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Key Points:

- Tremor increases and steam venting acoustic noise decreases after rainfall, suggesting enhanced steam condensation within the conduit
- Meteoric water input raises the hydrothermal water level and conduit pressure, potentially promoting variations in earthquake rates
- Integrated seismic, acoustic, and meteorological data can sensitively track transient hydrothermal changes in outgassing and steam condensation

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

D. Delle Donne,
dario.delledonne@ingv.it

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Author Contributions:

Conceptualization: Rebecca Sveva Morelli, Dario Delle Donne, Stefano Caliro, Lucia Nardone, Massimo Orazi
Data curation: Rebecca Sveva Morelli, Dario Delle Donne, Stefano Caliro, Lucia Nardone, Massimo Orazi, Prospero De Martino, Patrizia Ricciolino
Formal analysis: Rebecca Sveva Morelli, Dario Delle Donne
Funding acquisition: Stefano Caliro, Lucia Pappalardo
Investigation: Rebecca Sveva Morelli, Dario Delle Donne, Stefano Caliro, Lucia Nardone, Massimo Orazi

Seismo-Acoustic Evidence for Meteoric Water Modulation of Hydrothermal Fluid Discharge

Rebecca Sveva Morelli^{1,2} , Dario Delle Donne¹ , Stefano Caliro¹ , Lucia Nardone¹, Massimo Orazi¹, Alessandro Aiuppa³ , Ciro Buonocunto^{1,2}, Aldo Benincasa¹ , Antonella Bobbio¹, Antonio Caputo¹, Prospero De Martino¹, Sergio Gammaldi¹ , Danilo Galluzzo¹, Flora Giudicepietro¹, Francesco Liguoro¹ , Vincenzo Morra², Lucia Pappalardo¹ , Rosario Peluso¹, Patrizia Ricciolino¹, Francesco Rufino¹, Giovanni Scarpato¹, Maria Grazia Soldovieri¹, Anna Tramelli¹ , and Mauro Antonio Di Vito¹ 

¹Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli – Osservatorio Vesuviano, Napoli, Italy, ²DISTAR, Università di Napoli Federico II, Napoli, Italy, ³DiSTeM, Università di Palermo, Palermo, Italy

Abstract Deciphering the signal of external processes on active hydrothermal dynamics represents a critical challenge in understanding volcanic unrest. At the Pisciarelli hydrothermal site, located within the densely populated Campi Flegrei caldera (Italy), we investigate the role of meteoric water influx in modulating shallow hydrothermal fluid discharge. Our analysis reveals a persistent seismic tremor generated at shallow depths, whose amplitudes fluctuate noticeably and closely follow rainfall patterns. Hydrothermal activity also emits distinct acoustic signals related to boiling and steam venting. Importantly, we observe an inverse relationship between tremor and acoustic amplitudes: as tremor increases, acoustic emissions decrease. The influx of cold water is also linked to a rise in hydrothermal water level, indicating increased conduit pressure, which is supported by ground tilt data showing conduit inflation. We propose a conceptual model in which pressurization cycles in the shallow hydrothermal system result from the interplay between steam condensation, meteoric water influx, and steam outgassing. These pressurization cycles may promote seismicity, as evidenced by the seasonal patterns observed in earthquake rates. However, these seasonal effects are secondary to the dominant, accelerating multi-year trend of increasing earthquake rates due to volcanic unrest. Our findings demonstrate that seismo-acoustic monitoring provides a sensitive tool for detecting transient changes in hydrothermal dynamics, offering valuable insights into the interpretation of volcanic unrest signals. This, in turn, contributes to more refined volcanic hazard assessments. Although developed at Campi Flegrei, this approach holds potential for application to other active hydrothermal systems worldwide.

Plain Language Summary Understanding how weather and other external factors influence volcanic hydrothermal systems is important for interpreting signs of volcanic unrest. At Pisciarelli, a hot, steam-rich vent area inside the densely populated Campi Flegrei caldera in Italy, we studied how rainwater affects steam and gas discharge. When rainwater seeps into the shallow underground system, it cools the steam, causing it to condense into liquid. This process creates a steady vibration, called seismic tremor, that we detect with seismometers. We found that tremor strength increases after rainfall, while sound from steam venting decreases, suggesting that more steam is condensing within the conduit and no longer reaching the surface. Rainfall is also linked to rising water levels in the vent area suggesting water influx increases reservoir pressure. By combining several years of seismic, acoustic, and weather data, we show that these rainfall-driven pressure changes may influence local earthquake activity. While these seasonal effects are evident, they are small compared to the long-term increase in activity at Campi Flegrei. Our results show that listening to the ground and the air together can reveal subtle changes in hydrothermal systems, improving volcanic hazard assessments. This method can also be applied to other volcanic areas around the world.

1. Introduction

Hydrothermal activity is among the most prominent and observable manifestations of volcanic processes in active calderas and is typically expressed in the form of fumarolic emissions, degassing soils and boiling pools. These persistent surface features act as natural conduits for the discharge of volcanic gases, primarily water vapor and carbon dioxide (CO₂), into the atmosphere (e.g., Caliro et al., 2007; Edmonds et al., 2003; Moretti et al., 2018). In closed-conduit caldera systems, hydrothermal activity offers a window into deep magmatic processes, although

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Methodology: Rebecca Sveva Morelli, Dario Delle Donne

Project administration: Stefano Caliro, Massimo Orazi, Lucia Pappalardo, Mauro Antonio Di Vito

Resources: Rebecca Sveva Morelli, Dario Delle Donne, Stefano Caliro, Lucia Nardone, Massimo Orazi, Ciro Buonocunto, Aldo Benincasa, Antonella Bobbio, Antonio Caputo, Prospero De Martino, Sergio Gammaldi, Francesco Liguoro, Rosario Peluso, Patrizia Ricciolino, Francesco Rufino, Giovanni Scarpato, Maria Grazia Soldovieri

Software: Massimo Orazi, Francesco Liguoro, Rosario Peluso, Giovanni Scarpato

Supervision: Dario Delle Donne, Stefano Caliro, Massimo Orazi, Alessandro Aiuppa, Vincenzo Morra, Lucia Pappalardo

Validation: Rebecca Sveva Morelli, Dario Delle Donne, Alessandro Aiuppa, Danilo Galluzzo, Flora Giudicepietro, Anna Tramelli, Mauro Antonio Di Vito

Visualization: Rebecca Sveva Morelli, Dario Delle Donne

Writing – original draft: Rebecca Sveva Morelli, Dario Delle Donne

Writing – review & editing: Rebecca Sveva Morelli, Dario Delle Donne, Stefano Caliro, Lucia Nardone, Alessandro Aiuppa, Danilo Galluzzo, Flora Giudicepietro, Anna Tramelli, Mauro Antonio Di Vito

filtered by processes taking place within hydrothermal reservoirs. Hydrothermal fluids serve as primary agents of heat transfer from depth to the surface, and increased fluid flux can lead to overpressurization in shallow aquifers, potentially triggering hazardous phenomena, such as hydrothermal explosions or phreatic eruptions (Browne & Lawless, 2001; Fournier et al., 1991; Kato et al., 2015; Montanaro et al., 2022).

While magmatic degassing remains the fundamental driver of the hydrothermal activity, its surface expression can also be strongly modulated by shallow hydrogeological dynamics, such as subsurface meteoric water circulation, atmospheric pressure changes and ocean tides (De Siena et al., 2024; Petrosino et al., 2018, 2020; Sahoo et al., 2024). External processes can mask or mimic deeper magmatic signals, making it challenging to distinguish between internally or externally driven surface manifestations, essential for accurate monitoring. Nonetheless, these external processes may also induce phreatic explosions (Aizawa et al., 2022), dome collapse (Mastin, 1994), and trigger seismicity (Wang et al., 2024), highlighting the need for increasingly sensitive monitoring systems that also account for these phenomena. Moreover, the global increase in ocean temperatures driven by climate change is leading to a higher occurrence of extreme meteorological events, which could potentially exacerbate the role of external processes in triggering volcanic events (Farquharson & Amelung, 2020; McGuire, 2010).

In recent years, seismo-acoustic observations have emerged as valuable tools to indirectly assess volcanic dynamics, particularly at open-vent volcanoes. Infrasonic waves are generated by the rapid expansion of volcanic gases in the atmosphere (e.g., Fee & Matoza, 2013; Johnson & Ripepe, 2011), while seismic signals, such as harmonic tremor, may originate from the interaction of ascending magmatic and hydrothermal fluids with surrounding rocks at shallow depths (Girona et al., 2019; Kedar et al., 1998; Lane et al., 2001; Leet, 1988; Lipovsky & Dunham, 2015; Montegrossi et al., 2019; Nayak et al., 2020; Ripepe & Gordeev, 1999). Such geophysical techniques can then represent indirect but advantageous gas monitoring tools, especially considering that seismo-acoustic waves can propagate over long distances from the source, hence enabling safe data acquisition from remote locations, ultimately reducing exposures of operators and instruments to hazardous and harsh environments. However, real-time monitoring application of these methods in hydrothermal systems are still limited, as the typically lower temperature and pressure conditions result in weaker seismic and acoustic signals.

At Campi Flegrei caldera (CFc; Figure 1a), the recent bradyseismic unrest has prompted intensified monitoring efforts (e.g., Chiodini et al., 2022), revealing promising seismic signatures linked to outgassing activity (Chiodini et al., 2017; Gresse et al., 2018; Giudicepietro et al., 2019; Giudicepietro, Chiodini, et al., 2021; Giudicepietro, Ricciolino, et al., 2021; Esposito et al., 2023). These results highlight the potential of seismic observations as a complementary and innovative approach for real-time monitoring of gas emissions, even in complex caldera systems.

Here, we investigate the seismo-acoustic wavefield generated by continuous hydrothermal degassing at Pisciarelli, one of the main hydrothermal manifestations at CFc (Caliro et al., 2007; Chiodini et al., 2012, 2015; Tamburello et al., 2019). Our study focuses on the 2019–2024 period, when most of the gas was emitted from the main Soffione fumarole (Figures 1b and 1c), which opened in 2005 and has since produced a loud, intense and continuous overpressurized steam jet, generating a CO₂-rich gas plume that rises several tens of meters into the atmosphere. In addition, the site also hosts a ~20 m-wide thermal pool (~90°C), characterized by intense bubbling activity. The pool is fed by the upwelling of hydrothermal fluids transported by ascending gas within the system, as the local groundwater table lies at a depth of approximately 40 m below the surface. The site is continuously emitting a H₂O–CO₂-rich mixtures, with minor contributions of H₂S (Chiodini et al., 2021). Our objective is to characterize the physical processes generating seismo-acoustic signals, and to develop a conceptual model that explains the observed hydrothermal dynamics. To this end, we analyze the hydrothermal activity over a multi-year scale and report on the results of targeted experiments in which small-aperture seismo-acoustic arrays were temporarily deployed to characterize the wavefield associated with hydrothermal dynamics.

