DOI 10.4430/bgta0201

Detection of volcanic earthquakes and tremor in Campi Flegrei

M. La Rocca[1] and D. Galluzzo[2]

[1] *Università della Calabria, Cosenza, Italy*
[2] *Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy*

(Received: March 27, 2017; accepted: June 13, 2017)

ABSTRACT The Campi Flegrei Caldera is an active volcanic area located in southern Italy and characterized by very high volcanic risk. The seismic activity of the area is monitored by a dense multi-parametric network including a seismic array (ARF) located in the central part of the caldera. Analyses with array techniques carried out on continuous data provided by ARF array allows for the detection of coherent signals possibly related to the volcanic activity. The most interesting seismic event occurred on January 30, 2015, and was classified as volcanic tremor of hydrothermal origin. This tremor is characterized by low signal-to-noise ratio, a well defined backazimuth pointing to the SE and apparent velocity of about 0.7 s/km, while the most of energy is observed in the 1-3 Hz frequency band. The strongest bursts of tremor are recognized at many stations of the local network, and the relative arrival time joint with the results of array analysis permits a raw location of the epicentral area SW of Solfatara crater. Many other signals characterized by high coherence among the array stations were found, but often their classification is difficult. Uncertain classification remains for many events, particularly those located at sea near the shore.

Key words: Campi Flegrei, seismic array, hydrotermal tremor, volcanic earthquakes.

1. Introduction

Volcanic earthquakes like Long Period (LP), Low Frequency (LF) and tremor are seismic events commonly observed on active volcanoes. They have typical spectral features and waveforms different than other events like volcano-tectonic (VT) earthquakes, and are very important to understand the volcano dynamics (Chouet and Matoza, 2013). In volcanic environment characterized by high background noise, volcanic tremor is the seismic event more difficult to identify. It is a seismic signal observed at hundreds of active volcanoes worldwide (Konstantinou and Schlindwein, 2002; McNutt, 2005). Volcanic tremor is likely produced by the interaction of volcanic fluids with the surrounding rock, and occurs before and during eruptions. Therefore, it represents a very important marker of the volcano dynamics during eruptions, and it is an important precursor phenomenon in case of volcano awakening (Chouet and Matoza, 2013). For this reason detection of volcanic tremor in active volcanoes characterized by high hazard is very important. Identifying volcanic tremor recorded on volcanoes located in remote places is quite easy, but recognizing tremor signals in data recorded in highly urbanized areas may be a challenging task for seismologists. In this paper we describe our efforts to detect volcanic earthquakes, and in particular the volcanic tremor, in the Campi Flegrei caldera which is one of the highest risk volcanoes in the world due to the high number of inhabitants who live inside and nearby (Bevilacqua *et al.*, 2015).

Campi Flegrei is an active volcanic field characterized by a main collapse related to the eruption of the Campanian Ignimbrite at ca. 40 ka (Rosi and Sbrana, 1987; Orsi *et al.*, 1996) and from minor collapses linked to the Neapolitan Yellow Tuff eruption at ca. 15 ka (Orsi *et al.*, 1992). Inside the caldera more than 30 craters testify the many eruptions occurred during its past activity (Orsi *et al.*, 2004; Di Vito *et al.*, 2016). One of the most interesting phenomena that occurs at Campi Flegrei is the bradyseism, a very slow ground movement that alternates subsidence and uplift phases that last from years to centuries. After a subsidence phase of about 30 years that followed the last bradyseismic crisis occurred between 1982 and 1984, a new uplift course is going on since 2006 (Del Gaudio *et al.*, 2010). Low magnitude VT earthquakes are the most common seismic events observed in the area. Swarms of LF (1 Hz < fc < 5 Hz) and LP (fc < 1 Hz) earthquakes occur occasionally (Saccorotti *et al.*, 2007), while volcanic tremor has never been observed during the last 30 years. The increased flux of gas emitted from the ground, the increased fumarole activity (Chiodini *et al.*, 2016) and the increased uplift rate occurred in 2012 (D'Auria *et al.*, 2015) induced the civil protection to classify as "unrest" the current status of the volcano.

In 2010 a short period small aperture (400 m) seismic array (ARF) was installed in the middle of Campi Flegrei area to improve the monitoring capability (La Rocca and Galluzzo, 2012). The use of array data has improved the detection and analysis of local earthquakes, particularly those events characterized by emergent onset and low amplitude. In this paper, we describe the first episode of tremor recorded in the Campi Flegrei area which we classify as generated by hydrothermal activity, and show some events which have many features compatible with volcanic tremor but whose classification remains uncertain.

