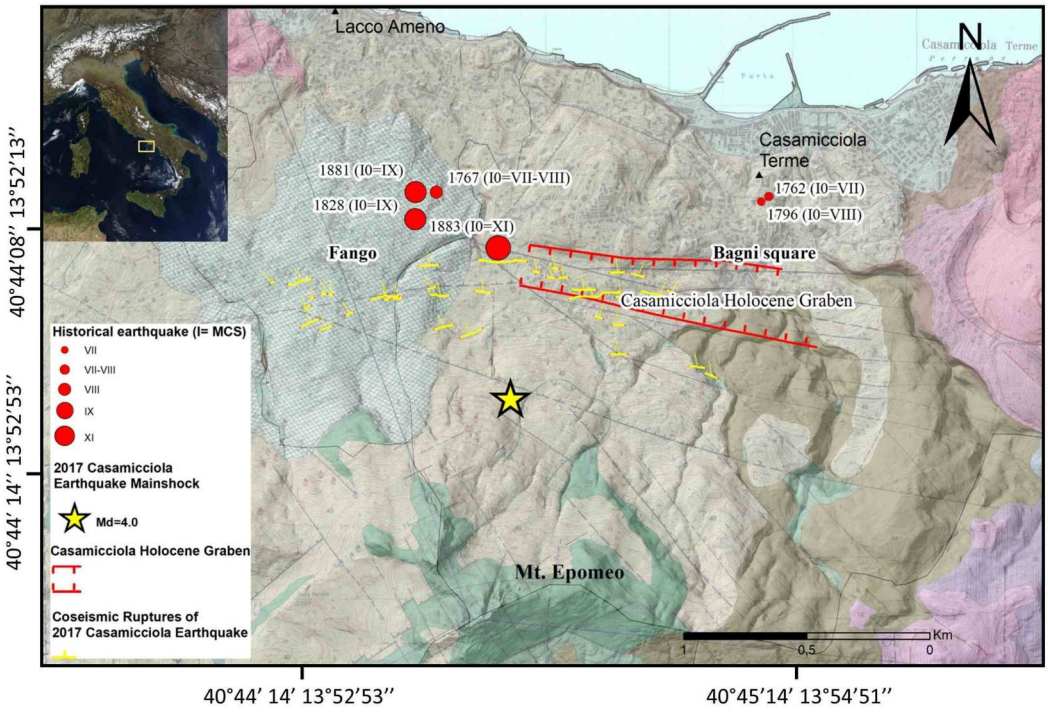

Figure 1. Seismotectonic sketch of the Casamicciola area (Ischia Island, Italy); geological map modified from Vezzoli (1988); historical earthquakes are from Selva et al. (2021); 2017 epicentral location and coseismic ruptures are from Nappi et al. (2018); Casamicciola Holocene Graben (CHG) trace from Tibaldi and Vezzoli (1998).

1828, 1881, and 1883 with epicentral intensity between VIII and XI Mercalli Cancani Sieberg (MCS) (Alessio et al., 1996; Carlino et al., 2010; Cubellis & Luongo, 1998; Luongo et al., 2006; Molin et al., 2003). The most catastrophic ones occurred on 4 March 1881 (Io = IX MCS) and on 28 July 1883 (Io = XI MCS) with macroseismically estimated magnitude Me of 4.3–5.2. Both events destroyed Casamicciola village and its surroundings, killing 120 and injuring 140 people in 1881, and claiming 2343 lives in 1883. These earthquakes repeat itself with similar characteristics over the historical time window. Their epicentral location, including the 21st August 2017, is systematically confined to the same area of about 4 km^2, extending between Fango locality and Bagni square in Casamicciola Terme (Figure 1). The Casamicciola Holocene Graben at the base of the northern flank of Mt Epomeo represents a clear stratigraphic and morphological trace of the long-term deformation due to the repetition of these earthquakes.

We aim at constraining the source fault model of the volcano-tectonic August 21, 2017 Casamicciola earthquake, supported by geological data of 2017 coseismic faulting and macroseismic observations (Nappi et al., 2018, p. 2025), in order to improve to the seismic hazard of Ischia. This seismic source was also responsible of the July 28th, 1883, Io = XI MCS earthquake, that caused more than 2300 casualties.

