



First multiparametric observation of a mud volcano eruption

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Abstract. Mud volcanoes (MVs) are geological structures emitting a mixture of gas (mostly methane), water, clayey
10 sediments and rock fragments. Their background activity is sometimes interrupted by paroxysmal events, consisting of
violent expulsions of huge amounts of these materials, determining geohazard conditions. Although MV eruptions have been
reported to have caused damages and casualties worldwide, their surveillance protocols are poorly developed, and
multiparametric instrumental recordings of paroxysmal phases have never been documented. Here we show the first-ever
15 multiparametric dataset capturing the pre-, syn-, and post-eruptive evolution of a paroxysmal event at Macalube di Aragona
(Italy) on 29 August 2025. Seismic, geodetic, geomorphological, hydro-meteorological and geochemical data, acquired
before, during and after the event allowed to reconstruct the eruption dynamics, identifying indicators for the implementation
of monitoring protocols. In particular, variations of physical-chemical parameters of mud pools, soil electric conductivity,
seismic tremor and ground deformation shed light on possible precursors, from days to minutes, of the paroxysmal phase.

1 Introduction

20 Mud volcanoes (MVs) are manifestations of cold degassing at the Earth's surface, arising from the ascent of gas-rich muddy
fluids through shallow, mechanically weak sedimentary layers (Dimitrov, 2002; Kopf, 2002; Mazzini and Etiope, 2017).
These systems are typically driven by overpressure accumulation within fine-grained formations and are sustained by the
continuous or episodic migration of fluids and gases, mainly methane and CO₂, along faulted and fractured pathways. MVs
are highly dynamic systems, capable of exhibiting rapid changes in activity over a wide range of spatial and temporal scales,
25 and they constitute a distinctive class of fluid-driven geohazards in both onshore and offshore settings. In addition to long-
lasting quiescent degassing, MVs may undergo sudden and violent eruptive episodes, commonly referred to as paroxysmal
or overturning (from the Arabic word maqlūbah) events (Bogatikov et al., 2003; Martinelli and Panahi, 2005; Bonini, 2009;
Mazzini and Etiope, 2017; Zharkov, 2025). These events are characterized by the abrupt expulsion of large volumes of mud,
fluids and gas, often accompanied by ground fracturing, mudflows, ballistic ejecta and ground deformation (Bogatikov et al.,
30 2003; Madonia et al., 2011; Aoki and Sidiq, 2014; Yetirmishli and Kazimova, 2023). Overturning events can have severe



environmental and social impacts, particularly in areas where MV fields are located close to urban settlements or infrastructures. Historical and recent episodes documented worldwide (Mazzini et al., 2007; Mazzini and Etiope, 2017; Gattuso et al., 2021) have caused injuries, fatalities, and significant damage, highlighting the need for a better understanding of the physical processes governing their triggering and evolution. Despite their relevance, the mechanisms controlling the transition from background degassing to paroxysmal activity remain poorly constrained. Most previous studies have relied on post-event field observations or on short-term monitoring focused on one or few parameters, such as gas/fluid fluxes, surface morphology, geoelectrical imaging or seismic tremor (Madonia et al., 2011; Lupi et al., 2016; Chicco et al., 2020; Gattuso et al., 2021; Carfagna et al., 2024; Fontana et al., 2024; Petrosino et al., 2025; Zharkov, 2025; Ferrari et al., 2026). As a result, the temporal evolution of MV systems before, during, and after eruptive episodes is still largely undocumented and the potential existence of observable precursors remains debated. This lack of integrated, continuous and multiparametric observations represents a major limitation in both the physical understanding of these systems and the development of effective monitoring and hazard assessment strategies. Recent advances in geophysical, geochemical and environmental monitoring have opened new opportunities to investigate MV dynamics within a unified framework. Seismic noise analysis, ground deformation measurements, hydrological and meteorological observations, as well as geochemical monitoring provide complementary insights into fluid migration, pressure variations, and mechanical responses of the shallow subsurface. However, only a few studies have attempted to combine these approaches for long-term monitoring (Feseker et al., 2014; Menapace et al., 2017) and, to date, no fully integrated multiparametric dataset has captured the complete cycle of a paroxysmal MV event, including its preparatory phase, the main eruptive stage, and the subsequent relaxation of the system.

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The Maccalube di Aragona MV field (Sicily, Italy; Fig. 1) represents a unique natural laboratory to address this gap. Active for more than two millennia, the Maccalube system is characterized by persistent degassing, both diffused from the soil and concentrated from vents and pools (GS1 and GS2 in Fig. 1c), muddy fluid emissions and episodic paroxysmal events (Etiope et al., 2002; Bonini, 2009; Cangemi and Madonia, 2014; Gattuso et al., 2021). Its long-term activity, together with its relatively small spatial extent and accessibility, makes it particularly suitable for detailed instrumental investigations. In recent years, the area has been the focus of multidisciplinary monitoring efforts, including geodetic measurements, hydrological and meteorological observations, dense seismic deployments and geochemical surveys, aimed at characterizing both the background behavior and transient phenomena associated with the subsurface fluid-driven dynamics (Etiope et al., 2002; Gattuso et al., 2021; Madonia et al., 2025; Petrosino et al., 2025). On 29 August 2025, the Maccalube di Aragona experienced a major overturning event that occurred while a multiparametric monitoring network was fully operational (Madonia et al., 2025; Petrosino et al., 2025). This circumstance provided a rare opportunity to observe, for the first time, the complete temporal evolution of a MV paroxysm through simultaneous geodetic, morphological, seismic, hydrological and geochemical measurements. The event was preceded by subtle changes in background activity and followed by post-eruptive signals, offering an unprecedented window into the preparatory, eruptive, and relaxation phases of a cold degassing system.