2. Data and methods

Campi Flegrei caldera is currently monitored by a modern network of multi-parametric geophysical instruments. The local seismic network consists of about 15 real time stations that provide data for an efficient surveillance, while more than 15 stand alone instruments (La Rocca and Galluzzo, 2015) are deployed for research purposes (Fig. 1). A stand alone seismic array of 10 short period stations is operating since 2010 in the middle of the caldera with the main aim of detecting volcanic tremor and any other seismic signals possibly related with volcanic activity (La Rocca and Galluzzo, 2012, 2015).

We start the search for volcanic events by the analysis with array methods of continuous data collected by the ARF seismic array. Looking at the semblance in time domain (Neidell and Taner, 1971) and coherence in frequency domain, and considering the propagation properties (slowness and backazimuth) of the seismic wavefield evaluated by array techniques Beam Forming and High Resolution (Capon, 1969), we can identify transient signals different from seismic noise and potentially interesting for monitoring purposes (La Rocca and Galluzzo, 2012). Usually this selection procedure, performed by default in 5 different frequency bands (from 1 to 5 Hz), yields tens of events per week, the most of which are local and regional

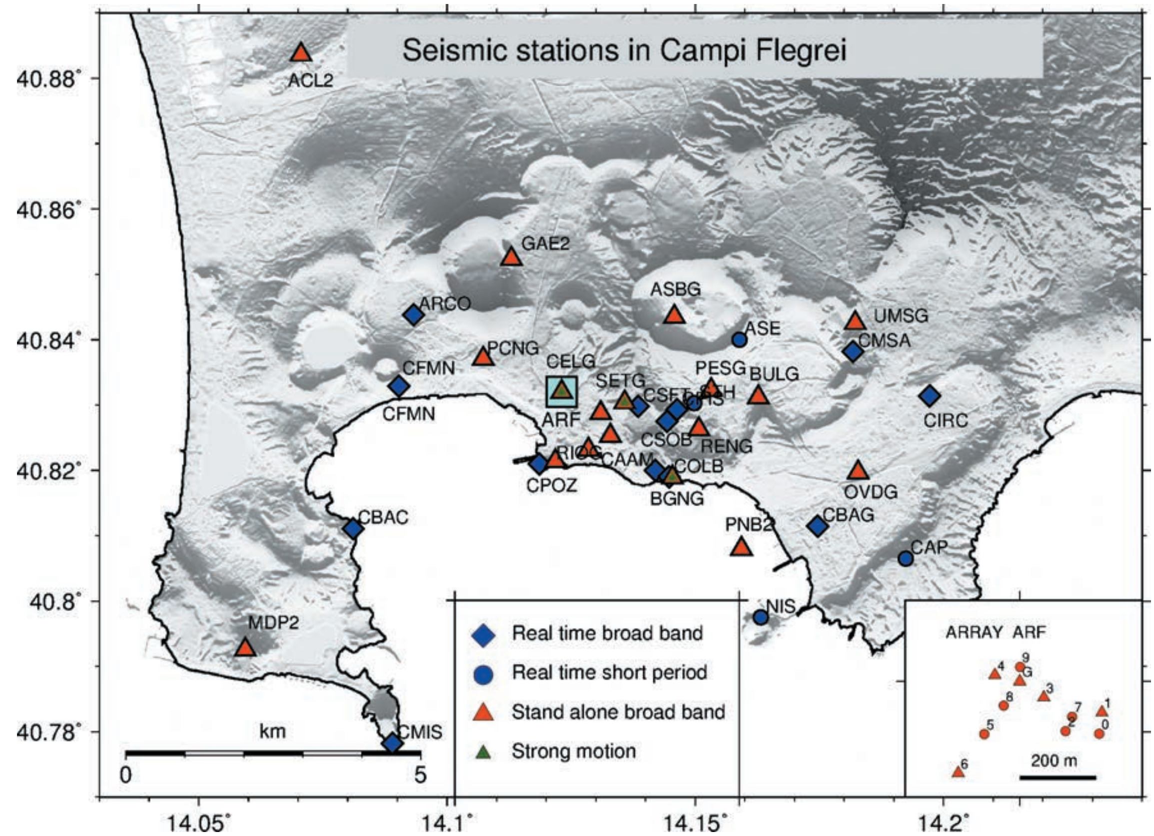

Fig. 1 - Map of Campi Flegrei caldera showing topography and seismic stations installed at the beginning of 2017.

