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## Insights into Mt. Etna's Shallow Plumbing System from the Analysis of Infrasonic Signals, August 2007–December 2009

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**Abstract**—Previous studies performed on Mt. Etna on short and discontinuous time intervals indicate the North East Crater (NEC) as the most active source of infrasound. The source mechanism of NEC infrasound events was modeled as a double resonance. This lead to infer the connection between the NEC and both the southeast crater (SEC) and the eruptive fissure (EF), that opened at the beginning of the 2008–2009 eruption. Nevertheless, there are still several open questions that need to be addressed. For instance, the steadiness of NEC event features should be studied, as well as the orderliness of spectral changes of NEC events time-related to eruptive activity of other vents. The investigation of such topics is strongly enhanced by the possibility of analysing infrasound signals during year-long time periods. With this aim about 40,000 infrasound events, recorded at Mt. Etna from August 2007 to December 2009 were analysed by using spectral and location techniques. It was noted in particular that the NEC events featured periods with very steady waveforms and spectral characteristics lasting from days to months with slow or sudden variations. The most important eruptive episodes occurring at the SEC or the EF were accompanied by significant spectral changes in NEC events. In light of such systematic behaviour the connection between the NEC and the SEC/EF plumbing systems was not considered temporary but rather stable even during a relatively long time interval (2006–2009). Moreover, study of NEC event spectral features and their changes over multiple years supports the double resonance source model. Such a model, together with the inferred connections between NEC and SEC/EF feeding systems, implies that level fluctuations of a magma column inside the NEC conduit correspond to magmatic pressure decrease/increase inside the main plumbing system. These

findings open up new and interesting possibilities for monitoring magma pressure changes inside the Mt. Etna plumbing system.

**Key words:** Infrasound, Shallow plumbing system, explosive activity, source modelling, Mt. Etna.

### 1. Introduction

Mt. Etna is a Quaternary stratovolcano located on the eastern coast of Sicily and characterised by Na-alkaline magmatism (CRISTOFOLINI and ROMANO 1982). The summit area of Mt. Etna is currently made up of four active craters: Voragine, Bocca Nuova, South East Crater and North East Crater (hereafter referred to as VOR, BN, SEC and NEC, respectively; see Fig. 1). Furthermore, a relatively new vent named “New South East Crater” (NSEC; PATANÈ *et al.* 2013) developed on the south-east flank of SEC during 2011–2014 eruptions. Volcanic activity may be divided into activity at the summit craters, characterised by phases of degassing, occasionally alternating with mild strombolian activity, fire fountains and lava overflows, and flank eruptions occurring from lateral vents usually located along fracture systems and often related to regional tectonics (MONACO *et al.* 2005).

Since 2006, a permanent infrasound network has been deployed by Istituto Nazionale di Geofisica e Vulcanologia (INGV), Osservatorio Etneo—Sezione di Catania. Since then different vents have been recognized as active sources of infrasound. In particular, until 2009 only two summit craters, the SEC and the NEC, were radiating infrasound (Fig. 1; CANNATA *et al.* 2009a, b) along with the lowest portion of the EF active during the 2008–2009 eruption

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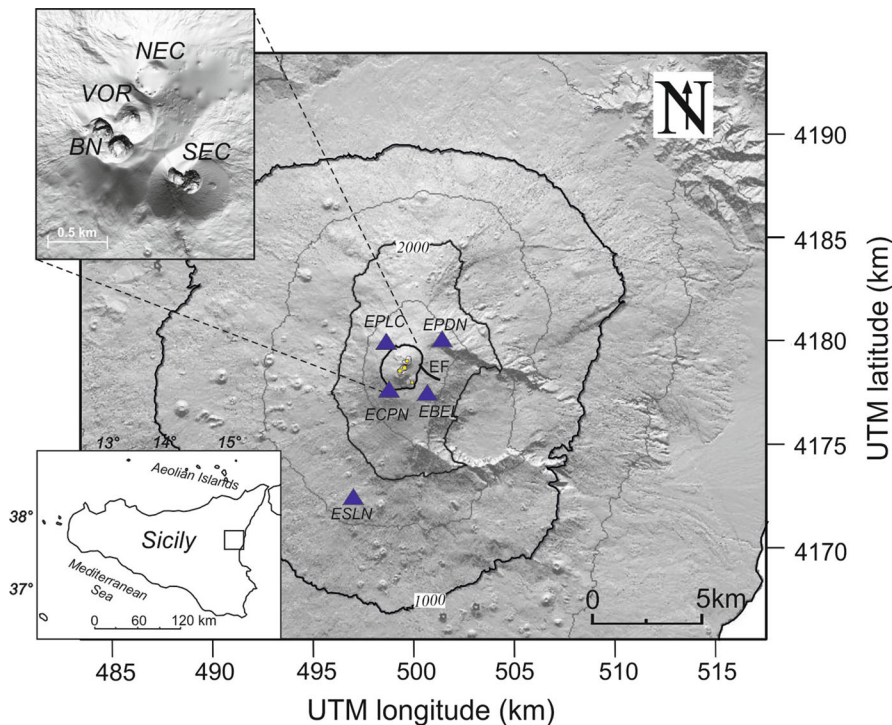


Figure 1

Digital elevation model (DEM) of Mt. Etna with locations of the five infrasound sensors (*triangles*), making up the permanent infrasound network, and the eruptive fissure that opened on 13 May 2008 (*thick black line*, “EF”). The DEM in the *upper left corner* shows the distribution of the four summit craters (*VOR* Voragine, *BN* Bocca Nuova, *SEC* South East Crater, *NEC* North East Crater). The distance of the reference station (EBEL) from the summit craters is 1.7, 1.8, 1.2, 2 km for *VOR*, *BN*, *SEC* and *NEC*, respectively. The southernmost termination of EF is 1 km away from the EBEL station

(Fig. 2; CANNATA *et al.* 2011a). *BN* generated infrasound during sporadic episodes of mild ash emission in 2010 (ANDRONICO *et al.* 2013) and during occasional strombolian activity in 2011–2013 (INGV STAFF 2007–2013). Finally, during 2011–2013 the *NSEC* generated infrasound signals and in February–March 2013 also *VOR* emitted infrasound signals during strombolian activity (INGV STAFF 2007–2013).

According to previous studies, the infrasonic signals at Mt. Etna are generally composed of discrete infrasonic events characterised by durations of <1 s to over 30 s, impulsive compressive onsets, and peaked spectra with most of the energy in the 0.3–6.0 Hz frequency range (MONTALTO *et al.* 2010; CANNATA *et al.* 2013; SCIOTTO *et al.* 2013). Every so often infrasonic tremors lasting from minutes to days are recorded during paroxysmal activities and degassing processes (CANNATA *et al.* 2009a, 2013; SCIOTTO *et al.* 2011).

It has been shown how distinct craters generate infrasound signals with different spectral features and duration (CANNATA *et al.* 2009a, b, 2011a, b; Fig. 2). Indeed, *SEC* and *EF* events have dominant frequencies above 2.5 Hz, impulsive compression onsets and short durations ( $\sim 1$  s). Furthermore, they are mainly recorded during explosive activity at their respective source craters (CANNATA *et al.* 2011a, b; ANDRONICO *et al.* 2013). On the contrary, *NEC* events occur almost continuously even during non-eruptive periods. They generally show frequency content lower than 2.5 Hz lasting up to tens of seconds and are characterised by a first pulse followed by decaying sinusoidal oscillations. It has also been noted that the spectral features of *NEC* events have previously changed during and/or after explosive *SEC* and *EF* activity (SCIOTTO *et al.* 2011, 2013).