For reliable seismic hazard assessment and for adequate urban development planning detailed geological data on fault characteristics are essential, such as location, complexity, kinematics, slip rate, and fault-zone length and width.

Our study is based on a multiscale and multidisciplinary geological/geophysical approach, which includes: (i) a drone aerial survey using a LiDAR (Light Detection and Ranging) scanner generating a 5–10 cm resolution DTM leading to identify the morphological signature of faulting and progressive offset along primary surface ruptures, particularly on the densely vegetated southern portion of the Holocene graben; (ii) a geophysical survey of the 2017 earthquake epicentral area conducted through 2-D Deep Electrical Resistivity Tomography (ERT) with three profiles across the Casamicciola Terme graben; and (iii) seismic ambient noise and array measurements to identify the occurrence of directional amplification effects caused by fault activity and rock fracturing at depth.

The result of our research is a map showing the precise position of the traces of the active fault systems in the Casamicciola Graben. This map represents a valuable contribution for seismic risk assessment, urban development planning and microzonation studies, providing information on where we expect surface faulting during moderate to strong earthquakes. Furthermore, it can constitute a fundamental hazard basis for further studies on the seismogenic characterization of the fault with the evaluation of the associated slip rates. Finally, this map can be useful in the framework of paleoseismological studies, being helpful for siting of future exploratory trenching.

2. Data and methods

Due to the dense vegetation covering the mountain fronts of the northern slope of Ischia Island, field recognition of tectonically controlled landforms is challenging. Therefore, to map fault traces in the study area we combine both remote analysis on high-resolution (2 m pixel data) Digital Elevation Model (DEM) (Nappi et al., 2010), and high-accuracy DTMs by drone-carried LiDAR systems (20 cm). We also integrated literature data (Nappi et al., 2010; Sbrana et al., 2018; Silva-Fragoso et al., 2024; Tibaldi & Vezzoli, 1998; Vezzoli, 1988) with field surveys, in order to validate remote sensing information.

We identified and digitalized fault traces through the geomorphological interpretation of airborne LiDAR-derived imagery. Subsequently, we compare the LiDAR data with ground truthing results and shallow geophysical prospections, to confirm the volcano-tectonic origin of the identified lineaments and fault-related geomorphic features.

2.1 UAV lidar data

The availability of high-resolution and high-accuracy DTMs generated by drone-based LiDAR systems constitute a new and further improvement of morphostructural analysis of active volcanicand tectonic areas (Bonali et al., 2019; Cirillo, 2020; Menichetti et al., 2023). Drone-based LiDAR allows safer access to hazardous areas with minimal human exposure. Its flexibility to operate at varying altitudes and speeds enables the collection of extensive topographic dataset at multiple resolutions. These characteristics are especially valuable in volcano – tectonic regions, where rugged terrain is often restricting direct access to areas that provide crucial evidence of surface deformation.

The slopes of the Mt. Epomeo represent an excellent test site due to recent volcano-tectonic deformations, geothermal activity and availability of recent coseismic geological effects mapping (Nappi et al., 2018, 2021).

This approach offers high spatial resolution mapping that can penetrate dense vegetation thanks to the laser beam capability of LiDAR sensors (Salomon et al., 2024; Silva-Fragoso et al., 2024). Additionally, we used the application UAV-LIDAR sensors as a reproducible methodology for deriving DEMs while enhancing a morpho-structural analysis of landform features.

A comprehensive UAV LiDAR survey, integrated with geological field measurements, is a robust approach for characterizing active faults. It provides optimal sampling in morphologically complex areas where topographic data is sensitivity to the active tectonic processes. Additionally, it enables a highly detailed analysis of coseismic rupture structures through precise offset measurements, as well as a more accurate and rigorous assessment of uncertainties compared to previous techniques.

This analysis utilized high-resolution topographic data from the Casamicciola Holocene Graben on Ischia Island (Figure 2).