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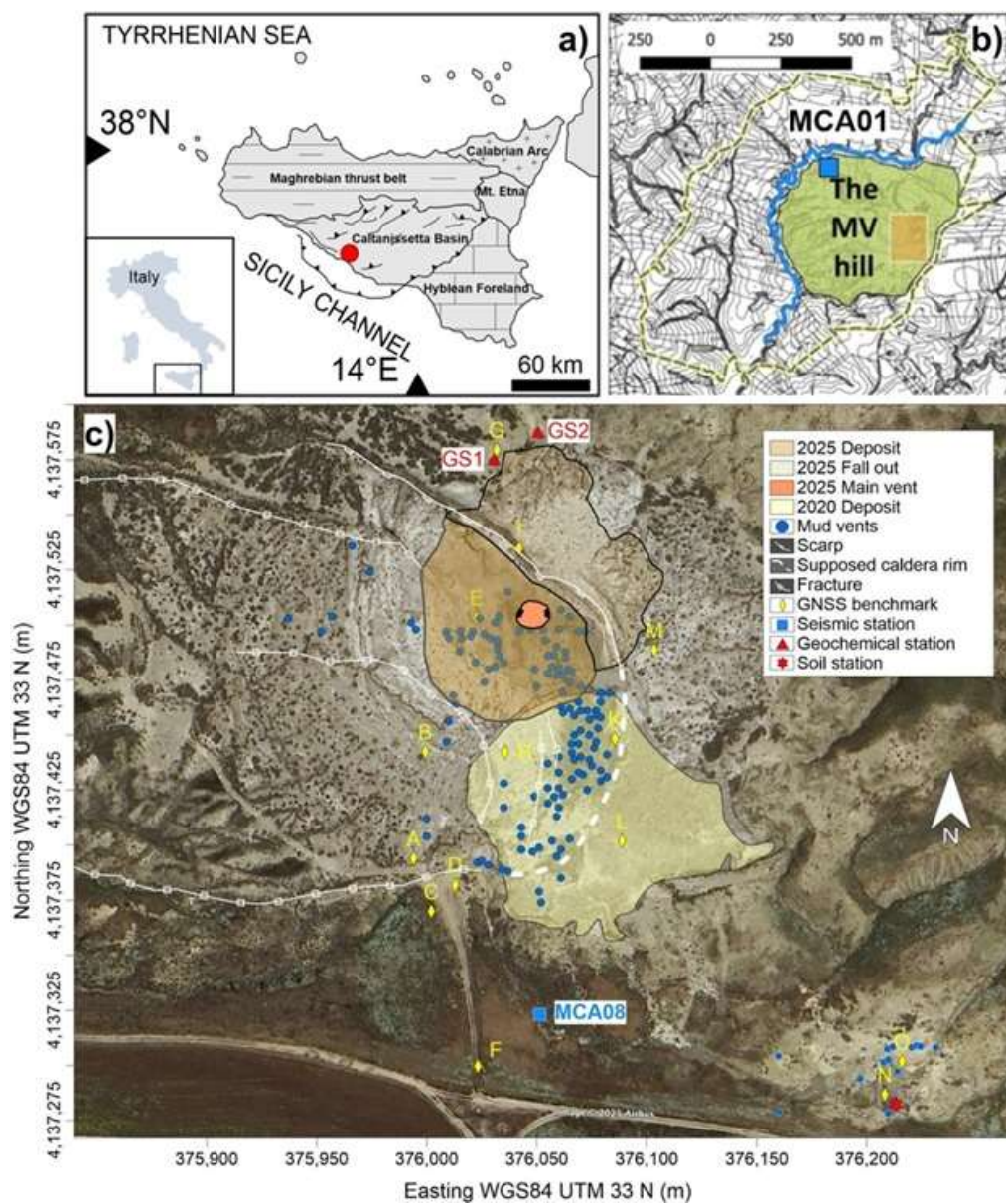




Figure 1: Location of the study area (a), general view of the Maccalube di Aragona hill (b) showing the stream deviated by the growth of the mud deposit (light blue line), the limit of the nature reserve (yellow line), the position of the seismic station installed outside the main vent area (orange rectangle), detailed in panel (c).

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In this study, we present a comprehensive multiparametric analysis of the 29 August 2025 Maccalube di Aragona overturning event. By integrating field-scale morphological observations, ground deformation data, seismic recordings, hydrological measurements and discrete and continuous geochemical data, we reconstruct the spatiotemporal dynamics related to this episode. Our objectives are to (i) identify the physical processes governing the transition from background degassing to paroxysmal activity, (ii) assess the consistency and complementarity of different observables in tracking fluid-driven instabilities and regime transitions, and (iii) explore the existence of measurable indicators that may be relevant for monitoring and hazard assessment in MV systems. The results provide new insights into the coupling between fluid migration, mechanical response, and surface expression in cold degassing environments and offer a framework for the interpretation of similar phenomena in other settings. The headings of all sections, including introduction, results, discussions, or conclusions must be numbered. Three levels of sectioning are allowed, e.g. 3, 3.1, and 3.1.1. The abbreviation "Sect." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence. Footnotes should be avoided in the text, as they tend to disrupt the flow of the text. If absolutely necessary, they should be numbered consecutively. Footnotes to tables should be marked by lowercase letters.

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2 Materials and Methods

2.1 Seismology

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Seismic data were recorded by two standalone seismic stations, MCA01 and MCA08. The acquisition system, described in Costanza et al. (2020) comprises a three-component low-power seismic sensor, a digitizer, and a solar-powered energy supply. The sensor is based on a set of three 4.5 Hz geophones, whose natural period is electronically extended to 5 s in the analog domain Fertitta et al. (2020). A chain of Finite Impulse Response (FIR) filters processes the digital samples, setting the final data rate to 200 sps. While the initial filtering stages primarily serve to suppress noise—thereby enhancing the effective resolution—the final stage defines the frequency response within the range of interest for geophysical analysis. This stage provides a flat passband, with a gain error within ± 0.003 dB from DC up to 37 % of the output data rate, and a bandwidth (-3 dB point) extending beyond 40 % of the data rate. The overall conversion factor, accounting for all intermediate stages from ground velocity to the output of the data processing chain, is 1.19617×10^{10} counts/(m/s). The sensors were buried at a depth of about 40 cm below the surface to limit wind disturbance and atmospheric thermal effects. In the current configuration, the two stations have been operating since 17 July 2024, in continuous acquisition mode.

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The covariance matrix method (Montalbetti and Kanasevich, 1970) was used to estimate the polarization properties of the seismic wavefield. The eigenvalues ($\lambda_1 \geq \lambda_2 \geq \lambda_3$) obtained from the diagonalization of the covariance matrix provide the following parameters:

- 100 1. Rectilinearity (RL) = $1 - [(\lambda_2 + \lambda_3)/(2\lambda_1)]$, which ranges from 0, corresponding to a spherical motion, to 1, for a purely rectilinear motion;
2. Azimuth of the polarization vector, defined as the clockwise angle between the projection of the polarization vector onto the horizontal plane and the North direction;
3. Incidence angle between the polarization vector and the vertical axis, where 90° indicates horizontal propagation and 0° a vertical incidence.

The analysis was performed in two frequency bands. Data were processed using sliding windows with a length equal to two cycles of the maximum period in each band and a 50% overlap (Petrosino and De Siena, 2021, 2021b). The average uncertainties associated with rectilinearity, azimuth and incidence angle are ± 0.1 , $\pm 25^\circ$ and $\pm 15^\circ$, respectively.

- 110 The root mean square (RMS) of the amplitude of the seismic signal filtered in the 1-5 Hz frequency band was calculated over a 1-h-long time window with no overlap and averaged over the three components of motion for each station.

2.2 Geodesy

Positions of mud emitting vents, mudflow, fallout area, scarp and fractures were acquired using a handled GNSS multi-constellation receiver Stonex, with SBAS correction and position errors better than 2 m, following a stop and go survey protocol. Benchmarks were periodically occupied using a Trimble R6 L1/L2 receiver, with differential corrections from the Spektra Network Real Time Kinematics (NRTK) local area network. A fast static survey protocol was adopted, accepting position solutions with both horizontal and vertical errors better than 0.05 m.

2.3 Hydrometeorology

- 120 Hydrometeorological data were acquired every 30 minutes in a permanent Licor Hobo MicroRX Station, equipped with 16-bit wireless Smart Sensors. Measurement resolution and accuracy were 0.2 mm and 0.2 mm for rain, 0.02 and 0.2 °C for air temperature, 0.001 dS m⁻¹ and 5% of the measure for soil electric conductivity, respectively; the soil sensor was placed at 30 cm depth.