earthquakes. Those not recognized as earthquakes are further investigated by looking at the data recorded by the other seismic stations to see the distance range they are recorded throughout the seismic network. This step permits us to exclude from successive analysis any signal that is recognizable only at the array, and hence produced by very weak sources, the most of which are artificial. Seismic signals with the features compatible with natural sources, like volcanic tremor, LP and LF earthquakes, that are visible at many stations, are then analyzed by using all available data. Array analyses at frequency lower than 1 Hz are performed on LP signals, while analysis at specific frequency are carried out on narrow band signals. Coherent signals are observed every day at the array ARF, but the most of them are produced by artificial sources located nearby. Signals produced by artificial sources sometimes are strong enough to be observed at many stations of the local network. Their classification as artificial events is inferred mainly from the very low propagation velocity, typical of surface waves, from the spectral content (often very narrow band and high frequency), and from the location in places where factories or other industrial activities are known to be effective. Low amplitude coherent signals propagating throughout the network from the south, with velocity of surface waves, have been observed in many cases. The origin of those events, that seems to be located at sea near the coast, is very difficult to establish because no seismic data are available from the Gulf of Pozzuoli.

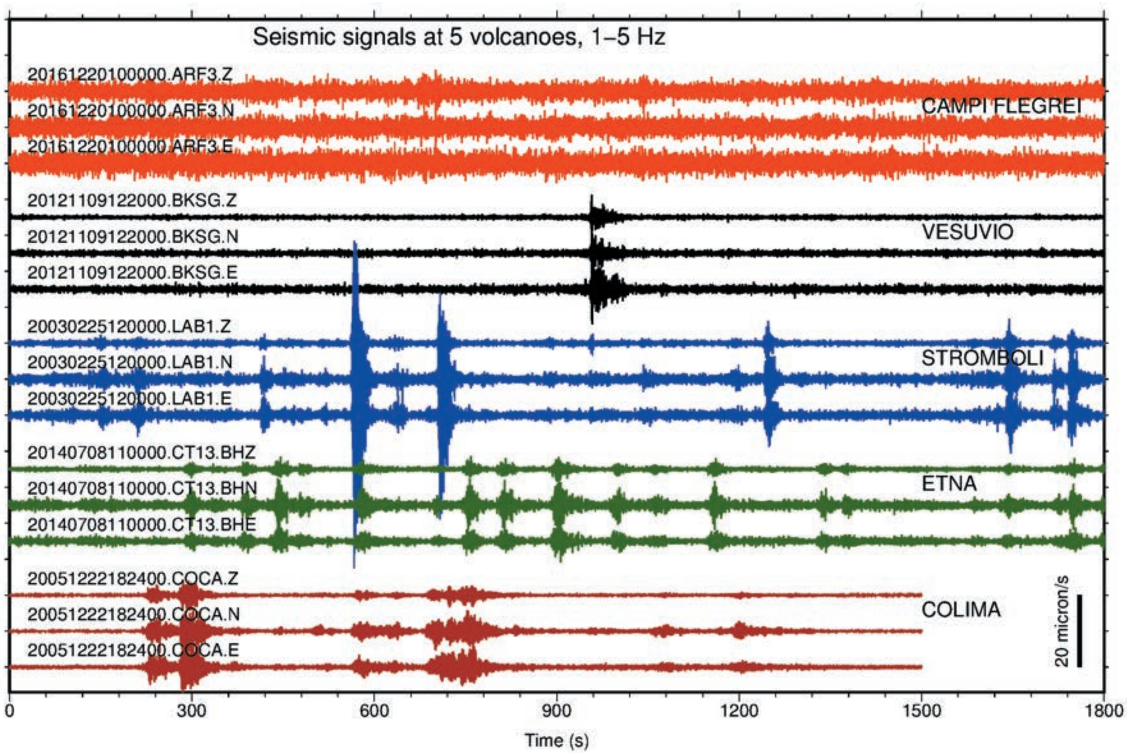

Fig. 2 - Seismic signals recorded by three component stations installed at 5 active volcanoes, filtered in the 1-5 Hz frequency band. From top to bottom: Campi Flegrei, Vesuvius, Stromboli, Etna, and Colima samples are shown with the same amplitude scale and different colour. The background noise level observed at Campi Flegrei is far greater than any others shown here.