Based on the described observations, *SEC* and *EF* events have been interpreted as resulting from a strombolian bubble vibration model (CANNATA *et al.*

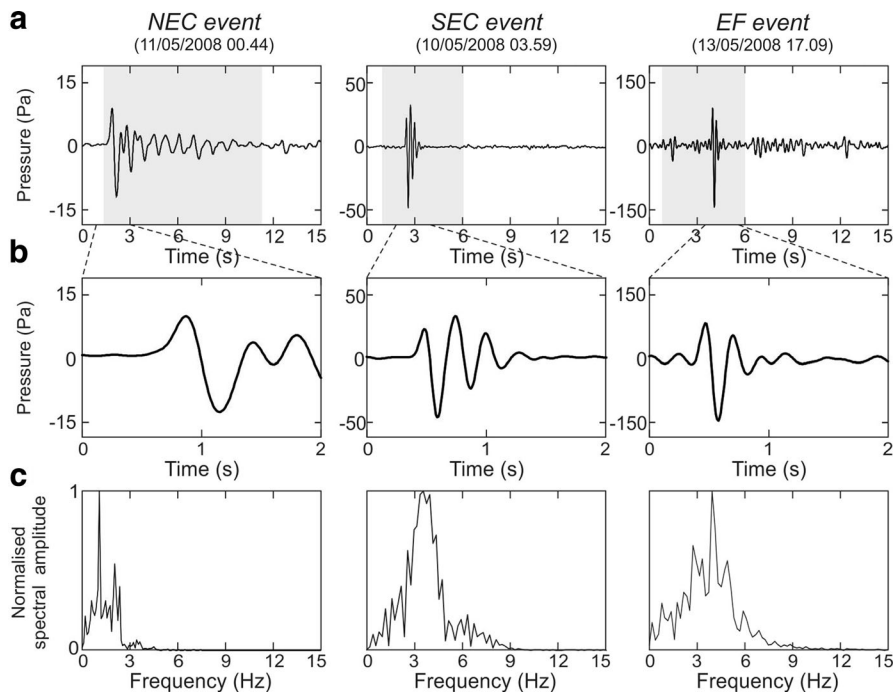


Figure 2

Infrasound events recorded by the EBEL station and related amplitude spectra performed on a 10.24 s (NEC event) and 5.12 s (SEC and EF events) time window. The grey areas in the top plots show the signal windows used to calculate the spectra

2009a, 2011a), while NEC events are interpreted as being resultant from resonance phenomena (SCIOTTO *et al.* 2011, 2013). In particular, SCIOTTO *et al.* (2013) attributed the two spectral components (0.4–0.7 and 1.5–2.0 Hz) of the NEC events recorded hours before the 2008–2009 eruption onset at the EF to Helmholtz and pipe resonances, respectively. In fact, authors inferred that the portion of the NEC conduit between the free magma surface (lower end) and a upward narrowing of the conduit (upper end) is the source of pipe resonance. Moreover, the outward flux of gas through the above-mentioned narrowing causes the same portion of the conduit to also behave like a Helmholtz resonator, akin to a bottleneck through which gas can escape. As a result, it also radiates low frequency and monochromatic infrasound (for a detailed description of the model see SCIOTTO *et al.* 2013).

Here we describe the infrasound activity of Mt. Etna from August 2007 to December 2009. The collected large infrasonic dataset gives us the opportunity to investigate the infrasound in the medium term (up to a few years) in order to verify the steadiness of the time-dependent phenomena recently observed in NEC

infrasonic events. In particular we want to address the following key questions:

1. How steady (or variable) are the waveform features of NEC events investigated during year-long time periods?
2. How systematic (or sporadic) are the spectral changes of NEC events time-related to eruptive activity of other vents?
3. Is the double resonator NEC model, proposed in previous papers, suited to explain all the observations made during the 2007–2009 period?
4. Are interpretations of the spectral changes, found in previously-investigated eruptions, confirmed? If so, may the changing sizes of resonating structures, due to level oscillations of the magma column, be used to estimate pressure fluctuations in the main plumbing system?

## 2. Volcanic Framework

The August 2007–December 2009 period was characterised by different kinds of volcanic activity at

Mt. Etna (INGV STAFF 2007–2013), including quiet degassing, ash emission, strombolian activity, fire fountain episodes and effusive activity. With the term “fire fountain,” a typical activity of Hawaiian-type eruptions, we refer to an almost continuous to fully sustained vigorous magma jet (ALPARONE *et al.* 2003) driving lava clots that can typically reach tens to hundreds of metres in height (PARFITT 2004). The term “strombolian” is used here to refer to eruptions characterised by discrete explosions, due to the breaking of over-pressurized bubbles at the surface of the magma column (VERGNOLLE *et al.* 1996). Even if indicated as a continuous activity in Figs. 3, 4 and 5, the strombolian episodes were at times effectively bursts of explosions separated from each other by intervals of decreasing activity. Finally, the term “ash emission” indicates mild explosive activity with the ejection of ash into the atmosphere rising up from few tens of meters to about 1 km (ANDRONICO *et al.* 2013).

In December 2006, after the end of the eruption, Mt. Etna’s activity consisted of sporadic and short lasting strombolian and fire fountain episodes occurring in a lateral pit on the eastern flank of the SEC. Up to four paroxysmal episodes were observed between March and May 2007. Then, mild explosive activity resumed once again at the SEC in mid-August 2007 (AIUPPA *et al.* 2010). On September 4–5 this explosive phase culminated in one of the most powerful fire fountains occurring in the last decade, both in terms of duration, about 12 h, and of lava and tephra volume,  $\sim 2\text{--}4 \times 10^6 \text{ m}^3$  (ANDRONICO *et al.* 2008). This eruptive episode was followed on November 23 and 24 by another fire fountain episode from the same crater, that lasted about 6 h. Thereafter, until the beginning of May 2008, the eruptive activity at Mt. Etna consisted of discontinuous and mild explosive activity at the SEC. On 10 May 2008 a fire fountain occurred at the SEC and on May 13 a new eruption took place from an eruptive fissure that opened east of the summit area (EF; Fig. 1). This eruption was characterised at the beginning by spectacular fire fountain activity and during the following months by phases of variably intense lava flows and strombolian activity (BONACCORSO *et al.* 2011a). This eruptive phase ended on July 6, 2009. It is noteworthy that during the time interval analysed

the NEC was mainly characterised by pulsatory degassing and loud booming sounds with no visible eruptive activity (INGV STAFF 2007–2013). Finally, only degassing was observed at BN and VOR during the targeted period.

### 3. The Infrasound Network

From August 2007 to December 2009 the permanent infrasound network at Mt. Etna consisted of between 2 to 5 stations (Fig. 1). At the beginning of this period the stations were EBEL, ECPN and ESLN and in September 2007 EPLC and EPDN were installed. The EBEL station recorded the longest time series and the best signal to noise ratio and, hence, was chosen as the reference station. Distances of this station from the NEC, SEC and EF southernmost extremities are approximately of 2, 1.2 and 1 km, respectively. The infrasound sensors consist of Monacor MC-2005 condenser microphones with a “theoretical” sensitivity of 80 mV/Pa in the 1–20 Hz infrasound band. At the beginning of November 2009 a G.R.A.S. 40AN microphone with a 50 mV/Pa sensitivity in the 0.3–20,000 Hz frequency range and  $\pm 3$  dB in the 0.1–0.3 Hz range was installed in place of the Monacor sensor at the EBEL station. Amplitude values, spectra and pseudospectrograms (reported below) are corrected for the experimental response curve of the Monacor microphones (for further details see SCIOTTO *et al.* 2013). Note that the sampling rate is equal to 100 Hz. Due to adverse weather conditions at the Mt. Etna summit recordings are not always continuous.

### 4. Data Analysis

As mentioned above infrasound signals generated by volcanic activity at Mt. Etna consist mostly of discrete events with a duration of seconds. In order to investigate Mt. Etna infrasound activity from August 2007 to December 2009 we detected and analysed  $\sim 40,000$  infrasound events. Two kinds of analyses were performed: (1) spectral analysis by the fast Fourier transform (FFT) algorithm; (2) source location analysis by semblance-brightness algorithm.