2.4 Physicochemical (CTD) data in the mud pool water column

In the water column of the MP1, temperature (T), electrical conductivity (EC) and pressure (P) were measured every 10 minutes using a CTD-DIVER submersible probe, installed in February 2025, at a fixed depth of 4.20 m, a few tens of



centimeters above the bottom surface. Water temperature has a resolution of 0.01°C and an accuracy of 0.1°C. The range for EC measurements has been set at 0-30.000 µS/cm and has a resolution of 0.1% of the readings and the accuracy is 1% of the readings. Finally, the water pressure resolution is 0.2 cmH₂O and its accuracy is 0.5 cmH₂O. Since the mud pool water level remains constant due to a natural overflow channel, the water column pressure can be converted in terms of average density (ρ_{av}). The average density of the water column, expressed in g/cm³, has been computed using the equation below:

$$\rho_{av} = \frac{P_{diver} - P_{atm}}{g \times h}$$

where P_{diver} is the pressure measured in the pool by the CTD diver probe expressed in Pa, P_{atm} is the atmospheric pressure expressed in Pa, g is the acceleration due to gravity (9.80665 m/s²) and h is the depth at which the sensor was installed (4.20 m). The average density resolution is 0.0005 g/cm³ and its accuracy is 0.0012 g/cm³.

2.5 Geochemistry of the gas emission: chemical and isotopic composition

To prevent air contamination, a steel funnel, a three-direction valve, and a syringe were employed to collect gaseous samples in pyrex bottles equipped with vacuum valves at both ends (more details in Buttitta et al., 2023). The chemical composition (He, H₂, H₂S, O₂, N₂, CO, CO₂, CH₄) of gas samples was analysed by an Agilent 7890B gas chromatograph combined with a Micro GC analyser by Inficon. Concentrations of CO₂ were determined by the Micro GC analyser with He as carrier and equipped with a Poraplot-U column and TCD detector (quantification limit about 450 ppm, 0.5 %, and 500 ppm, respectively). All the other gases were determined by the GC system with Ar as carrier, equipped with a 4-m Carbosieve S II column. A thermal conductivity detector (TCD) was used to measure the concentrations of He, H₂, O₂, N₂ (quantification limit about 10 ppm, 10 ppm, 0.1 % and 0.5 %, respectively), while a flame ionization detector (FID) was used for CH₄ and CO (quantification limit about 5 ppm). The analytical errors were less than 10% for He and H₂, and less than 5% for the remaining gases.

The isotopic ratio ³He/⁴He and ⁴He were measured by a split-flight tube mass spectrometer (Thermo Helix SFT) equipped with a double collector system that enabled simultaneous detection of ion beams after purification of the sample from the major gaseous species and separation from the other noble gases. The precision of the isotopic ratio measurement is within ±0.5 %, using purified atmospheric helium as a standard. A multicollector Thermo-Helix MC Plusmass spectrometer is being utilized to measure ²⁰Ne, after purification procedure into a stainless steel ultra-high vacuum line distinct from that of He and following cryogenic trap purification.

The carbon isotopic composition of CO₂ was measured using a Delta Plus XP isotope ratio mass spectrometer equipped with a Thermo TRACE GC and a Thermo GC/C III interface. The ¹³C/¹²C ratios of CO₂ are reported in delta notation (‰) relative



to VPDB (i.e., $\delta^{13}\text{C-CO}_2$) with analytical errors lower than 0.1 ‰. From May 2025 the carbon isotopic composition of CO_2 was measured by using a Thermo Fisher Scientific Delta Q mass spectrometer, connected through a ConFlo IV to a Thermo Trace 1610 gas chromatograph (GC) physically connected at the module Isolink II. The $^{13}\text{C}/^{12}\text{C}$ ratios of CO_2 are reported in delta notation (‰) relative to VPDB (i.e., $\delta^{13}\text{C-CO}_2$) with analytical precision of $\pm 0.08\text{‰}$ and an accuracy within $\pm 0.1\text{‰}$.

160 3 Results

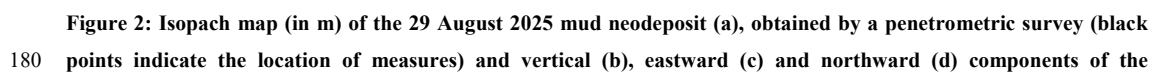
3.1 Event description and morphological changes

Based on the timing of the seismic signal, the overturning occurred on 29 August 2025 at 23:16 UTC (30/08/2025 at 01:16 local time, daylight saving included). The main vent opened in the area delimited northward by the scarp and south-eastward by the mud flow deposit of the previous paroxysmal event, dated May 2020 (Fig.1c). The scarp blocked to the north the mud
165 flow along the topographic surface, resulting in an asymmetrical deposit oriented south-westward. This deposit is mirrored north-eastward by the fallout area, characterized by the presence of mud fragments, reconstructing a comprehensive centrifugal pattern of the erupted materials, centred on the main vent.

The GNSS survey, carried out 48 hours after the eruption, depicted a concentric tensional fracture field, delimited north-eastward by the scarp, and south-westward by a net slope change of the topographic surface, suggesting the existence of a
170 caldera-like structure where the main vent field is located.

The location of the vents, as from a GNSS survey dated May 2025, follows the eastern rim of the calderic structure, describing a semi-circular alignment including the August 2025 main vent.

The total volume of the mud deposit was estimated by means of a penetrometric survey, carried out by the personnel of the nature reserve on 4-5 September, and described in Fig. 2a. The maximum thickness recorded over the main vent was 4 m,
175 with a total volume of the emitted materials equal to 8800 m^3 ; the isopachs pattern evidences a lobated structure, following aspect changes of the pre-existing topographic surface.