Events different than VT earthquakes and possibly related with volcanic activity are common, but the most of them are very small, characterized by low signal-to-noise ratio (hereafter SNR) and emergent onset, and for these reasons their study is difficult. In fact the background seismic noise in the area is quite high (Del Pezzo *et al.*, 2013), and this makes the detection threshold of seismic events higher than usually observed in other monitored volcanoes. To give an idea of this feature, Fig. 2 shows a comparison of seismic noise observed at Campi Flegrei with signals recorded by the same short period instruments operated in four volcanoes (Vesuvius, Stromboli, Etna, Colima), all at distance of about 1.5 km from the active crater. The most of transient signals visible in the seismograms from other volcanoes, all produced by the volcanic activity, would not be recognizable in the signals of Campi Flegrei seismic network because smaller than the background noise. A further complication arises for events located at sea in the Gulf of Pozzuoli because no seismic data are available in that area of the caldera.

The classification as LP, LF and tremor of those events that show the typical features of volcanic seismicity is based mainly on their waveform and spectral content. The apparent velocity estimated from array analysis is a strong constrain to distinguish signals produced at surface by artificial sources (whose wavefield is composed mostly of surface waves) from signals produced by natural sources at some depth. However, in some cases the discrimination between natural and artificial sources remains uncertain due to the low SNR, thus the classification is unknown.

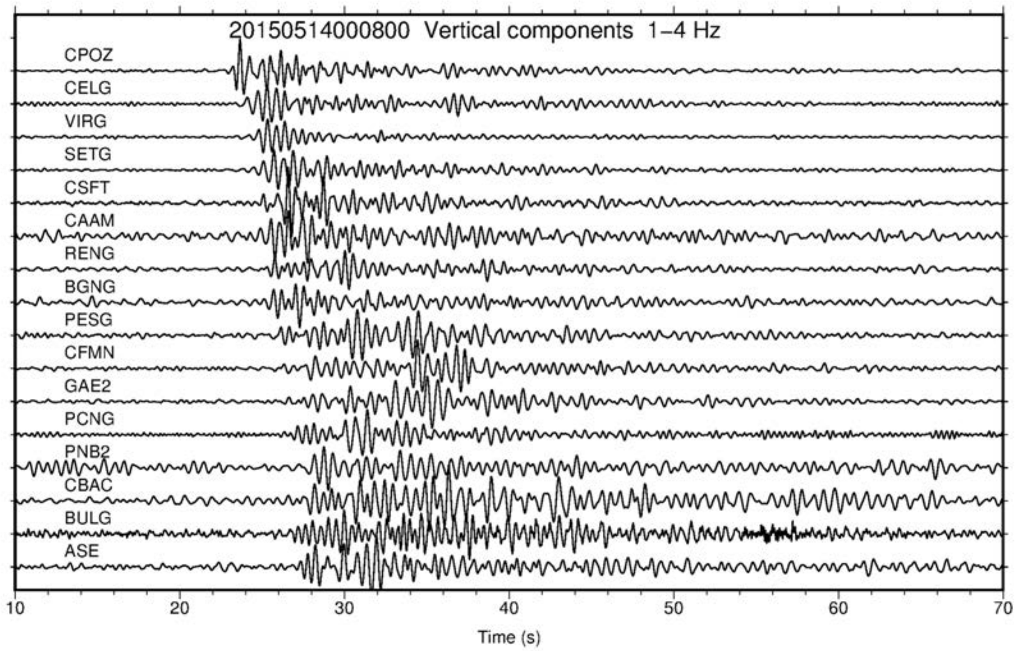

Fig. 3 - LF earthquake recorded on May 14, 2014, by all seismic stations in Campi Flegrei caldera.