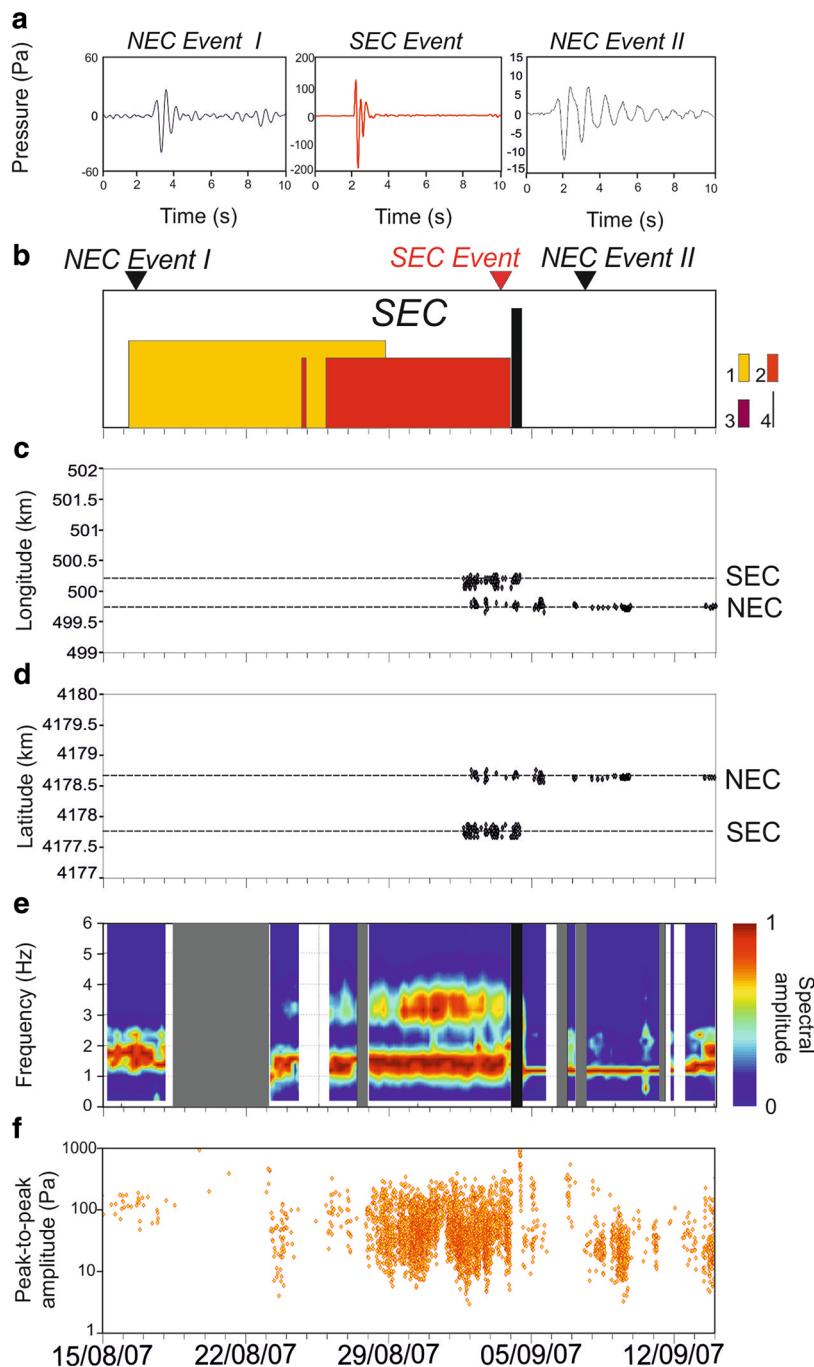


Figure 3

**a** Waveforms of two NEC infrasound events and a SEC infrasound event recorded by the EBEL station during period I; **b** sketch of the volcanic activity of Mt. Etna at SEC during period I (1 ash emission; 2 strombolian activity; 3 effusive activity; 4 fire fountain); **c** longitude of infrasound events located during the first period; **d** latitude of infrasound events located during the first period; **e** normalised pseudospectrogram, **f** peak-to-peak amplitude of the infrasound events occurring at Mt. Etna during period I and recorded by the EBEL station. *Triangles at top of b* indicate the time of occurrence of the events shown in **a**. In **e** grey rectangles represent periods of partial or complete lack of triggered events as a result of bad weather conditions/station malfunctioning. In **e** black rectangles show periods of partial or complete lack of triggered events because of infrasonic tremors. *White rectangles in e* indicate periods when the pseudospectrograms could not be calculated because of the small number of triggered events, even in good signal to noise ratio conditions

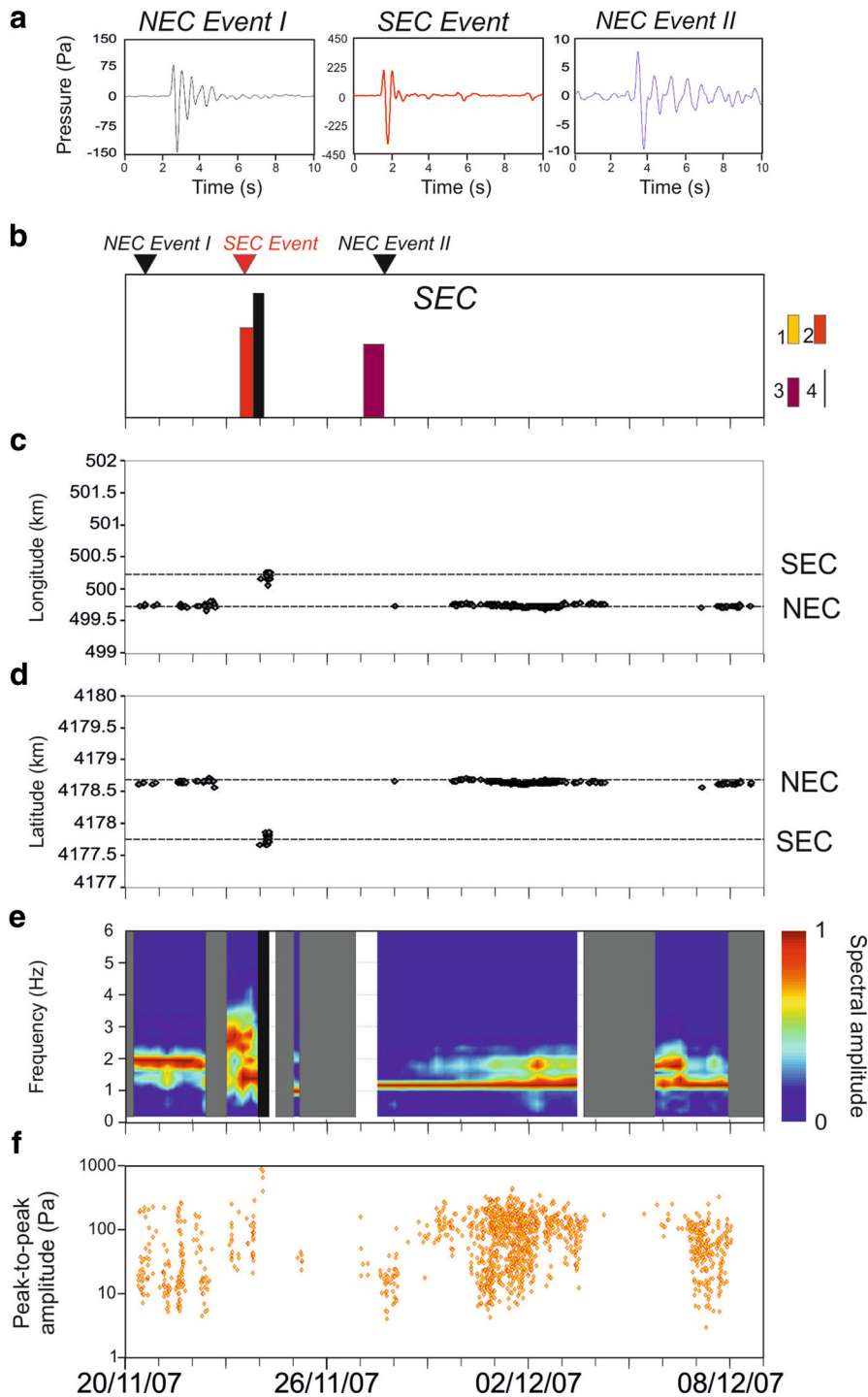


Figure 4

**a** Waveforms of two NEC infrasound events and a SEC infrasound event recorded by the EBEL station during period II; **b** sketch of the volcanic activity of Mt. Etna at SEC during period II (1 ash emission; 2 strombolian activity; 3 effusive activity; 4 fire fountain); **c** longitude of infrasound events located during the second period; **d** latitude of infrasound events located during the second period; **e** normalised pseudospectrogram, **f** peak-to-peak amplitude of the infrasound events occurring at Mt. Etna during period II and recorded by the EBEL station. Other symbols as in Fig. 3

