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Volcanic tremor at Mt Vesuvius associated with low frequency shear failures

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Mt Vesuvius has been dormant since the eruption occurred in 1944, after which the conduit closed and the volcano entered a quiescent state. Only a minor seismic activity, characterized by low magnitude volcano-tectonic (VT) earthquakes, testifies that the magmatic system is still active. In this paper we report the fist quantitative analysis of volcanic tremor discovered at Vesuvius through the analysis of array data. A seismic array installed in 2012 improved the monitoring performance of the local network, permitting the identification of low amplitude coherent signals. Many of such coherent signals recorded during the last few years have been classified as volcanic tremor. We selected 22 tremor events based on their amplitude and on the number of available stations, and performed detailed analysis aimed at location and characterization of the source. They are characterized by low frequency, duration of a few minutes, and the strongest episodes are recorded at distance up to 90 km from the volcano. In many cases we could identify P–S wave pairs in the seismograms that allowed a precise location of the source depth, which is in the range between 5 km and 6.5 km below the crater. Waveform features, spectral analysis, and comparison with VT earthquakes located at the same depth indicate that the source mechanism of the Vesuvius non-eruptive tremor is a sequence of low frequency shear failures.

1. Introduction

After the discovery of Pompeii ruins in the second half of the 18th century, Mt Vesuvius suddenly became popular all over the world. At that time the volcano was very active with a persistent smoke plume and frequent strombolian and effusive eruptions. The last activity period started in 1631 with a strong explosive eruption, and ended in 1944. Since it is surrounded by a densely populated area, Vesuvius is one of the highest risk volcanoes in the world. A modern network of geophysical instruments provides data for monitoring through multidisciplinary techniques trying to catch any feeble signals that could represent a precursor of unrest. However, during the last decades only low magnitude ($M < 3.6$) VT earthquakes have been detected and located at shallow depth below the crater (Del Pezzo et al., 2004; D'Auria et al., 2013). Some temporary seismic arrays deployed in the past 20 ys allowed for detailed analysis of the background noise (Del Pezzo et al., 1999; Saccorotti et al., 2001) and permitted the discovery of rare Low Frequency (LF) earthquakes (Bianco et al., 2005; Cusano et al., 2013). More LF earthquakes and several episodes of volcanic tremor have been detected through the analysis of continuous array data that became effective after the installation of a permanent array in 2012 (La Rocca and Galluzzo, 2014, 2015).

Volcanic tremor is a low amplitude seismic signal observed at hundreds of active volcanoes before and during eruptions (McNutt, 2005). Common features of volcanic tremor are the emergent onset and long duration (from minutes to months) compared to normal earthquakes, while the spectrum is usually rich of low frequency, with the most of energy in the 1–6 Hz range (Konstantinou and Schlindwein, 2002). The most of observed volcanic tremors are obviously related with eruptive activity, often starting from hours to months before the volcano unrest (Chouet and Matoza, 2013). For this reason source models are based on a tight coupling between fluids (both magma and gas) and the conduits through which they move upward (Chouet, 1996, 2003). The interaction of magmatic gas with the local hydrothermal system can also play an important role in the generation of volcanic tremor and low frequency earthquakes (LF). For these reasons volcanic tremor is one of the most important precursor phenomena in case of volcanic unrest (Chouet and Matoza, 2013). The source location of volcanic tremor is usually affected by a large uncertainty due to the lack of impulsive phases recognizable at the stations of a local seismic network. Usually the source is located below the eruptive crater where the

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most of activity occurs, while the depth ranges from hundreds meters to few kilometers.

The observations of volcanic tremor at closed conduit volcanoes, not related with any eruption nor with any unrest episode, are scarcely documented. Bursts of non-eruptive volcanic tremor have been observed at few volcanoes like Kilauea, Hawaii (Aki and Koyanagi, 1981; Wech and Thelen, 2015), Deception Island, Antarctica (Almendros et al., 1997), Iwate and Bandai, Japan (Nishimura et al., 2002; Nishimura and Ueki, 2011), Teide (Almendros et al., 2007) and Copahue, Argentina (Ibanez et al., 2008). In this paper we describe volcanic tremor observed during the last decade at Mt Vesuvius volcano without any apparent relationships with the volcano dynamics.