2. Methods

2.1. Data and Instrument Setup

To investigate the seismo-acoustic wavefield related to the hydrothermal degassing, a temporary four-element seismo-acoustic array was deployed in September 2020 at approximately 80 m from the active hydrothermal area of Pisciarelli (Figure 1c). The array comprised three-component short-period seismometers and acoustic sensors, totaling 16 channels, recorded with high-resolution, GPS-synchronized digitizers. The deployment lasted

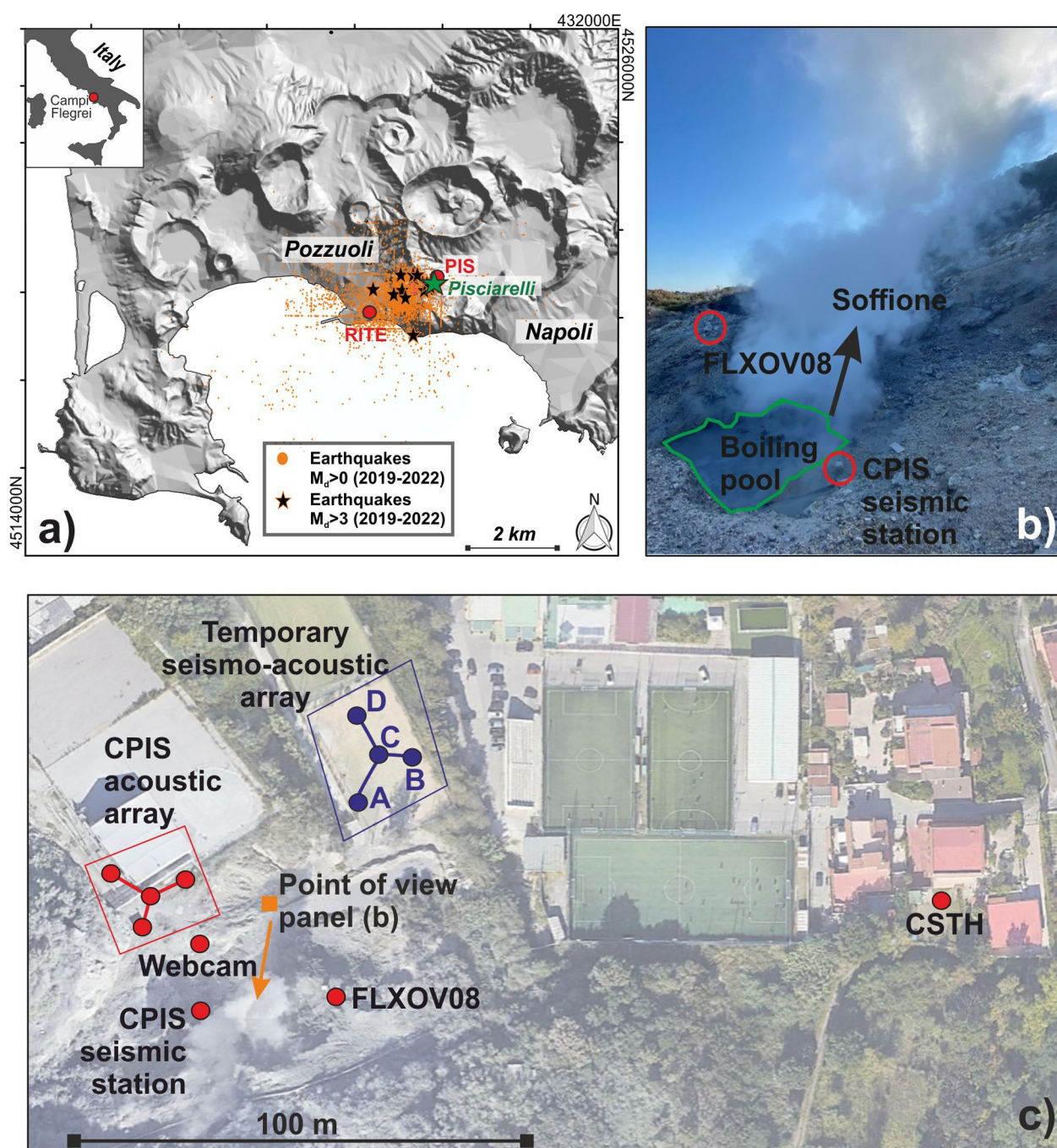


Figure 1. (a) Map of the Campi Flegrei caldera showing the location of the Pisciarelli hydrothermal field (green star), with the closest GPS stations PIS and RITE, along with the epicenters of the earthquakes recorded in the area between 2019 and 2022 with magnitude $M_D > 0$ (orange dots) and $M_D > 3$ (black stars) (Ricciolino et al., 2024). (b) Photo of the Pisciarelli hydrothermal area highlighting the Soffione fumarole and the boiling pool, as well as the positions of the geochemical station FLXOV08 and the seismic sensor CPIS. (c) Detailed map of the Pisciarelli hydrothermal field showing the viewpoint from which the photo in panel (b) was taken, the CPIS acoustic array and the seismic sensor, the CSH seismic station, the FLUXOV08 geochemical station and the monitoring webcam. The temporary seismo-acoustic array from the September 2020 experiment (blue) is also indicated.

about 10 days. Due to space constraints imposed by the site's urbanization and physical barriers, the array aperture was limited to approximately 30 m, with inter-station distances around 10 m. To accommodate the expected short time delays between sensors, we set sampling rates of 200 Hz for seismic channels and 500 Hz for acoustic channels (e.g., Yamakawa et al., 2018). The high acoustic sampling rate enabled capturing also signals in the audible bands (>20 Hz), leveraging the Chaparral M25 sensors' frequency response up to 200 Hz.

Results from this temporary deployment are complemented with results streamed from two permanent broadband stations, CPIS and CSTD, operated by the Istituto Nazionale di Geofisica e Vulcanologia—Osservatorio Vesuviano (INGV-OV), providing longer-term seismic and acoustic data (Buonocunto et al., 2011; Nardone et al., 2025; Orazi et al., 2011). CPIS station, installed in 2010 just a few meters from the thermal pool (Figures 1b and 1c), is equipped with a Guralp CMG-40T seismic sensor with a sensitivity of 800 V/(m/s), a 60 s eigenperiod and, since December 2023, has also been equipped with a permanent acoustic array, enabling continuous monitoring of the hydrothermal activity. Before 14 June 2021, the CSTD station was designated as STD, operating as an analog short-period station. On that date, it was replaced with a digital broadband station. For our analyses, the transition between the old and new data sets was managed using an overlap period, during which we compared and calibrated the amplitudes of the two seismometers within the frequency band of interest. Data set used in this study is available as Morelli et al. (2026).

We also integrated other independent data sources, including webcam images monitoring the Pisciarelli area, the GPS stations PIS and RITE (De Martino et al., 2022; Figure 1a), high rate (1 Hz) temperature measurements within the fumarolic gas plume (FLXOV08, Caliro, Avino, et al., 2025; Figure 1c), and rainfall records from a nearby meteorological station (archive of 3bMeteo: <https://www.3bmeteo.com/meteo/pozzuoli/storico>; last accessed on July 2025).

2.2. Seismic and Acoustic Source Localization Using Frequency–Wavenumber Array Processing

The use of array methods allowed us to analyze the seismic and acoustic signals by extracting the coherent components of the wavefield propagating across the array. This enabled us to perform azimuthal localization and to estimate the apparent velocity of the various wavefronts, allowing us to distinguish the hydrothermal signal components from incoherent noise unrelated to hydrothermal activity. For this purpose, we employed frequency–wavenumber (FK) analysis of the wavefield using the MatSeis software package (Harris & Young, 1997). The FK analysis estimates the power distribution as a function of slowness and direction of arrival in the frequency domain (Capon, 1969). Apparent velocities (v_{app}) and back-azimuths (bkz) were estimated using a grid search over a range of possible slowness vectors (s_x and s_y) within the ideal plane containing the array sensors, identifying the combination that maximizes the coherent energy of the summed wavefield across the array using the following formulas:

$$bkz = \arctan\left(\frac{s_{yMAX}}{s_{xMAX}}\right) \quad (1)$$

$$v_{app} = \frac{1}{\sqrt{s_{xMAX}^2 + s_{yMAX}^2}} \quad (2)$$

where s_{xMAX} and s_{yMAX} are the slowness values associated with the maximum coherence within the grid search. Further details on FK array analysis can be found in Rost and Thomas (2002) and in Yamakawa et al. (2018). The analysis was conducted on both tremor and acoustic signals using 2-s moving time windows with a 1-s overlap. For the seismic data, we focused on the 4–6 Hz frequency band, while for the acoustic data we examined the 2–5 Hz and 10–30 Hz bands. These frequency ranges were chosen because they provided the highest signal-to-noise ratio.

2.3. Seismic Tremor Source Localization Using Amplitude Distribution Analysis

Seismic tremor location has been estimated using the amplitude source location method (Battaglia & Aki, 2003; Taisne et al., 2011, among the others), which proved to successfully work with fuse-shaped and continuous seismic signals without a well-defined onset in waveforms. The method assumes an isotropic radiation pattern, where the observed seismic root mean squared (RMS) amplitudes A_i at the i th station, taken at a distance from the seismic source and averaged within a time window sufficiently long to neglect the time delays due to wave propagation, are related to source amplitude A_0 at 1 m distance following this relation:

$$A_i(r) = A_0 \frac{e^{-Br}}{r^\alpha} S_i \quad (3)$$

with

$$B = \frac{\pi f}{Qc} \quad (4)$$

where r is the hypocentral distance from the seismic source, A_0 is the source amplitude, f is frequency, c is the wave velocity, Q is the quality factor, and S is the site amplification coefficient at the i th station. The coefficient α equals 1 for body waves and $\frac{1}{2}$ for surface waves. Accurately constraining the attenuation coefficient B is generally essential for reliable seismic source localization. While the signal frequency is known and the wave velocity has been measured from array analysis, Q can be estimated for the Campi Flegrei area using the frequency-dependent relationships reported by Del Pezzo and Bianco (2013). Based on these relations and assuming a central frequency of the seismic signal of 10 Hz, we obtain Q values ranging between 57 and 110, with an average value of approximately 83.