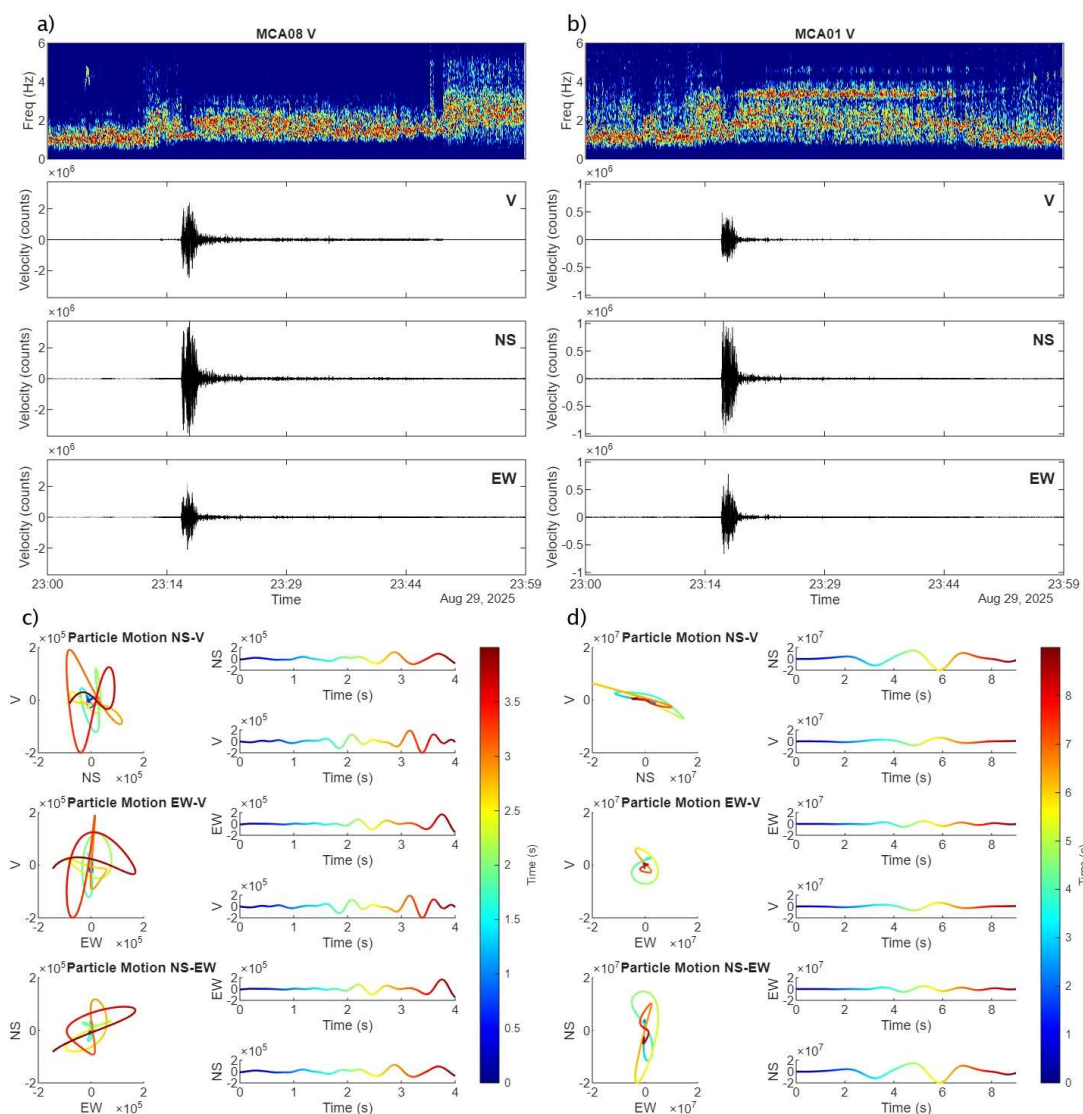




benchmarks displacements measured through GNSS RTK campaigns. The horizontal grey bands indicate the maximum of measurement error.

3.2 Seismology

Two seismic stations were operating during the 29 August 2025 overturning event: MCA08, located near the main vent area, and MCA01, about 800 m away from the vent field (Fig. 1). The seismic signal started around 23:16 UTC, with the most energetic phases (largest amplitude on the N–S component) lasting approximately three minutes, followed by a long tail of about 30 minutes (Fig. 3a). At MCA08 the event was preceded by about three minutes of a slight increase in background tremor in the 1–4 Hz frequency band, during which the polarization incidence angle increases from about 40°–60° to nearly 80° (Supplementary Fig. S1), indicating progressively more horizontal particle motion. Spectrograms show that the wavefield is dominated by energy between 1–5 Hz, yet the frequency content evolves over time (Fig. 3a). The onset phase (first 3–4 s) has low amplitude and main frequency peaks in the 1–3 Hz range. Polarization parameters are consistent with Rayleigh waves (Fig. 3c), with rectilinearity (RL) around 0.5, low incidence angle (15–20°), and azimuth mainly between 15°–20°, corresponding to the direction of the vent field. After 3–4 seconds, a phase with a dominant long period component (~0.4 Hz) arrives. The first 8 s of this phase are characterized by large amplitudes; however the long period component persists with lower energy throughout the remaining part of the signal. The waveform is strongly polarized (RL close to 1), with azimuth still around 15°–20° (remaining stable until the end of the tail), whereas incidence angle (~70°) becomes shallower (Fig. 3d). After the 8-s long phase, the dominant frequency content is restricted in a narrow band between 1–2 Hz, then it broadens up to 3 Hz throughout the low-amplitude long tail (Fig. 3a). The incidence angle decreases to about 60°–50° and the RL fluctuates between 0.7–0.95 (Supplementary Fig. S1). The end of the tail is marked by three strongly polarized (RL ~ 0.95) wave packets with 1–2 minutes of duration (Supplementary Fig. S1), characterized by a further decrease in the incidence angle (~40°). In addition, an abrupt frequency shift from 1–3 Hz to 1–5 Hz marks the transition to a persistent background tremor lasting several hours (at least until 06:00 UTC on 30 August 2025), clearly visible only in the filtered waveforms (Fig. 3a). Throughout the tremor, on average, the incidence angle remains around 40°, the azimuthal direction is still consistent with that observed for the main signal, and RL shows higher variability (0.55–0.9). This continuous tremor is occasionally interrupted (between 04:05–05:05 UTC) by transient bursts with frequency centered at 1.7–1.8 Hz (Supplementary Fig. S2). During these transients the polarization azimuth still points towards the main vent field, whereas incidence angle drops below 30° (Supplementary Fig. S2).



210 **Figure 3: Spectrograms, waveforms, and particle motion of the 29 August 2025 overturning event. (a) Spectrogram and three-component waveforms recorded at station MCA08. (b) Spectrogram and three-component waveforms**



recorded at station MCA01. (c) Particle motion on the vertical (NS-V, EW-V) and horizontal (NS-EW) planes at MCA08 in the 1–3 Hz band, associated with the onset phase (~4 s). Time is referenced to the picked arrival ($t = 0$). (d) Particle motion on the vertical (NS-V, EW-V) and horizontal (NS-EW) planes at MCA08 in the 0.2–0.9 Hz band, associated with the long period, large-amplitude phase following the onset. Time is referenced to the picked arrival ($t = 0$).

At MCA01 station, the main signal has a similar duration (~3 min) and dominant frequencies between 1–2 Hz (Fig. 3b); the long period component (~0.4 Hz) has a very low amplitude (visible only in the filtered waveform). During the tail, the spectral content becomes broader (1–4 Hz), showing two- or three-band structure with the most of the energy concentrated around 3.5 Hz (Fig. 3b). Polarization features remain generally stable throughout the recording, with the only exception of the incidence angle which is equal to 60° at the event onset, then it stabilizes at about 80° – 90° , indicating nearly horizontal polarization. Unlike MCA08, in the following hours MCA01 did not record post-event tremor with peculiar spectral characteristics.

Overall, the sequence of the seismic recordings captures a complex temporal evolution starting with: 1) increasing low frequency (1–4 Hz) background tremor; 2) low frequency (1–3 Hz) Rayleigh-type onset waves; 3) long period phase (~0.4 Hz) superimposed on narrow-band low frequency signal (1–2 Hz); 4) low frequency (1–3 Hz) tail; 5) long-lasting low frequency (1–5 Hz) tremor and sporadic nearly monochromatic (1.7–1.8 Hz) transient bursts.

3.3 Geodesy

A total of 14 benchmarks were positioned shortly after the 2020 overturning (Fig. 1c) and periodically occupied for GNSS RTK measurements. Figs. 2 b-d report the cumulative relative variations in the three components (Z, E, N) exceeding the instrumental error. All the benchmarks outside the caldera rim and far from the secondary SE vent group (C, D, F, G, M) did not show any displacement. All the others exhibited vertical displacements (Fig. 2 b), since at least 2023, mostly negative (E, H, I, K, L), with the exception of the two located in the SE secondary vent area (N, O), first moving upward and reverting to deflation in 2025 and 2024, respectively. The main deflation, down to -0.45 m, was recorded at benchmarks H and K, located in the 2020 eruption area, while point E was not measured after the 2025 eruption because it was buried by the mudflow. On the horizontal plane, a westward displacement was observed in A, B, E, H, K (Fig. 2c), with a very strong motion in A and B, up to 1.1 m, following the 2025 eruption; the S-N displacement was of minor entity, recorded only in A and B with a maximum southward component of 0.22 m. On the contrary, benchmark N, located over the main cone of the SE vent group, resumed the initial northward trend shown until 2023, and later interrupted by a modest southward motion until March 2025, for a total displacement of 0.11 m (Fig. 2d).