2. Data analysis and results

Seismic activity at Mt Vesuvius is monitored by a network of more than 20 stations (Orazi et al., 2013; La Rocca and Galluzzo, 2015; Fig. 1). A seismic array of 10 short period stations (named VAS) is used to improve the monitoring performance of tremor-like signals since 2012 (La Rocca and Galluzzo, 2014). Array data are analyzed by applying Beam Forming (BF) and High Resolution methods (HR, Capon, 1969) in the frequency domain, and the Semblance method in time domain (Neidell and Taner, 1971). These analyses, performed at several different frequencies in the range 1 Hz–5 Hz, permits the identification of coherent phases in the background signal. Moreover, the results of array analysis provide an estimation of propagation direction and apparent velocity of the coherent signal, a crucial information to distinguish between surface sources (possibly artificial) and deep sources (obviously natural).

The catalog of volcanic tremor analyzed in this work includes 22 events that have occurred since 2004 (Table 1). Fourteen of these tremors occurred after the installation of the array VAS (early 2012), that gave an important contribution to their detection and analysis. The increasing number of events during the last few years is not representative of an increased activity, but it is rather a consequence of the higher number of installed instruments and of the improved detection capability. Tens of events with similar characteristics but lower amplitude have been excluded from our analysis because they have a very low signal to noise ratio, are recognized

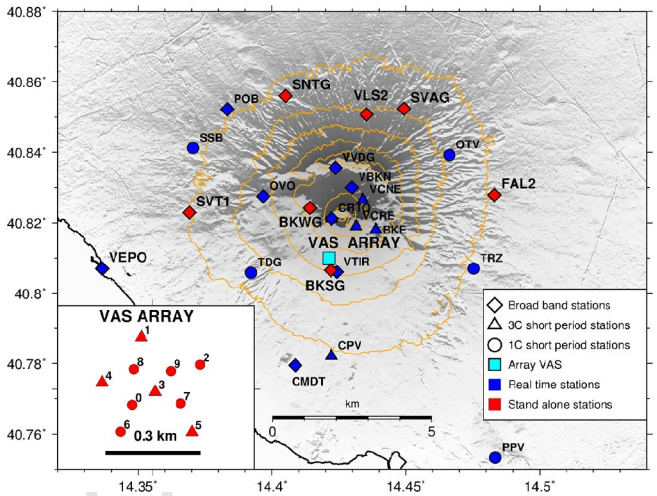

Fig. 1 Mt. Vesuvius seismic network. Topography map of Mt. Vesuvius showing the seismic stations currently installed. Different symbol indicate broad band, 3C and 1C short period stations, while blue and red colors indicate real time and stand alone instruments respectively. The inset shows the configuration of VAS array. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

only at few stations, and therefore cannot be analyzed properly. Here we provide a detailed description of one event among those with the highest signal to noise ratio and longest duration (Table 1), which occurred on March 29, 2012, but its features are common to all identified tremors. Seismograms of this tremor at many stations of the local network are shown in Fig. 2, while the signals stacked at the VAS array are shown in Fig. 3. Although the onset is emergent, the signal envelope at the stations upon and around the volcano indicates that the source is located below the crater, while the signal relative amplitude and the distance range of 90 km where the event was recorded suggest a depth of at least several km.

2.1. Location of the tremor source

Results of array analysis show coherent phases characterized by small incidence angle (slowness in the range 0.1 s/km–0.2 s/km)

Table 1
Volcanic tremor catalog.