This localization is strongly influenced by local site conditions, which can distort amplitude patterns. To correct for this, site amplification factors were estimated using records from eight local volcano-tectonic earthquakes ($M_D > 0$) within the tremor frequency band (5–15 Hz, Giudicepietro et al., 2019). Events were selected from the INGV-OV database (Ricciolino et al., 2024, Table S1 in Supporting Information S1, for the raw waveforms see Morelli et al., 2026) at distances beyond the network's maximum station spacing (~ 200 m) to isolate site effects. Relative amplifications were calculated via spectral ratios against a reference station, and seismic amplitudes were corrected accordingly.

The inversion approach for seeking the source position is made by using the amplitude ratios with respect to a reference station (Taisne et al., 2011). From Equations 3 and 4 we can derive the following relationship:

$$\frac{A_i}{A_{\text{ref}}} = \frac{S_i}{S_{\text{ref}}} \left(\frac{r_{\text{ref}}}{r_i} \right)^\alpha e^{B(r_{\text{ref}} - r_i)} \quad (5)$$

where A_i and A_{REF} are the RMS amplitudes, recorded respectively at the i th station and at the reference station, which is arbitrarily chosen among the stations of the network, r_i and r_{REF} are the distances of the i th and reference stations from the source. S_i and S_{REF} are the site amplification factors. Notably, the derived equation depends only on the source's position relative to the stations, not on its amplitude. Therefore, any temporal variation in the amplitude ratios necessarily indicates a change in the relative position between the stations and the seismic source, pointing to a spatial variation of the seismic source (e.g., Taisne et al., 2011). In addition, this property was also leveraged to track long-term source migration using data from the two permanent seismic stations, Csth and CPIS. Tremor location was made using a grid searching method, with a 10-m-spaced three-dimensional grid, which was built to include all the station positions of the network and extending at depths of 1,000 m below the surface. For each grid node with coordinates (x, y, z) , we computed the distances to all stations and used Equation 5 to estimate the expected amplitude ratios, which were then compared to the observed ones to identify the most likely source location. The best-fit position was determined by minimizing the following misfit function, $\epsilon(x, y, z)$, which quantifies the difference between observed and predicted amplitude ratios, with:

$$\epsilon(x, y, z) = \sum_{i=1}^N \left(\left(\frac{A_i}{A_{\text{REF}}} \right)_{\text{OBS}} - \left(\frac{A_i}{A_{\text{REF}}} \right)_{\text{CALC}} \right)^2 \quad (6)$$

This is calculated for every node (x, y, z) of the search grid as the quadratic sum of the residuals between observed and calculated amplitude ratios associated with the total number (N) of seismic stations.

2.4. Long-Term Analysis of Tremor and Acoustic Amplitudes and Their Associated Frequency Content

The long-term investigation of tremor and acoustic amplitudes between 2019 and 2022 was made possible only through single-station amplitude analysis. This approach lacked the noise-filtering capabilities of array processing, which is particularly limiting in an urbanized area like the CFC, where anthropogenic noise often dominates over the hydrothermal signal. For this purpose, we focused on the two permanent seismic stations CPIS and Csth, located within ~ 200 m of the hydrothermal area (Figure 1c), which offered the best signal-to-noise

conditions. To minimize ambient noise interference, the analysis was restricted to nighttime hours, specifically from 00:00 to 02:00 GMT, when noise levels were generally at their lowest. We computed the average RMS seismic amplitude in the 5–15 Hz band and calculated for each day the Power Spectral Density (PSD), constructing long-term spectrograms to identify spectral components and track their temporal evolution.

2.5. Deriving Tilt From Seismometers

Hydrothermal system dynamics have sometimes caused ground deformation effects that can be quantified using broadband seismometers, where such deformation manifests as measurable tilt. Although broadband seismometers typically record ground velocity, they are also sensitive to tilt variations occurring at timescales longer than their natural eigenperiod. Modern broadband instruments employ a force-balance design, which enhances both frequency response and linearity. In this configuration, any movement of the internal mass is counteracted by an electrically generated feedback force, resulting in a signal proportional to ground acceleration. A static (low-frequency) motion induces a constant signal i.e. directly proportional to the tilt angle (e.g., Aoyama & Oshima, 2008; Genco & Ripepe, 2010). Therefore, apparent displacement can be converted into radians using a static conversion factor derived from:

$$\tau = \frac{-\omega_0^2 u}{g} \quad (7)$$

where τ is the tilt amplitude in radians, u is the measured seismic displacement (m), g is the gravity acceleration, and ω_0 is the seismometer's natural frequency of oscillation. This allows ground tilt to be estimated from seismometer recordings, as experimentally verified from co-locating broadband seismometers a Guralp CMG-40T and a Pinnacle borehole tilt (Genco & Ripepe, 2010). For the seismometer model used here, the displacement to tilt conversion factor $\frac{-\omega_0^2}{g}$ is approximately 1.1 $\mu\text{rad/mm}$ (Equation 7).

2.6. Seismic Wave Polarization Analysis

Polarization analysis was used to detect seismic phase arrivals and identify signals potentially linked to a change over time in the tremor source position. In particular, for P-waves and Rayleigh waves, azimuth and incidence estimation provide the direction to the source. Variations in polarization over time are interpreted as changes in phase arrivals or in the source position. Polarization angles were calculated by solving the covariance matrix's eigenproblem (Jurkevich, 1988) applied on the seismic signal filtered in the 5–15 Hz band, which encompasses most of the seismic energy of the analyzed tremor (Giudicepietro et al., 2019). After determining azimuth and incidence angles for each time window, data were filtered using a rectilinearity threshold of 0.5. Angles were then grouped in 60-s intervals to create frequency histograms. Analysis of amplitude, peak frequency, and polarization angles revealed temporal trends that provide valuable insights into the interpretation of hydrothermal tremor.

2.7. Deriving Gas Flow Rates From Acoustics

The persistent acoustic signals recorded at Pisciarelli can be attributed to gas outflow from both the Soffione fumarole and the boiling pool (Figures 1b and 3), which exhibit two distinct degassing dynamics: a continuous high-velocity jetting from the fumarole and an intermittent bubbling from the pool. This prompted us to adopt two different sound generation models to estimate the total acoustic gas flow rate from the system. For bubbling activity, characterized by signal regularity and relatively low overpressures involved, acoustic gas flow rates were estimated adopting the linear acoustic equation (Johnson & Ripepe, 2011; Lighthill, 1952), allowing us to obtain the volumetric flow rate time histories $q(t)$ from acoustic waveform $p(t)$ using the following equation:

$$q(t) = \frac{2\pi r}{\rho} \int_0^t p \left(t + \frac{r}{c_A} \right) dt \quad (8)$$

where r is the station to vent distance, ρ is the atmospheric density (1.08 kg/m^3 @ 25°C), and c_A is the sound speed in air ($\sim 340 \text{ m/s}$). To convert from volumetric to mass flow rate, gas density is required. Based on the composition

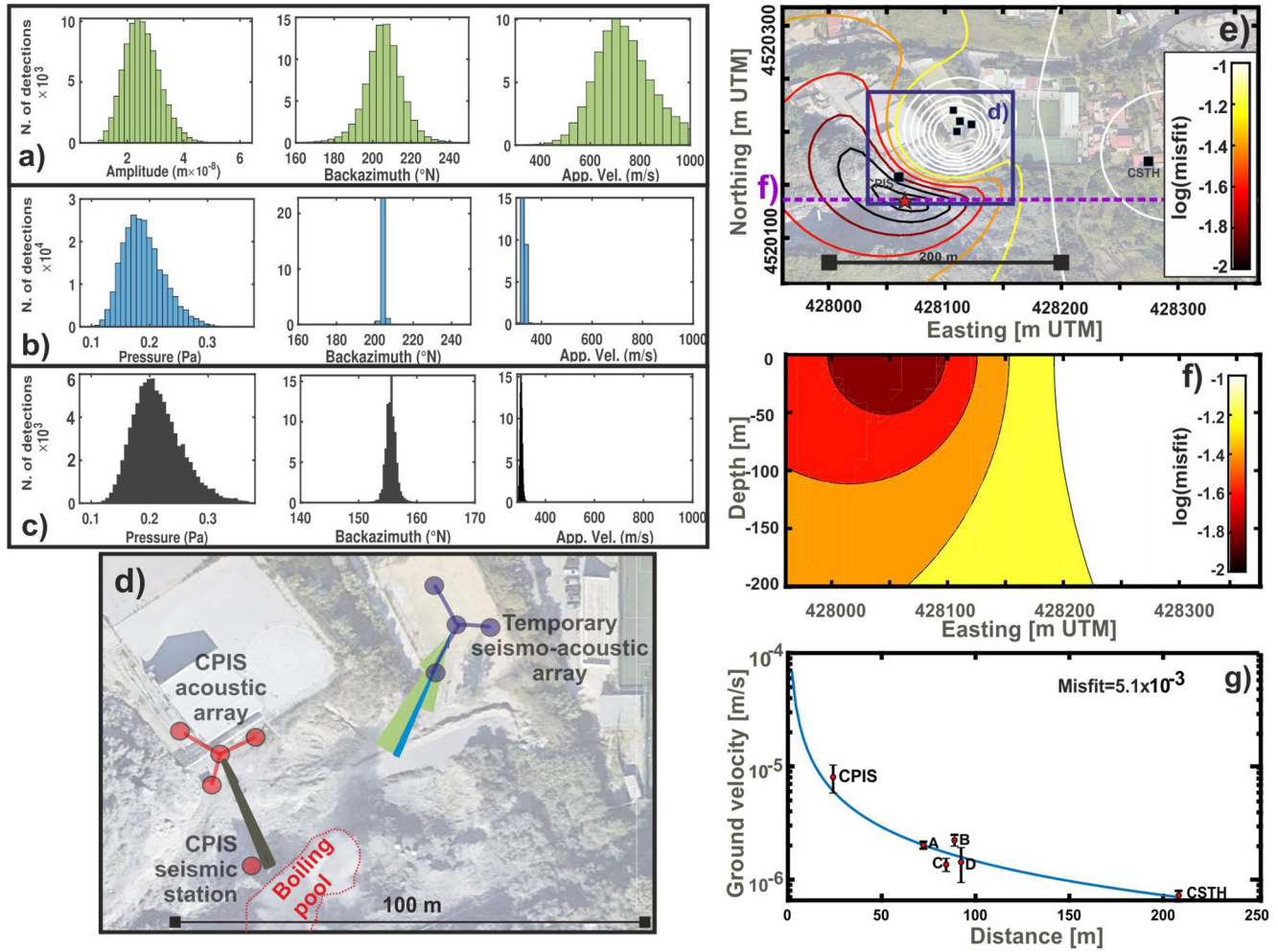


Figure 2. Distributions of amplitude, back-azimuth, and apparent velocity for the seismic (a) and acoustic detections obtained from (b) the temporary seismo-acoustic array deployed in September 2020 and (c) the CPIS acoustic array deployed in November 2023. Seismic and acoustic sources are both located within the hydrothermal field, as shown in panel (d) by their associated azimuth histograms. (e) Misfit distribution map at 9 m depth from the seismic amplitude-based source location method assuming body-wave propagation, with the minimum-misfit area (black outline, star) coinciding with the hydrothermal field. (f) Misfit distribution along a vertical east–west cross-section (location indicated by the purple line in panel e) constrains the seismic source to shallow depths, with the minimum misfit at 9 m below the hydrothermal field. (g) Observed seismic amplitudes at the stations, including confidence intervals, decay with distance from the minimum-misfit position in agreement with the theoretical body-wave decay curve (blue line).

and gas temperature reported by Caliro et al. (2007), we estimated a very stable gas density of $0.71 \pm 0.02 \text{ kg m}^{-3}$ for the Pisciarelli fumarole over a period of ~ 6 yrs.

