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Key Points:

- Fumarolic tremor indicates a new increase of the Pisciarelli hydrothermal activity linked to the current large-scale unrest at Campi Flegrei
- The fumarolic tremor analysis allowed us to identify an episode of enlargement of Pisciarelli mud emissions
- We propose a method for monitoring the hydrothermal system based on proximal measurements of fumarolic tremor

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Insight Into Campi Flegrei Caldera Unrest Through Seismic Tremor Measurements at Pisciarelli Fumarolic Field

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Abstract Within a general volcanic unrest in the densely urbanized area of Campi Flegrei caldera (Italy) an increase in the activity of Pisciarelli hydrothermal area is occurring. The seismic amplitude of Pisciarelli fumarolic tremor is a proxy for the fluid emission rate of the entire Solfatara-Pisciarelli hydrothermal system. The long-term analysis indicates a significant increase, by a factor of ~3 of the fumarolic tremor amplitude since May 2017. This increment matches with the trend of geochemical and seismic parameters observed in Campi Flegrei, therefore highlighting that Pisciarelli is a key site to monitor the volcanic unrest underway in this high-risk caldera. The analysis of data from three closely spaced seismic stations provided new clues about the source mechanism of the tremor. Analyzing the fumarolic tremor amplitude we could also identify an episode of enlargement of the emission area close to the main fumarole of Pisciarelli. We propose a monitoring system based on the fumarolic tremor analysis, which provides real-time information on the Pisciarelli hydrothermal activity and therefore on the current unrest in Campi Flegrei caldera.

1. Introduction

The Campi Flegrei volcanic complex is a collapse caldera of about 12 km in diameter, located in southern Italy (Figure 1). The edges and the caldera itself have been densely populated since ancient Greek times and large cities, such as Naples, Pozzuoli, and Cuma are located in this area. Nowadays, these cities form a seamless urban area that is home to over 2 million inhabitants.

After the last eruption in 1538 (Monte Nuovo eruption), the Campi Flegrei were subsiding, but since the beginning of the 1950s, they started to show repeated unrest episodes characterized by large uplifts (Del Gaudio et al., 2010; Giudicepietro et al., 2017). In particular the subsidence of the caldera, which followed the 1538 eruption, was interrupted by a first up-lift episode in 1950 (about 73 cm, Del Gaudio et al., 2010). Successively, remarkable episodes of up-lift occurred between 1968 and 1972 (about 177 cm) and from 1982 to 1985 (179 cm). This last event was accompanied by about 16,000 earthquakes (Calò & Tramelli, 2018; D'Auria et al., 2011). Following the 1982–1985 unrest, the Campi Flegrei caldera underwent a phase of subsidence, which led to an overall ground lowering of about 92 cm. During this subsidence phase, which ended in 2000 (Del Gaudio et al., 2009), no significant seismicity was recorded except in 1988–1989, 1994, and 1998 when three minor uplift episodes occurred (D'Auria et al., 2011; Orsi et al., 1999).

Since 2000 the seismic activity began to reappear and the ground level showed some variations (Lanari et al., 2004) without a clear upward trend until 2004. In July 2000, the first appearance of long-period events was observed, followed in August by a swarm of volcanotectonic events (Saccorotti et al., 2001; Bianco et al., 2004; D'Auria et al., 2011). In the following years, the ground level, albeit slowly, began to uplift.

Starting from 2004, changes in seismicity (Chiodini et al., 2017; D'Auria et al., 2011; Saccorotti et al., 2007), deformation (Troise et al., 2007; Trasatti et al., 2008; D'Auria et al., 2012; De Martino et al., 2014; Giudicepietro et al., 2016; Iannaccone et al., 2018), and degassing activity (Cardellini et al., 2017; Chiodini et al., 2015; Chiodini et al., 2016; Tamburello et al., 2019) became evident in the Campi Flegrei caldera. These changes were the subject of scientific investigations that resulted in a remarkable production of articles over the recent years (Amoruso et al., 2014; De Siena et al., 2017; Di Luccio et al., 2015; Giudicepietro

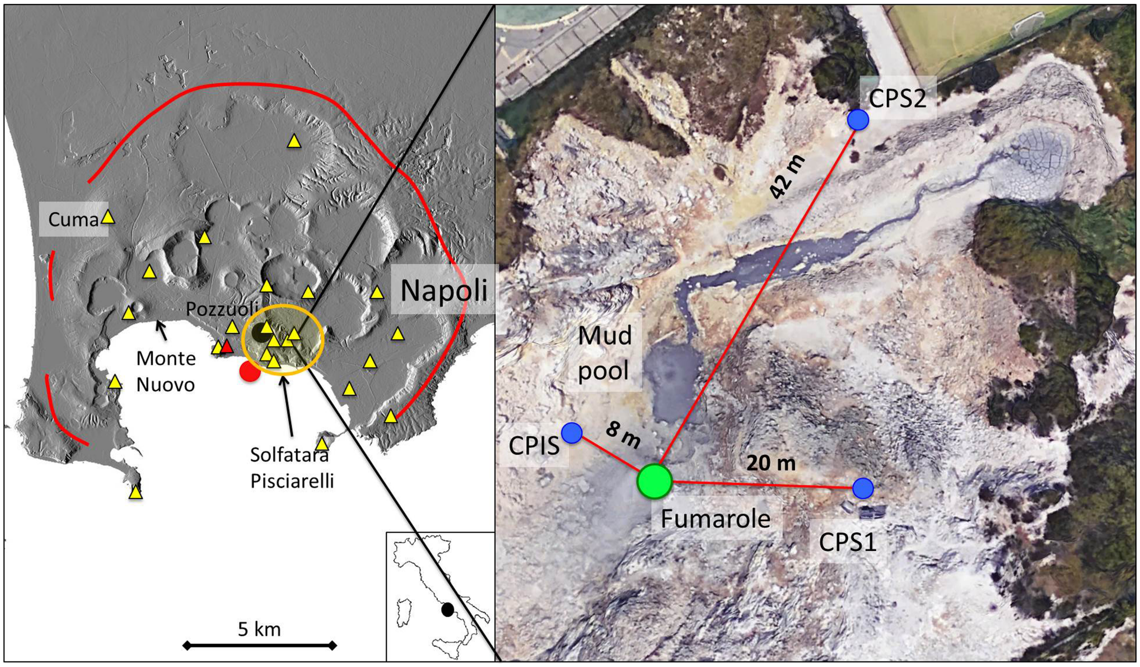

Figure 1. Maps of Campi Flegrei caldera (on the left) and Pisciarelli hydrothermal area (on the right). In the left plot, the red line indicates the rim of the 39 ka caldera, the yellow triangles indicate the seismic network, the red triangle is the RITE GPS station location, the red circle indicates the maximum uplift area (about 57 cm in the last 15 years), the orange circle highlights the Solfatara-Pisciarelli hydrothermal area and the black circle indicates the locations of Bocca Grande and Bocca Nuova fumaroles. In the right plot, the Pisciarelli fumarolic field is shown. The blue circles indicate the seismic station positions and the green circle indicates the main fumarole position. The red lines report the distances between the seismic stations and the main fumarole. In the image the mud pool is visible.

et al., 2017; Kilburn et al., 2017; Zaccarelli & Bianco, 2017; Zollo et al., 2008). In December 2012, the civil protection authorities raised the alert of the caldera from green level (base) to the current yellow level (attention) as consequence of a further increase in the deformation rate, seismicity and degassing (Chiodini et al., 2012). This period of relative increase of the uplift rate and of the seismicity, which ended in 2013, was interpreted by different authors as caused by a magmatic intrusion at shallow depth (D'Auria et al., 2015; Trasatti et al., 2015). Regardless of this interpretation, after a brief period of quiet, in 2014, inflation resumed and started a period characterized by low magnitude shallow earthquakes (<2 km). At the time of writing this article the deformation measurements indicate a maximum caldera ground uplift (starting from 2004) of about 57 cm (Tamburello et al., 2019) and measurements of the fluxes of CO_2 in the hydrothermal areas of Pisciarelli and Solfatara (Figure 1) point to a progressive escalation of the degassing rate (e.g., Aiuppa et al., 2013; Cardellini et al., 2017; Chiodini et al., 2016; Queißer et al., 2017; Tamburello et al., 2019).