N°	Date	Time	Duration at summit stations (s)	Amp max at BKWG (micron/s)	Corner frequency at summit stations	$T_s - T_p$ at summit stations (s)
1	20041112	0437	75	–	5	1.3 BKE
2	20060104	2256	300	–	4	1.3–1.5 BKE
3	20070802	2116	180	–	3	1.4 BKNG
4	20080824	2253	70	–	4	1.3 BKE, 1.5 POB, 1.3 OVO
5	20090606	2238	200	8.5	3	1.4 BKSG
6	20090617	0354	200	–	3	1.5 BKSG, 1.54 CRTO
7	20100309	0626	120	5.2	6	1.3 BKE, 1.3 BKWG, 1.6 VCRE
8	20110806	0640	150	9.1	4	1.35–1.5 BKWG 1.4 BKSG, BKE
9	20120329	0012	210	6.4	5	1.35 BKWG
10	20120511	0106	420	11.2	4	1.3 BKE, BKWG, BKN
11	20120620	2218	240	2.0	3	1.5 BKE
12	20120709	0050	360	2.0	6	1.4 BKWG, 1.4 BKSG
13	20120820	2306	300	10.6	3	1.4 BKE
14	20130125	0440	60	7.0	4	1.35 VASS
15	20130818	2028	240	6.4	4	1.45 BKE, 1.55 BKWG
16	20130920	0458	180	4.3	3	1.4 BKE, 1.45 BKWG, 1.5 BKSG
17	20131225	0717	140	4.8	4	1.45 VASS BKWG
18	20140117	1246	270	5.6	4	1.3 VAS (cc)
19	20140223	0600	90	2.8	5	1.25 VAS (cc)
20	20140424	1646	160	7.0	5	1.35 VAS (cc) 1.3–1.5 BKE
21	20141201	1652	90	3.2	5	1.4 VASS
22	20150620	2204	130	1.6	5	1.4 VASS

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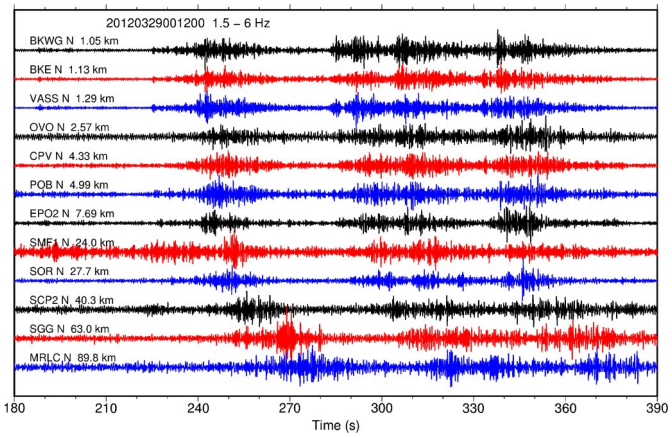

Fig. 2. Seismograms of a volcanic tremor that occurred on March 29, 2012, at Mt Vesuvius and was recorded at distances up to 90 km from the epicenter. Signals are bandpass filtered between 1.5 Hz and 6 Hz. For each station the distance from the crater is indicated.

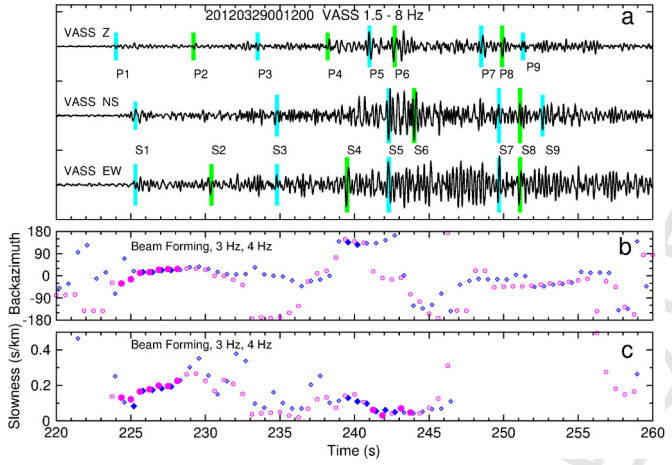

Fig. 3 a) Array stacked signals of the tremor shown in Fig. 2. Many P–S wave pairs characterized by the same time lag T_s–T_p of about 1.3 s are recognized through a careful observation of the waveform. P waves in the vertical components seismogram are pointed by upward arrows, while S waves are shown by arrows pointing to the horizontal components. b) Backazimuth and c) slowness estimated with the BF method focused at 3 Hz (blue) and 4 Hz (magenta). Bigger full symbol shows the results of most coherent signals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) Q5