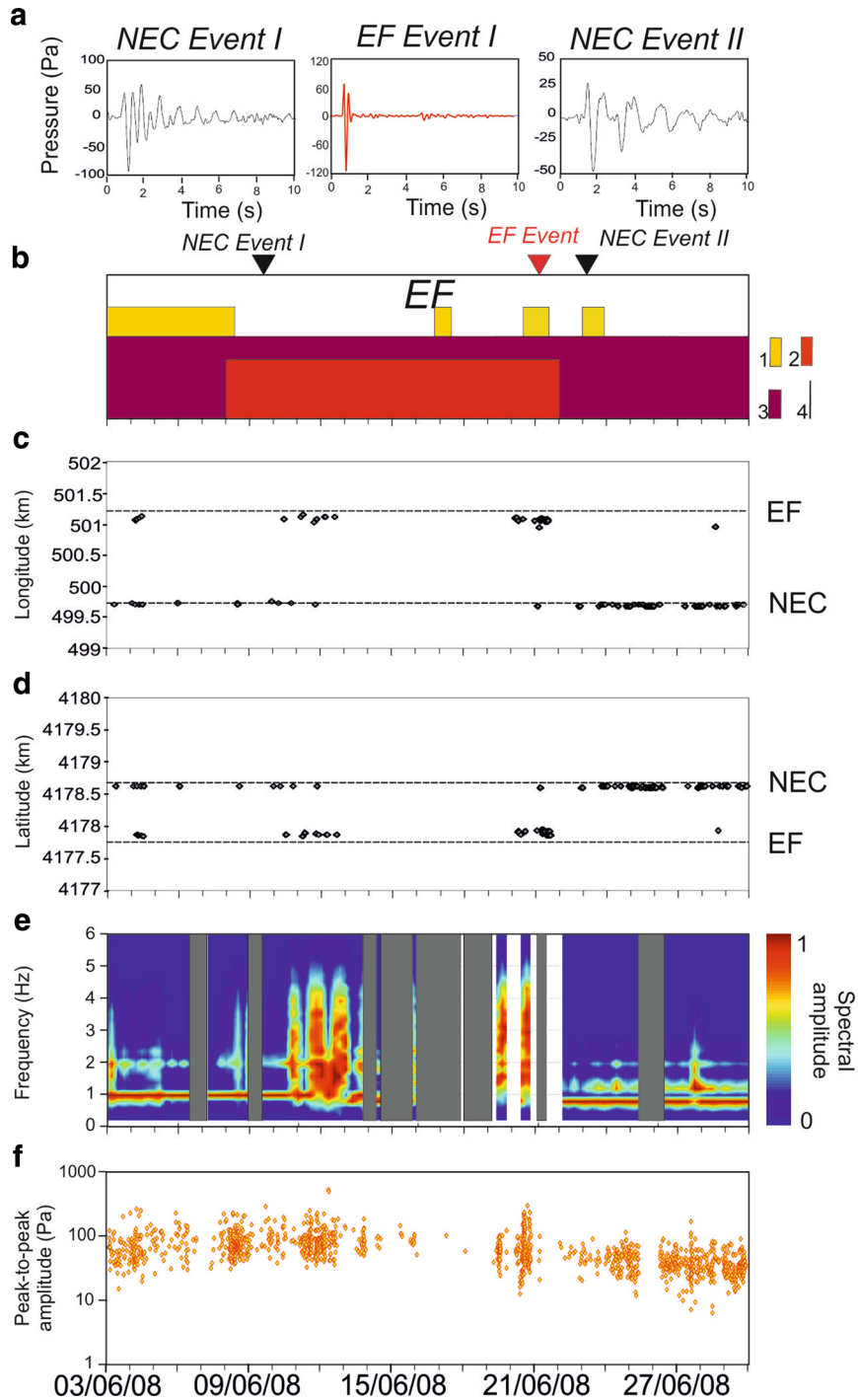


Figure 5

**a** Waveforms of two NEC infrasound events and an EF infrasound event recorded by EBEL station during period III; **b** sketch of the volcanic activity of Mt. Etna at EF during period III (1 ash emission; 2 strombolian activity; 3 effusive activity; 4 fire fountain); **c** longitude of infrasound events located during the third period; **d** latitude of infrasound events located during the third period; **e** normalised pseudospectrogram, **f** peak-to-peak amplitude of the infrasound events occurring at Mt. Etna during period III and recorded by EBEL station. Other symbols as in Fig. 3

#### 4.1. Spectral Analysis

In order to study spectral variations of the infrasound events over time we performed FFT analysis. Since Mt. Etna's infrasound events last from a few seconds to tens of seconds and occur within tens of seconds to hours and occasionally days apart, the classic short time Fourier transform (STFT) would mainly be made up of noise spectra (mostly wind noise), that would hide the spectral features of infrasound events related to volcano activity. For this reason, instead of classic spectrograms pseudospectrograms have been calculated as follows.

Infrasonic events recorded at the EBEL station were detected using the classic short term averaging/long term averaging (STA/LTA) algorithm. Then, by the FFT algorithm we calculated one spectrum for each event using an  $\sim 5$ -s-long window, starting 0.5 s before the onset of the event. Next, an averaging process of the computed spectra was performed. Such a process implied the stacking in the frequency domain of the amplitude spectra of all the events falling in fixed time-windows, sliding through the investigated time-interval. The duration of such sliding windows is a critical factor, since it must be a compromise between the need for detailed time information (short time interval) and continuity in the representation, requiring the occurrence rate of infrasound events to be taken into consideration (long time interval). Thus, we chose 6-h-long windows. Successively, each averaged spectrum, representing the spectral content of all the events occurring in a 6-h-long window, was normalised by its maximum value. Finally, we gathered the 6-h normalised averaged spectra as columns in a single matrix arranged in temporal order. This matrix was visualised as a pseudospectrogram (Figs. 3e, 4e, 5e). Hence, time is reported in the  $x$ -axis, the frequency in the  $y$ -axis and the colour scale shows spectral amplitude.

We visually verified the steadiness/variability of the infrasound waveforms within 6-h-long time windows. In order to do that, we superimposed in the time domain the waveforms of the events taking place during 6-h-long windows and visualised them. We noted that during such a time-step the waveforms remain fairly steady with a few

exceptions of periods characterised by important changes in volcano activity. An example of such NEC steadiness is given in Fig. 6 where all the events occurring in four consecutive windows of 6 h are superimposed.

Moreover, in order to verify whether the averaging procedures hid important frequency variations, we also drew pseudospectrograms by gathering the spectra of all the events sorted in temporal order (without the averaging step; Fig. 7). No significant frequency variations were observed regarding the pseudospectrograms shown in Figs. 3, 4, and 5.

It is noteworthy that pseudospectrograms, even if differently named, have been used several times in literature to analyse groups of "discrete" seismic and acoustic signals (SACCOROTTI *et al.* 2007; MOLINA *et al.* 2008; MORAN *et al.* 2008; DI GRAZIA *et al.* 2009; ALPARONE *et al.* 2010).

#### 4.2. Location Analysis

About 3,500 events characterised by a high signal to noise ratio at at least 3 out of 4 summit stations (EBEL, ECPN, EPLC, EPDN) were selected for location analysis. The location of the infrasound source was estimated by a 2D grid searching procedure, using a 3 km  $\times$  3 km grid with spacing of 25 m covering the summit area and coinciding with the topographic surface. We assumed a point source and a speed of sound of 340 m/s in the air. The infrasound source was assumed to be in each node of the grid and for each node we first calculated the theoretical travel times at the four sensors. Then, by using these theoretical travel times, infrasound signals at the different stations were delayed and a value of semblance and brightness were calculated. Therefore, the source was finally located in the node where the delayed signals showed the largest composite semblance-brightness value (Figs. 8, 9; more details on this location technique can be found in CANNATA *et al.* 2011a).

No infrasound source locations were determined for August 2007 and the whole of 2009 because of the small number of properly working stations (only 1–2 stations).

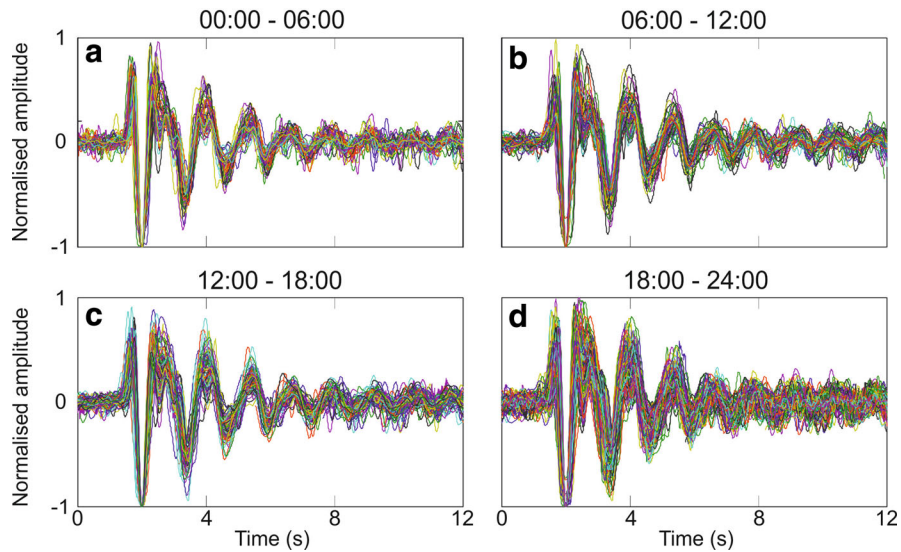


Figure 6

Superimposed traces of NEC infrasonic events recorded at the EBEL station taking place during 27 September 2008 at 00:00–06:00 (a), 06:00–12:00 (b), 12:00–18:00 (c) and 18:00–24:00 (d)

### 5. Results

Different infrasound sources can be recognised during August 2007–December 2009: the SEC, the EF and the NEC. Our long-term analyses confirmed that the first two sources were systematically active at the same time as sporadically explosive activity took place at the source vents, while the NEC source generated infrasound events almost continuously, even during non-eruptive periods, through the whole analysed time interval. In agreement with previous studies (CANNATA *et al.* 2009a, b, 2011a), frequency content of the SEC and EF events studied in this work mostly ranged from 2.5 to 5 Hz, while the NEC events had frequencies below 2.5 Hz (Fig. 9). Furthermore, it was noted how most NEC events lacked any seismic counterpart or were accompanied by very weak seismic signals. On the contrary, SEC and EF events were often associated with seismic signals related to explosive activity.