Among the different signs of reawaking, the most evident changes occurred in the hydrothermal site of Pisciarelli (Figure 1) where opening of new fumarolic vents and shallow seismic activity occurred in the last decade. In order to enhance the monitoring of the Pisciarelli hydrothermal area, in January 2010 a seismic station (CPIS) was positioned near the main fumarole (Figure 1) with the specific purpose of measuring the seismic tremor generated by the activity of the Pisciarelli fumarole and to test the possibility of obtaining a proxy of the hydrothermal fluid fluxes. A recent work (Chiodini et al., 2017), based on January 2010 to May 2017 data, has shown how the fumarolic tremor is a powerful tool to monitor the current period of hydrothermal unrest at Campi Flegrei.

Aims of this work are both to update the fumarolic tremor data, which continued to show remarkable variations, and to compare it with hydrothermal activity data of the Pisciarelli-Solfatara area. A further objective is to test the validity of the continuous analysis of the fumarolic tremor amplitude as a monitoring tool for sudden changes in hydrothermal activity of Pisciarelli that can culminate in local phreatic activity. In fact, even small phreatic explosions can be very dangerous, like the case of the Ontake volcano has

Table 1
Characteristics of the Seismometric Instruments and Operating Intervals

Station ID	Sample rate (Hz)	Sansor type	Sensor frequency limits	Time
CPIS	100	3C Velocimeter (Guralp CMG 40T)	0.0167–50 Hz	From January 2010 to July 2019
CPS1	100	3C Velocimeter (Guralp CMG 40T)	0.0167–50 Hz	29 August 2018 to July 2019
CPS2	100	3C Velocimeter (Lennarz 3-D lite)	1–100 Hz	29 August 2018 to 22 September 2018

demonstrated (Maeno et al., 2016), and an accurate proximal monitoring can be effective in the mitigation of the risk associated with these processes.

2. The Data Set

The data set used in this article includes the seismic data recorded by the permanent CPIS station of the Osservatorio Vesuviano, Istituto Nazionale di Geofisica e Vulcanologia (OV-INGV) and by the two additional stations, CPS1 and CPS2, temporarily installed to study the wave field of the fumarolic tremor. The CPIS seismic station continuously transmits data to the OV-INGV acquisition center, whereas CPS1 and CPS2 are stand-alone stations that locally record data in memory cards. CPIS and CPS1 stations are equipped with three-component CMG 40T Guralp broadband velocimetric sensors, sensitive to periods up to 60 s. CPS2 station is equipped with three-component Lennartz 3-D lite short period sensor, sensitive to 1- to 80-Hz frequency band. The signals are acquired using the GILDA datalogger (Orazi et al., 2006) configured to record data at a sampling rate of 100 samples per second. Table 1 shows the summary of the data used in the present work and the characteristics of the seismometric instruments.

In this paper, we also use the Campi Flegrei earthquake locations carried out by the OV-INGV seismic laboratory. The data set of the hypocentral locations includes 1,019 events recorded between 1 January 2000 and 10 April 2019.

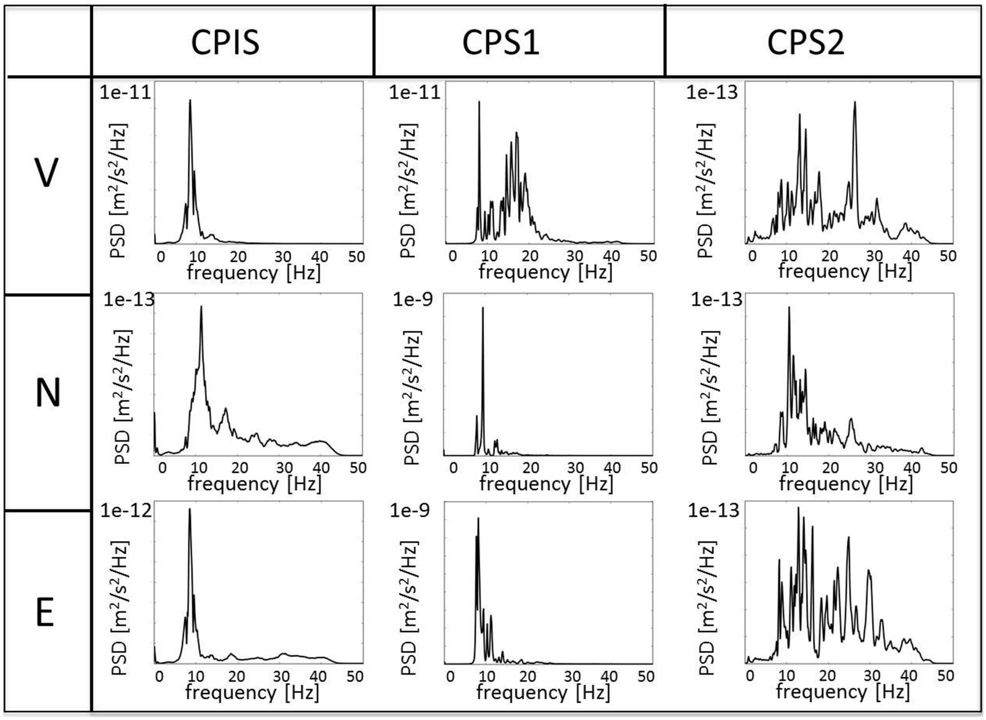

Figure 2. Spectral analysis of the seismic data. Each plot shows the stacking of 240 spectra of 1-min signal window (4 hr) recorded on 7 September 2018 between 00:00 and 04:00 UTC. The columns indicate the three seismic stations (CPIS, CPS1, and CPS2). The rows show the three component stacked spectra. The spectral amplitude is normalized in each plot.

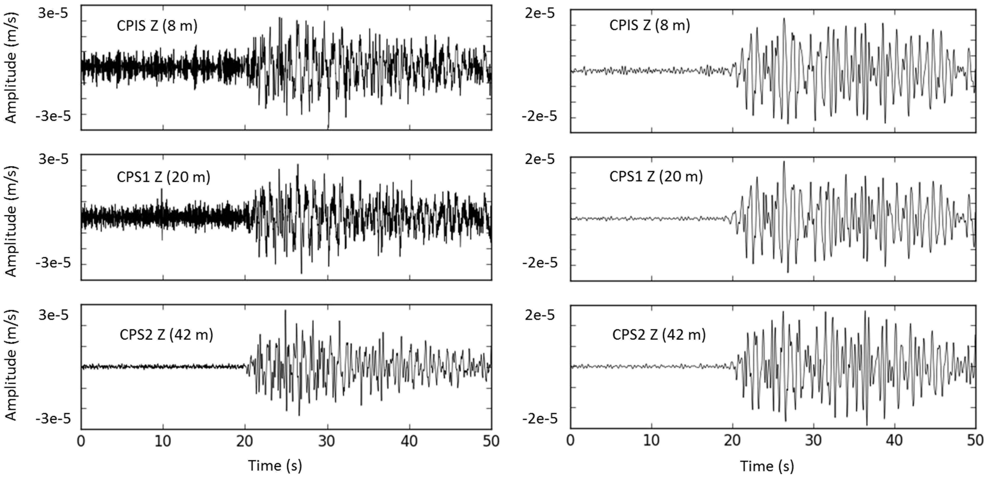

Figure 3. Left column: Vertical component seismograms of the Greek 5.2-mb earthquake that occurred on 31 August 2018 (origin time 07:12:26 UTC), filtered in the 1- to 10-Hz frequency band. Note the effect of the distance from the main fumarole, shown in brackets after the station code, on the tremor amplitude compared to the earthquake signal. Right column: the seismograms, filtered in the 1- to 3-Hz frequency band.