associated with backazimuth to the North (Fig. 3), and phases with nearly vertical incidence (slowness smaller than 0.1 s/km, backazimuth unreliable in such case), indicating a source located at some depth below the crater. A careful observation of the three component seismograms of the stations characterized by the highest signal to noise ratio, and particularly of the array stacked signals, shows the presence in the tremor signals of many P–S wave pairs with constant $T_s - T_p$ (Fig. 3a) that we interpret as VT earthquakes. In some cases this feature of the tremor signal is also evidenced by the cross-correlation between vertical and horizontal components, as already observed for nonvolcanic tremor (La Rocca et al., 2009, 2010). Some of the analyzed tremors begin with a sequence of small VT earthquakes; then the signal amplitude increases and individual P–S phases are no longer recognizable. This feature has been observed for many of the analyzed tremors in the signals stacked over the array stations, and sometimes it is seen also at the summit stations BKWG, VCRE, BKE (Fig. 1), when the signal to noise ratio is high enough. As an example, Fig. 3a shows the beginning of the tremor 20120329 at VAS array. The array stacked signals contain many pulses on the vertical component (P waves) followed after 1.35 s by a corresponding pulse on at least one of the

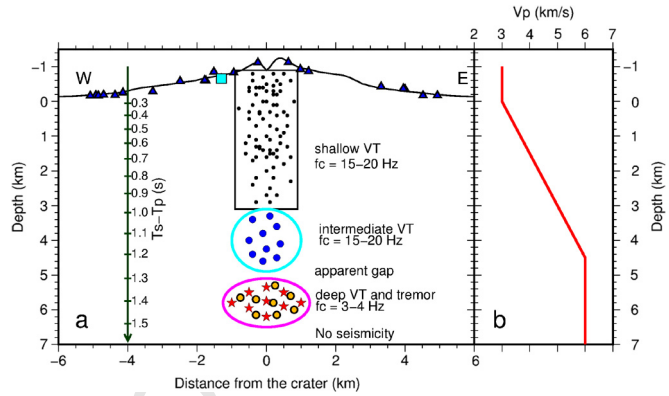

Fig. 4 a) Vertical EW cross-section of Mt Vesuvius with a schematic location of the sources of volcanic tremor (red star), deep VT (yellow circle), and intermediate VT (blue circle) analyzed in this paper. Black dots represent shallower VT not analyzed in this paper. Blue triangles show the relative position of seismic stations (distance from the crater and elevation) with VAS array shown by a cyan square. The inner vertical axis shows the $T_s - T_p$ time corresponding to the summit stations computed for the velocity model shown in plot b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) Q6

horizontal components (S waves). The estimated $T_s - T_p$ of such VT events in the volcanic tremor is in the range $1.3\ \text{s} \le T_s - T_p \le 1.5\ \text{s}$ at the summit stations. Since it is not possible to recognize the same phase at many stations due to the chaotic nature of the wavefield, we cannot locate the source of individual P–S wave pairs through the inversion of time picking at the network stations. Therefore the estimated $T_s - T_p$ time is the most important information to locate the tremor source. Looking at the envelope of filtered signals at the network stations we can establish that the epicenter is roughly in the crater area, while the source depth is well constrained by the $T_s - T_p$ estimated at the summit stations, those closer to the epicenter. Following this procedure we estimated a raw location of the tremor source assuming the epicenter in a radius of 1 km around the crater and computing the depth from the estimated $T_s - T_p$, as shown in Fig. 4a. The source depth was computed by using the simple velocity model shown in Fig. 4b, that is a smooth 1D average among the 3D models estimated for Mt Vesuvius from tomography studies (Zollo et al., 1996; Lomax et al., 2001; Scarpa et al., 2002). The $T_s - T_p$ of volcanic tremor estimated in the range $1.3\ \text{s} \le T_s - T_p \le 1.5\ \text{s}$ at the summit stations corresponds to a source depth between 5 km and 6.5 km below sea level (Fig. 4).