3.4 Hydrometeorology

Data of soil electric conductivity (EC) and its variance, air temperature and rainfall amount are illustrated in Fig. 4 for the period 10 August - 8 September. From 10 to 15 August soil EC decreased, showing a high daily variance, due to the progressive drying of the soil. On 15 and 16 August a light rain, accompanied by a decrease in air temperature, wetted the soil, inverting the EC trend and reducing its variance. Anomalous signals started on 22 August, when EC variance experienced a further reduction without any variation in atmospheric parameters, followed in the next two days by the disappearance of its daily cycle and the superimposition of a high frequency component. Since the second half of 25 August the EC signal resumed normal behavior, which lasted until the last hours of 28 August, when the variance suddenly dropped, followed the day after by a high frequency disturbance in the EC signal. The eruption occurred at the end of 29 August, and after the event the EC variance resumed higher values, but with no more evidence of a daily modulation.

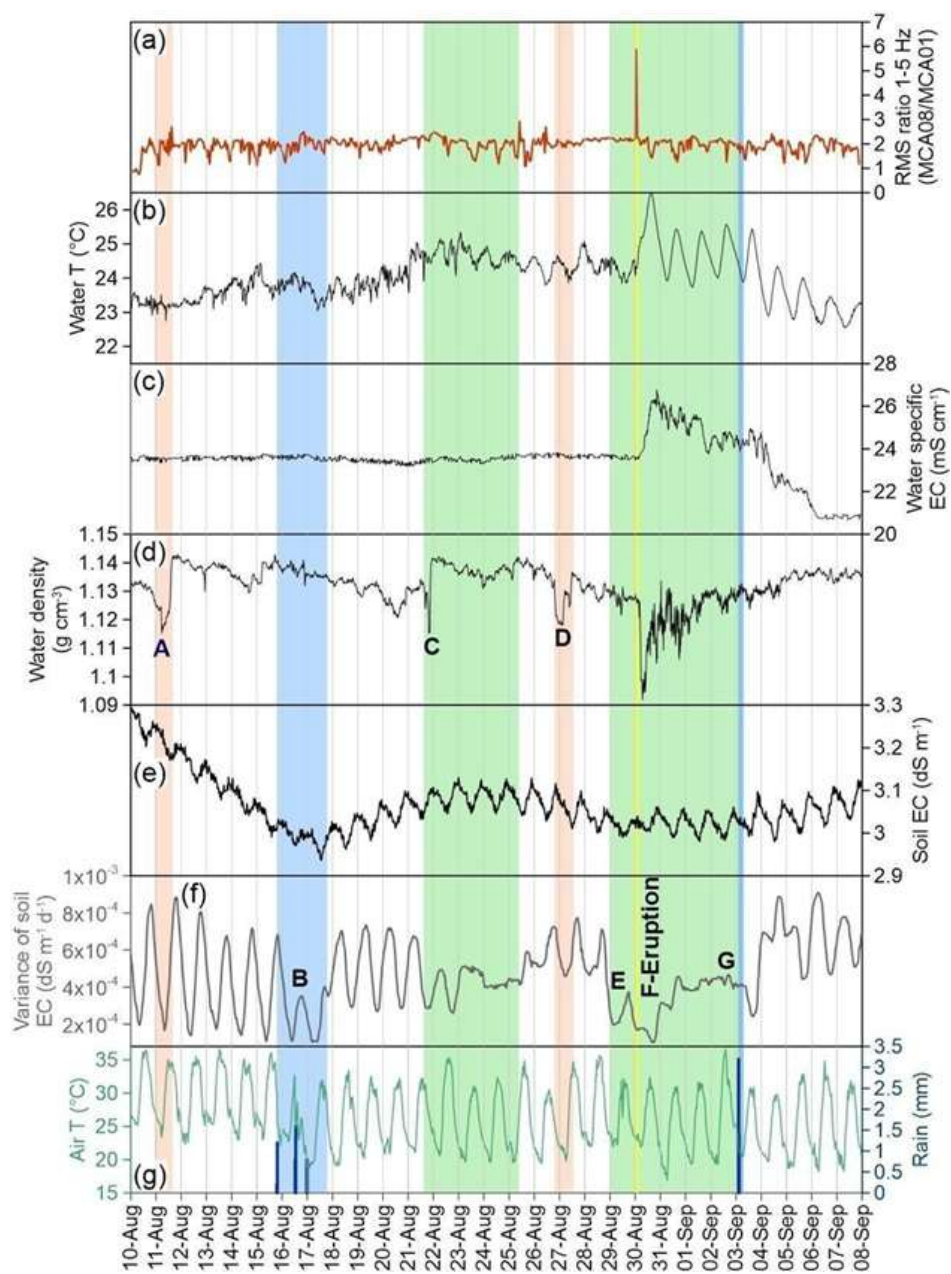




Figure 4: Time series (10 August - 8 September 2025) of: a) ratio of the RMS amplitude of the seismic noise recorded at MCA08 and MCA01 stations in the 1-5 Hz band; b) temperature, c) electric conductivity and d) average density of the water column of the MP1; e) soil electric conductivity and f) its variance; g) air temperature and rainfall amount. The main anomalies are marked by capital letters (positioned in the panel related to the first parameter reporting an anomaly) and bands of different colors indicate periods/anomalies based on their origin (blue for meteoric, green for soil and MP1, peach for MP1 only). Time is here expressed as local (GMT+2) according to the main reference used in the acquisition of the different parameters.

3.5 Physicochemical properties of the mud pool water column

The temporal trends of water temperature, electrical conductivity (EC) and average density (ρ_{av}) measured in one of the mud pools (MP1) by probe GS1 (Fig. 1c) from 10 August to 8 September 2025, are shown in Figs. 4b-d. The overturning of 29 August was marked by significant changes in all three monitored parameters. The observed changes differ considerably in timing, duration and behavior.

Fig. 4b shows the time series of water temperature, with values ranging from 23°C to 26°C. From 10 to 29 August, water temperature was relatively stable, varying between 23°C and 25.1 °C, with an average of 24.0°C. Daily cycles are present, even if they are quite smoothed and very often irregular. On 30 August at 2:08 UTC, about 3 hours after the overturning, water temperature suddenly increased, reaching a maximum value of 26.0°C at 15:08 UTC, the highest value ever recorded. Subsequently, from 30 August to 8 September, the daily fluctuations became more regular with highest values recorded in the afternoon (between 15:00 and 17:00 UTC) and lowest values in the morning, with the minimum temperature occurring approximately at 6:00 UTC. On 4 September a cooling trend began, during which temperatures dropped to a minimum of 22.8°C. Moreover, from 30 August to 4 September, the difference between the daily maximum and minimum temperature ranged between 1.3°C and 1.9°C, which is particularly large compared with the daily fluctuation amplitude during both the 8-days period preceding the overturning (0.1-0.6°C from 21 to 29 August) and during the final part of the selected time interval (0.3-1°C from 4 to 8 September).