In contrast, the high-frequency acoustic signals from the intense steam emissions at Soffione are complex and often characterized by short bursts, indicative of turbulent flow and jet noise radiation (e.g., Tam et al., 1996). This is supported by the spectral similarity to theoretical jet noise spectra (Matoza et al., 2018; Tam, 2019). In such cases, the sound is expected to be strongly directional (e.g., Iezzi et al., 2023), making the simple monopole model, which assumes sound is emitted equally in all directions, inapplicable. Consequently, the signal amplitude is strongly dependent on the relative position between the jet and the recording station. To estimate the gas flow rate, we therefore relied on the peak frequency of the jet-noise spectrum, f_{pck} , as it is less affected by directivity effects (e.g., Seiner, 1984):

$$v_g = \frac{f_{\text{pck}} D}{S_t} \quad (9)$$

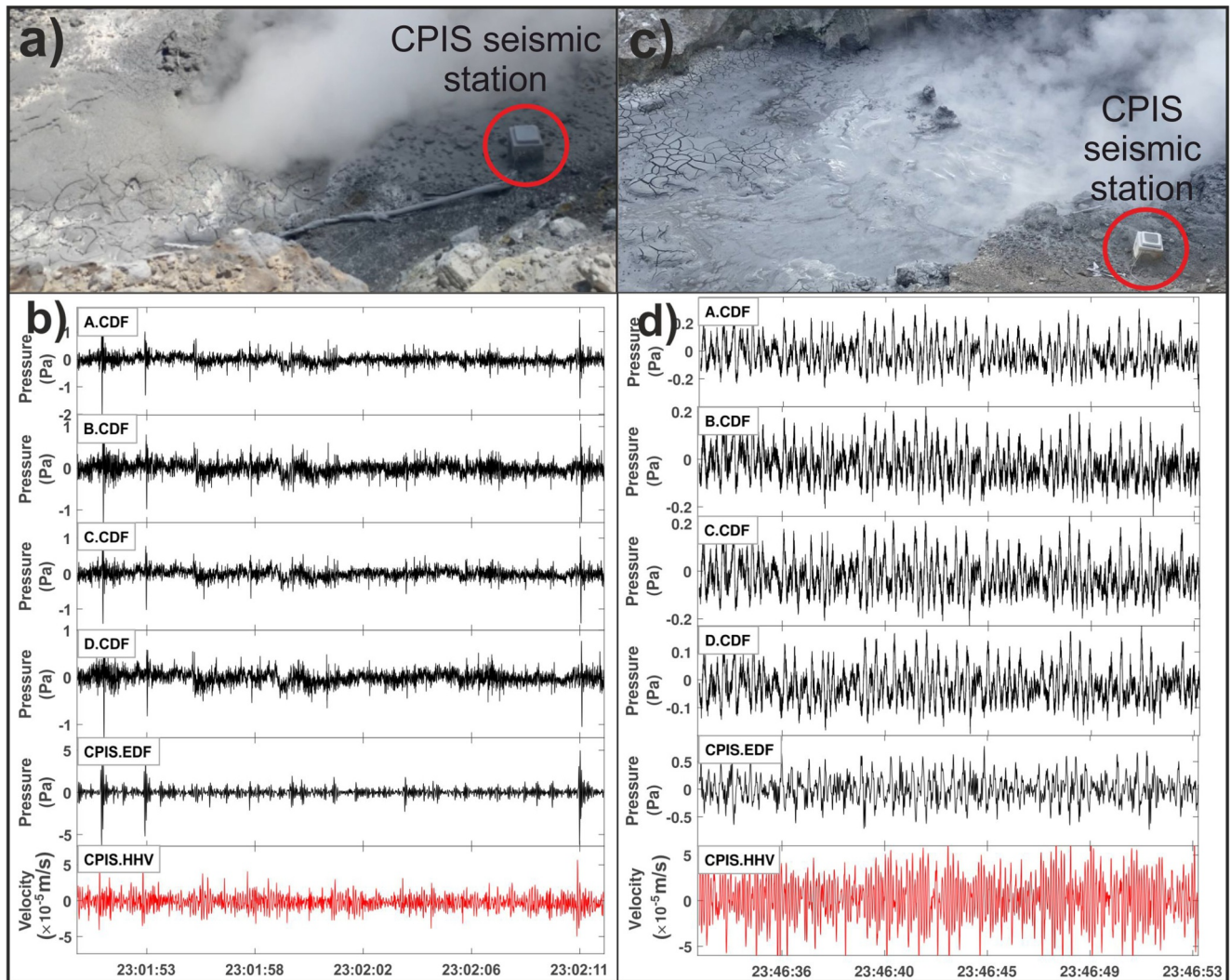


Figure 3. (a, c) Photographs of the Pisciarelli hydrothermal field showing two distinct phases of activity: (a) the dry-pool phase (23 September 2020), characterized by an empty pool and intense steam emissions from fumarolic vents, and (c) the boiling-pool phase (24 September 2020), marked by vigorous boiling activity and reduced steam emission. (b, d) Seismic (red) and acoustic (black) recordings over 20-s intervals corresponding to the dry-pool (b) and boiling-pool (d) phases. During the dry-pool phase (b), acoustic waveforms exhibit high-frequency noise (~ 0.1 Pa at 80 m) frequently interrupted by repetitive impulsive signals (~ 1 Pa at 80 m), typical of jet-noise radiation, and are associated with relatively low-amplitude seismic tremor ($< 1 \times 10^{-5}$ m/s at CPIS). In contrast, during the boiling-pool phase (d), the acoustic signal consists of lower-amplitude, near-monochromatic oscillations (2–5 Hz, ~ 0.2 Pa at 80 m), while seismic tremor amplitude increases threefold ($\sim 3 \times 10^{-5}$ m/s at CPIS). For scale, the CPIS station box shown in the photographs is approximately 1 m $\times$ 1 m in size.

where v_g is the gas exit velocity, D is the vent diameter, estimated to be around 50 cm, and S_r is the Strouhal number, considered constant over a wide range of emission (Yamamoto and Arndt, 1979; Woulff & McGetchin, 1976; Haney et al., 2018). We used a Strouhal number of 0.19, following Tam et al. (1996) and McKee et al. (2017). Once the gas velocity was determined, the flow rate was calculated by multiplying the velocity by the vent cross-sectional area, based on the diameter D .

3. Results

3.1. Localization of Seismic and Acoustic Sources Through Array Processing and Seismic Amplitude Distribution

The array analysis from the September 2020 experiment identifies coherent and persistent signals in the seismic record (Figure 2a), propagating with a back-azimuth aligned with the Pisciarelli hydrothermal area (Figure 2d; see also Figure S1a in Supporting Information S1). Seismic arrivals exhibit a low apparent velocity of 770 ± 170 m/s

(Figure 2a), indicating a relatively shallow seismic source (see also Giudicepietro et al., 2019). This apparent velocity value is consistent with Spatial Autocorrelation analysis (Bettig et al., 2001) results that confirm extremely low seismic velocities within the upper 40 m (Figure S2 in Supporting Information S1).

Seismic tremor source localization based on the spatial distribution of amplitudes was performed integrating data from both the permanent seismic stations and the temporary array. Notably, amplitude decreases by an order of magnitude over ~ 200 m, highlighting strong attenuation (from 8×10^{-6} m at CPIS to 7.3×10^{-7} m at CSH; Figure 2g). To assess whether the Pisciarelli tremor is primarily associated with body (P and S) or surface wave radiation, we analyzed the amplitude decay using theoretical models representative of each wave type. Application of the body wave model yielded a seismic source location with a significantly lower misfit (Equation 6; 5.1×10^{-3} ; Figures 2e–2g) compared to that obtained from the surface wave model (18×10^{-3} ; Figure S3 in Supporting Information S1). Under the body wave assumption, the tremor source is located at a depth of approximately 9 m, below the main fumarolic vents and the boiling pool (Figure 2f). This location is consistent with the back-azimuth estimate derived independently from array analysis. Conversely, the surface wave model places the source outside the hydrothermal system, further supporting the body wave hypothesis (Figure S3 in Supporting Information S1).

Array analysis on acoustic record (Figure 2b) from the same day yields results consistent with the seismic tremor data: the backazimuths show a preferential direction that aligns with the hydrothermal site (Figure 2d; see also Figure S1b in Supporting Information S1). The acoustic signals display RMS Amplitudes ranging from 0.1 to 0.3 Pa, with apparent velocities between 320 and 340 m/s, consistent with acoustic waves originating from a source at the same elevation as the array. Array-based localizations using data from the permanent array installed in late 2023, approximately 30 m northwest of the Pisciarelli hydrothermal site (Figure 2c), indicate that the acoustic source exhibits a stable back-azimuth directed toward the hydrothermal area (Figure 2d). Despite being acquired at different times, the combined array localizations effectively constrain the acoustic source to within the Pisciarelli hydrothermal site, revealing a persistent and temporally stable emitter of seismic and acoustic energy linked to shallow hydrothermal processes.