NEC events featured periods with very steady waveforms and spectral features lasting from days to months with slow or sudden variations. A clear example of steady spectral features for some-month-long period is shown in Fig. 10a, exhibiting the pseudospectrogram during July–October 2008. Some examples of the NEC event waveforms and

spectra are shown in Fig. 11 to highlight their variability as well as common characteristics. NEC event changes mostly coincided with variations in activity at the SEC or EF. One of the most evident spectral content variations of the NEC events took place during the 2008–2009 eruption at the EF. It is difficult to determine the frequency range of the NEC events preceding the beginning of the eruption on 13 May 2008 because of the fire fountain on 10 May at the SEC and the consequent modifications of the NEC events (see DI GRAZIA *et al.* 2009). After the eruption beginning at the EF, the NEC events during June 2008 were characterised by two peaks at  $\sim 1$  and 2 Hz, successively by three peaks at  $\sim 0.8$ , 1.5 and 2.2 Hz (Fig. 5), and finally the two higher peaks (1.5 and 2.2 Hz) gradually disappeared giving rise to an almost monochromatic signal (Fig. 10a). At the end of the eruption (6 July 2009) the dominant frequency was 0.8 Hz, one of the lowest frequency values observed during the studied interval. During the months following the end of the eruption the dominant frequency peak was gradually at higher frequencies (up to  $\sim 1.2$  Hz at the end of the analysed time interval) confirming that such low frequency peaks of the NEC events were somehow related to the eruption at the EF (Fig. 10b).

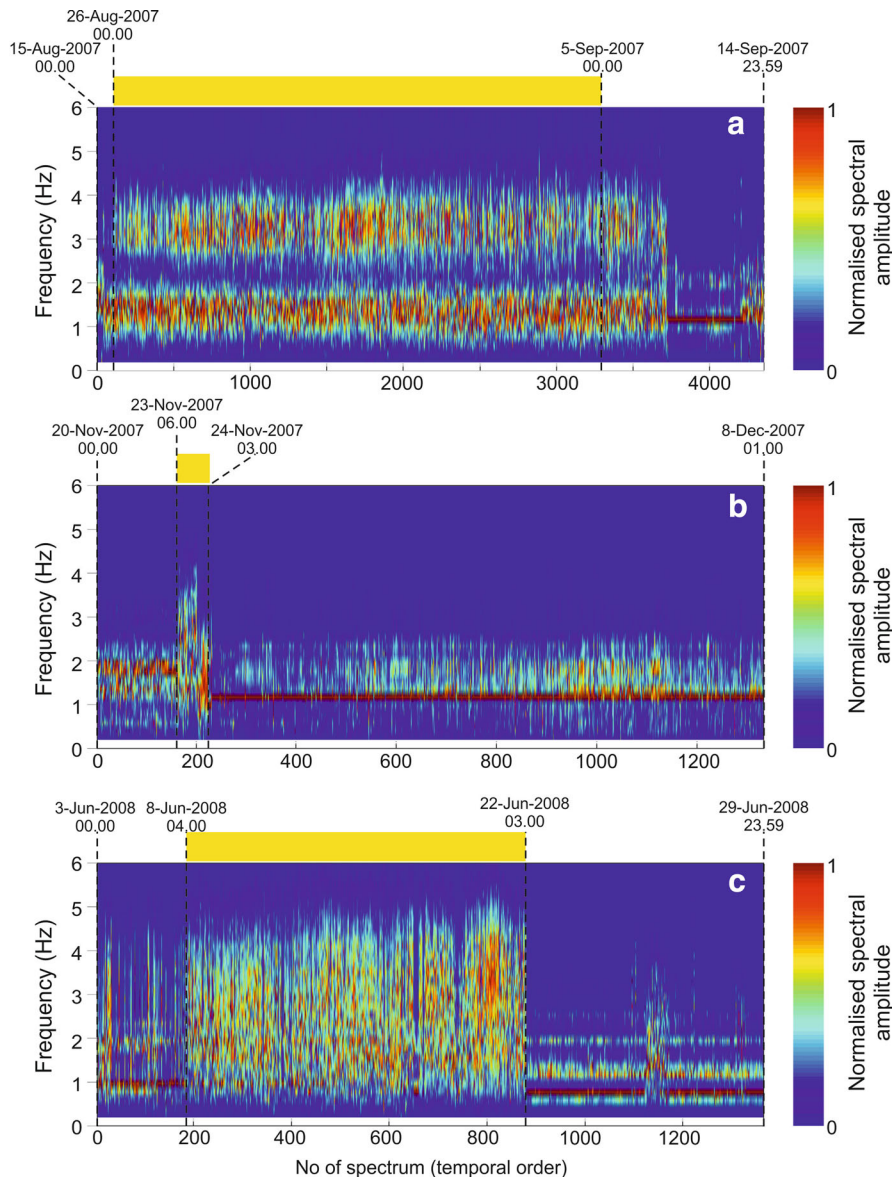


Figure 7

Pseudospectrograms gathering the spectra of the infrasound events recorded at the EBEL station during period I (a), II (b) and III (c). Unlike the pseudospectrograms in Figs. 3, 4, 5, these do not involve an averaging process and the  $x$ -axis shows the number of spectrum in place of the time. The *yellow bars* at the *top* of the plots indicate the time intervals characterised by strombolian activity and/or fire fountain at SEC (a, b) and EF (c)

The evolution in time of the spectral features of infrasound events during three short periods is shown in Figs. 3, 4 and 5: (1) 15 August–14 September 2007; (2) 20 November–8 December 2007; (3) 3–29 June 2008. The first period was characterised by explosive activity at the SEC, consisting of ash

emission and strombolian activity, culminating in a fire fountain episode on September 4–5 (Fig. 3b). In the normalised pseudospectrogram of Fig. 3e such activity is highlighted by high spectral amplitudes at frequencies above 3 Hz with the frequency content of the SEC infrasound events accompanying explosive