Fig. 4c shows the temporal variation of the water EC. The MP1 waters are brackish with EC values in the range from 20400 $\mu\text{S/cm}$ to 26800 $\mu\text{S/cm}$. Before the overturning, in the period 10 August - 30 August, EC remained stable and remarkably constant around 23500 $\mu\text{S/cm}$. Similar to water temperature, a rapid increase of the EC values was observed a few hours after the paroxysmic event. On 30 August at 4:38 UTC, the EC values rapidly rose to a maximum exceeding 26800 $\mu\text{S/cm}$ at 20:45 UTC of the same day. Following the peak, a general downward trend was recorded and the EC showed irregular fluctuations characterized by high amplitude. EC reached a first minimum value of 23750 $\mu\text{S/cm}$ on 1 September at 20:48 UTC. Afterwards, from September 1 and for about 3 days, the EC varied in a restricted range between 23700 and 25000 $\mu\text{S/cm}$ without regular oscillations. On 4 September, the decreasing trend started again, reaching a new minimum EC value



285 on 6 September at 6:48 UTC at about 20750 $\mu\text{S}/\text{cm}$. The final period up to 8 September is characterized by another stable phase, with the EC values around 20800 $\mu\text{S}/\text{cm}$, which is markedly lower than the initial period.

Fig. 4d depicts the time evolution of ρ_{av} with values ranging between 1.086 g/cm^3 and 1.142 g/cm^3 . Density values higher than pure water (approximately 0.9973 g/cm^3 at 24°C) are mainly due to the presence of suspended sandy-clay sediment particles with a density of about 1.8-2.0 g/cm^3 . An increase in ρ_{av} is also due to the relatively high total dissolved salts in the water, though to a lesser extent. The density of brackish waters with a salinity of about 14 g/L is approximately 1.008 g/cm^3 (Mazzini and Etiope, 2017) at 25°C. Conversely, gas bubbles rising along the water column are far less dense than water ($\text{CH}_4 \sim 6.5 \times 10^{-4} \text{ g}/\text{cm}^3$ at SATP) and thus lead to a decrease of the total weight of the water column.

290 The temporal evolution of ρ_{av} can be divided into three main phases. During the first phase, from 10 to 29 August, ρ_{av} showed quite stable values ranging between 1.115 and 1.14 g/cm^3 with three marked episodes of sudden changes, characterized by a similar magnitude of variation but slight differences in timing, occurred on 11, 21 and 27 August respectively (Fig. 4d). On 11 August at 4:48 UTC, the ρ_{av} values rapidly decreased, reaching a minimum of 1.115 g/cm^3 at 5:38 and suddenly increased up to a value of 1.14 g/cm^3 at 16:28 UTC. A similar behavior was observed also on August 21: at 14:08 UTC the ρ_{av} values rapidly decreased, reaching a minimum of 1.115 g/cm^3 at 20:28 UTC and after about 3 hours, the values rapidly increased to a value of 1.14 g/cm^3 . Just after this sudden increase, ρ_{av} started a decreasing trend towards a value of 1.125 g/cm^3 , which was reached on 29 August at 14:18 UTC. This trend was interrupted by a third episode of drastic drop with a minimum at a ρ_{av} value of 1.125 g/cm^3 centered on 27 August at 1:00 UTC. The second phase from 30 August to 4 September, straddling the overturning, was characterized by high turbulence. A short period of stability (8-10 hours) around a value of 1.125 g/cm^3 preceded the paroxysm. Then, on 30 August at 2:25 UTC, a few hours after the paroxysm, ρ_{av} showed high frequency fluctuations with rapid declines towards the lowest values ever recorded (1.08 - 1.09 g/cm^3) followed by sudden increases allowing to recover on 4 September the pristine density values (1.13 - 1.135 g/cm^3). Finally, by the third phase, the ρ_{av} values remained substantially stable around a value of 1.135 g/cm^3 .

3.6 Gas geochemistry

In the study area bubbling gases are emitted from two main mud pools (hereafter MPs) and MVs. The position and distribution of the latter are variable over time.

310 In 2025 we collected gases in both these emissions from February to October (Table 1). According to previous investigations (Etiope et al., 2002; Grassa et al., 2004) the emitted gases are CH_4 -dominated (up to 99%). Both N_2 and O_2 amounts are lower than 1%. However, we also recognized CH_4 amounts lower than 90% and they are associated with an increase of both the N_2 and O_2 amounts that indicates an atmospheric contamination of the collected samples.

Our data show that CO_2 amounts are between 0.82 and 2.46%, and CO_2 amounts are typically higher in MVs than MPs (Table 1). It is worthy of note that there is a large difference in the carbon isotopic composition of CO_2 emitted at the MPs and MVs, being between -1.3‰ and -13.2‰ and 8.4‰ and 16.2‰ respectively. ^4He , ^{20}Ne and H_2 are in traces (Table 1).



The $^4\text{He}/^{20}\text{Ne}$ ratios in these gas samples are between 35 and 4075, it is orders of magnitude higher than the same ratio in air (0.318) indicating that the contribution of He from air is negligible (Figure 5; e.g., Buttitta et al., 2023). The He isotopic ratio ($^3\text{He}/^4\text{He}$) is between 0.67 and 0.76Ra (Ra is the $^3\text{He}/^4\text{He}$ in air, 1.39×10^{-6}) showing that He in MPs and MVs is a mixing between a He crustal component (0.01-0.03Ra) and a continental mantle component ($6.3 \pm 0.3\text{Ra}_{26}$).

Sample	date	$^3\text{He}/^4\text{He}$	He/Ne	He	H ₂	O ₂	N ₂	CH ₄	CO ₂	$\delta^{13}\text{C}_{\text{CO}_2}$
MP1	18/2/25	0,67	478,70	145,35	2,90	1,92	8,83	87,28	1,25	13,3
MP1	23/4/25	0,68	205,6	134,09	1,20	3,90	15,10	77,80	0,94	13,3
MP1	3/9/25	0,76	1538,0	136,33	n.a.	0,06	0,62	99,00	0,98	16,0
MP1	16/10/25	0,71	1062,2	133,05	14,88	0,03	0,94	96,20	0,87	16,2
MP2	18/2/25	0,67	463,4	133,68	n.a.	5,29	19,58	71,98	0,87	8,4
MP2	3/9/25	0,75	35,30	109,92	1,10	0,16	0,77	99,00	0,82	14,7
MP2	16/10/25	0,69	3592,8	131,96	n.a.	0,01	0,41	97,10	0,84	14,0
MV2	23/4/25	0,66	1034,5	136,29	1,60	0,19	1,28	97,88	1,48	-2,4
MV3	23/4/25	0,67	1783,9	147,85	1,60	0,18	0,98	98,67	1,37	-1,3
MV1	18/2/25	0,67	12,1	80,11	1,80	8,63	31,82	53,94	1,98	-10,1
MV1a	3/9/25	0,70	2276,4	161,25	1,00	0,06	0,44	98,49	2,46	-4,3
MV2a	3/9/25	0,70	4075,4	135,63	1,00	0,07	0,47	99,67	1,14	+1,0
MV3a	16/10/25	0,70	2553,0	151,77	0,97	0,04	0,40	95,80	1,73	-4,9
MV3b	16/10/25	0,71	3914,6	133,81	n.a.	0,03	0,32	97,00	1,22	-13,2

Table 1: Analysis of Helium isotope ratios, gas abundance and stable isotope composition of CO₂ ($\delta^{13}\text{C}_{\text{CO}_2}$) in gas samples from MP and MV. $^3\text{He}/^4\text{He}$ ratios are expressed as R/Ra where Ra is the $^3\text{He}/^4\text{He}$ in air, 1.39×10^{-6} . Gas abundances are reported in %Vol except for H₂ and He that are expressed in ppmVol. $\delta^{13}\text{C}_{\text{CO}_2}$ values are expressed in ‰ vs V-PDB.