3. Data analysis: Methods and Results

3.1. Wave Field Characterization and Implications for Its Source Mechanism

Chiodini, Selva, et al. (2017) have showed that Pisciarelli fumarolic tremor, recorded 8 m away from the fumarole-mud pool alignment (CPIS station), has the following characteristics: (1) it has a spectral peak in a narrow frequency band around 10 Hz; (2) its polarization is almost vertical; and (3) the frequency content and the polarization parameters (azimuth, inclination, and rectilinearity) have not significantly changed from January 2010 to May 2017. Furthermore, even if the Campi Flegrei seismic network is very dense, the fumarolic tremor with characteristic frequency around 10 Hz is not detectable by seismic stations located 200 or 300 m away from the fumarole.

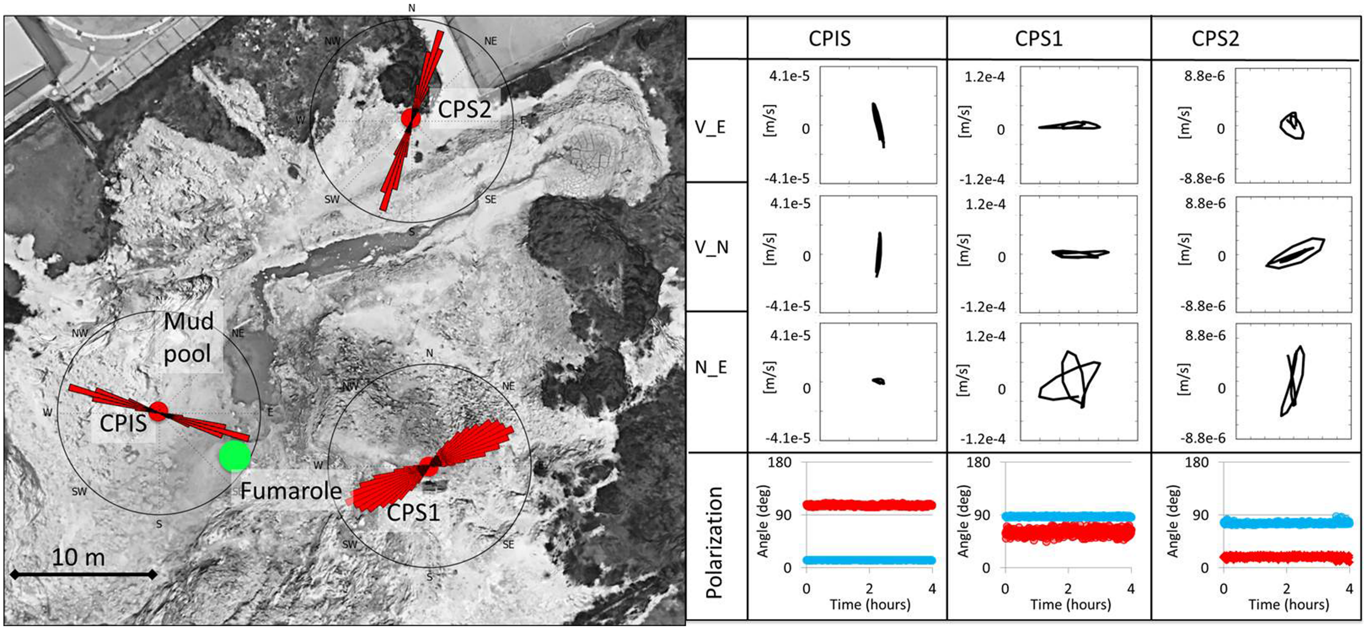

Figure 4. Particle motion and polarization analysis of the three seismic station signals filtered in 5- to 15-Hz frequency band. On the left, the rose diagrams of the azimuths calculated for 7,200 two-second-long windows (00:00–04:00 7 September 2018) of three-component signals. On the right, the particle motion of 0.2-s signal windows for each component of each station. The bottom row shows the azimuth (red) and the incidence (blue) angles versus time for the three stations.

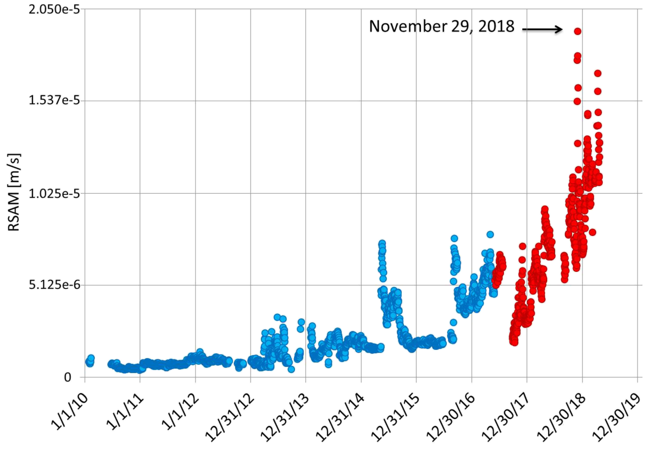

Figure 5. RSAM of the CPIS station vertical component. The blue dots represent the time series published in Chiodini, Selva, et al. (2017). The red dots indicate the updated time series from 1 May 2017 to 23 April 2019. We marked the absolute maximum of the time series (29 November 2018) for the studied period.

The data of the two stations (CPS1 and CPS2) that we installed near the fumarole-mud pool system in August 2018, together with the CPIS station data, allowed us to better characterize the fumarolic tremor of Pisciarelli. The three stations worked jointly from 30 August to 20 September. During the recording period we can consider the tremor as a stationary signal that showed no significant changes. Therefore, we have chosen the first 4 hr of 7 September 2018 records for performing spectral and polarization analyses, which we carried out by using Obspy utilities (Krischer et al., 2015). Looking at the spectral analysis of the CPS1 and CPS2 signals and comparing it with that of the CPIS station (Figure 2), we have noticed that the characteristic frequency band of the fumarolic tremor around 10 Hz, evident at CPIS station, is very weak at the CPS2 station, which is about 42 m away from the fumarole. At CPS1 station, about 20 m from the fumarole, located on the opposite side of the fumarole-mud pool alignment and about 6 m higher than CPIS position (Figure 1), the 10 Hz signal is evident only on the horizontal components.

In order to better visualize the tremor amplitude on the vertical component of the three stations, in Figure 3 (left panels) we display the seismogram of a 5.2-mb Greek earthquake recorded on 31 August 2018 in the Pisciarelli area, filtered in the 1- to 10-Hz frequency band. The figure shows that the onset of the earthquake is easily recognizable on the signal of the CPS2 station, 42 m away from the main fumarole, whereas it is hidden by the tremor in the recordings of the CPS1 and CPIS stations, 20 and 8 m from the main fumarole, respectively. The right panels show the same seismograms, filtered in a lower-frequency band (1–3 Hz).

The polarization analysis (Flinn, 1965; Jurkevics, 1988; Montalbetti & Kanasewich, 1970) confirms that the seismic wave field generated by Pisciarelli hydrothermal activity is local and inhomogeneous. The particle motion and polarization parameters, such as azimuth and incidence angles, of the 5- to 15-Hz band-pass-filtered seismic signals highlighted that the ground motion at CPIS station is vertically polarized, whereas the ground motion is essentially horizontal at CPS1 station, about 27 m away from CPIS on the other side of the fumarole-mud pool alignment (Figure 4). On the horizontal plan the rose diagrams show that the

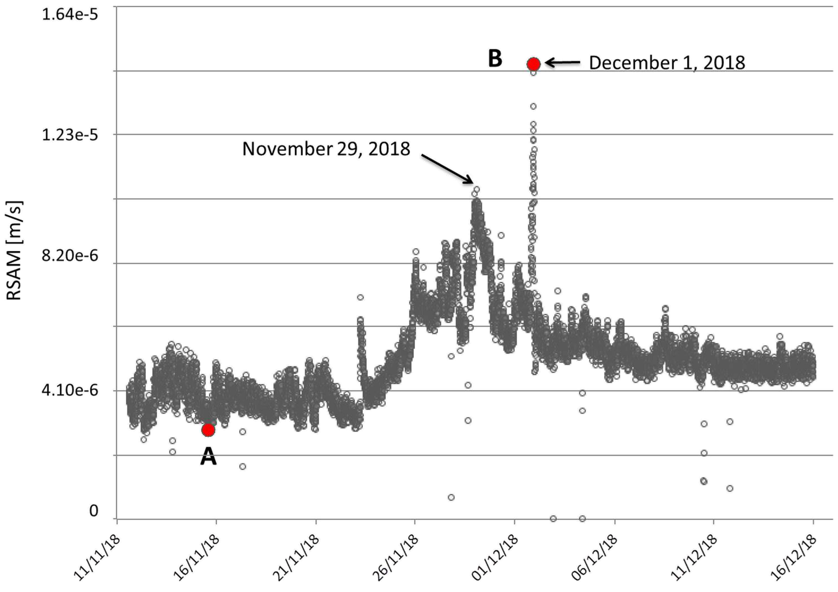

Figure 6. RSAM of the CPIS station vertical component in the period 11 November to 16 December 2018 computed using the continuous signal, filtered in 5- to 15-Hz frequency band. The sliding window is 5 min. A and B points indicate the time of the seismograms and spectrograms shown in Figure 7.