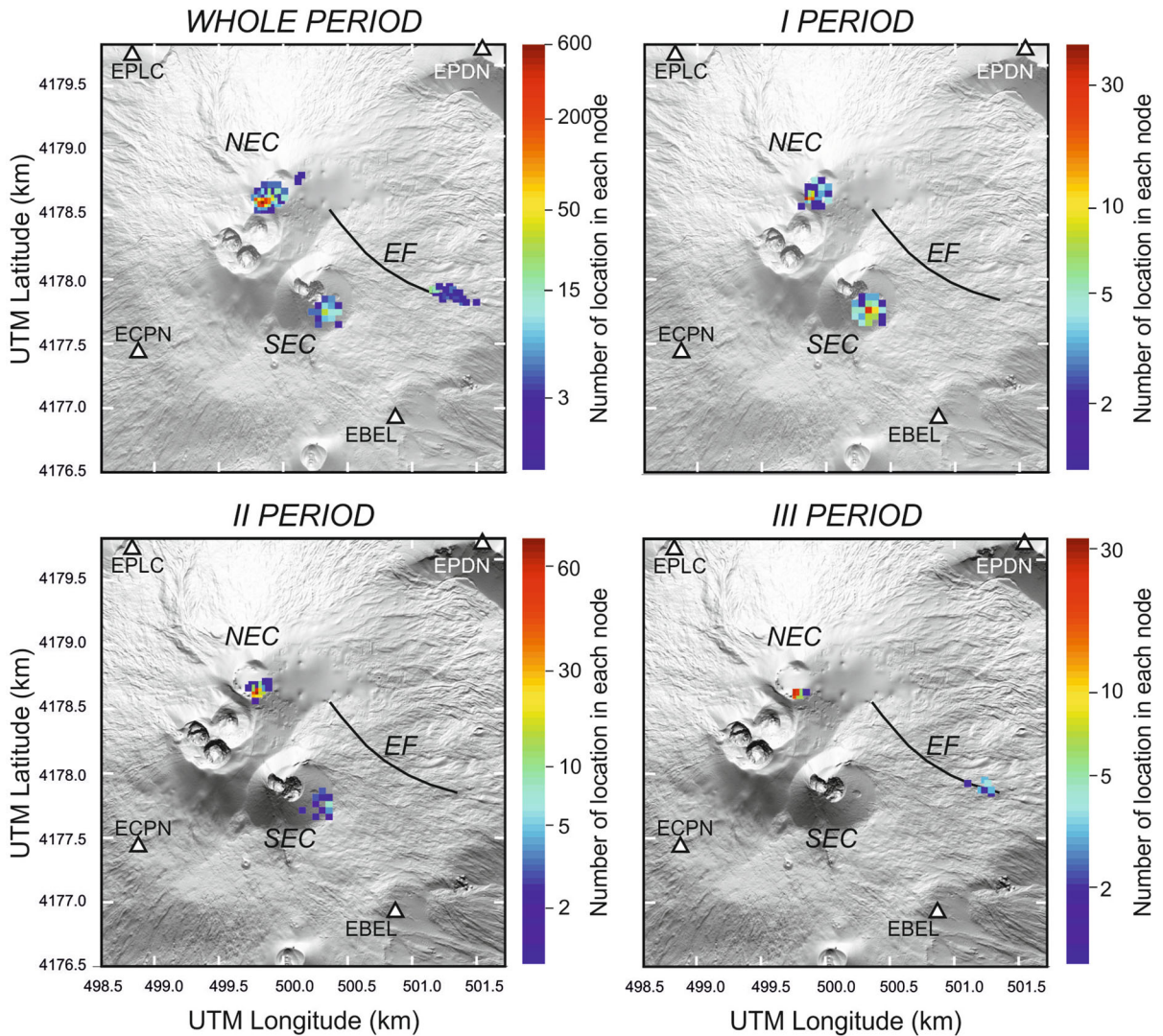


Figure 8

Digital elevation model of the Mt. Etna summit with source locations of infrasound events, indicated by *coloured rectangles*, occurring during September 2007–December 2008 (*top left panel*), and during each of the three analysed periods. Each *coloured rectangle* corresponds to a cell of the localization grid where the number of localized events within the cell is represented by a *fixed colour* (see the *colourbar* at the right side of each map). The sites of the four summit infrasound sensors are categorized using *triangles*

activity mostly ranging from 2.5 to 5 Hz (Fig. 9). The lack of detected infrasound events during the fire fountains is due to the powerful infrasound tremor accompanying this eruptive activity, preventing the distinguishing of individual events (CANNATA *et al.* 2009a). Most of the infrasound energy radiated at the NEC was in the 1.5–2.4 Hz band at mid-August (before both strombolian activity and fire fountain), whereas the events were mostly monochromatic with a frequency peak of  $\sim 1.2$  Hz after the fire fountain

(Fig. 3e), with these peaks remaining invariant throughout the end of the first period (Fig. 7a). An increase in the duration of the NEC events is clearly highlighted by the waveform examples shown in Fig. 3a. Furthermore, a slightly lower average peak-to-peak amplitude of the NEC events was observed 10 days after the fire fountain compared to the values during the few days preceding it (Fig. 3f).

The second period was characterised by a fire fountain occurring at the SEC on November 23–24

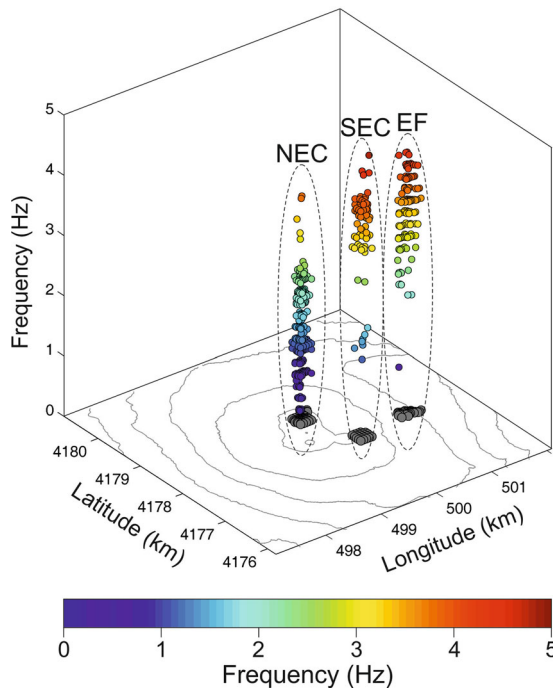


Figure 9

Relation between source/vent location and frequency content of the infrasound events. *Coloured dots* represent infrasound event locations plotted against their peak frequencies (reported in the  $z$ -axis and *colourbar*, too). *Grey dots* indicate the projection of the *coloured dots* on the  $x$ - $y$  plane

2007, which was preceded by some hours of strombolian activity (Fig. 4b). Similar to the previous period, the infrasound events radiated by the SEC during such explosive activity produced peak frequencies above 2.5 Hz. Likewise, in this case the frequency peak of the NEC events changed from  $\sim 2$  Hz to 1.0–1.2 Hz at the end of the eruptive activity (Fig. 4e). The steadiness of the spectral features of the NEC events within the pre-eruptive and the post-eruptive periods is also confirmed by the pseudospectrogram in Fig. 7b.

Finally, the third period (June 3–29, 2008) was a part of the 2008–2009 eruption starting on 13 May 2008. This period was considered meaningful from the eruptive point of view because, at that time, a renewal of explosive activity at the EF took place (Fig. 5b). In particular, intense strombolian activity took place from June 8 to June 21, 2008. The infrasound events radiated by the EF during the strombolian activity showed frequencies above

2.5 Hz (Fig. 5e). The NEC infrasound events were characterised by two sharp frequency peaks at  $\sim 1$  and 2 Hz before this activity, and by three peaks at  $\sim 0.8$ , 1.5 and 2.2 Hz after (Figs. 5e, 7c). The peak-to-peak amplitude values of the NEC events slightly decreased after strombolian activity at the EF (Fig. 5f).

It is worth noting that the replacement of the Monacor sensor with the G.R.A.S. microphone at the EBEL station in November 2009 extended our observation capability down to 0.1 Hz. A very low frequency peak ( $<0.5$  Hz; Fig. 11m, n) was systematically observed for the NEC events together with the previously observed frequency content of 0.8–2.3 Hz. Before the installation of the new sensor these low frequency values were observed only prior to the fire fountain of May 10, 2008 and on May 12–13, 2008 before the onset of the 2008–2009 eruption (DI GRAZIA *et al.* 2009; SCIOTTO *et al.* 2013). In both cases they were clearly recorded, although their frequency was not in the flat interval of the Monacor's response curve.

## 6. Discussion

The large dataset analysed in this work enables investigation of NEC events, previously studied only during short-time intervals, in a longer period. In Sect. 1 four key issues were introduced. In the following discussion we will try to solve them based on observations during August 2007–December 2009.

It was noted how NEC events featured periods with very steady waveforms and spectral features lasting from days to months (for instance July–October 2008 in Fig. 10a) with slow or sudden variations (see issue 1, Sect. 1). The steadiness of the waveforms during long periods highlights the repetitive nature of NEC infrasound events and then of their source mechanism. The most important variations of NEC event waveforms occurred after, before and during eruptive episodes at the SEC and EF; Table 1 summarizes the most important changes of the NEC event frequency, related to eruptive activity at the SEC and EF, both observed in this work and in literature. According to our observations, these NEC infrasound variations can be