3.2. Seismo-Acoustic Signature Associated With Hydrothermal Outgassing Dynamics

Results from the September 2020 experiment indicate that seismic and acoustic signals respond in a coherent manner to macroscopic changes within the Pisciarelli hydrothermal vent system. This has been shown previously to alternate periodically between two distinct activity states (Fedele et al., 2021): (a) a *dry-pool* state, characterized by the absence of thermal water in the boiling pool and intense steam-jet emissions from the Soffione fumarole (Figure 3a); and (b) a *boiling-pool* state, where steam emissions are reduced and vigorous boiling occurs within the water-filled pool (Figure 3c).

Our results show that, during the dry-pool state, when the thermal pool is empty, the tremor amplitude is low and the acoustic signal is dominated by high-frequency noise, intermittently interrupted by explosion-like bursts (~ 1 Pa) (Figure 3b), which can occasionally be heard as faint ticking sounds within the continuous roar produced by the Soffione fumarole. The PSD shows a broad peak centered at around 16–20 Hz, consistent with features typical of turbulent jet noise radiation (Matoza et al., 2009; McKee et al., 2017; Tam, 2006; Tam et al., 1996) (Figure 4a). With a vent diameter of ~ 50 cm for the Soffione vent, the gas flow rate can be inferred at 6–8 kg/s from the observed peak frequency of ~ 16 –20 Hz (Figure 4a). This corresponds to exit velocities of 42–44 m/s, consistent with direct field measurements conducted using a Pitot tube, which yielded velocities ranging between 31 and 43 m/s.

In contrast, the boiling-pool state (Figure 3c) is characterized by lower-frequency acoustic signals (~ 2 –5 Hz; Figure 4a), lower amplitudes (~ 0.2 Pa) and a quasi-monochromatic, continuous train of pulses (Figure 3d). We model the acoustic emissions from the boiling pool as monopole radiation produced by the rhythmic release of gas bubbles, and estimate an average total gas emission rate of approximately 1.5 kg/s. When compared to the dominant contribution from the Soffione vent, the thermal pool accounts for only about 17%–20% of the total gas flow rate. Overall, the total gas flow rate responsible for generating acoustic waves at Pisciarelli is estimated to range between 7.5 and 9.5 kg/s. For comparison, Stromboli's puffing activity has been associated with gas flow rates ranging from 7 to 26 kg/s (Delle Donne et al., 2026; Harris & Ripepe, 2007), placing the Pisciarelli system at the lower end of this volcanic degassing scale.

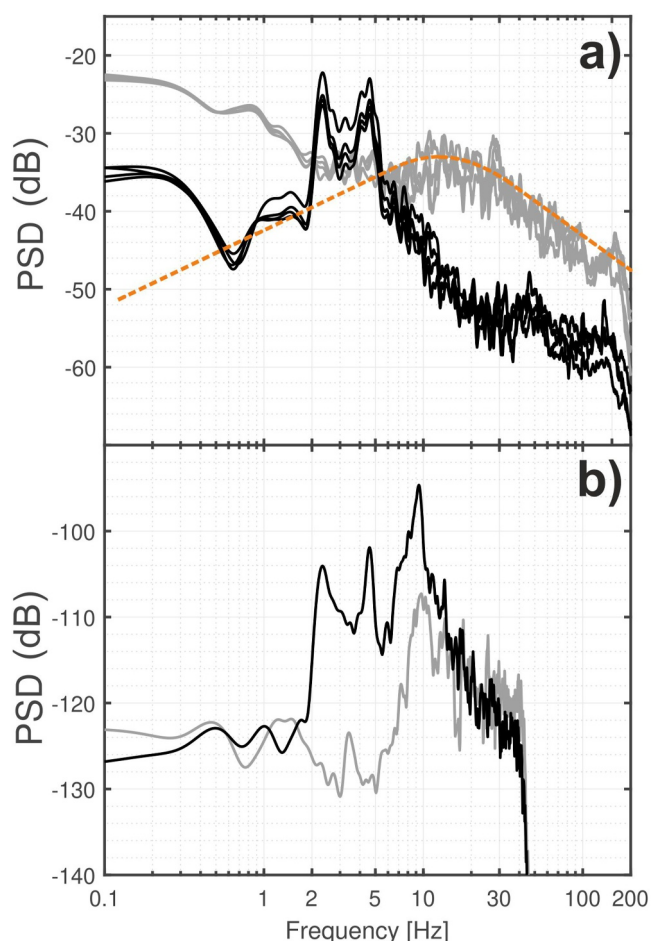


Figure 4. Comparison between the Power Spectral Density associated with the acoustic (a) and seismic (b) signals associated with the two distinct hydrothermal phases: dry-pool (gray) and boiling-pool (black). The two phases show a substantial change in the spectral shape associated with the acoustic signal: the dry-pool phase exhibits a broad spectral peak centered around 16–20 Hz, which closely fits the theoretical jet noise spectrum (orange curve), while the boiling-pool phase is characterized by sharper spectral peaks in the 2–5 Hz range and reduced energy at higher frequencies. In contrast, the seismic signal shows greater similarity between the two phases, with a dominant spectral peak consistently observed near ~10 Hz. During the boiling-pool phase, a partial spectral overlap is observed between secondary seismic peaks and the primary peaks in the acoustic spectrum, suggesting a degree of coupling between subsurface and surface source processes.

Seismically, both boiling and dry-pool phases are characterized by a dominant spectral peak around 10 Hz (Figure 4b). During the boiling-pool phase, an additional minor energy contribution emerges in the 2–5 Hz band, with an amplitude approximately 10 dB lower than the dominant 10 Hz component and a spectral pattern closely resembling that of the acoustic signal (Figure 4a), suggesting a possible seismic–acoustic coupling within this frequency range (Ichihara et al., 2021). However, array-derived propagation velocities of ~340 m/s for acoustic waves and ~770 m/s for seismic waves indicate distinct wavefields, implying that seismic–acoustic coupling likely plays only a minor role in tremor generation.

3.3. Groundwater Control on Seismic Tremor Amplitudes and Acoustic Flow Rates

Results from the permanent network allow us identifying multiple events in which tremor amplitude responded to macroscopic changes of the boiling pool. Notably, analyses of webcam footage (Figure 5, Movies S1 and S2) allows us to document the seismo-acoustic signatures associated with transitions between the dry-pool and boiling-pool states. On 28 August 2021, following an extended dry period, a heavy rainfall triggered a sharp increase in seismic tremor amplitude (Figure 5d), coinciding with a rapid rise in the water level of the thermal pool (Figures 5a–5c, Movie S1). Using the known length of the pole near the hydrothermal pool (1.5 m; Figure 5c, circled in yellow) as a metric reference, we estimated that the water level rose by approximately 3 m. In contrast, on 10 September 2021 a desiccation event of the pool was observed (Figures 5e–5g, Movie S2), accompanied by a marked decrease in tremor amplitude (Figure 5h). The examples presented here illustrates a recurring dynamic at the Pisciarelli hydrothermal site (Figure S4 in Supporting Information S1), highlighting the strong seismo-acoustic sensitivity to meteoric water influx in the hydrothermal system.

We present a detailed analysis of the water-rise event occurred on 28 August 2021 (Figure 5d). Specifically, Figure 6 shows the evolution of both acoustic and seismic records during the transition from a dry-pool to a boiling-pool state. Along the acoustic trace from the CPIS sensor, the peak phase of the torrential rainfall is well identifiable, marked by a sharp increase in the acoustic amplitude, attributed to the combined effects of strong winds and heavy raindrops impacting the sensor housing (Figure 6a). As the water level rises in the thermal pool and reaches its peak during the torrential rainfall (between frames of Figures 5a and 5b), the acoustic recordings and corresponding spectrograms show a transition in signal pattern (Figures 6a and 6b). The high-frequency turbulent noise (~20 Hz), marked by high-amplitude (~2 Pa) explosion-like bursts and associated with a high-flow rate degassing regime (6–8 kg/s), progressively weakens until it vanishes.

This phase is followed by continuous, lower-frequency (~2–5 Hz), lower-amplitude (~1 Pa), nearly monochromatic oscillations, characteristic of the low-flow rate (~1.5 kg/s), sustained boiling-pool phase.

The water-rise event also generated a long-period signal on the horizontal components of the CPIS seismometer, with a period well below its 60-s eigenperiod, which we interpret as ground tilt (Figures 6c and 6d). The estimated tilt amplitude of ~100 μ rad indicates uplift of the thermal pool relative to the CPIS station, corresponding to a downward tilt toward the northwest (Figure 6e). This deformation is attributed to pressurization within the feeding conduit, consistent with local inflation.

The inferred pressurization is temporally correlated with the rising of the water column (Figures 5a–5c), the increase in tremor amplitude (Figure 5d), the shift in the acoustic spectrum (Figure 6b) and the concurrent reduction in acoustic amplitude (Figure 6a). Polarization analysis, shown as frequency–time histograms of