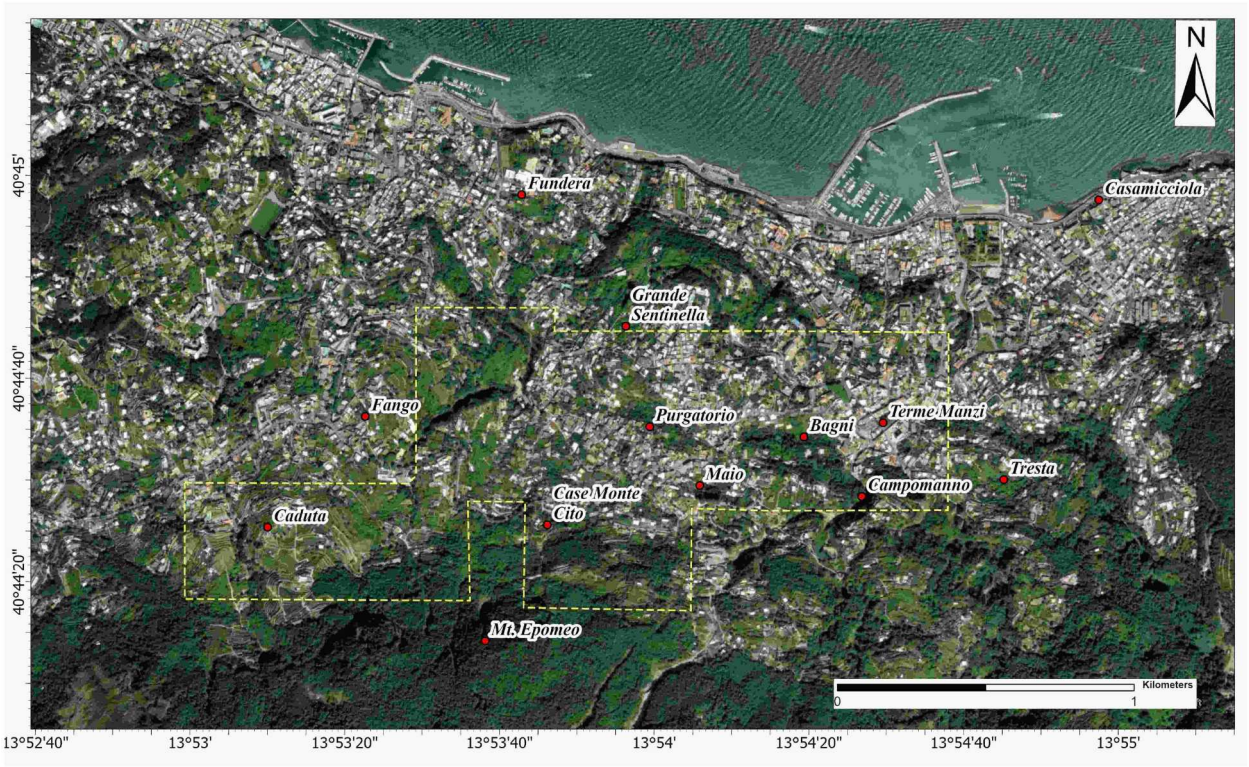

Figure 2. Northern sector of the Ischia Island. The yellow dashed line indicates the area covered by the UAV-LiDAR survey.

For this work, we conducted the drone-based LiDAR survey by employing a DJI Matrice 600 UAV equipped with a Geosun gAirHawk GS-100C LiDAR system, designed for lightweight and high-precision data acquisition. This system integrates a Livox laser scanner, GNSS, and IMU sensor for positioning and attitude determination. It is capable of capturing up to 240,000 points per second with a precision of 2 cm, detecting three echoes within a 70° field of view (FOV) and featuring a minimal laser beam divergence (iFOV) of 0.28° by 0.03°.

We piloted five flights to ensure a complete data coverage (Figure 2). Each flight consisted of multiple strips with a 30% overlap, maintained at a consistent altitude of 80 m above the ground level and a steady speed of 5 m/s. The LiDAR laser footprint width was measured at 0.39 m. The total surveyed area was 1.27 km^2 on the lower slopes of Mt. Epomeo, encompassing residential zones, roads, and dense Mediterranean vegetation, particularly in canyon regions.