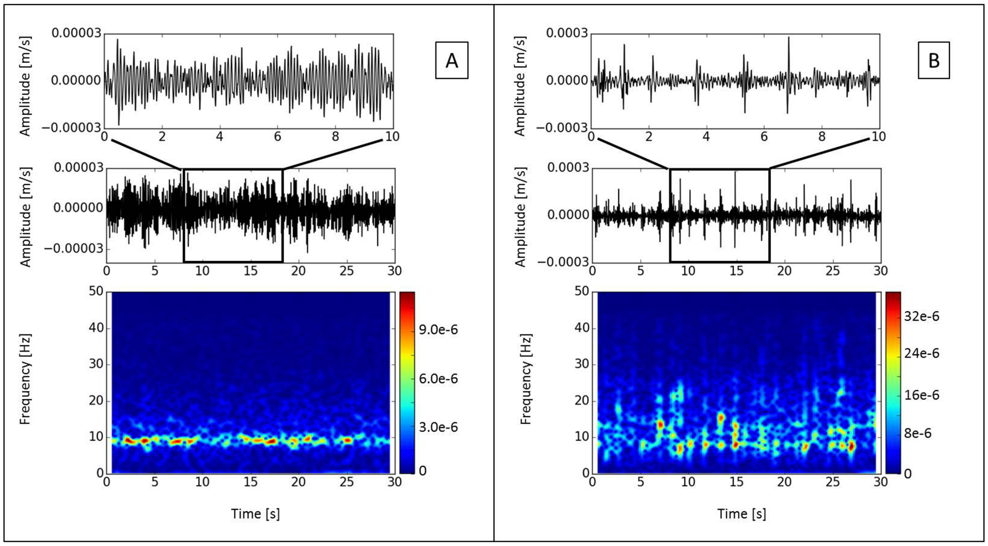

Figure 7. Comparison of spectrograms (bottom plots) and seismograms (middle plots) of two 30-s-long fumarolic tremor windows, and a zoom of 10 s (upper plots). Panels (a) and (b) correspond to A (15 November 2018 09:00:00–09:00:30) and B (1 December 2018 20:00:30–20:01:00) time marked in Figure 6. Panel (b) shows the waveform and the spectrogram of the impulsive tremor episode occurred on 1 December 2018. The upper plot in panel (b) shows the details of the individual short-duration events.

ground motion, in the 5- to 15-Hz frequency band, at CPIS and CPS2 is almost radial with respect to the main fumarole (Figure 4). The azimuth of CPS1 is more disperse and is not coherent with that of the others two stations. The strong topography around CPS1 station could explain this polarity difference compared to the other two stations that are located on flatter areas.

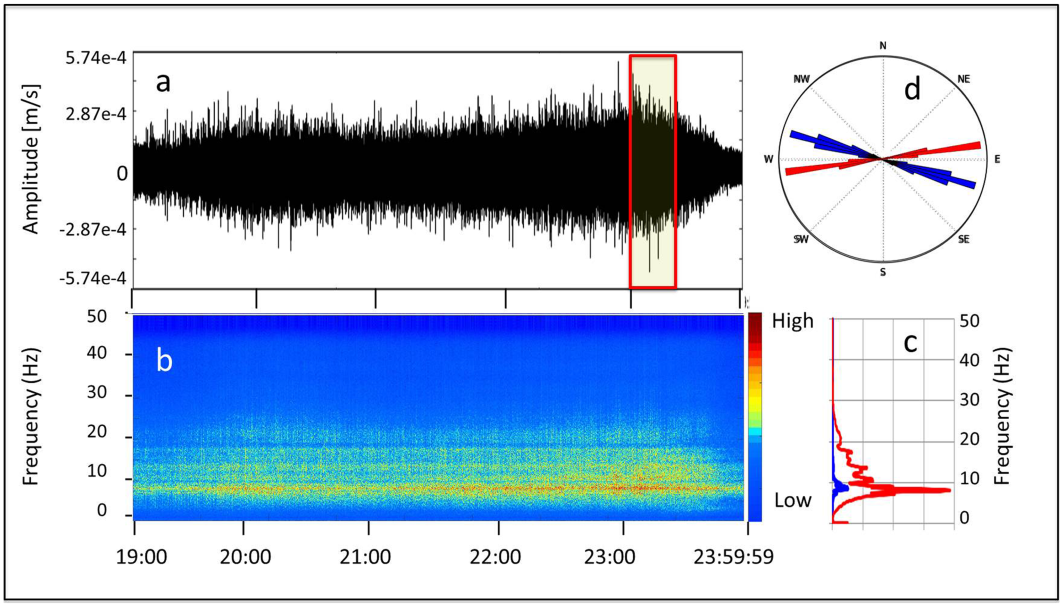

Figure 8. Five-hour seismogram (a) and spectrogram (b) of the CPIS vertical component during the impulsive tremor episode of 1 December 2018. Panel (c) compares the stacked spectral amplitude during the 5-hr impulsive tremor episode (red line) with the stacked spectral amplitude recorded during the first 5 hr of 7 September 2018 (blue line). Panel (d) compares the polarization azimuth (red rose diagram) of the 30-min signal of impulsive tremor marked by the red rectangle on panel (a), with the polarization azimuth of the signal recorded during the first 5 hr of 7 September 2018 (blue rose diagram). The incidence angle, not reported in the figure, is about 12° and about 20° from the vertical direction, on 7 September and 1 December 2018 respectively.