3. Results

From 2010 to 2016 a dozen of volcanic earthquakes different than VT have been detected in Campi Flegrei. The most of them, classified as LF events, are characterized by low SNR, emergent onset and duration of less than 1 minute. A precise source location of such events, particularly the depth, is often a challenging task due to the lack of impulsive phases and classical methods of localization cannot be used. However, all of them are located south of the array ARF, as inferred from the signal envelope and relative amplitude at the network stations and confirmed by the backazimuth computed by array analysis which always points in a range from SE to SW. One of the strongest LF earthquakes of the last decade was recorded on May 14, 2015, by all stations of the local network. Vertical component band pass filtered (1-5 Hz) seismograms associated with this event are shown in Fig. 3. The epicentre of this LF event is located near the harbour of Pozzuoli town (very close to the station CPOZ, Fig. 1), while the low apparent velocity at ARF array and throughout the seismic network indicate a very shallow depth. LF events smaller than that shown in Fig. 3 have been detected occasionally by ARF array during the last years. They usually appear as small coherent signals of peak frequency 1.5-2.0 Hz, and duration of 10-15 s. In some cases these events are recognizable only at the array ARF and at few stations nearby, thus they cannot be located reliably because too small. In most of cases, the backazimuth estimated by array analysis points to the south or SE, while the apparent velocity smaller than 1 km/s indicates a shallow source.

Seismic signals with some different features, never observed before, were revealed by array analysis performed on the data recorded on January 30, 2015. The results of array analysis for the seismograms filtered between 1.5 and 2.0 Hz showed the presence of nearly continuous coherent signals for some hours during the day, particularly from 12:00 to 15:00 (Fig. 4).

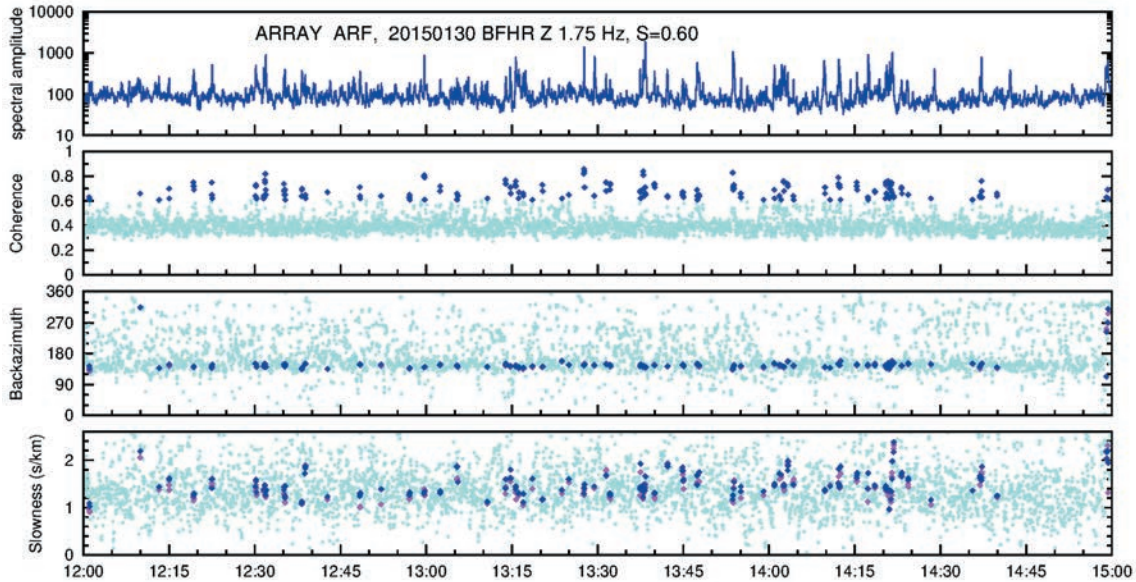

Fig. 4 - Results of BF (blue) and HR (magenta) array analysis at frequency 1.75 Hz for three hours of seismic signals recorded at array ARF starting from 12:00 UTC of January 30, 2015. Bold blue and magenta symbol show the results for windows with coherence greater than 0.6.