We applied a methodological workflow to transition from the conventional airborne LiDAR to drone-based LiDAR technology enabling higher-resolution data acquisition (Silva-Fragoso et al., 2024)

The resulting digital elevation model has a 20 cm resolution and is provided in GeoTIFF format (Figure 3). The spatial reference system is WGS 1984 UTM Zone 33N with a vertical coordinate transformation applied to convert WGS84 ellipsoidal heights to the EGM 2008 geoid-based vertical coordinate system. Primary data products include the Digital Surface Model (DSM) and the Digital Terrain Model (DTM), while the secondary derivatives consist of slope and aspect maps. The interpretation of geomorphic indicators, linear structures, and aerial patterns from LiDAR-derived datasets facilitated a detailed structural mapping of the Holocene Casamicciola Graben (Figure 3).

2.2 Geophysical investigations across the fault systems: ERT profiles and ambient noise measurements

In order to provide additional information on the subsurface location and geometry of the fault zone, we investigated the subsoil over three transect (labeled ERT1, ERT 2 and ERT 3, Figure 4) running approximately N-S direction and nearly orthogonal to the inferred fault traces. We acquired three different scale-resolution 2-D ERT profiles by using a Syscal R2 (IRIS Instrument) and stainless-steel electrodes. For ERT1 and ERT2 we used a set of 64 and 48 electrodes spaced 5 m, for a total profile length of 128 and 96 m, respectively. Conversely, ERT3 was acquired with a set of 32 electrodes, 5 m spaced for a total profile length of 160 m.

For reaching different depths of investigation and gain a reasonable compromise between vertical and horizontal resolution of the retrieved resistivity bodies, we acquired data considering both dipole–dipole (DD) and Wenner-Schlumberger (WS) configurations. The data inversion was carried out by combining DD and WS, finally retrieving reasonable values for the absolute error, that is given by the sum of the quadratic difference between observed and modelled data after the last interaction, ranging from 1.3% and 8.1%.

We installed eight temporary seismic stations (squares in Figure 5) to record ambient noise equipped with a high-dynamic seismic digitizer Lennartz-MarsLite, and a three-component seismic sensor having an eigen period of 5 s (Lennartz LE-5 s). They recorded ambient noise varying from 1 to 2 hours during daytime, with a sample rate of 100 samples per second. All measurements were performed in the absence of rain, with a wind speed lower than 5 m/s according to SESAME (Acerra et al., 2004). They

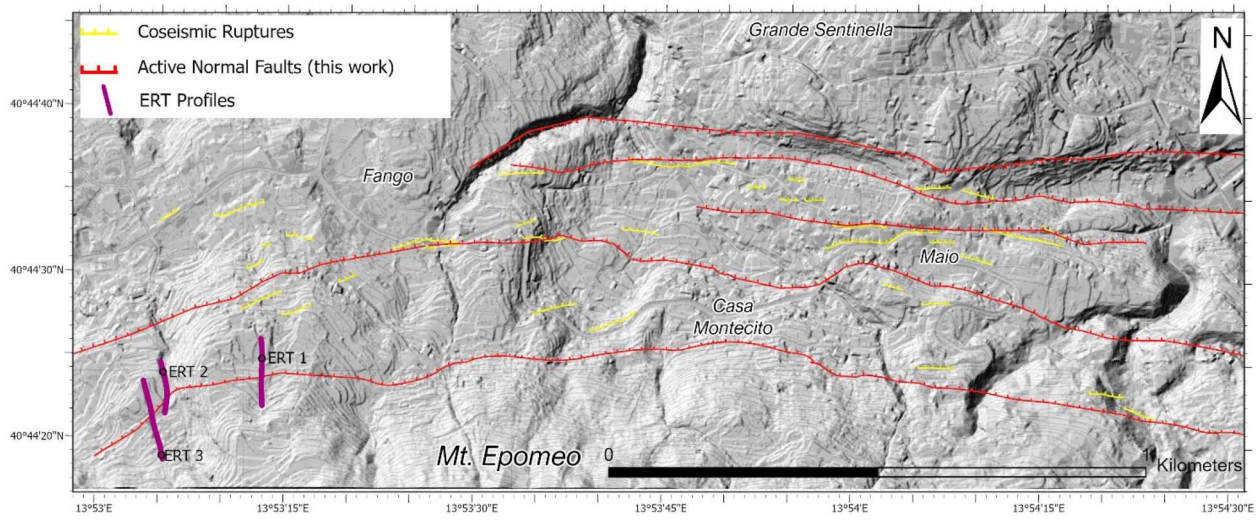

Figure 3. The Casamicciola fault system (red lines) from UAV LiDAR images and 2-D ERT profiles (purple lines) on a smoothed shaded relief image derived from the 20 cm-resolution DEM (modified after Silva-Fragoso et al., 2024).