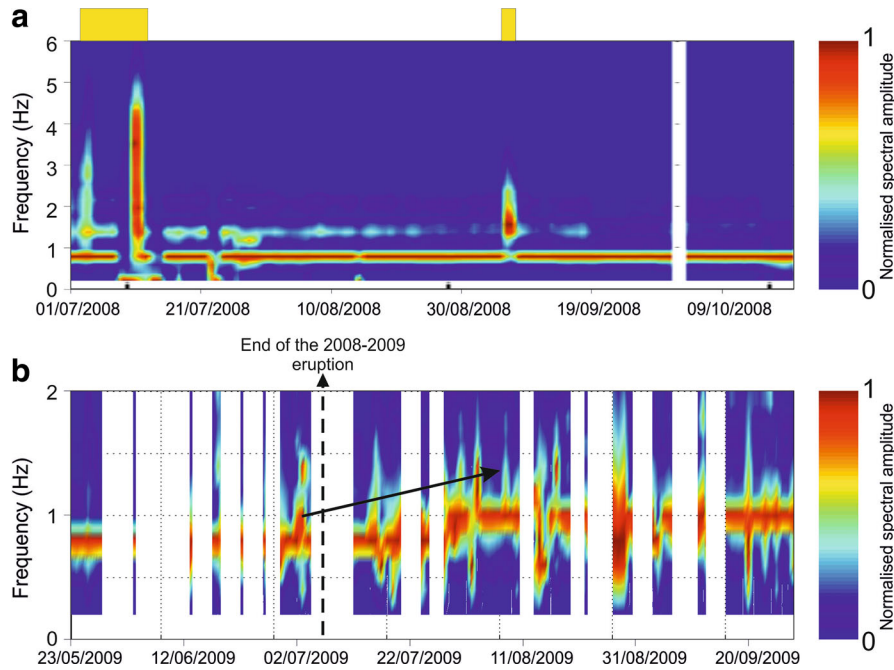


Figure 10

**a** Normalised pseudospectrogram of the infrasound events occurring at Mt. Etna during 1 July–20 October 2008 and recorded by EBEL station; **b** normalized pseudospectrogram between 23 May and 23 September 2009. Due to the long duration of the considered periods and the low occurrence rate, the pseudospectrograms averaging process was performed on 24 h windows. The *dashed vertical line* in **b** represents the end of the 2008–2009 eruption. The *black arrow* in **b** highlights the post-eruption frequency increase. Please note that *white stripes* in (**a–b**) take into account: (1) stations out of order; (2) noisy periods (due to strong wind); and, (3) lack of infrasound events. The *yellow bars* at top of the plots indicate the time intervals characterised by strombolian activity at EF. It is worth noting that spectral changes smaller than the spectral resolution ( $\sim 0.2$  Hz) cannot be detected in these plots

Table 1

*Episodes of explosive activity documented at the SEC and the EF, associated with the NEC event feature changes*

Date	Eruptive phenomena	Frequency variation	Inferred conduit length variation ( $c = 575$ m/s)	Inferred magmatic pressure variation (magma density = $700\text{--}2,700$ kg/m <sup>3</sup> )	References
16 Nov 2006	strombolian activity	1.2 → 1.0 Hz	~50 m	–0.3 to –1.3 MPa	SCIOTTO <i>et al.</i> (2011)
4–5 Sep 2007	Lava fountain	2.0 → 1.2 Hz	~100 m	–0.7 to –2.6 MPa	Present work
23–24 Nov 2007	Lava fountain	2.0 → 1.2 Hz	~100 m	–0.7 to –2.6 MPa	Present work
10 May 2008	Lava fountain	2.0 → 1.2 Hz	~100 m	–0.7 to –2.6 MPa	DI GRAZIA <i>et al.</i> (2009)
13 May 2008	2008–2009 eruption onset	0.4 → 0.7 Hz	~ –200 to –400 m	1.5 to 11.0 MPa	SCIOTTO <i>et al.</i> (2013)
8–21 June 2008	strombolian activity	1.0 → 0.8 Hz	~70 m	–0.4 to –1.9 MPa	Present work

The frequency peak variations, together with the inferred conduit length variations, the corresponding magmatic pressure variations and the references, are also indicated. The negative and positive inferred conduit length variations correspond to decreases and increases in length of the resonating portion of the column. The negative and positive inferred variations of magmatic pressure indicate a decrease and increase in pressure inside the plumbing system

considered systematic, hence answering to the second issue. In particular, we noticed a decrease in the dominant frequencies right after (or during, taking into account the whole 2008–2009 eruption) the renewal of activity at the SEC/EF, or vice-versa,

their increase right before (as before the 2008–2009 eruption onset; see SCIOTTO *et al.* 2013). Therefore, on the basis of this study it is possible to assert the connection between the NEC and the SEC/EF plumbing systems is not simply temporary, but

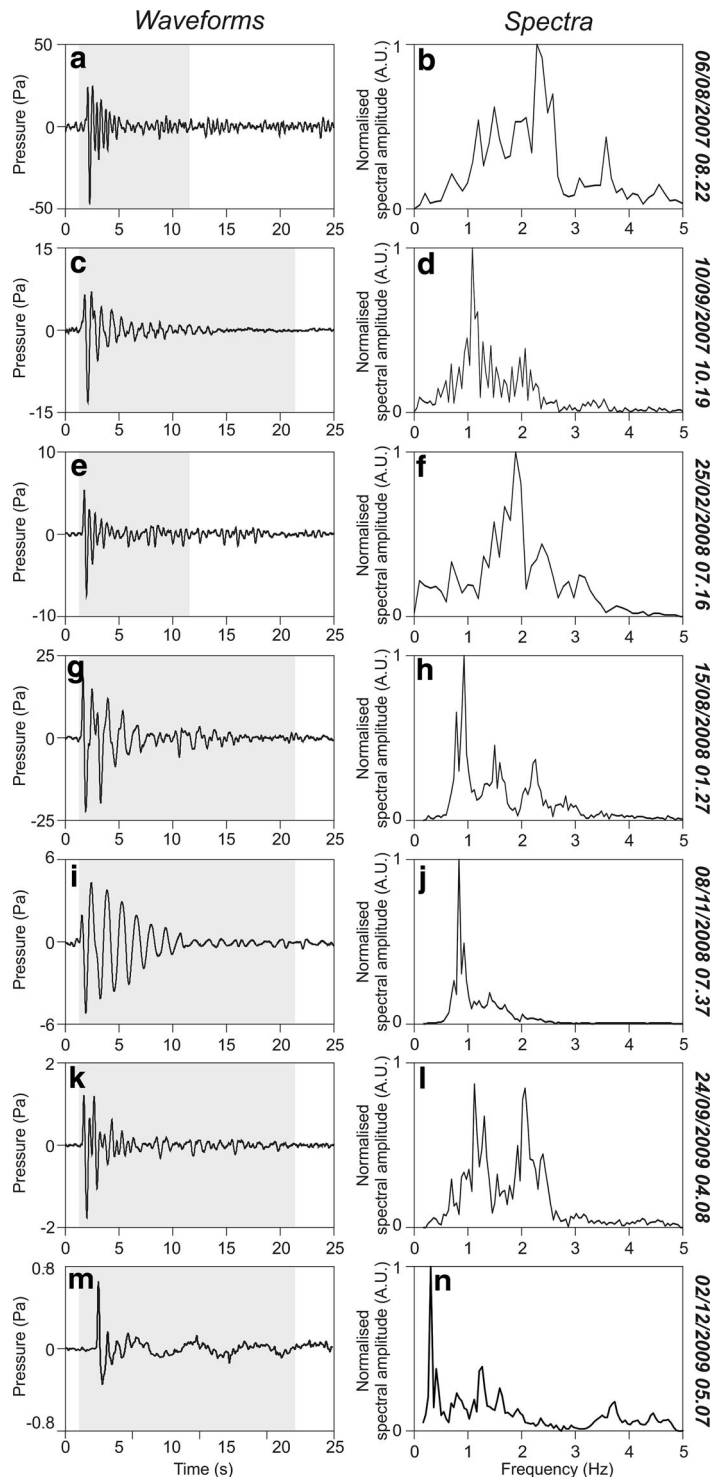


Figure 11

Infrasound events generated by the NEC and recorded by the EBEL station (the recording time is reported on the *right* of the plots) and corresponding spectra. The *grey areas* show the signal windows used to calculate the spectra. The event in **m** was recorded via broadband microphone (G.R.A.S. 40 AN). The two NEC frequency components are clearly visible; please note that the decay of the low frequency is not visible in the selected time-window because of its short duration

rather stable on a long time interval (at least 2006–2009 for the SEC–NEC connection and the entire duration of the 2008–2009 eruption for the EF–NEC connection).

In regards to the third and fourth issues, concerning the interpretation of such systematic changes, our data (enhanced by the G.R.A.S. microphone installed in November 2009) and analyses confirm the validity of the double source mechanism (SCIOTTO *et al.* 2013). On the basis of such model the spectral content variations, time-related to the eruptive activity (which in this work can be observed only in the NEC higher frequency band because of the described microphones response curve), could be related to an increase in the length of the resonator and/or decrease in the acoustic wave velocity, according to the following equation (HAGERTY *et al.* 2000):

$$f_0 = \frac{c_c}{2L} \quad (1)$$

where  $f_0$  is the fundamental frequency,  $L$  is the conduit length and  $c_c$  the fluid sound speed inside the conduit. Figure 12 displays values of the fundamental

frequency for different values of conduit length and acoustic wave velocity. Fixing the acoustic velocity at 500–600 m/s (MORRISSEY and CHOUET 2001; KUMAGAI and CHOUET 2000), a decrease in the dominant frequency leads us, via the fundamental law of pipe resonance (Eq. 1), to infer a lengthening of the resonating conduit from 125–150 m to about 200–250 m after the end of the first and second eruptive episodes. In the third episode we infer that the length of the conduit increased from 250–300 m to about 310–380 m (Table 1).