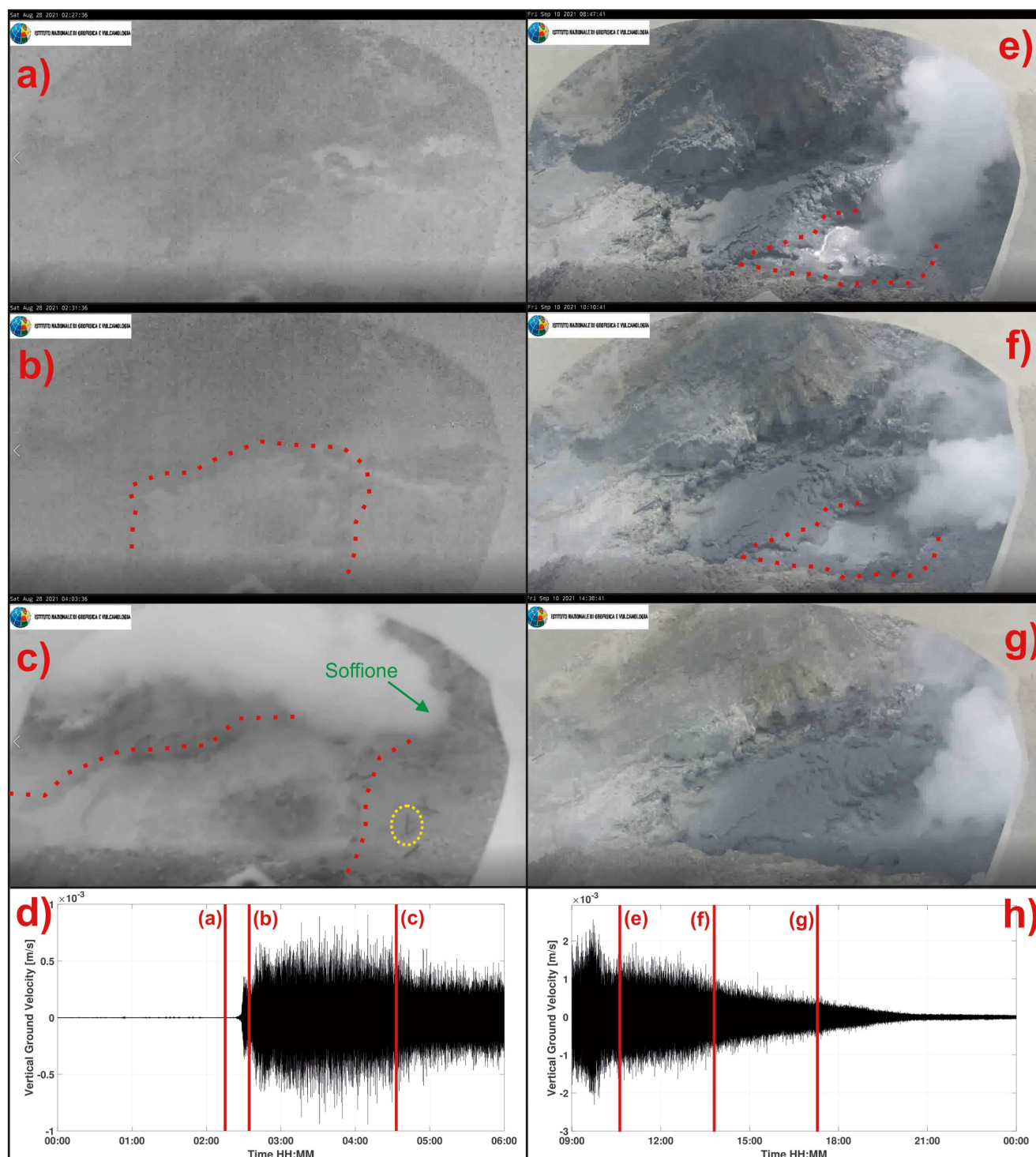


Figure 5. Webcam images from 28 August 2021 showing the transition from dry (a) to boiling pool (b, c) during heavy rainfall, marked by a rapid rise in water level and a simultaneous sharp increase in seismic tremor amplitude (d). Webcam images from 10 September 2021 showing the transition from boiling (e, f) to dry pool (g), accompanied by a marked decrease in tremor amplitude (h). The boundary of the hydrothermal water at the different stages is marked by red dotted curves. The 1.5 m-long pole used as a metric reference within the image is indicated by the yellow dashed circle.

polarization angles (Figures 6g and 6h), reveals a strongly polarized seismic signal at CPIS, consistent with body wave radiation (see also Giudicepietro et al., 2019). During the transition from the dry-to boiling-pool phase, subtle but significant changes in both azimuth and incidence angles are observed.

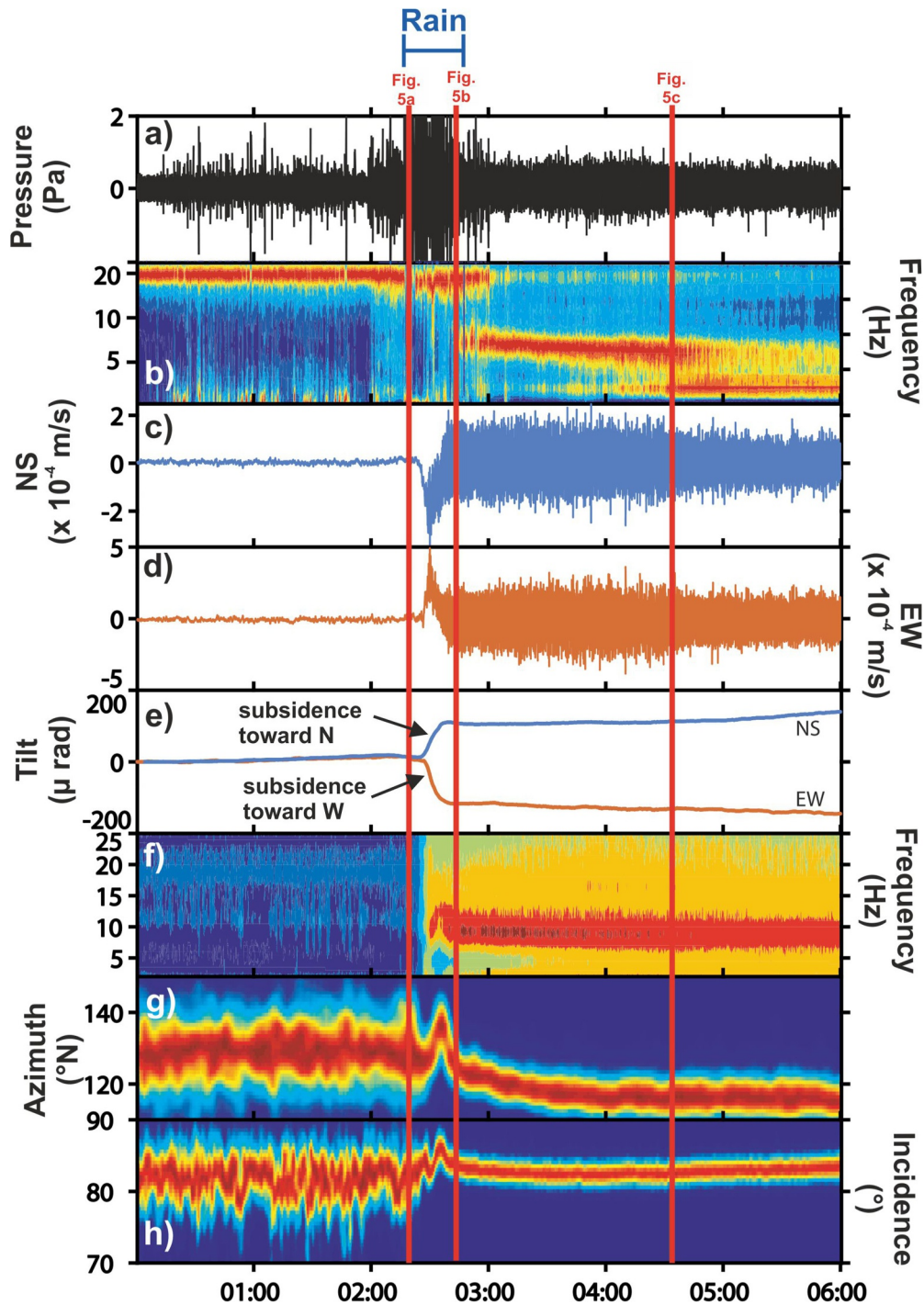


Figure 6. Seismo-acoustic records of the dry-to-boiling pool transition observed on 28 August 2021, triggered by a rainfall event. Red vertical lines indicate the times of webcam images shown in Figures 5a–5c, which capture the rise of thermal water within the pool. (a) Acoustic signal before the transition, dominated by high-frequency noise (~ 20 Hz) punctuated by explosive-like transients with amplitudes of ~ 2 Pa, characteristic of the dry-pool phase. After the rainfall event, evident in the acoustic record as bursts exceeding 2 Pa due to wind and raindrop impacts on the sensor box, the signal transitions to lower-frequency (~ 2 –5 Hz), lower-amplitude, near-monochromatic oscillations typical of the boiling-pool phase. (b) Acoustic spectrogram highlighting the shift from high-frequency noise to low-frequency oscillations. (c, d) Seismic horizontal ground velocity components (NS and EW) showing a marked amplitude increase and a very low-frequency pulse, consistent with the timing of the rainfall. (e) Ground tilt components derived from the seismic data (NS and EW) revealing a transient tilt of ~ 100 μ rad, with the sensor inclining toward the northwest. This is interpreted as an inflation/pressurization of the boiling pool. (f) Seismic spectrogram showing a stable dominant frequency near 10 Hz, which is more evident after the transition. (g–h) Azimuth and incidence angle distributions derived from polarization analysis, indicating a counterclockwise rotation of approximately 15° – 20° , suggesting a slight lateral migration, along with a shallowing of the source during the phase transition.

3.4. Recurrent Seismo-Acoustic Response to Rainfall

To obtain further insight into the dynamics observed at Pisciarelli, the CPIS station was equipped in December 2023 with a four-element acoustic array (Figure 1c). This configuration integrates acoustic array data and broadband seismic recordings along with hydrothermal steam temperature measurements. Key results are presented in Figure 7, together with rainfall intensity (Figure 7a) over four-month period from December 2023 to April 2024. This period is entirely characterized by a boiling-pool state, with concurrent activity at the Soffione vent, but no transition is observed. Nevertheless, the same rain-induced modulation of the signals can still be observed. In particular, acoustic amplitude displays a generally increasing trend over time, interrupted by abrupt drops (Figure 7b) that consistently align with phases of enhanced seismic tremor amplitude (Figure 7d), confirming that the anti-correlation between seismic and acoustic signals previously observed (Figure 6), is a persistent characteristic of the seismo-acoustic wavefield, even in the absence of a dry-to-boiling transition. These sharp decreases in acoustic amplitude, accompanied by concurrent increases in tremor amplitude, coincide with periods of rainfall (Figure 7a), and are also associated with transient, simultaneous drops in steam temperature measured at the Soffione vent (Figure 7c).

4. Discussions

4.1. Steam Condensation as the Likely Mechanism Generating Hydrothermal Tremor

Fluid-induced seismic tremor at volcanoes and within hydrothermal systems has been interpreted through a wide range of mechanisms and conceptual models. These include elastic resonance processes generating periodic pressure fluctuations within fluid-filled conduits, beneath permeable caps, or within crack networks (e.g., Aki et al., 1977; Chouet, 1988; McNutt & Nishimura, 2008; Girona et al., 2019), hydrothermal boiling and bubble dynamics (Kedar et al., 1998; Leet, 1988), and mechanically forced bubble coalescence under confined conditions (Ripepe & Gordeev, 1999).