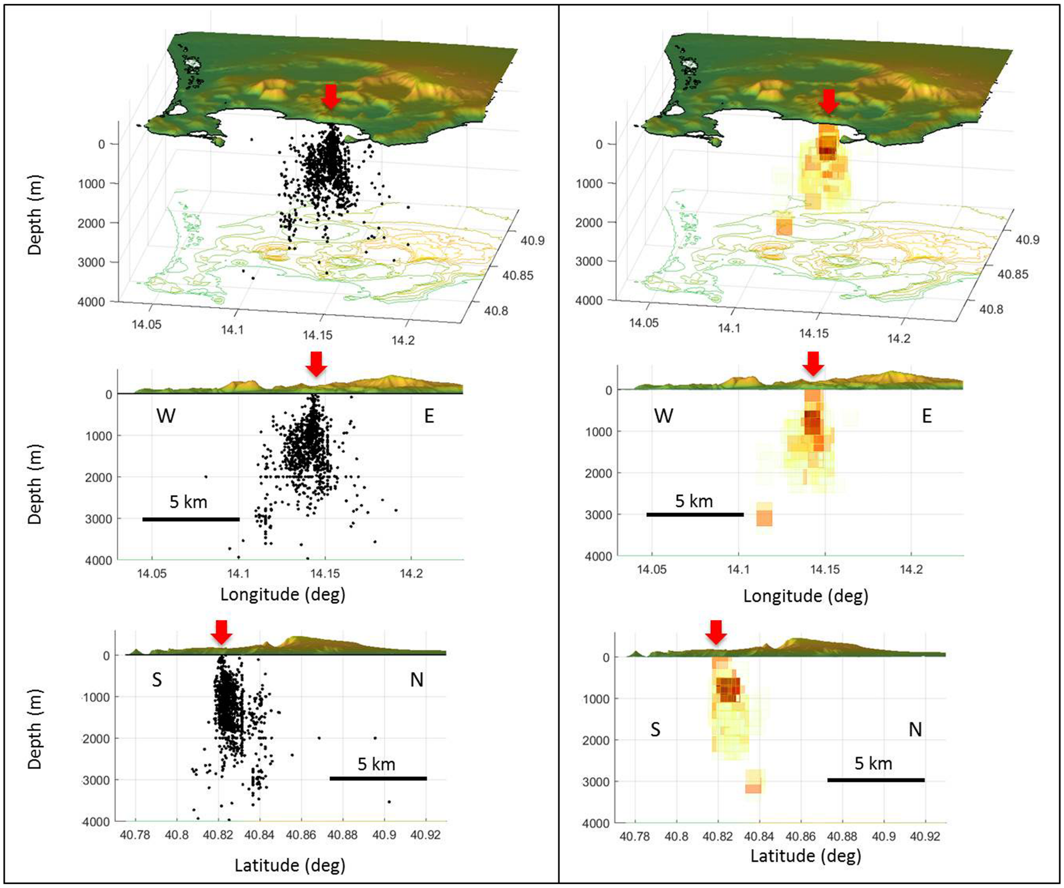

Figure 9. Seismicity at Campi Flegrei since 2000. (left column) Location of the earthquakes recorded in the Campi Flegrei since 2000. (right column) Hypocenter densities on a 200-m-spaced grid cells. The minimum value is two earthquakes per cell; the maximum is 10 earthquakes per cell. The red arrow indicates the position of the Pisciarelli hydrothermal area. The plots have a vertical exaggeration of 2.

Similar signals, recorded at Old Faithful geyser in Yellowstone National Park (USA), have been analyzed by Kedar et al. (1996), who found the harmonic motion to be caused by elastic waves reverberating in a solid medium such as a near-surface soft layer. Applying the Kedar formula $f = \mathrm{Vs}/4h$ to our data with $f = 10$ Hz and Vs = 200 m/s (Bruno et al., 2007), it gives us the result of $h = 5$ m. This estimate is consistent with the results reported in the literature for the hydrothermal areas of Solfatara and Pisciarelli (Amoroso et al., 2018; Bruno et al., 2007; De Landro et al., 2017; Di Giuseppe & Troiano, 2019; Gresse et al., 2018). The study of the fumarolic tremor source mechanism is important to define quantitative relationships between the generation of the seismic signal and the dynamics of hydrothermal fluids (gas and bubbling mud) at Pisciarelli. To better investigate this aspect, further seismic measurements would be needed.

3.2. Long-Term Analysis of the Fumarolic Tremor Amplitude

We updated the RSAM (Real time Seismic Amplitude Monitoring) time series of the Pisciarelli fumarolic tremor, following the same procedure used in Chiodini, Selva, et al. (2017). Considering the polarization of the seismic signal of the CPIS station, we used the vertical component for the analysis. To avoid anthropic noise, we selected the first 4 hr of each day. We filtered the data in the 5- to 15-Hz frequency band, which represents the most energetic part of the spectrum and the one generated by the fumarole-mud pool system. We divided the signal into eight intervals of 30 min, and we calculated the RSAM as the average of the absolute values of the counts of each interval. We chose the minimum of the 8 values to select the least noisy window, obtaining a daily RSAM value [see Chiodini, Selva, et al., 2017, for details]. Figure 5 shows the time series of the CPIS RSAM updated to 23 April 2019.

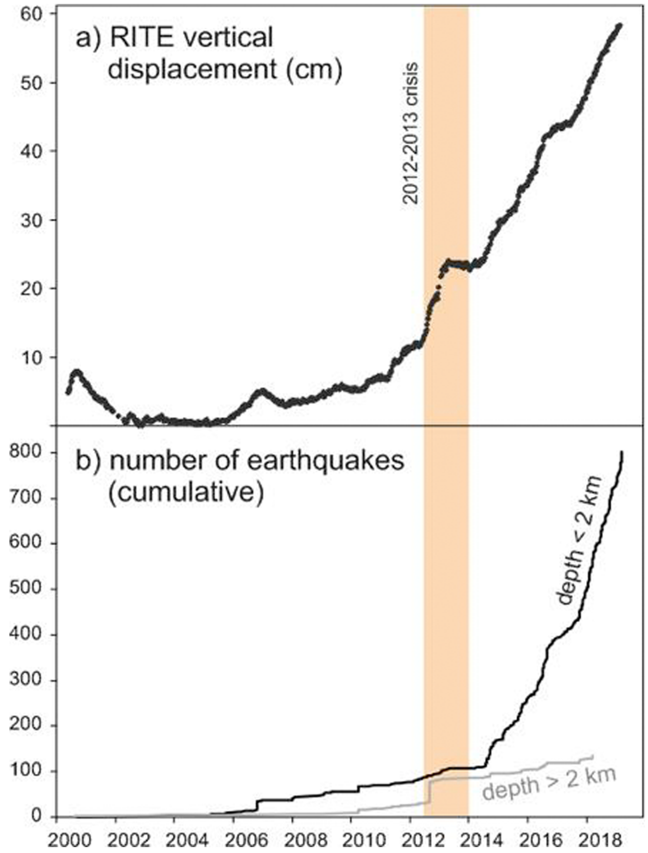

Figure 10. (a) Vertical component of RITE GPS station (red triangle in Figure 1) [after Tamburello et al., 2019]. (b) Cumulative number of the located earthquakes occurred in Campi Flegrei caldera. The gray line indicates earthquakes with hypocentral depth >2 km and the black line indicates earthquakes with hypocentral depth <2 km.

The analysis showed a dramatic increase of the Pisciarelli fumarolic tremor amplitude with a maximum on 29 November 2018. Indeed, in only 2 years, the RSAM has increased by a factor of 3, which corresponds to an increase in the seismic energy released by a factor of 9. To finer investigate the period around the peak of 29 November 2018 we repeated the RSAM analysis on the 24-hr continuous signal from 11 November to 16 December 2018 using a 5-min sliding window (Figure 6).

3.3. The Episode of 1 December 2018

The analysis of the continuous signal has revealed an episode of abrupt increase that occurred on 1 December 2018 between 19:15 and 23:45, with a maximum around 23:00 UTC. During this episode, the waveform of CPIS station was characterized by short-lived impulsive transients (Figure 7b) that are not observed when the fumarolic tremor remains at lower levels (Figure 7a).

This impulsive tremor episode lasted for about 5 hr and was characterized in CPIS signals by amplitude increase, broader spectral content that includes the characteristic 10-Hz band and higher-frequency peaks and by changes of the polarization parameters (Figure 8). The duration of the short impulsive transients is in the range 0.5–1 s, and the interval between two events is about 1–2 s. During the same episode the signal of CPS1 station (about 25 m from CPIS station) also shows amplitude increase, but it does not show any significant change in polarization and the short-lived impulsive transients are not recognizable. As it was observed in the field that there was a significant enlargement of the emission area between end November and early December (source OV-INGV), we consider this enlargement to have taken place during this period of abnormal seismic activity.