Although the amplitude and SNR are very low, the results of array analysis are very clear and worth of attention. The backazimuth of signals with coherence greater than 0.6 is very stable in the range 135°-150°, thus pointing to the SE, while the slowness takes values in the range 1.0 - 2.0 s/km, indicating a shallow source. The bursts of energy coherent at the array ARF are easily recognized in the signals recorded by many stations in the central part of the caldera (Fig. 5). The highest SNR is observed in the frequency band between 1.2 and 2.6 Hz (Fig. 6). A careful inspection of the three component filtered seismograms excludes dislocation mechanisms among the possible sources because no impulsive P or S waves are recognized at any stations. On the contrary, both waveform features and spectral content suggest that each bursts of coherent energy can be considered as a small shallow LF earthquake like those detected occasionally. However, counting individual events in the signal of January 30 is not possible because often they are too close in time to each other and they have different amplitude among them. Therefore, the resulting signal looks like a tremor produced by a nearly continuous source. This hypothesis is strongly supported by the distribution of backazimuth values, where the directions between 130° and 160° (the same of the strongest burst of energy) are the most common even for the less coherent background signal (Fig. 4). Therefore, this signal is likely composed of a sequence of LF earthquakes produced by the same source or by many sources so close each other to yield similar backazimuth in the array analysis. The low apparent velocity indicates the predominance of surface waves in the wavefield suggesting a shallow source depth, while P and S waves are not seen in the waveform at any stations where the signal is recognizable. The absence of impulsive phases excludes a fault dislocation source and prevent a precise location. On the other hand, a source related with magmatic activity is unlikely at shallow depth because no other phenomena like VT earthquakes or ground deformations have been observed in the same area for months before and after the tremor. Therefore, considering

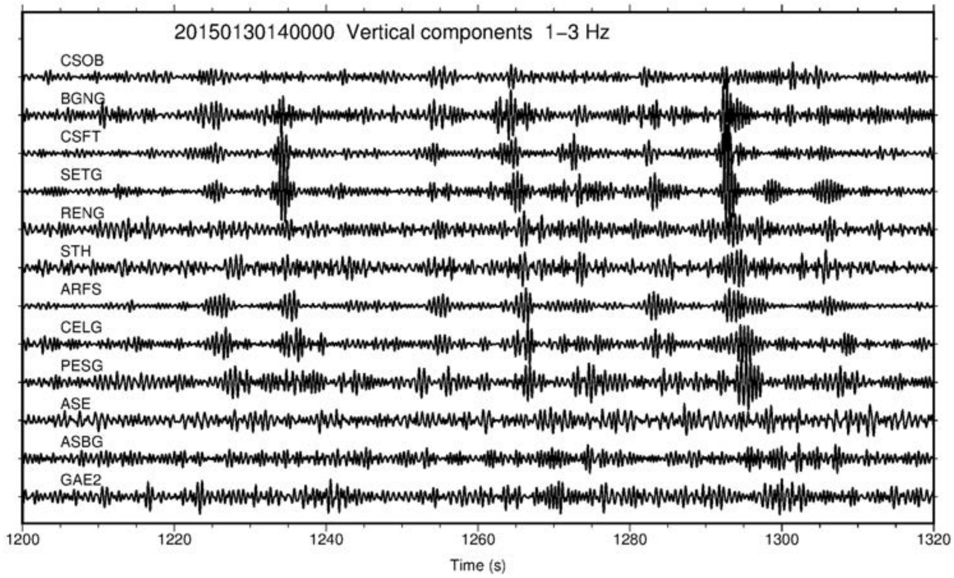

Fig. 5 - Vertical component seismograms of many seismic stations in the central area of the Campi Flegrei caldera showing busts of tremor. ARFS is the signal stacking among array stations.

all features of the observed signals, we classify the event of January 30, 2015 as hydrothermal tremor. This hypothesis is supported by the occurrence of occasional LF events interpreted as related with the hydrothermal system in Campi Flegrei, and considering that such kind of events are quite common at a number of active volcanoes (Chouet and Matoza, 2013).

The observation of relative amplitude and signal envelope at the network stations, taking into account the backazimuth from ARF array, allowed for a raw location of the epicentral area, although with a large uncertainty. We are confident that the source of this tremor is located in the area shown by the red circle in Fig. 7. A better location is not possible because at that time no seismic stations were operating in the epicentral area. Regarding the source depth, we believe it must be quite shallow, probably no more than 0.5 km, as suggested by the low apparent velocity.

Occasionally other types of coherent signals have been detected through the analysis of array data, but in some cases their features make the classification and analysis very difficult. One