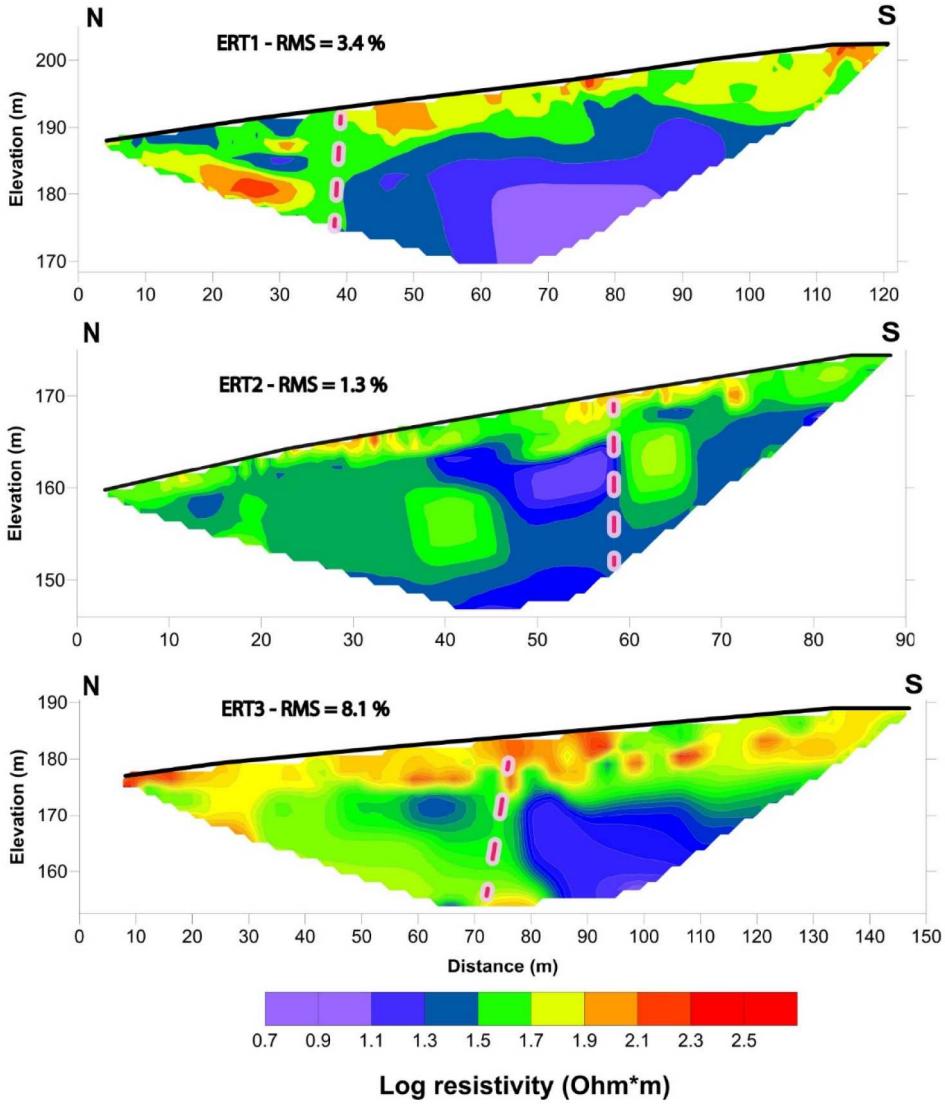

Figure 4. Recovered resistivity models from the top to the bottom related to ERT 1, 2, and 3. RMS values range from 1.3 to 8.1%.

complete a previous deployment involving 70 temporary seismic stations (Nardone et al., 2023; Pischiutta et al., 2022), installed by the INGV EMERSITO task force after the 21st August 2017 Md 4.0 earthquake, when the northern sector of the Ischia Island suffered a maximum Intensity value of VIII EMS damage. According to Pischiutta et al. (2022), we have investigated ground motion directional amplification effects by: (i) the HVSR calculation after rotating the two horizontal components; (ii) the covariance matrix analysis in the time domain.