4 Discussion

The multiparametric dataset presented in this study provides a rare and comprehensive view of the dynamics of a MV evolving from ordinary to paroxysmal activity. Unlike most previous investigations, which have focused on individual observables or post-event evidence, the simultaneous availability of geodetic, morphological, seismic, hydrological, and



geochemical measurements allows us to interpret the 29 August 2025 Maccalube di Aragona overturning as the surface expression of a tightly coupled fluid–mechanical process, evolving across multiple temporal and spatial scales. This perspective is consistent with the current view of mud volcanism as a structurally controlled manifestation of overpressured fluids, where gas seepage and changes in surface activity are closely linked (Mazzini and Etiope, 2017; Gattuso et al., 2021). Although MPs and MVs at Maccalube di Aragona are intimately linked with each other, there is a notable difference in their behavior: while the position of the two main MPs have remained fixed and their activity persistent for decades, MVs are more dynamic, frequently shifting locations and exhibiting episodic or intermittent activity. This distinction suggests that MPs are linked with a non-surficial segment of the fluid release system. The chemical and isotopic characterization of emitted gases constrains the origin and dynamics of the feeding system. According to Grassa et al. (2004) and Etiope et al. (2003), the Maccalube gases are CH₄-dominant as in many other MVs areas (e.g., Buttitta et al., 2023) with minor CO₂ contents. In contrast to the gases emitted from MVs located in the north of Italy, the Maccalube gases preserve a mantle component similar to those recognized in other fluid emissions associated to the thermal basins of the central-western Sicily (Caracausi et al., 2005; Caracausi and Sulli, 2019). However, this contribution is lower than that recognized in the MVs close to the Mt. Etna volcano (Fig. 5). Moreover, previous investigations²⁴ highlighted that MVs in Southern Sicily, including Maccalube di Aragona, exhibit hydrocarbon isotopic signatures consistent with a thermogenic-microbial mixing origin; however, a combined analysis of molecular and isotopic ratios $\delta^{13}\text{C}_{\text{CH}_4}$ and Bernard ratios (C1/C2+C3) invalidates such a simple mixing scenario. This discrepancy necessitates the invocation of post-genetic processes (Etiope et al., 2002; Grassa et al., 2004; Tassi et al., 2012). Two main hypotheses are open: first, that microbial gas has undergone subsequent oxidation; second, that thermogenic gas compositions have been significantly altered by fractionation during vertical migration. Consistently, our new data further support the interpretation of a structurally controlled plumbing system, where deep-sourced fluids interact with a shallow sedimentary reservoir before surface release.

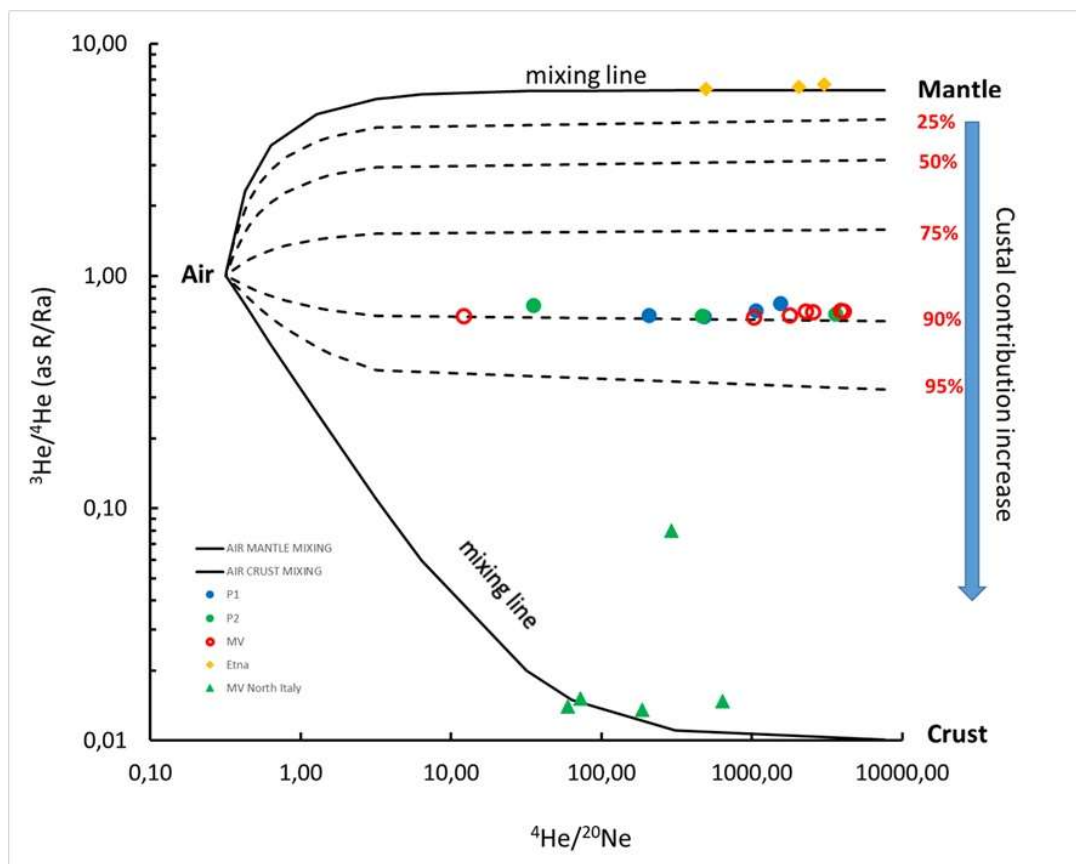


Figure 5: $^3\text{He}/^4\text{He}$ ratios (as R/Ra) plotted against the $^4\text{He}/^{20}\text{Ne}$ ratios. The line shows the mixing between the three possible end-members: air, crust, and mantle, showing a mantle contribution of about 10%. The typical crustal He endmember, dominated by ^4He production due to U and Th decay in the crust, is 0.01–0.02Ra27. Because the investigated thermal systems are in a continental region, we made calculations assuming a subcontinental lithospheric mantle (SCLM), with a He-isotope ratio of $6.3 \pm 0.39\text{Ra}26$, as mantle source in the area.

A key result of this study is the recognition of a preparatory phase preceding the overturning event, during which coherent changes are observed across different datasets. Analyzing Fig. 4 to extract a coherent interpretation of the reported observables, it should be noted that the relative timing and behavior of the anomalous signals are consistent with



pressurization of the system, leading to an impulsive eruption once overpressure exceeds the lithostatic load, as commonly invoked to model MV dynamics (Dimitrov, 2002; Kopf, 2002; Mazzini and Etiope, 2017).

Water density (Fig. 4d) was affected by four anomalies, the last one coinciding with the violent eruption, with progressively shorter intervals: 10, 6, 3 days, respectively. This behavior is compatible with the occurrence of several pulses of gas release, likely resulting from a pressure increment within the fluid-feeding pathways. The plumbing system has evolved through repeated perturbations, separated by partial recoveries, rather than through a monotonic trend before definitely exceeding the threshold thus leading to the overturning. The shape of the water density anomalies, characterized by rapid drops, followed by sudden recoveries, suggests the release towards the surface of batches of gas rather than a reduction of the amount of suspended particles. This interpretation is broadly consistent with previous long-term observations at active MVs, where transient pore-pressure and methane-emission changes have been linked to evolving subsurface conditions (Kopf et al., 2010).