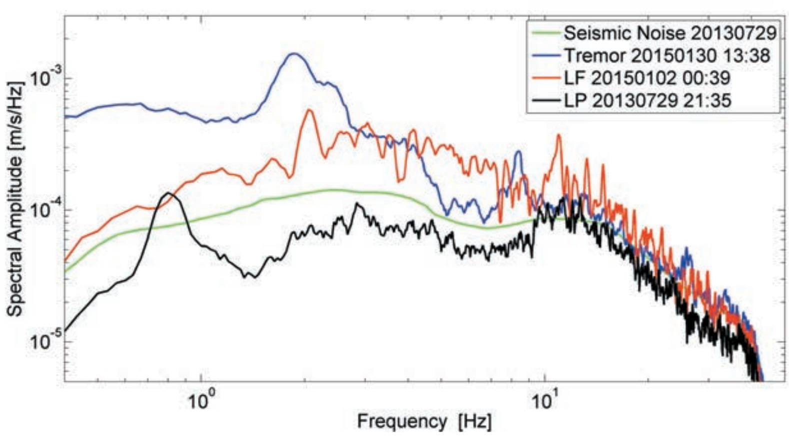

Fig. 6 - Spectra of seismic events recorded by the station ARF3. Average spectra among the three components of motion for a LP event (black), LF event (red), tremor (blue) burst and seismic noise (green). The noise spectrum was evaluated and averaged on noise windows selected on one day of seismic signal. The spectral analysis for LP, LF and tremor was performed on 30 s signal windows.

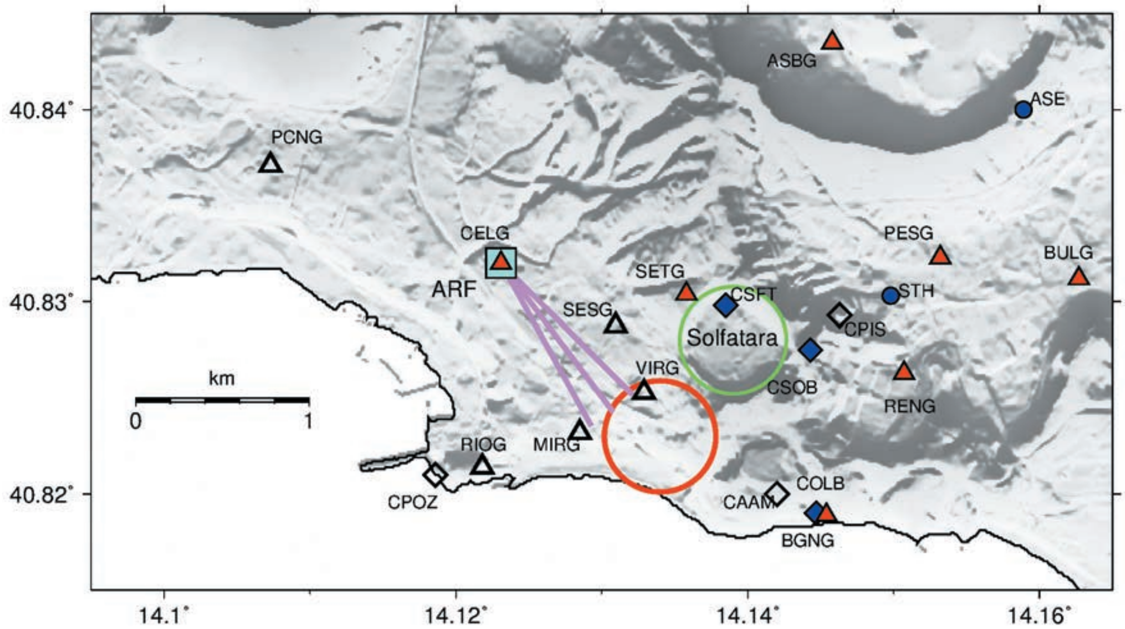

Fig. 7 - Source location of the hydrothermal tremor occurred on January 2015. Magenta lines indicate the range of backazimuth direction of tremor signals, while the red circle shows the epicentral area of the tremor source. Solfatara crater is marked by the green circle. Seismic stations shown by empty symbol were not operating at that time.

example is shown in Fig. 8, where seismograms from many stations of the local network are plotted. This LP signal is observed in the seismograms bandpass filtered between 0.4 and 1.2 Hz in a large area of Campi Flegrei caldera, but a reliable location has not been achieved with the available data. The signal envelope and amplitude at the network stations and the backazimuth pointing to the south from ARF array indicate a raw source position in the Gulf of Pozzuoli, near the coast, not very far from the source of the hydrothermal tremor. We classified this event as LP based on the peak spectra at frequency lower than 1 Hz, but many doubts persist about the source due to the narrow band spectrum (Fig. 6) that could reveal an artificial origin.