3. Results

3.1 Fault system mapping from geomorphic analysis

Geomorphological analysis highlighted many linear features visible as rectilinear or curvilinear topographic traces on the northern slope of Mt. Epomeo. These are characterized by the continuity of the same slope values along a surface, a dominant aspect class, the density of the same strike direction and slope breaks along the same elevation (Silva-Fragoso et al., 2024). This approach enabled the identification of comparable morphological patterns a long different fault segments, refining the geometry of fault traces with high precision. We also identified other fault structures previously not reported in the available geological maps. We analysed in detail the morphological scarp through topographic profiles on the slopes. We identified a series of terraced surfaces with slope breaks, delimited by scarps (Nappi et al., 2025 submitted). Their morphometric values and their field validation allowed us to define a detailed geometry of the fault structures in the Casamicciola Holocene Graben (Figure 3 and Figure 6). In the southern part of the CHG, we mapped the southernmost synthetic faults at the base of Mt. Epomeo, north-dipping: the Monte Cito fault which represents the main fault, the Maio fault, the Purgatorio and Nizzola fault (Figure 3); the antithetic faults, in the northern part

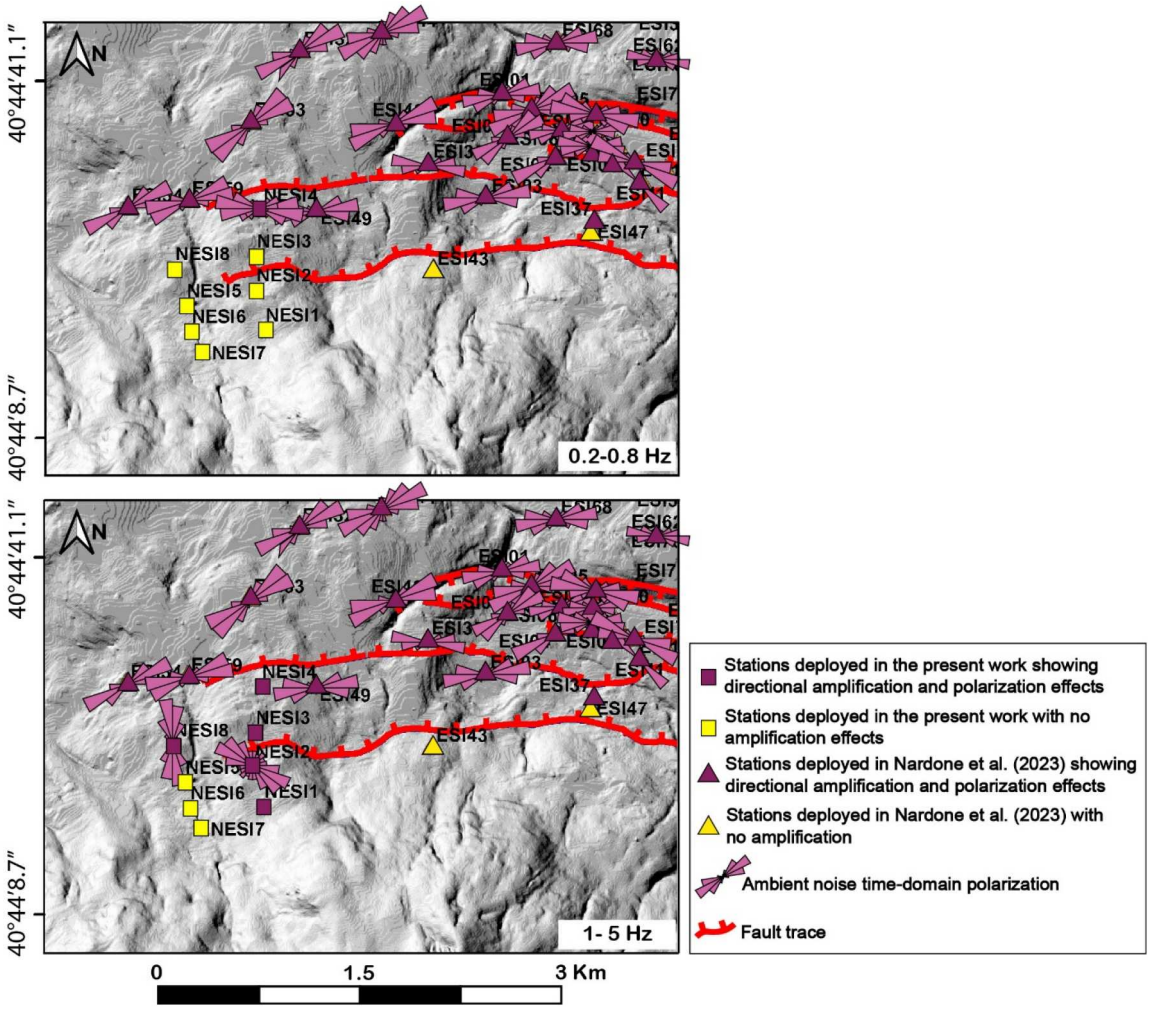

Figure 5. Polarization results gained in the two frequency bands, 0.2–0.8 Hz (upper panel) and 1–5 Hz (bottom panel), through the covariance matrix analysis at stations NESI. Yellow squares indicate no amplification and polarization effects. Stations without the wind rose (purple squares) are affected by not-directional amplification. We also add results retrieved at stations in Pischiutta et al. (2022) and identified through purple or yellow triangles, if affected or not by directional amplification, respectively.

of the Graben, such as the Grande Sentinella fault, which correspond to the main structures reported in the literature by Tibaldi and Vezzoli (1998).