4. Discussion

Many observations indicate that Pisciarelli (Figure 1) is a key site to monitor the evolution of the current unrest underway at Campi Flegrei. It is at Pisciarelli, and at the nearby Solfatara, that Campi Flegrei caldera emits large amounts of hydrothermal fluids through vigorous fumarolic vents and diffuse degassing (Aiuppa et al., 2013; Chiodini et al., 2001). Geochemical studies have repeatedly shown recent significant increases in the emission of hydrothermal-volcanic gases from the two sites, which currently have a degassing comparable to that of the plume emission of open-conduit volcanoes (e.g., Cardellini et al., 2017; Tamburello et al., 2019). Since 2000, the seismicity of the Campi Flegrei is concentrated below these areas and several authors have argued that most of the earthquakes are linked to preferential paths for the fluid transfer from depth to the Pisciarelli-Solfatara hydrothermal sites (Cusano et al., 2008; D'Auria et al., 2011; D'Auria et al., 2012). The b value estimated for the 2007–2019 period is 1.03 ± 0.008. This estimate is higher than the b value referred to the 1983–84 and 1989–2010 periods reported in D'Auria et al. (2011), which were 0.72 ± 0.04 and 0.92 ± 0.25, respectively. This progressive increase in b value over time is consistent with the hypothesis of an increased contribution of the hydrothermal system fluids to seismogenic processes, in recent years. Moreover, considering the stress field associated with the seismicity of the Campi Flegrei caldera it can be noticed that the field is dominated by a subvertical σ_1 (D'Auria et al., 2015) due to the effect of the ground deformation source with a roughly axisymmetric distribution (Giudicepietro et al., 2016; Macedonio et al., 2014). Therefore, the preferential concentration of the earthquake hypocenters below the Pisciarelli-Solfatara area can be interpreted as the effect of the local hydrothermal system. The distribution of the post-2000 earthquakes and hypocentral density (Figure 9) gives a spectacular image of this process: earthquake locations and hypocentral density delineate the paths of the fluids that move from a wide zone within the hydrothermal system at a depth of 1–2

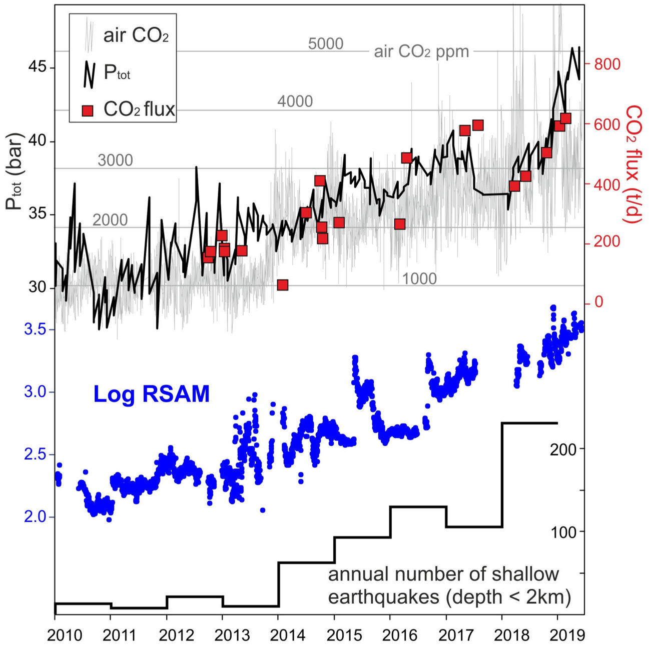

Figure 11. Comparison of the fumarolic tremor of Pisciarelli (blue dots) with the air CO_2 concentrations (gray line), Pisciarelli fumarole CO_2 flux measurements (red squares) [after Tamburello et al., 2019], pressure of the hydrothermal system, derived from the Solfatara fumaroles composition data (black line) [after Tamburello et al., 2019], and annual number of shallow earthquakes, that is, with hypocentral depth <2 km, (bottom histogram).

km toward the Pisciarelli-Solfatara hydrothermal sites where the events concentrate at very shallow depths (<1.0 km).

It is worth noting that this hydrothermal seismicity is increasing over time (Figure 10) (at the time of writing this article, shallow earthquakes reached a number >800) concurrently with a visible increase in the hydrothermal activity. In particular, it is at Pisciarelli that the increase in hydrothermal activity has shown, and continue to show, the clearest signs that include the opening of new vents and of mud pools, and a remarkable increase in the measured CO_2 fluxes that from <200 t/d in 2012 passed to >500 t/d in 2019 (Tamburello et al., 2019).

The measurements of three closely spaced seismic stations have shown that Pisciarelli fumarolic tremor is well recorded only within a distance of a few tens of meters from the main fumarole-mud pool system. Moreover, the polarization analysis (Figure 4) has shown that the wave field is inhomogeneous. The strong topography of the area where CPS1 is installed may contribute to the complexity of the Pisciarelli seismic wave field.

The continuous analysis of the fumarolic tremor amplitude at CPIS single station allowed us to identify an abnormal seismicity on 1 December 2018, which coincides with an enlargement of the fluid emission area. During this episode, the seismicity was characterized by short-lived impulsive transients (Figure 7). Similar transients, recorded at the Dashgil mud volcano in Azerbaijan, are described by Albarello et al. (2012) as associated with methane bubbling. Microevents, defined as short-duration events, have been also recorded by ocean bottom seismometers (OBS) deployed over soft sediments in the western part of the Sea of Marmara (Turkey). These microevents, characterized by durations of less than 0.8 s, were studied by Tary et al. (2012) and were interpreted as generated by a source very close to the sensor and associated to episodes of gas discharge from the seabed (Embriaco et al., 2014), moving inside the soft sediments. These mechanisms seem similar to those active in the hydrothermal area of Pisciarelli and suggest that the anomalous seismicity of 1 December 2018 should be interpreted as an increase in the boiling activity of the mud pool. It is worth noting that the fumarolic tremor proved to be sensitive to sudden short-term variations, such as abrupt increase of the hydrothermal activity, so to be a potential precursor of phreatic activity, which by its nature is difficult to predict.

The trend of the fumarolic tremor amplitude over time shows a further remarkable increase in the hydrothermal activity since May 2017. Comparing the RSAM to the air CO_2 concentrations (Figure 11), measured at 40-cm height by an automatic station installed 20 m downwind of the Pisciarelli vent, the two time series show a similar trend confirming the link between the fumarolic tremor amplitude and the degassing activity of the fumarole-mud pool system highlighted in Chiodini et al [2017]. Moreover, Figure 11 shows that the air CO_2 concentration matches with the Pisciarelli fumarole CO_2 flux measurements, marked by red squares, and with the trend of the pressure derived from the $H2O$-H_2-CO_2-CO gas equilibria estimated using the data of “Bocca Grande” and “Bocca Nuova” Solfatara fumaroles (Tamburello et al., 2019) (Figure 1). Also the shallow seismicity (hypocentral depth <2 km) shows correlation with the amplitude of fumarolic tremor (Figure 11). The comparison of the geochemical parameters of the Solfatara-Pisciarelli hydrothermal system, with Pisciarelli fumarolic tremor and seismicity of the Campi Flegrei caldera, which is mainly concentrated in the area of Pisciarelli, suggests a common origin of the different processes that are an expression of the unrest in progress for many years at Campi Flegrei caldera.

5. Conclusions

Our results indicate that the hydrothermal processes observed at Pisciarelli have been controlled by the dynamics of the unrest underway in Campi Flegrei since the early 2000s. For this reason, the monitoring of this area is important to gain insight into the progress of the general large-scale unrest of Campi Flegrei caldera. The sensitivity of Pisciarelli tremor to hydrothermal changes and the fact that it can only be measured at a short distance from the main fumarole-mud pool system, confirm the need to use this parameter to monitor the hydrothermal activity of the area. In particular, the fumarolic tremor recorded in Pisciarelli appears as a proxy for the CO_2 flux (Chiodini, Selva, et al., 2017), which is usually measured through discrete campaigns (Figure 11). On the contrary, the fumarolic tremor, thanks to its high sampling rate (100 samples per second), can provide continuous information on the CO_2 flux and on the temperature-pressure condition of the Solfatara-Pisciarelli hydrothermal system. Currently, the hydrothermal activity at Pisciarelli shows an escalation characterized by an increase in the CO_2 flux, which in 2019 exceeded 500 t/day (Tamburello et al., 2019) and the fumarolic tremor amplitude shows a remarkable increase by a factor of 3 in the last 2 years. In light of these trends, the monitoring of the Pisciarelli area is also significant at the local level because the hydrothermal area is affected by the risk of phreatic events. The continuous analysis of the fumarolic tremor amplitude calculated using short-duration windows (5 min) actually allowed us to identify a sudden increase linked to the enlargement of the emission area on 1 December 2018. This proves that this method is suitable also for monitoring possible precursors of local phreatic activity.