4. Discussion and conclusions

The detection and analysis of coherent signals in volcanic environment is improved by the use of seismic arrays, particularly for events characterized by emergent onset and low amplitude, as testified by a number of successful applications (Metaxian *et al.,* 2002; Matsumoto *et al.,* 2013; Almendros *et al.,* 2014). In closed conduit volcanic systems, a comprehensive study of the volcano dynamics requires the detection of the smallest possible signals produced by internal sources in order to recognize any variations that may be a precursor phenomenon. In the case of Campi Flegrei the analysis of ARF array signals allowed for the discovery of hydrothermal tremor that occurred in January 2015, some LF and LP earthquakes, and other seismic signals of uncertain origin. The hydrothermal tremor detected in 2015 is the first observation with modern instruments of such kind of events. This tremor has been interpreted as a sequence of small LF earthquakes likely related with the local hydrothermal system. Our classification as

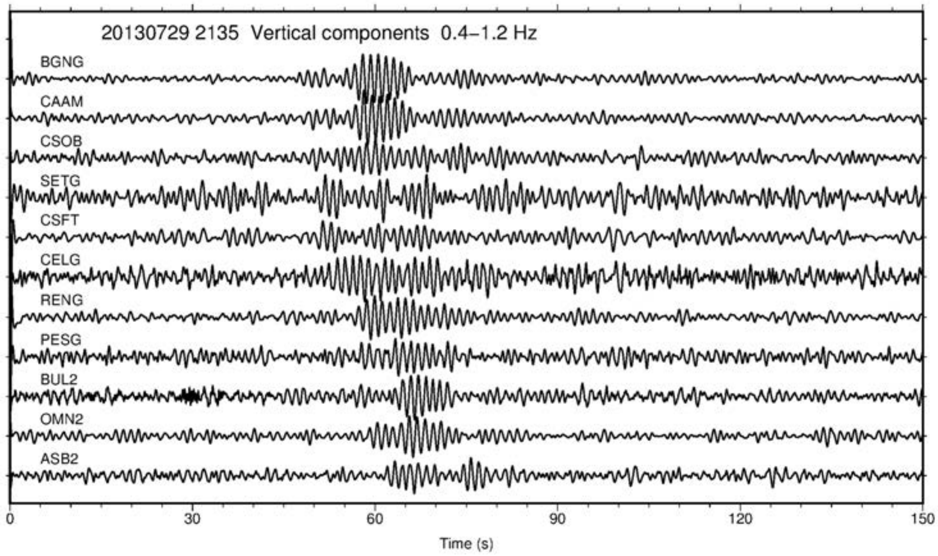

Fig. 8 - Long-period event recorded on July 29, 2013 by seismic stations in the middle of the Campi Flegrei caldera.

hydrothermal tremor, based on the lack of impulsive phases and on the spectral contents, is consistent with similar LF and LP events which are common in many active volcanoes. The source mechanism of shallow LP and LF events in volcanic environment is often associated with the hydrothermal system (Chouet, 1996). LFs and LPs have been observed in Campi Flegrei in the past. The most important case was the swarm of more than 800 LP earthquakes occurred during a week in October 2006 (Saccorotti *et al.*, 2007; Cusano *et al.,* 2008). Those events were located at depth between 0.5 and 1 km below the Solfatara Crater (Fig. 7) and had a predominant frequency of 0.8-1.0 Hz. On the contrary, the tremor of January 2015 is located about 1 km SW of the 2006 LP source area. After 2006, only a few LPs were observed in the area of Solfatara crater, but they were always much smaller than those observed in 2006. Some other LP events have also been detected, but their location and relationship with the hydrothermal system is far from obvious, like the case shown in Fig. 8.

The occurrence of the hydrothermal tremor on January 30, 2015 does not seem to be correlated with any other phenomena observed in the area. We investigated possible correlations both in space and time with swarms of VT earthquakes, with the ground uplift which is going on for more than 10 years, with the rate of gas emission from the fumaroles, and with the rainfall, but could not find out anything. Therefore, although the successful detection and analysis of an episode of low amplitude tremor proves the usefulness and efficiency of the monitoring system, we are aware that further efforts are needed to understand the dynamics of Campi Flegrei caldera. In fact the occurrence of only one episode of hydrothermal tremor in seven years of array monitoring opens a question about the reasons that make such kind of event so rare, the conditions necessary for that happening, and eventually the triggering mechanism.

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Corresponding author: Danilo Galluzzo
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano
Via Diocleziano 328, 80124 Napoli, Italy
Phone: +39 081 6108327; e-mail: danilo.galluzzo@ingv.it