2.2. Investigation of the tremor source

The short duration, deep source, and rare occurrence of Vesuvius tremor contrast with the volcanic tremor commonly observed at erupting volcanoes, where it is usually located at shallow depth and it is likely produced by the interaction of magmatic fluids with conduits and with the hydrothermal system. On the other hand, some cases of volcanic tremor observed during eruptions of Mt St. Helens and Redoubt volcano have been interpreted as nearly continuous sequences of stick slip earthquakes between high viscosity magma and the surrounding conduit (Iverson et al., 2006; Hotovec et al., 2013). Vesuvius tremor looks more like this second kind of source, rather than the resonance of fluid filled cavities. Important clues in this direction come from a comparison with VT earthquakes located at the same depth of tremor.

The most of VT earthquakes recorded at Mt Vesuvius during the last decades are located below the crater at depth shallower than the volcanic tremor analyzed here (Bianco et al., 1999; Del Pezzo et al., 2004; D'Auria et al., 2013). Only a few small VT earthquakes occur at the same depth of the tremor, and noth-

Table 2
Deep VT earthquakes.

N°	Date	Time	Max amplitude at BKE (1–6 Hz)	Corner frequency at summit stations (Hz)	$T_s - T_p$ at summit stations (s)
1	20120511	010909	9.4	2	1.3 BKE,VAS, BKWG, BKN
2	20130430	014508	9.4	3	1.45 VAS,1.35 BKE
3	20130430	014639	1.2	4	1.35 BKE,1.4 VAS,1.4 BKWG
4	20130430	014915	1.8	6	1.35 BKE,1.4 VAS,1.4 BKWG
5	20130430	014950	3.1	6	1.35 BKE,1.4 VAS,1.4 BKWG
6	20130430	020034	3.1	6	1.35 BKE,1.4 VAS,1.4 BKWG
7	20130430	020315	1.8	6	1.35 BKE,1.4 VAS,1.4 BKWG
8	20130510	005748	1.2	4	1.3 BKE,1.4 VASS
9	20131214	013337	1.6	6	1.35 BKE,1.4 BKWG
10	20131214	013401	3.1	6	1.4 BKE,1.45 BKWG
11	20131218	162604	9.4	5	1.3 VASS
12	20140115	075029	9.5	5	1.4 BKE,1.6 VASS
13	20140228	075626	9.4	4	1.4 BKE,1.4 VASS
14	20140228	080326	6.2	4	1.35 BKE,1.3 BKWG,1.5 VASS
15	20140228	080403	9.4	5	1.3 BKE,BKWG
16	20140829	033400	3.1	5	1.3 BKE,VASS
17	20141208	022828	3.2	2	1.3 VASS
18	20150122	060509	2.8	2	1.4 VASS
19	20150221	193527	3.3	4	1.4 VASS
20	20150620	220520	1.8	5	1.4 VASS

Table 3
Intermediate VT earthquakes.

N°	Date	Time	Corner frequency	Magnitude	$T_s - T_p$ at summit stations
1	20130119	035134	18 Hz	1.4	1.0 s
2	20130311	021444	20 Hz	1.5	1.1 s
3	20130408	001319	18 Hz	1.2	1.1 s
4	20130421	061906	22 Hz	1.0	1.0 s
5	20130715	021325	22 Hz	1.2	1.0 s
6	20131019	024704	15 Hz	1.3	1.2 s
7	20131101	122108	15 Hz	1.9	1.1 s
8	20131211	092129	15 Hz	1.4	1.1 s
9	20141123	192319	20 Hz	1.2	1.1 s