Our analysis indicates that seismic tremor at Pisciarelli is confined to the shallow subsurface beneath the active hydrothermal area (Figure 2e). The signal is continuous, persistent, and remarkably stable over timescales ranging from hours to months (Figures 6 and 7, Figures S1 and S5 in Supporting Information S1), suggesting that tremor represents a steady-state process within the hydrothermal system. Tremor amplitude consistently increases during rainfall events. This, in conjunction with the simultaneous, transient decreases in steam temperature (Figure 7c), points to a process driven by the influx of meteoric water. We suggest that the infiltration of cold meteoric water cools the hydrothermal fluids, hence promoting steam condensation within the shallow conduit system, and reducing the amount of steam reaching the surface (Figure S6 in Supporting Information S1). This interpretation is further supported by the concurrent decrease in acoustic emissions during rainfall episodes (Figures 6 and 7), indicating a net reduction in total fluid discharge coincident with enhanced seismic tremor.

We caution that alternative tremor source process cannot entirely be ruled out. However, we can argue that the strong correlation existing between meteoric water inflow and tremor amplitude makes models based on structural or rheological discontinuities, such as mechanically forced bubble coalescence (Ripepe & Gordeev, 1999) or bubble accumulation beneath a permeable cap (Girona et al., 2019), less likely, considering that these latter mechanisms are expected to be largely insensitive to external factors like meteoric water input. Rather, our observations at Pisciarelli are most consistent with the subcooled harmonic tremor model of Leet (1988) and Kedar et al. (1998). In this framework, seismic tremor would be generated by resonance within a conduit, where rising steam bubbles collapse upon encountering cooler meteoric water, producing seismic waves through rapid condensation and the resulting pressure drop within the conduit.

According to this model, the dominant tremor frequency (f) is related to the effective length (L) of the conduit segment involved in steam condensation and the seismic wave velocity in the fluid (v_f), according to $L = v_f/(2f)$. Assuming $v_f \approx 1,500 \text{ m s}^{-1}$, appropriate for hydrothermal fluids at $\sim 94\text{--}95^\circ\text{C}$ (Figure 7), the observed dominant tremor frequency of $\sim 10 \text{ Hz}$ (Figures 4b and 6f) would correspond to an effective conduit length of approximately 75 m. Seasonal cyclic variations in tremor dominant frequency over the four-year monitoring period (Figure S5d in Supporting Information S1), with lower frequencies in winter and higher frequencies in summer, indicate systematic changes in the effective length of the condensation zone, from ~ 60 to $\sim 125 \text{ m}$, in response to seasonal variations in rainfall. A variable condensation length, modulated by meteoric recharge, would also be consistent with the slight spatial migration and progressive shallowing of seismic polarization angles observed during

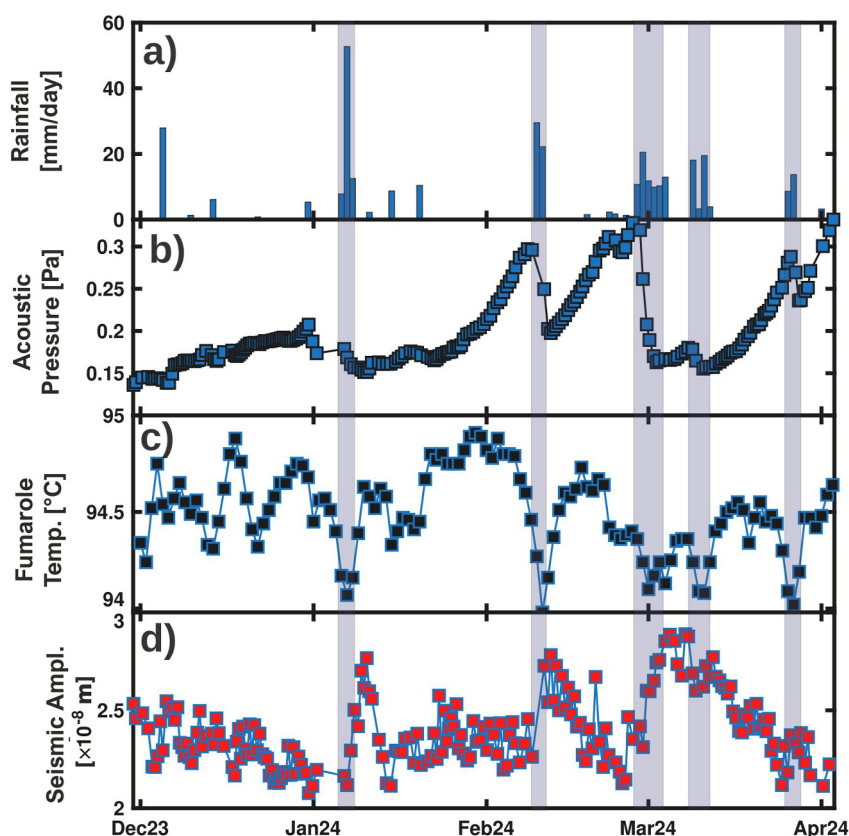


Figure 7. Seismo-acoustic trends (b, d) recorded between December 2023 and April 2024 show coherent fluctuations with (a) rainfall data from the village of Pozzuoli (Figure 1a) (source: 3B Meteo, <https://www.3bmeteo.com/meteo/pozzuoli/stori-co>; last access July 2025) and with (c) fumarole temperature. Acoustic amplitude (b) and fumarole temperature display sharp decreases during major rainy periods (highlighted in gray), which coincide with increases in seismic tremor amplitude (d).

thermal water rise events (Figures 6g and 6h). Together, these observations further support a tremor source generated by steam condensation within the hydrothermal conduit.

4.2. Tracking Cyclic Pressure Variations Through Water Level Changes in the Pisciarelli System

A key finding is that the transition from a dry to a boiling pool following rainwater infiltration not only triggers seismic tremor, likely due to enhanced steam bubble condensation, but also coincides with conduit inflation, as indicated by tilt variations at CPIS (Figure 6e). This suggests a pressurization of Pisciarelli's shallow feeding system (e.g., Tanabe et al., 2023), which drives the ascent of water within the thermal pool, tending to re-establish hydrostatic equilibrium at a new level. Although it cannot be precisely quantified due to the availability of only a single tilt measurement, the water level of the thermal pool appears to reflect the pressurization state of the system and may serve as a proxy for its temporal evolution (Figure 6).

From the webcam images (Figures 5a–5c), it is possible to estimate a variation in the hydrothermal water level of at least 3 m. A rise in the water level of this magnitude would correspond to a minimum overpressure of approximately 30 kPa, assuming a fluid density of $1,000 \text{ kg/m}^3$. In this context, monitoring water levels within the conduits could serve as a valuable indicator of system pressure. Given the strong correlation between tremor activity and water level, temporal changes in the position of the tremor source may likewise reflect pressure variations within the system. These can be effectively tracked using the amplitude ratio between the nearby CPIS and the more distant CSTD station (Figure 8c). While both stations faithfully record the tremor variations during this period (Figures S5a and S5b in Supporting Information S1), only the amplitude ratio is sensitive to source migration (e.g., Taisne et al., 2011). Assuming that the tremor source is linked to steam condensation, the CPIS/CSTD ratio may serve as a proxy for the depth of the condensation front: an increasing ratio indicates shallowing, whereas a decreasing ratio suggests deepening of the condensation zone.

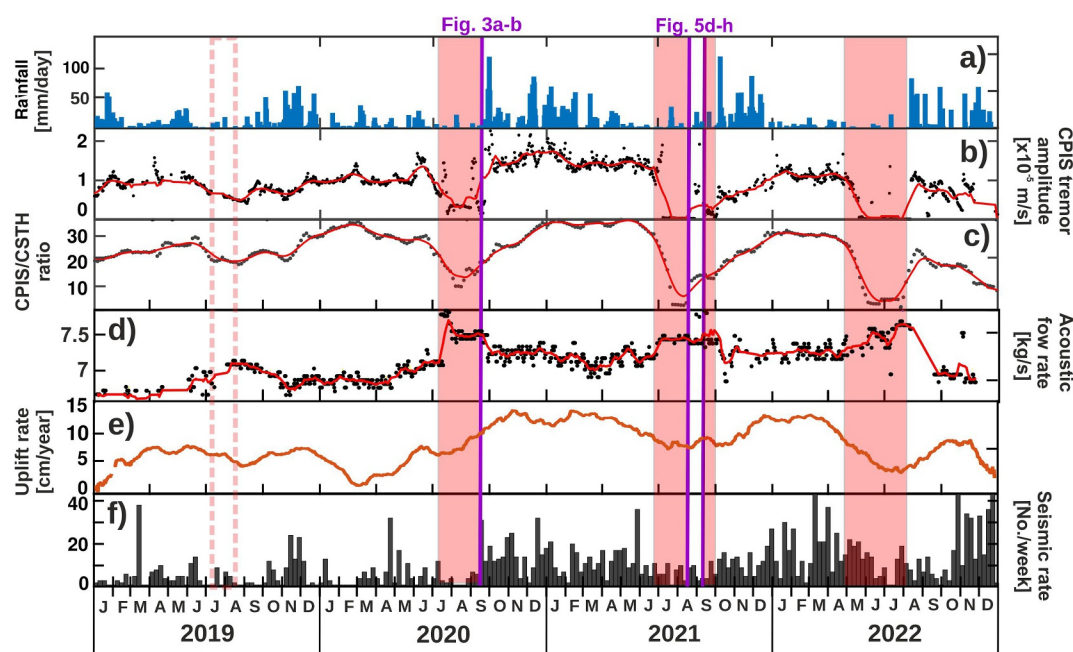


Figure 8. Four-year time series (2019–2022) showing: (a) rainfall, (b) hydrothermal tremor amplitude from the CPIS station (a 60-day moving average is shown as a red line), (c) hydrothermal water level inferred from the CPIS/CSTH amplitude ratio (a 60-day moving average is shown as a red line), (d) acoustic flow rate from the Soffione fumarole (a 30-day moving average is shown as a red line), (e) uplift rate from the PIS GPS station, and (f) weekly averaged rate of occurrence in the earthquakes located within a 2 km radius of the Pisciarelli site. All time series display seasonal modulations: summer months, characterized by low precipitation, correspond to lower hydrothermal tremor, reduced hydrothermal water level (highlighted by pink vertical bands), and reduced seismicity, but higher acoustic flow rates. These seasonal variations, however, are secondary to the dominant long-term trend of increasing acoustic flow rate and seismicity rate.