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References

Aiuppa, A., Tamburello, G., Di Napoli, R., Cardellini, C., Chiodini, G., Giudice, G., et al. (2013). First observations of the fumarolic gas output from a restless caldera: Implications for the current period of unrest (2005-2013) at Campi Flegrei. *Geochemistry, Geophysics, Geosystems*, *14*(10), 4153–4169. https://doi.org/10.1002/ggge.20261

Albarello, D., Palo, M., & Martinelli, G. (2012). Monitoring methane emission of mud volcanoes by seismic tremor measurements: A pilot study. *Natural Hazards and Earth System Sciences*, *12*(12), 3617–3629. https://doi.org/10.5194/nhess-12-3617-2012

Amoroso, O., Festa, G., Bruno, P. P., D'Auria, L., De Landro, G., Di Fiore, V., et al. (2018). Integrated tomographic methods for seismic imaging and monitoring of volcanic caldera structures and geothermal areas. *Journal of Applied Geophysics*, *156*, 16–30. https://doi.org/10.1016/j.jappgeo.2017.11.012

Amoruso, A., Crescentini, L., Sabbetta, I., De Martino, P., Obrizzo, F., & Tammaro, U. (2014). Clues to the cause of the 2011-2013 Campi Flegrei caldera unrest, Italy, from continuous GPS data. *Geophysical Research Letters*, *41*, 3081–3088. https://doi.org/10.1002/2014GL059539

Bianco, F., Del Pezzo, E., Saccorotti, G., & Ventura, G. (2004). The role of hydrothermal fluids in triggering the July–August 2000 seismic swarm at Campi Flegrei, Italy: Evidence from seismological and mesostructural data. *Journal of Volcanology and Geothermal Research*, *133*(1-4), 229–246. https://doi.org/10.1016/s0377-0273(03)00400-1

Bruno, P. P. G., Ricciardi, G. P., Petrillo, Z., Di Fiore, V., Troiano, A., & Chiodini, G. (2007). Geophysical and hydrogeological experiments from a shallow hydrothermal system at Solfatara Volcano, Campi Flegrei, Italy: Response to caldera unrest. *Journal of Geophysical Research*. *112*, B06201. https://doi.org/10.1029/2006jb004383

Calò, M., & Tramelli, A. (2018). Anatomy of the Campi Flegrei caldera using enhanced seismic tomography models. *Scientific Reports*, *8*(1), 16254. https://doi.org/10.1038/s41598-018-34456-x

Cardellini, C., Chiodini, G., Frondini, F., Avino, R., Bagnato, E., Caliro, S., et al. (2017). Monitoring diffuse volcanic degassing during volcanic unrests: The case of Campi Flegrei (Italy). *Scientific Reports*, *7*, 6757. https://doi.org/10.1038/s41598-017-06941-2

Chiodini, G., Caliro, S., De Martino, P., Avino, R., & Gherardi, F. (2012). Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and physical simulations. *Geology*, *40*(10), 943–946. https://doi.org/10.1130/G33251.1

Chiodini, G., Frondini, F., Cardellini, C., Granieri, D., Marini, L., & Ventura, G. (2001). CO_2 degassing and energy release at Solfatara volcano, Campi Flegrei, Italy. *Journal of Geophysical Research Solid Earth*, *106*(B8), 16,213–16,221. https://doi.org/10.1029/2001jb000246

Chiodini, G., Giudicepietro, F., Vandemeulebrouck, J., Aiuppa, A., Caliro, S., De Cesare, W., et al. (2017). Fumarolic tremor and geochemical signals during a volcanic unrest. *Geology*, *45*(12), 1131–1134. https://doi.org/10.1130/g39447.1

Chiodini, G., Paonita, A., Aiuppa, A., Costa, A., Caliro, S., De Martino, P., et al. (2016). Magmas near the critical degassing pressure drive volcanic unrest towards a critical state. *Nature Communications*, *7*, 13712. https://doi.org/10.1038/ncomms13712

Chiodini, G., Selva, J., Del Pezzo, E., Marsan, D., De Siena, L., D'Auria, L., et al. (2017). Clues on the origin of post-2000 earthquakes at Campi Flegrei caldera (Italy). *Scientific Reports*, *7*(1), 4472. https://doi.org/10.1038/s41598-017-04845-9

Chiodini, G., Vandemeulebrouck, J., Caliro, S., D'Auria, L., De Martino, P., Mangiacapra, A., & Petrillo, Z. (2015). Evidence of thermal-driven processes triggering the 2005–2014 unrest at Campi Flegrei caldera. *Earth and Planetary Science Letters*, *414*, 58–67. https://doi.org/10.1016/j.epsl.2015.01.012

Cusano, P., Petrosino, S., & Saccorotti, G. (2008). Hydrothermal origin for sustained long-period (LP) activity at Campi Flegrei Volcanic Complex, Italy. *Journal of Volcanology and Geothermal Research*, *177*(4), 1035–1044. https://doi.org/10.1016/j.jvolgeores.2008.07.019

D'Auria, L., Massa, B., Cristiano, E., Del Gaudio, C., Giudicepietro, F., Ricciardi, G., & Ricco, C. (2015). Retrieving the stress field within the Campi Flegrei caldera (Southern Italy) through an integrated geodetical and seismological approach. *Pure and Applied Geophysics*, *172*(11), 3247–3263. https://doi.org/10.1007/s00024-014-1004-7

D'Auria, L., Pepe, S., Castaldo, R., Giudicepietro, F., Macedonio, G., Ricciolino, P., et al. (2015). Magma injection beneath the urban area of Naples: A new mechanism for the 2012–2013 volcanic unrest at Campi Flegrei caldera. *Scientific Reports*, *5*, 13100. https://doi.org/10.1038/srep13100

D'Auria, L., Giudicepietro, F., Aquino, I., Borriello, G., Del Gaudio, C., Lo Bascio, D., et al. (2011). Repeated fluid-transfer episodes as a mechanism for the recent dynamics of Campi Flegrei caldera (1989–2010). *Journal of Geophysical Research*, *116*, B04313. https://doi.org/10.1029/2010JB007837

D'Auria, L., Giudicepietro, F., Martini, M., & Lanari, R. (2012). The 4D imaging of the source of ground deformation at Campi Flegrei caldera (southern Italy). *Journal of Geophysical Research*, *117*, B08209. https://doi.org/10.1029/2012jb009181

De Landro, G., Serlenga, V., Russo, G., Amoroso, O., Festa, G., Bruno, P. P., et al. (2017). 3D ultra-high resolution seismic imaging of shallow Solfatara crater in Campi Flegrei (Italy): New insights on deep hydrothermal fluid circulation processes. *Scientific Reports*, *7*(1), 3412. https://doi.org/10.1038/s41598-017-03604-0

De Martino, P., Tammaro, U., & Obrizzo, F. (2014). GPS time series at Campi Flegrei caldera (2000-2013). *Annals of Geophysics*, *57*(2), S0213. https://doi.org/10.4401/ag-6431

De Siena, L., Chiodini, G., Vilardo, G., Del Pezzo, E., Castellano, M., Colombelli, S., et al. (2017). Source and dynamics of a volcanic caldera unrest: Campi Flegrei, 1983-84. *Scientific Reports*, *7*(1), 8099. https://doi.org/10.1038/s41598-017-08192-7

Del Gaudio, C., Aquino, I., Ricciardi, G. P., Ricco, C., & Scandone, R. (2010). Unrest episodes at Campi Flegrei: {A} reconstruction of vertical ground movements during 1905-2009. *Journal of Volcanology and Geothermal Research*, *195*, 48–56. https://doi.org/10.1016/j.jvolgeores.2010.05.014

Del Gaudio, C., Aquino, I., Ricco, C., & Serio, C. (2009). Monitoraggio Geodetico dell'Area Vulcanica Napoletana: Risultati della Livellazione Geometrica di Precisione Eseguita ai Campi Flegrei a Settembre 2008. *Quaderni di Geofisica*, *66*.