Results of the ERT profiles are shown in Figure 4 as sections representing the 2-D distribution of electrical resistivity down to a depth of about 20 meters below the ground level (bgl) for ERT 1 and ERT 2, and of 30 m bgl for ERT 3. ERT 1 (top panel) reveals an electro-stratigraphic arrangement of the subsoil characterized by the presence of an uppermost layer with variable thickness (totally less than 5 m), and average resistivity values of about 100 Ω·m. Below, and up to

Figure 6. The photo shows the morphologic profile of Casamicciola Holocene Graben (white dashed line).

the bottom of the section, there is a low-resistive anomaly, with resistivity value of about 10 Ω·m. Moreover, a clear sub-vertical discontinuous band between metric 50 and 60 m along the transect (dashed lined in the Main Map) is highlighted by a sharp resistivity contrast separating an alternation of thin and sub-horizontal electrical units with different resistivities in the northern side to a low-resistive layer in the southern side.

Profile ERT2 (Figure 4 middle panel) evidences the shallowest layer with an average resistivity of 100 Ω·m, here with a variable thickness (up to 5 m). Below, this is a low-resistive anomaly (< 10 Ω·m) observed almost continuously in ERT1 is displayed only in the centre of the profile, setting among a moderate resistive background with resistivity of about 50 Ω·m. Also, in ERT2 profile (Figure 4) a lateral resistivity contrast separating is observed, approximately between 40 and 60 m distance (dashed lined in Figure 4).

The same resistivity pattern is again shown by the ERT3 section (Figure 4 bottom panel), with an uppermost high-resistivity layer (about 150 Ω·m) with thickness varying from 5 to 10 m roughly, over a low-resistivity layer (about 10 Ω·m). Again, in the middle of the section between metric 70 and 80 mt, there is a sub-vertical weak contrast (dashed lined in Figure 4), that has resistivity values increasing towards North.

Therefore, the three ERT profiles (Figure 4) accordingly identify the presence of lateral vertical contrasts at depth, confirming the volcano-tectonic nature of morphological scarps observed at the surface in the western sector.