The evolution towards unstable conditions of the shallow segment of the fluid release system, a clue of an imminent eruption, is given by the superimposition of soil EC anomalies (Fig. 4e-f), starting on 23 August, after the second water density perturbation. These changes cannot be attributed to exogenous factors (e.g. rainfalls). Rainfall episodes produce a different signature, affecting only soil EC and its variance, but not generating a comparable response in the pool-water parameters nor in the seismic signal (anomaly B in Fig. 4, and panels a, d-g). Fig. 4 further suggests that, in this system, EC variance can be more diagnostic than the raw signal itself: in the case of soil EC, the disappearance of the daily modulation is more informative than the absolute EC value, which is strongly affected by daily moisture changes.

The seismic observations provide further constraints on this preparatory stage. The increase in low frequency tremor is compatible with shallow fluid-induced processes such as gas migration and fracture reactivation. An additional feature is the reduced short-term variability of the amplitude ratio during about three days before the paroxysm (Fig. 4a), indicating that a common dominant process emerges over diffuse local (site/environmental) contributions. The relative partitioning of seismic energy between the vent-proximal and distal sites becomes more stable through time, consistent with the emergence of a persistent source. The differential behavior of the amplitude ratio is therefore insightful not only because it enhances source-related changes, but also because its stabilization suggests that the system evolved towards a more coherent pre-eruptive state. This is in line with recent studies showing that shallow gas release and vent dynamics in MVs generate a variety of seismic signals, from bubbling-related tremor to impulsive transients (Albarelo et al., 2012; Lupi et al., 2016; Carfagna et al., 2024; Brindisi et al., 2025; Petrosino et al., 2025; Ferrari et al., 2026).

The overturning event itself marks a rapid transition from the preparatory regime to a higher-energy eruptive and post-eruptive phase, which lasted until 6 September, marked by relevant changes in amplitude and frequency of parameters recorded both in MP1 and in the soil, and confirmed by field observations. The rapid post-event increase in MP1 water temperature and EC, which reached the highest values ever recorded (Fig. 4b-c), indicates the ascent of warmer and more saline fluids, probably sourced from deeper levels and rapidly mixed into the shallow pool system immediately after the eruption. This is further supported by the decrease in water density (Fig. 4d). The response in the physicochemical



parameters (CTD data) of the MP1 water is delayed relative to the seismic onset, with the strongest changes in water temperature, density, and EC occurring only hours after the beginning of the seismic sequence (Fig. 4). This offset likely reflects the spatial organization of the system: polarization analysis indicates that the seismic signal originated from a persistent and geometrically constrained source within the main vent area, where the paroxysmal process initiated, whereas
405 the MP1 belongs to a peripheral, hydraulically connected, part of the plumbing system. The CTD anomalies in the MP water therefore represent the response to the subsequent propagation of pressure perturbation, migration and mixing of shallow fluids. The transient seismic bursts superimposed on the post-event background tremor, observed a few hours after the main event (Supplementary Fig. S2) and nearly concomitant with the physicochemical anomalies further support this interpretation and likely reflect fluid transfer and pressure redistribution within the hydraulically connected vent–pool
410 system.

After the eruption, the system entered a prolonged relaxation phase characterized by persistent tremor (Fig. 3), and hydrological and physicochemical re-equilibration (Fig. 4), rather than a simple return to background. The smooth decrease in water temperature, the large density oscillations and the stabilization of water EC at values lower than before the overturning, indicate that eruption-induced changes in fluid circulation persisted within the MP1 peripheral system. In
415 addition, the emergence of larger and more regular diurnal oscillations in water temperature, together with the temporary disappearance of the pre-event daily modulation in soil-EC variance, suggests that the paroxysmal event temporarily modified the coupling between atmospheric forcing, shallow permeability and subsurface fluid circulation.

The morphological and geodetic observations indicate that this fluid ascent is strongly modulated by morphostructural features. The concentric fracture pattern, the semi-circular vent alignment, and the long-term deflation inside the caldera-like
420 depression shown by GNSS data, which likely reflects fluid redistribution, all point to pressurization and weakening of the SW sector of the MV field. In this framework, the NE scarp delimiting the main emission area appears to have acted as a barrier to deformation, which propagated predominantly towards the SW, further indicating that local morphology controlled both fluid distribution and the spatial pattern of deformation. This interpretation is consistent with the broader view that mud volcanism preferentially exploits faults and mechanically weak zones and other structural discontinuities (Mazzini and
425 Etiope, 2017; Gattuso et al., 2021).

Taken together, these observations support a conceptual model where the Maccalube di Aragona system evolves through a sequence of stages driven by the upward migration of deep, methane-rich fluids along structurally controlled pathways, generating coupled hydrological, geochemical and mechanical responses in the shallower system. The plumbing system
430 approaches eruption likely through repeated subcritical perturbations, first expressed both in hydrological observables and in CTD data and later in the seismic response. Once fluid overpressure exceeds the lithostatic load, mechanical failure occurs along pre-existing or newly formed structural discontinuities, resulting in the abrupt expulsion of gas-rich muddy fluids. The eruptive phase is marked by anomalies in most of the monitored parameters, which become more mutually consistent. The following hours or days correspond to a progressive pressure re-equilibration, gas/fluid pathway redistribution, until a new



435 metastable state is reached. In this sense, the post-eruptive state should not be seen as a mere recovery of the pre-eruptive background, but rather as the establishment of a modified equilibrium.

This interpretation has two broader implications. First, no single observable is sufficient to capture the full dynamics of a MV unrest. Conversely, the consistency and temporal sequence of the anomalies across different parameters (Ricco et al., 2021) are more informative than any isolated variations and provide a robust basis for identifying fluid-driven regime transitions and distinguishing among preparatory, eruptive, and post-eruptive stages. Second, the results suggest that MVs may exhibit detectable precursory behavior, even if the exact timing of paroxysmal events remains difficult to predict. In this perspective, the temporal patterns of MP water density, soil EC variance, and stabilization of the inter-station RMS ratio, may together provide a more robust warning framework. This is particularly relevant for Maccalube di Aragona, where paroxysmal events pose a non-negligible local hazard.

445 **5 Conclusions**

This study demonstrates the value of integrated multiparametric monitoring for unraveling the dynamics of MV degassing systems. By capturing the complete life cycle of a MV overturning event, we provide new insights into the coupling between deep fluid migration and surface expression in sedimentary environments. These results strengthen the idea that fluid-driven geohazards can be better understood, and potentially forecast, through multidisciplinary observations.

450 Some limitations of this study should be acknowledged. The interpretations presented here are based on a single, albeit exceptionally well-documented, event, and the extent to which the proposed model applies to other MV systems or to less energetic eruptions remains to be tested. The timing and consistency of the variations of multiparametric data are therefore highly diagnostic, but they still need to be tested against a larger number of unrest episodes, including those that do not culminate in a paroxysm.

455 **Data availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supplement materials

Supplementary materials in Madonia_NHESS_SM.pdf



460 **Author contributions**

Conceptualization: A.CA., F.G., P.C., P.M., S.P.; Data curation: A.CA., A.CO., P.C., F.G., G.F., P.M., S.P.; Formal analysis: F.G., P.M., S.P.; Investigation: A.CA., A.CO., P.C., F.G., G.F., P.M., S.P.; Writing - original draft: F.G., P.M., S.P.; Writing - review & editing: A.CA., P.C., F.G., P.M., S.P.; Project administration: P.C.

Competing interests

465 The authors declare no competing interests.

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