It must be noted that the fundamental frequency of resonance may change in response to both variation in acoustic wave velocity or in geometrical resonance properties of the conduit. However, we discard the hypothesis of variation in the acoustic velocity. Indeed, neglecting the frequency component <0.5 Hz, the lowest frequency values at the NEC (0.8–1.0 Hz) were reached during the eruption at the EF and increased only after it ended. In fact, maximum lengthening of the resonating conduit is reasonable during the 2008–2009 eruption, considering the

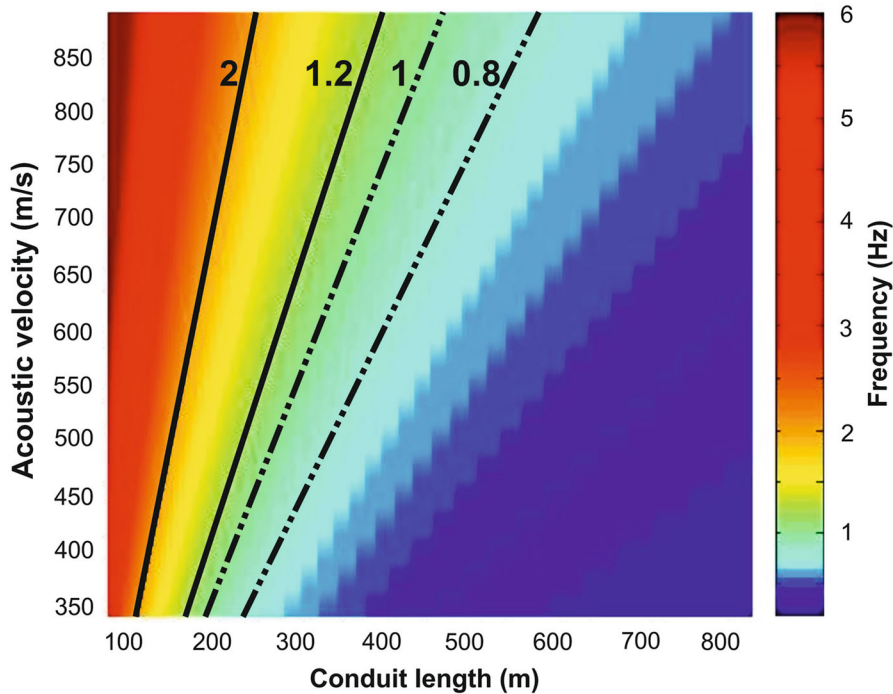


Figure 12

Fundamental frequency of the resonating conduit for variable length and acoustic velocity. The *solid black lines* represent the dominant frequencies, observed during the I–II periods, before (2 Hz) and after (1.2 Hz) eruptive activity. Likewise, the *dashed black lines* refer to the dominant frequencies observed during period III, before (1 Hz) and after (0.8 Hz) eruptive activity

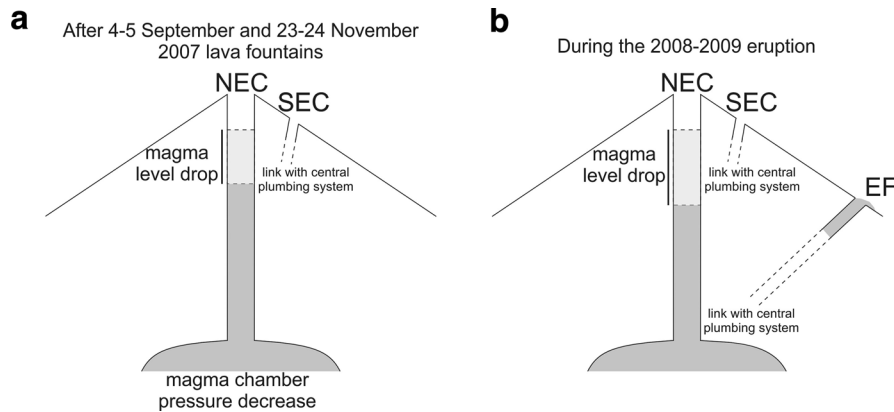


Figure 13

**a** Mt. Etna sketch section shows the drop in the magma level inside the NEC conduit due to pressure decrease in the magma chamber, taking place after the fire fountains of September 4–5 and November 23–24; **b** Mt. Etna sketch section showing the drop in the magma level inside the NEC conduit due to the effective magma drainage from the topographically low EF vents. See text for details. Note that this model is completely qualitative

effective magma drainage within the shallow plumbing system (and consequently magma surface drop) concomitant with activity of topographically low EF vents (Fig. 13b). Moreover, mismatch between stability of the dominant frequency at 0.8 Hz (lasting from the June 2008 to the end of the eruption) and the large variability of the gas plume composition during the same period, evidenced by the  $\text{CO}_2/\text{SO}_2$  ratio values reported by AIUPPA *et al.* (2010), suggests that spectral variations were likely generated by changes in geometry rather than in acoustic wave velocity. Nevertheless, we cannot rule out minor contributions by the latter or interplay between the two factors.

The inferred drop in the magma level inside the plumbing system is also reasonable after the fire fountains taking place during September 4–5 and November 23–24, 2007 (periods I and II, respectively). Further support for this inference comes from observation that the occurrence of fire fountains is generally accompanied/followed by slight deflation due to plumbing system depressurization (BONACCORSO *et al.* 2011b). If we consider a simple plumbing system composed of a magma chamber connected to a vertical open-conduit, the pressure in equilibrium conditions inside the chamber must be balanced by the magmastatic pressure of the conduit (WITHAM and LLEWELLIN 2006). Therefore, a pressure decrease in the magma chamber causes the magma to flow from the conduit back into the chamber, with a consequent

magma level drop inside the conduit (Fig. 13a). In light of such evidence the solution to the third issue is: the observations made in this work strengthen the interpretations of the NEC infrasound changes time-related to eruptive activity given in previous studies (especially SCIOTTO *et al.* 2013).

Such a geometrical interpretation has important implications concerning pressure changes over time inside the plumbing system. In fact, the fragmentation level drop was estimated roughly equal to  $\sim 70\text{--}100$  m in all three episodes considered (Figs. 3, 4, 5). Assuming a constant value of magma density inside the conduit in the  $700\text{--}2,700$   $\text{kg/m}^3$  range (gas magma foam and bubble-free magma, respectively; PINKERTON *et al.* 2002), we calculated a pressure decrease inside the plumbing system due to a drop in the magmastatic pressure of  $\sim 0.4\text{--}2.6$  MPa (Table 1), following the explosive activities at the SEC and EF. Since there are major uncertainties in this evaluation related to several assumptions the order of magnitude of such pressure variations has to be taken into account.

## 7. Concluding Remarks

We analysed  $\sim 40,000$  infrasound events continuously recorded at Mt. Etna during 2007–2009 by a permanent network and mainly generated by the

NEC. The following points summarize the main findings of this study by addressing the four questions posed in Sect. 1:

1. The NEC events featured periods with very steady waveforms and spectral features lasting from days to months, with slow or sudden variations. Steadiness of the waveforms during long periods highlights the repetitive nature of the NEC infrasound events, and, consequently, of their source mechanism.
2. Variations of the NEC event spectra taking place during the most important eruptive episodes at other vents are systematic, implying the stable and “relatively” long-lasting connection between the NEC and SEC/EF plumbing systems.
3. Observations made in this work strengthen interpretations of the NEC infrasound changes given in previous studies; according to these previous interpretations the changes are due to resonator length variations, mostly caused by magma level fluctuation inside the NEC conduit.
4. Based on our study and previous investigations we can infer that, due to the connections between the NEC and the SEC/EF feeding systems, the magma level fluctuations inside the NEC conduit correspond to magmatic pressure decrease/increase inside the main plumbing system. This finding opens up new and interesting possibilities for monitoring magma pressure changes inside the Mt. Etna plumbing system. In order to have reliable estimations we should be able to set up an experimental device able to measure sound velocity in the gas mixture. Indeed, in our hypothesis the NEC acts like a piezometer and realistic evaluation of variable free magma surface elevation is almost equivalent to estimating pressure variations inside the plumbing system, and aids in evaluating the velocity of the feeding system returning to equilibrium.

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