We also analysed ambient noise measurements conducted in the northern sector of Ischia Island for identifying the occurrence of directional amplification effects potentially caused by active faults in the Casamicciola Holocene Graben.

These new measurement sites suggest that:

- Station NESI 4 shows a directional amplification effect in the frequency band 0.2-0.8 Hz along N90° azimuth (Figure 5, top panel). This station was installed close to the main fault, where Pischiutta et al. (2022) recognized a near-fault parallel polarization at a high number of stations. They interpreted such findings in terms of fault-guided waves, and/or furthermore, the role of intense fluid circulation in the hydrothermal system, causing the 90° flip of polarization (and seismic anisotropy). A similar effect is found at station NESI2 but at 1.3 Hz.
- Stations NESI1 and NESI3 show not-directional amplification (Figure 5).
- Stations NESI5, 6 and 7 do not show any amplification effects (Figure 5)

4. Conclusions

Analysis of high-resolution LiDAR images acquired by UAVs was integrated with morphometric analyses and field surveys, along with newly gathered data from 2D Electrical Resistivity Tomography (ERT) profiles. This comprehensive approach yielded a detailed 1:5000 scale map of the active traces of the Casamicciola fault system along the northern flank of Mount Epomeo.

Ambient noise measurements revealed the presence of fault-parallel polarization near the main fault, consistent with previous studies (e.g. Pischiutta et al., 2023). This effect is mainly controlled by the active fault system, which exhibits a complex surface pattern extending roughly 2 km with a strike of approximately N90°. The fault system's surface expression comprises multiple deformation zones with several subparallel traces, characterizing both antithetic and synthetic fault sets. The newly produced map significantly enhances the positional accuracy of the fault network and provides a detailed understanding of surface segmentation. LiDAR data proved instrumental in reliably identifying and mapping most fault segments; however, integration and validation with field-based geological investigations remain essential for confirmation.

Geological and structural data were indispensable for validating the kinematics of the fault system. Integration of these data with the coseismic rupture dataset available from PANGAEA (Nappi et al., 2020) facilitated validation of the geological interpretations derived from the LiDAR survey. Notably, the coseismic ruptures overlap only with specific segments of the synthetic fault system.

This spatial mismatch underscores the complex segmentation of the Casamicciola fault system and suggests that the 2017 earthquake reactivated only a subset of the pre-existing fault structures. In volcanic settings, limited surface rupture propagation is often attributable to the shallow depth of the earthquake, which can confine rupture to localized segments, and to the geomechanical properties of the terrain that affect slip distribution within the fault system (e.g. Tringali et al., 2023). The structural complexity of the Casamicciola area, including antithetic and synthetic faults, nested grabens, and variable fault geometries, can cause heterogeneous stress distributions, promoting rupture segmentation and spatial discrepancies between morphologically mapped faults and coseismic rupture traces.

The coseismic fractures documented from the 2017 earthquake, combined with the newly acquired geological-structural data, offer a first-time comprehensive insight into the dynamics and kinematics of the fault system characterizing the Holocene Casamicciola graben. This understanding carries significant implications

for seismic hazard and fault displacement risk assessments at the local scale also in terms of site-specific fault displacement hazard analyses (Baize et al., 2019).

The main map provides a fundamental contribution to the assessment of surface faulting hazard, constraining the length of the 1883 and 2017 seismogenic faults (Nappi et al., 2021), and providing a solid basis for detailed paleoseismological studies that could further clarify the history of surface faulting. Furthermore, these results provide essential input for microzonation efforts and urban development planning aimed at mitigating seismic and fault-displacement risk in a densely populated and touristic area like the island of Ischia.

In conclusion, the integrated application of UAV LiDAR, geophysical surveying, and seismic noise analysis, complemented by ongoing and future geological fieldwork and comprehensive dataset comparisons, establishes a powerful and robust framework for advancing seismic hazard assessment. This multidisciplinary methodology can serve as a benchmark for analogous studies in other tectonically and volcanically complex regions worldwide.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The coseismic ruptures dataset in Nappi et al. (2018) is available at https://doi.org/10.1594/PANGAEA.911773. Lidar Data details are available as supplementary material in https://www.mdpi.com/2072-4292/16/11/1899.

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