ing has been detected deeper. To investigate the deep seismicity we looked at all available recordings of VT earthquakes occurred in the past 25 years and located at depth greater than 4 km bsl in the catalog. Among those earthquakes we could not find any VT with $T_s - T_p$ greater than 1.5 s at the stations near the epicenter. This means that the very few earthquakes catalogued with depth greater than 6.5 km are mislocations or they were located by using a faster velocity model. Our selection based on the $T_s - T_p$ time difference avoids any possible doubts related with the velocity model or with wrong phase picking used in the source location. We found 20 VT earthquakes characterized by $1.3\ \mathrm{s} \le T_s - T_p \le 1.5$ s at the summit stations (deep VT hereafter, Table 2 and Fig. 4), the same values observed for the tremor signals, and used them to investigate the source of volcanic tremor that have the same $T_s - T_p$. Furthermore we selected 9 VT earthquakes with $1.0\ \mathrm{s} \le T_s - T_p \le 1.2$ s, located at depth between 3.5 and 4.5 km bsl (intermediate VT hereafter Table 3 and Fig. 4), and computed the displacement signal spectra for all events. Spectra of deep VT, intermediate VT, volcanic tremor and seismic noise recorded at the summit station BKWG are shown in Fig. 5, while the seismograms for one event of each type and their spectra are shown in Fig. 6. A comparison of the spectral contents suggests a tight relation between the source of tremor and deep VT earthquakes. In fact volcanic tremor and deep VT have spectra very similar to each other in the frequency band between 4 Hz and 10 Hz, where they have the highest signal to noise ratio, while the difference between them and intermediate VT is striking (Figs. 5 and 6b). Intermediate VT earthquakes (located at around 4 km bsl) are characterized by corner frequency between 15 Hz and 22 Hz (Table 3), the same of shallower earthquakes not shown here, while deep VT and tremor (both located deeper than 5 km bsl) are characterized by corner frequency from 2 Hz to 6 Hz (Table 1 and Table 2). A such strong difference cannot be explained invoking a higher attenuation at depth but must be a source signature likely due to rock properties at depth where deep VT and tremor occur. The spectral similarity of deep VT and tremor is a strong constrain on the hypothesis that both types of events are produced by the same source mechanisms.

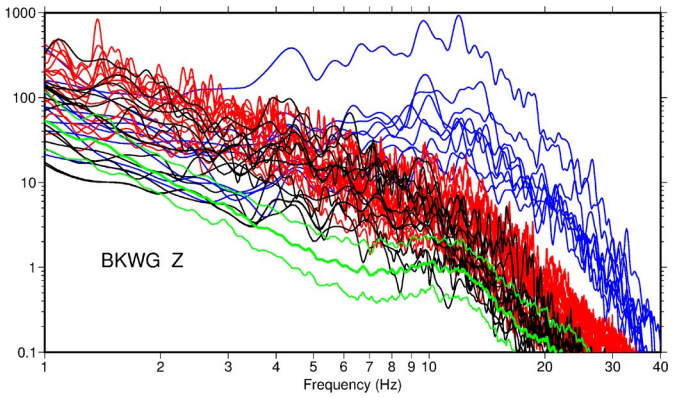

Fig. 5 Signal displacement spectra of volcanic tremor (red, $1.3\ \mathrm{s} \le T_s - T_p \le 1.45$ s), deep VT earthquakes (black, $1.3\ \mathrm{s} \le T_s - T_p \le 1.45$ s), and intermediate VT earthquakes (blue, $1.0\ \mathrm{s} \le T_s - T_p \le 1.2$ s). The average spectrum of seismic noise selected before tremor and earthquakes is shown with its standard deviation by green lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) Q7

We estimated the source spectrum starting from the signal spectra and taking into account the attenuation estimated in the Vesuvius area (Bianco et al., 1999). Various source spectral