Di Giuseppe, M. G., & Troiano, A. (2019). Monitoring active fumaroles through time-lapse electrical resistivity tomograms: An application to the Pisciarelli fumarolic field (Campi Flegrei, Italy). *Journal of Volcanology and Geothermal Research*, *375*, 32–42. https://doi.org/10.1016/j.jvolgeores.2019.03.009

Di Luccio, F., Pino, N. A., Piscini, A., & Ventura, G. (2015). Significance of the 1982–2014 Campi Flegrei seismicity: Preexisting structures, hydrothermal processes, and hazard assessment. *Geophysical Research Letters*, *42*, 7498–7506. https://doi.org/10.1002/2015gl064962

Embriaco, D., Marinaro, G., Frugoni, F., Monna, S., Etiope, G., Gasperini, L., et al. (2014). Monitoring of gas and seismic energy release by multiparametric benthic observatory along the North Anatolian Fault in the Sea of Marmara (NW Turkey). *Geophysical Journal International*, *196*(2), 850–866. https://doi.org/10.1093/gji/ggt436

Flinn, E. A. (1965). Signal analysis using rectilinearity and direction of particle motion. *Proc. I.E.E.E.*, *53*, 1874. https://doi.org/10.1109/proc.1965.4462

Giudicepietro, F., Macedonio, G., D'Auria, L., & Martini, M. (2016). Insight into vent opening probability in volcanic calderas in the light of a sill intrusion model. *Pure and Applied Geophysics*, *173*(5), 1703–1720. https://doi.org/10.1007/s00024-015-1190-y

Giudicepietro, F., Macedonio, G., & Martini, M. (2017). A physical model of sill expansion to explain the dynamics of unrest at calderas with application to Campi Flegrei. *Frontiers in Earth Science*, *5*. https://doi.org/10.3389/feart.2017.00054

Gresse, M., Vandemeulebrouck, J., Byrdina, S., Chiodini, G., Roux, P., Rinaldi, A. P., et al. (2018). Anatomy of a fumarolic system inferred from a multiphysics approach. *Scientific Reports*, *8*(1), 7580. https://doi.org/10.1038/s41598-018-25448-y

Iannaccone, G., Guardato, S., Donnarumma, G. P., De Martino, P., Dolce, M., Macedonio, G., et al. (2018). Measurement of Seafloor Deformation in the Marine Sector of the Campi Flegrei Caldera (Italy). *Journal of Geophysical Research: Solid Earth*, *123*, 66–83. https://doi.org/10.1002/2017jb014852

Jurkevics, A. (1988). Polarization analysis of three-component array data. *Bulletin of the Seismological Society of America*, *78*(5), 1725–1743.

Kedar, S., Sturtevant, B., & Kanamori, H. (1996). The origin of harmonic tremor at Old Faithful geyser. *Nature*, *379*(6567), 708. https://doi.org/10.1038/379708a0

Kilburn, C. R., De Natale, G., & Carlino, S. (2017). Progressive approach to eruption at Campi Flegrei caldera in southern Italy. *Nature Communications*, *8*, 15312. https://doi.org/10.1038/ncomms15312

Krischer, L., Megies, T., Barsch, R., Beyreuther, M., Lecocq, T., Caudron, C., & Wassermann, J. (2015). ObsPy: A bridge for seismology into the scientific Python ecosystem. *Computational Science & Discovery*, *8*(1), 014003. https://doi.org/10.1088/1749-4699/8/1/014003

Lanari, R., Berardino, P., Borgström, S., Del Gaudio, C., De Martino, P., Fornaro, G., et al. (2004). The use of IFSAR and classical geodetic techniques for caldera unrest episodes: Application to the Campi Flegrei uplift event of 2000. *Journal of Volcanology and Geothermal Research*, *133*(1-4), 247–260. https://doi.org/10.1016/s0377-0273(03)00401-3

Macedonio, G., Giudicepietro, F., D'Auria, L., & Martini, M. (2014). Sill intrusion as a source mechanism of unrest at volcanic calderas. *Journal of Geophysical Research: Solid Earth*, *119*, 3986–4000. https://doi.org/10.1002/2013JB010868

Maeno, F., Nakada, S., Oikawa, T., Yoshimoto, M., Komori, J., Ishizuka, Y., et al. (2016). Reconstruction of a phreatic eruption on 27 September 2014 at Ontake volcano, central Japan, based on proximal pyroclastic density current and fallout deposits. *Earth, Planets and Space*, *68*(1), 82. https://doi.org/10.1186/s40623-016-0449-6

Montalbetti, J. F., & Kanasewich, E. R. (1970). Enhancement of teleseismic body phases with a polarization filter. *Geophysical Journal International*, *21*(2), 119–129. https://doi.org/10.1111/j.1365-246X.1970.tb01771.x

Orazi, M., Martini, M., & Peluso, R. (2006). Data acquisition for volcano monitoring. *Eos, Transactions American Geophysical Union*, *87*(38), 385–392. https://doi.org/10.1029/2006eo380002

Orsi, G., Civetta, L., Del Gaudio, C., De Vita, S., Di Vito, M. A., Isaia, R., et al. (1999). Short-term ground deformations and seismicity in the resurgent Campi Flegrei caldera (Italy): An example of active block-resurgence in a densely populated area. *Journal of Volcanology and Geothermal Research*, *91*(2-4), 415–451. https://doi.org/10.1016/S0377-0273(99)00050-5

Queißer, M., Granieri, D., Burton, M., Arzilli, F., Avino, R., & Carandente, A. (2017). Increasing CO_2 flux at Pisciarelli. *Campi Flegrei, Italy: Solid Earth Discussions*. https://doi.org/10.5194/se-2017-70

Saccorotti, G., Bianco, F., Castellano, M., & Del Pezzo, E. (2001). The July-August 2000 seismic swarms at Campi Flegrei Volcanic Complex, Italy. *Geophysical Research Letters*, *28*(13), 2525–2528. https://doi.org/10.1029/2001GL013053

Saccorotti, G., Petrosino, S., Bianco, F., Castellano, M., Galluzzo, D., La Rocca, M., et al. (2007). Seismicity associated with the 2004–2006 renewed ground uplift at Campi Flegrei Caldera, Italy. *Physics of the Earth and Planetary Interiors*, *165*(1-2), 14–24. https://doi.org/10.1016/j.pepi.2007.07.006

Tamburello, G., Caliro, S., Chiodini, G., De Martino, P., Avino, R., Minopoli, C., et al. (2019). Escalating $CO_2$$ degassing at the Pisciarelli fumarolic system, and implications for the ongoing Campi Flegrei unrest. *Journal of Volcanology and Geothermal Research*, *384*, 151–157. https://doi.org/10.1016/j.jvolgeores.2019.07.005

Tary, J. B., Géli, L., Guennou, C., Henry, P., Sultan, N., Çağatay, N., & Vidal, V. (2012). Microevents produced by gas migration and expulsion at the seabed: A study based on sea bottom recordings from the Sea of Marmara. *Geophysical Journal International*, *190*(2), 993–1007. https://doi.org/10.1111/j.1365-246x.2012.05533.x

Trasatti, E., Casu, F., Giunchi, C., Pepe, S., Solaro, G., Tagliaventi, S., et al. (2008). The 2004-2006 uplift episode at Campi Flegrei caldera (Italy): Constraints from SBAS-DInSAR ENVISAT data and Bayesian source inference. *Geophysical Research Letters*, *35*(7). https://doi.org/10.1029/2007GL033091

Trasatti, E., Polcari, M., Bonafede, M., & Stramondo, S. (2015). Geodetic constraints to the source mechanism of the 2011–2013 unrest at Campi Flegrei (Italy) caldera. *Geophysical Research Letters*, *42*, 3847–3854. https://doi.org/10.1002/2015gl063621

Troise, C., De Natale, G., Pingue, F., Obrizzo, F., De Martino, P., Tammaro, U., & Boschi, E. (2007). Renewed ground uplift at Campi Flegrei caldera (Italy): New insight on magmatic processes and forecast. *Geophys. Res. Lett.*, *34*, L03301. https://doi.org/10.1029/2006GL028545

Zaccarelli, L., & Bianco, F. (2017). Noise-based seismic monitoring of the Campi Flegrei caldera. *Geophysical Research Letters*, *44*, 2237–2244. https://doi.org/10.1002/2016gl072477

Zollo, A., Maercklin, N., Vassallo, M., Dello Iacono, D., Virieux, J., & Gasparini, P. (2008). Seismic reflections reveal a massive melt layer feeding Campi Flegrei caldera. *Geophysical Research Letters*. *35*, L12306. https://doi.org/10.1029/2008gl034242