4.3. The Pisciarelli Hydrothermal Site in the Context of the Campi Flegrei Unrest

The cyclic variations we report represent a highly localized and shallow phenomenon, driven by the interaction between ascending volcanic fluids and meteoric water in the vent feeding system (Figure 8). Yet, Pisciarelli is one of the main degassing sites at CFC, raising the question of whether localized hydrothermal pressure changes can propagate downward and perturb the deeper hydrothermal system, widely considered the primary source of unrest-related seismicity (Tramelli et al., 2022). To explore this potential connection, Figure 8 compares seismicity, ground deformation, and meteorological data with tremor amplitude, acoustic flow rates, and inferred water-level variations at Pisciarelli (2019–2022). Seismicity is expressed as the weekly number of events within 2 km from the site, and deformation as 30-day averaged uplift rates from the nearby PIS GPS station. The boiling water level, inferred from the seismic amplitude ratio, exhibits pronounced seasonal variability (Figure 8c): it peaks in winter, coinciding with high tremor amplitude, and remains sustained through May due to the persistence of meteoric water in shallow aquifers, despite declining rainfall, and drops to a minimum in July–August when the pool dries out. These low water levels, associated with reduced condensation and absence of surface water, coincide with enhanced degassing (Figure 8d), suggesting that steam emission intensifies when condensation is limited. Acoustic flow rates, derived inverting the peak frequency associated with the turbulent jet-noise radiation, display a first-order increasing trend, reaching 6.8–7.7 kg/s.

Over this 4-year interval, the seismicity rate displays a general upward trend (Figure 8f), accompanied by a persistently positive uplift rate reaching nearly 12 cm/year (Figure 8e), in line with ongoing caldera unrest (e.g., Caliro, Chiodini, et al., 2025; Scaillet et al., 2025). Variations in seismicity rate occur in phase with corresponding changes in ground deformation rate, a relationship previously documented at CFC (Giudicepietro, Chiodini, et al., 2021).

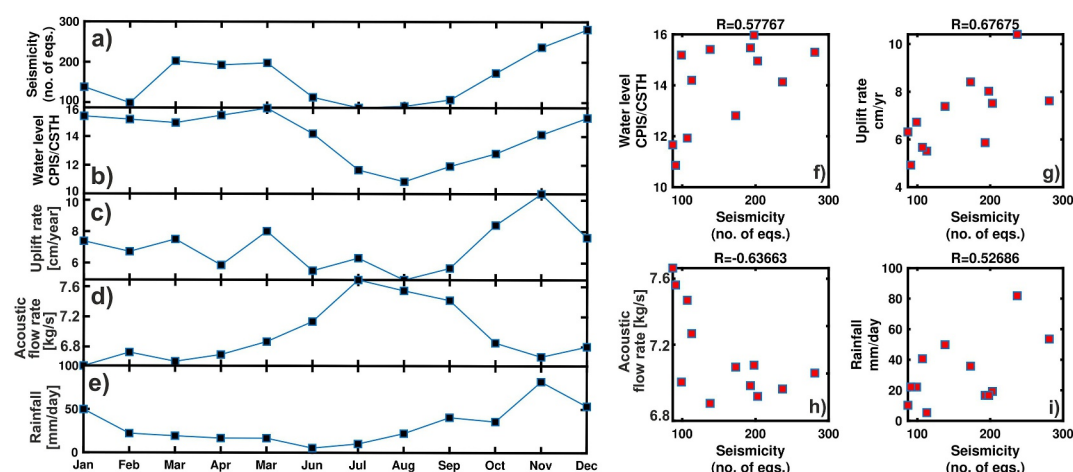


Figure 9. (a) Monthly cumulative number of earthquakes, stacked over the 2019–2022 period (see Figure 8), to highlight seasonal seismicity fluctuations. During the summer months (June–September), the total number of events (~ 100) is approximately half that observed during spring (March–May) and autumn. (b–e) Monthly averages of: (b) CPIS/CSTH ratio (used as a proxy for hydrothermal water level), (c) ground uplift rate, (d) acoustic flow rate from the Soffione fumarole, and (e) precipitation, all averaged over the same 4-year period shown in Figure 8. The plots reveal a seasonal pattern where the summer months are characterized by both reduced seismicity (a) and lower hydrothermal water levels, as indicated by the CPIS/CSTH ratio (b). In contrast, gas flow rate (d) shows a notable increase during summer, likely due to reduced steam condensation. (f–i) Scatter plots of each parameter (CPIS/CSTH ratio, uplift rate, acoustic flow rate, and rainfall) plotted against seismicity rate to explore potential correlations. Positive correlations are observed between seismicity and CPIS/CSTH ratio, uplift rate, and rainfall, while an inverse correlation emerges between acoustic flow rate and seismicity.

The correlation between fluctuations in seismic, deformation rates and seismo-acoustic signals is not so straightforward. Notably, however, periods of low water levels, characterized by low CPIS/CSTH amplitude ratios and enhanced gas flow rate, coincide with relative minima in seismicity (Figure 8f).

To emphasize the seasonal component of the observed cyclic behavior, we segmented and stacked the time series into 12-month intervals (Figure 9). This analysis reveals that, during summer, the seismic rate is on average half that observed in the other seasons (e.g., Sahoo et al., 2024) and is directly correlated with the inferred height of the water level ($R \approx 0.6$; Figure 9f) while being inversely correlated with seasonal fluctuations in acoustic flow rate ($R \approx -0.6$; Figure 9h). Rainfall shows a weaker correlation with seismic rate ($R \approx 0.5$; Figure 9i), displaying partial correspondence with increased seismicity in autumn but not in spring. In contrast, uplift rate exhibits the strongest correlation with seismic rate ($R \approx 0.7$; Figure 9g), confirming a previously recognized link between seismicity and deformation (e.g., Giudicepietro, Chiodini, et al., 2021; Giudicepietro, Ricciolino, et al., 2021).

Overall, the observed correlations among seismic rate, rainfall (Figure 9i) and seismo-acoustic signals (Figures 9f and 9h) suggest that meteorically driven hydrothermal degassing dynamics may influence the deeper hydrothermal system by modulating its seismic release (Scafetta & Mazzarella, 2021; Vanorio et al., 2025). This could occur through local pressure changes, with magnitudes inferred from this work of at least 30 kPa, which are sufficient to affect the local stress field and promote shallow volcano-tectonic seismicity (Wang et al., 2024).

However, these seasonal effects remain secondary. While meteoric forcing may influence reservoir pressure and promote seismicity by up to 50% during rainy periods (Figure 9), such fluctuations are superimposed on a dominant long-term increase in seismicity, uplift, and degassing that drives the evolution of unrest (Figures 8 and 9). This becomes particularly evident when extending the analysis over the past decade (Figure S7 in Supporting Information S1): both uplift and seismicity rates exhibit exponential growth, whereas cumulative rainfall has remained relatively constant (~ 1.5 m/year), indicating that correlations among seismicity, deformation and rainfall do not persist on multi-year timescales. Although meteoric water influx may help trigger seismicity under critically stressed conditions, it is unlikely to be the main driver of the ongoing caldera unrest, which more plausibly reflects deeper processes within the magmatic–hydrothermal system operating independently of surface hydrology (Caliro, Chiodini, et al., 2025; Chiodini et al., 2016; Kilburn et al., 2023).

4.4. Estimating Outgassing Flow Rates From Acoustic Record

This study also lays the foundation for using acoustic signals as a proxy for gas flow rate (e.g., Delle Donne et al., 2026), offering a valuable addition to hydrothermal monitoring strategies alongside established geophysical and geochemical approaches. Quantifying gas flow rates is critical for understanding volcanic system dynamics; however, direct measurements remain challenging and are typically limited to spectroscopic methods or point-based concentration surveys carried out during field campaigns, which provide only discrete, time-limited observations (e.g., Tamburello et al., 2019 and references therein). In contrast, acoustic monitoring provides a valuable alternative, as acoustic wave amplitudes are directly linked to gas release into the atmosphere.

Here we analyzed the overpressurized gas emissions from Soffione fumarole and the boiling activity within the thermal pool to estimate the total acoustic output associated with hydrothermal degassing. Uncertainties in acoustic-derived gas flow rates arise mainly from time-dependent variations in vent geometry, which strongly affect the reliability of the estimates (see Method Section 2.7), but the assumption of a constant vent diameter of approximately 50 cm is supported by the relatively stable morphological conditions observed during the 2019–2022 period, which enabled consistent tracking of frequency variations in the acoustic signal throughout this extended interval. Based on this assumption, the estimated gas flow rate is approximately 7.5–9.5 kg/s, which corresponds to a CO₂ flow rate of ~130–165 t/d. For comparison, independent CO₂ flow rate estimates at Pisciarelli between 2012 and 2016, based on laser absorption spectroscopy, range from 171 to just under 284 t/d, considering only the main fumarolic emissions and excluding diffuse soil degassing (Aiuppa et al., 2015; Pedone et al., 2014; Queißer et al., 2017). These values are higher than our acoustic-based estimates but remain within the same order of magnitude, supporting the reliability of the acoustic method for deriving real-time gas flow rates. However, a more precise and robust comparison between the two methods would require measurements conducted over the same time interval. Therefore, this should be considered only an order-of-magnitude comparison, which nonetheless appears promising for future investigations into the performance of the acoustic method.

5. Conclusions and Implications for Monitoring

Our study highlights the correlation between meteoric water and variation in hydrothermal degassing, which we suggest result from steam condensation. The resulting dynamics may promote or inhibit seismicity through pressure variations within the hydrothermal reservoir. Overall, our results demonstrate that seismo-acoustic monitoring is an effective tool for tracking hydrothermal processes, enabling real-time detection of internal pressure changes and gas flow rate variations. This provides an additional tool that can contribute to hazard mitigation associated with hydrothermal activity, that under certain condition may potentially trigger hydrothermal and phreatic explosions (e.g., Aizawa et al., 2022), similar to those documented in geyser systems.

Although Pisciarelli differs significantly from other geyser-like systems known for explosive activity, primarily because it lacks the abundant liquid water that plays a critical role in those systems (Fournier, 1999; Nayak et al., 2020; Tanabe et al., 2023), the recent overall increase in gas emissions across Campi Flegrei caldera (Giudicepietro et al., 2025), combined with the growing likelihood of extreme meteorological events driven by climate change, may generally increase the probability of such more energetic hydrothermal events occurring (Farquharson & Amelung, 2020).

For these reasons, INGV-OV has recently implemented extensive seismo-acoustic monitoring within the Campi Flegrei caldera highly urbanized area to enhance prevention and public safety. This work underscores the importance of seismo-acoustic monitoring for real-time detection of potential anomalous hydrothermal activity, which may precede major hydrothermal explosive events.

Disclaimer

The views and conclusions expressed in this study are those of the authors and do not necessarily reflect the official policies or positions of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) or the Dipartimento della Protezione Civile.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data supporting the findings of this study are openly available as Morelli et al. (2026).

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