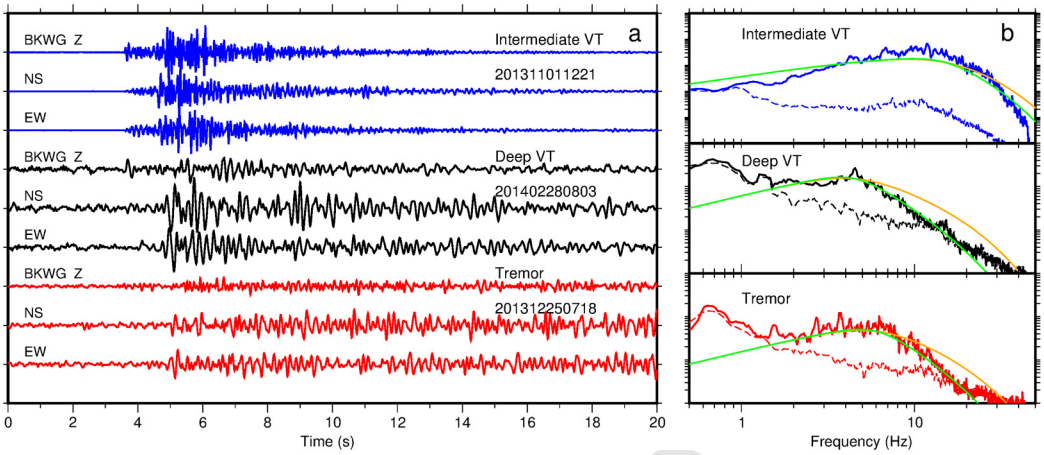

Fig. 6 a) Seismograms of an intermediate VT ($T_s - T_p = 1.1$ s, blue), a deep VT ($T_s - T_p = 1.4$ s, black) and a tremor ($T_s - T_p = 1.4$ s, red) recorded at the summit station BKWG, high pass filtered at 1.5 Hz. b) Average spectra among the three components of the events shown in (a) (thick line) compared with the average spectra of seismic noise selected 1 minute before each event (dashed line). The theoretical source models ω^{-2} and ω^{-3} are shown by orange and green lines respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Source features of the analyzed seismicity.

Type	Seismic moment M_0	M_w	Corner freq.	Source radius	Stress drop	Rupture velocity
Interm. VT	7.7×10^{10}–9.5×10^{11} Nm	1.0–1.9	15–25 Hz	30–40 m	7–40 bar	0.9 V_S (V_S = 3.3 km/s)
Deep VT	1.1×10^{11}–1.7×10^{12} Nm	1.3–2.1	2–6 Hz	110–210 m	0.2–2 bar	0.9 V_S (V_S = 3.0 km/s)
Tremor	5–70 cm^2 (reduced displacement)	–	3–6 Hz	–	–	–

models and scaling laws have been used in literature to explain the differences among VT, LF, and tremor events (Madariaga, 1976; Boatwrigth, 1980; Deichmann, 1997; Ide et al., 2007; Harrington et al., 2015). The different source features are explained mainly invoking rupture velocity and stress drop. In our case the best fit of observed spectra for intermediate VT, deep VT and tremor is given by the ω^{-3} source model with $Q_\beta = 80\ f^{-0.1}$, very close to the attenuation value found for Mt Vesuvius by Bianco et al. (1999), $Q_\beta \approx 60$ in 1–24 Hz frequency band). The ω^{-3} high frequency spectral decay has been observed in some cases of volcanic tremor (Patanè et al., 1994) and nonvolcanic tremor (Zhang et al., 2011). Site effects were assumed negligible for the summit stations BKE and BKWG used in our calculation (Galluzzo et al., 2009). The results for the three types of events are summarized in Table 4. For volcanic tremor we estimated the reduced displacement (Aki and Koyanagi, 1981) instead of seismic moment. Assuming a rupture velocity of 0.9 Vs, we obtain source radius (Madariaga, 1976) $R \approx 30$–40 m for intermediate VT (f_c = 15–22 Hz, source V_S = 3.0 km/s), but $R \approx 110$–210 m for deep VT and tremor (f_c = 2–6 Hz, V_S = 3.3 km/s). A source size of 0.2–0.4 km, associated with $\sigma < 2$ bar (Table 4), seems unrealistic for deep VT and tremor. However, smaller Vs (2 km/s) and lower rupture velocity (0.6 Vs) would lower the source size (Deichmann, 1997) of tremor and deep VT to values of less than 0.1 km, more similar to intermediate VT and compatible with the small size of faults expected below Mt Vesuvius, where the low magnitude of current seismicity (Del Pezzo et al., 2004; D'Auria et al., 2013) does not suggest the existence of larger faults. Another possibility to fit the observed spectra is given by much smaller source size associated with higher stress drop but lower rupture velocity.

3. Discussion and conclusions

We could not find deep VT with the spectral features of intermediate VT nor intermediate VT with the spectral features of deep VT, therefore we conclude that their striking difference must be related with the rock properties at depth where deep VT and tremor are located. Unfortunately we have very little information about the physical properties of rock at such depth below Vesuvius. One possibility to explain the observed difference is a significant change of the medium mechanical properties with depth, reasonably in terms of stiffness, temperature, and perhaps the presence of nearly melt material. A significant change of these properties at depth below 5 km bsl would explain the lower frequency contents of tremor and deep VT in terms of lower stress drop compared with the VT located at shallower depth. This hypothesis would explain also the absence of any seismic waves radiated by sources deeper than about 6.5 km bsl. On the other hand, the presence of melt material at depth of about 8 km was inferred from the study of active sources shot for a tomography experiment (Auger et al., 2001). Our results suggest a significant change of medium mechanical properties starting at around 5 km bsl, where the rock stiffness decreases and low stress drop shear failures radiate energy at lower frequency. The absence of seismic waves radiated from depth greater than about 6.5 km bsl is consistent with rock temperature higher than the brittle limit, and perhaps a significant amount of melt material.

Spectral similarity, the sequences of P–S wave pairs recognized in many seismograms, and the very similar source location indicate beyond reasonable doubts that the volcanic tremor observed at Mt Vesuvius is generated by sequences of shear failures that occur like a swarm in a small volume. However, such sequence of failures does not occur on the same fault plane. Since we could not identify the same P–S waveform repeating in the tremor signal, we conclude that the various P–S wave pairs are produced by sources with different focal mechanisms among them. While each deep VT is produced by an individual shear failure, the tremor signal is produced by a swarm of many failures occurring in a short time and in a volume small enough to produce similar $T_s - T_p$. A source model where highly viscous, partly crystallized magma, occasionally moves (not necessarily upward) inside a conduit or a dike

may well describe the observed tremor signals (White et al., 2011; Green et al., 2015). Stick slip of volcanic material in a conduit cavity would radiate energy from several different points where the normal stress is higher, hence the individual small fault planes would have different orientations. This explains why the observed P and S wave pulses have different shape and relative amplitude (Fig. 3). Based on the available data, we are not able to establish if such small occasional movement of magma at depth is driven by a pressure increase or it is produced by settlement of hot material residual of the last eruption.

Another feature of Vesuvius seismicity is the low number of intermediate VT and the apparent gap between them and the deep VT and tremor (Fig. 4a). We could not find any VT earthquake with $T_s - T_p$ in the range 1.2 s–1.3 s among those recorded during the last two decades. Therefore we do not observe a smooth transition between intermediate VT (with corner frequency of 15–22 Hz) and deep VT (with corner frequency of 2–6 Hz), but a seismic gap. Based on the available data we do not know the reason of such apparent gap. Investigating the roots of Mt Vesuvius is a complex matter because appropriate data are not available. Local seismicity related with volcanic activity is confined to the shallowest 6.5 km, while local seismicity of tectonic origin located in the crust below and around the volcano is absent. Therefore it is impossible to observe high frequency seismic signals that along their path propagate through the deep structure of the volcano. On the other hand low frequency teleseismic signals do not allow for a sufficient resolution of the deep structure.

The discovery of volcanic tremor at Mt. Vesuvius was somewhat unexpected because the volcano is in a quiescent state since 1944, the seismic activity has been very low during the last decades, and no other phenomena related with its activity are observed. At present we are not able to establish any relationships between the occasional bursts of tremor and the volcano dynamics.

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Highlights

- Observation of volcanic tremor at Mt Vesuvius discovered from the analysis of array data.
- P–S wave pairs with constant $T_s - T_p$ time permits a precise estimation of the source depth.
- The source is located at depth between 5 km and 6.5 km bsl.
- Vesuvius tremor has the same spectral contents of VT earthquakes located at the same depth.
- Vesuvius tremor is a sequence of low frequency shear failures occurring in a transition zone.

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