Advances in the study of geophysical signals from Mt. Etna volcano.

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Abstract

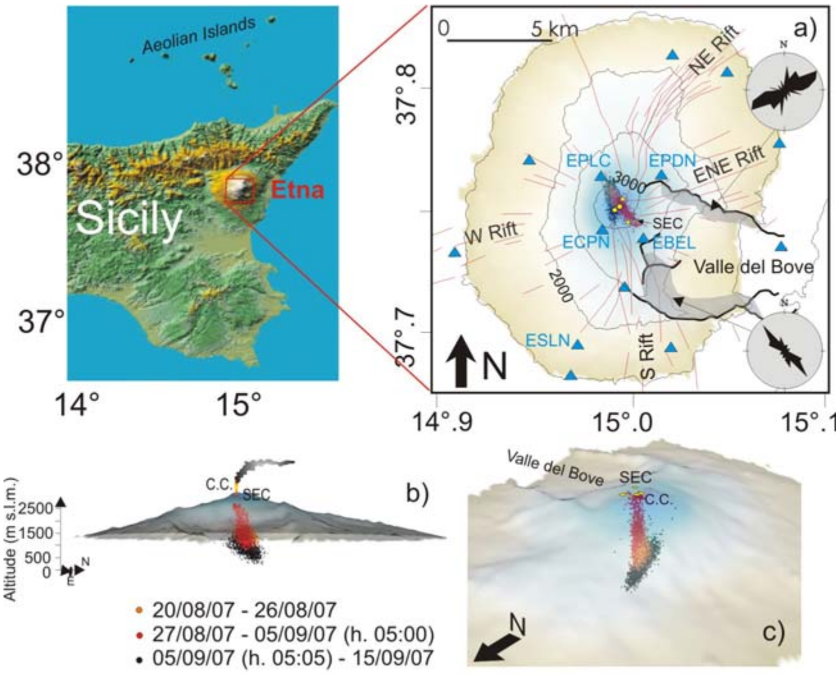
Long-period seismic signals, including LP events and tremor, observed on many volcanoes worldwide, may play a crucial role in the forecasting of volcanic eruptions as these signals are direct indicators of sub-surface magma dynamics. Their location is widely agreed to be useful for mapping the extension and geometry of the plumbing system and also for quantifying pressure transients caused by resonance or movement of fluids along the conduits. At Mt. Etna detailed investigations on these signals started systematically only after the installation of a broad-band seismic network (since 2003). Thereafter, we present the main results recently obtained on this volcano by analysing tremor, LP and VLP events during two eruptive episodes in the second half of 2007.

We also discuss results of cross analysis performed between tremor and gravity sequences acquired simultaneously at Mt. Etna during the 2002-03 eruption and during the December 2005-January 2006 period of quiescence. We detected common anomalies which are indicative of a quasi-closed system, becoming progressively enriched in volatiles.

These studies, carried out in the framework of the VOLUME Project, provide new insight into the shallow plumbing system of Etna and grant valuable tools for volcanic hazard forecasting and risk mitigation.

Introduction

At Mt. Etna, detailed investigations of low-frequency signals, including volcanic tremor, has been accomplished systematically since the installation of the broadband network (late 2003). Sustained Long-Period (LP) and Very-Long-Period (VLP) activities



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have been observed both during quiescence periods and summit eruptive phases (Saccorotti et al., 2007).

The broad-band permanent network is composed of 23 stations equipped with Nanometrics Trillium seismometers, with flat response within the 40-0.01 s period range. A total of 14 stations are installed atelevations between 1100 and 3000 m a.s.l. and distances from the summit craters between 1.5 and 9 km. A mini-array of three gravity stations has been installed since 1998. The stations (each within a few meter from a seismic broadband station) are equipped with LaCoste and Romberg spring gravimeters (Fig. 1a).

Low frequency events location is considered a useful tool to map the shallow plumbing system and to quantify pressure transients caused by movement of fluids within the conduis (Chouet, 1996). Instead, fast (minutes to hours) gravity changes are indicative of mass redistributions within the shallow plumbing system, due to changes in the physical and chemical properties of a magma body (Carbone et al., 2006)

In the frame of the VOLUME Project, we investigate volcanic tremor, LP and VLP events recorded at Mt. Etna during a 7-month period (June–December 2007), focusing our analysis on the two lava fountaining episodes which occurred on September 4-5 and on November 23-24. In particular, we studied the time evolution of the tremor and of LP-VLP activity in terms of source movement, change of the waveforms, temporal evolution of the 'dominant' resonance frequencies and the source quality factor (Q) for the LP events.

We also carried out joint gravity/tremor analysis. The common anomalies were acquired at Mt. Etna during the 2002-03 eruption and during the December 2005-January

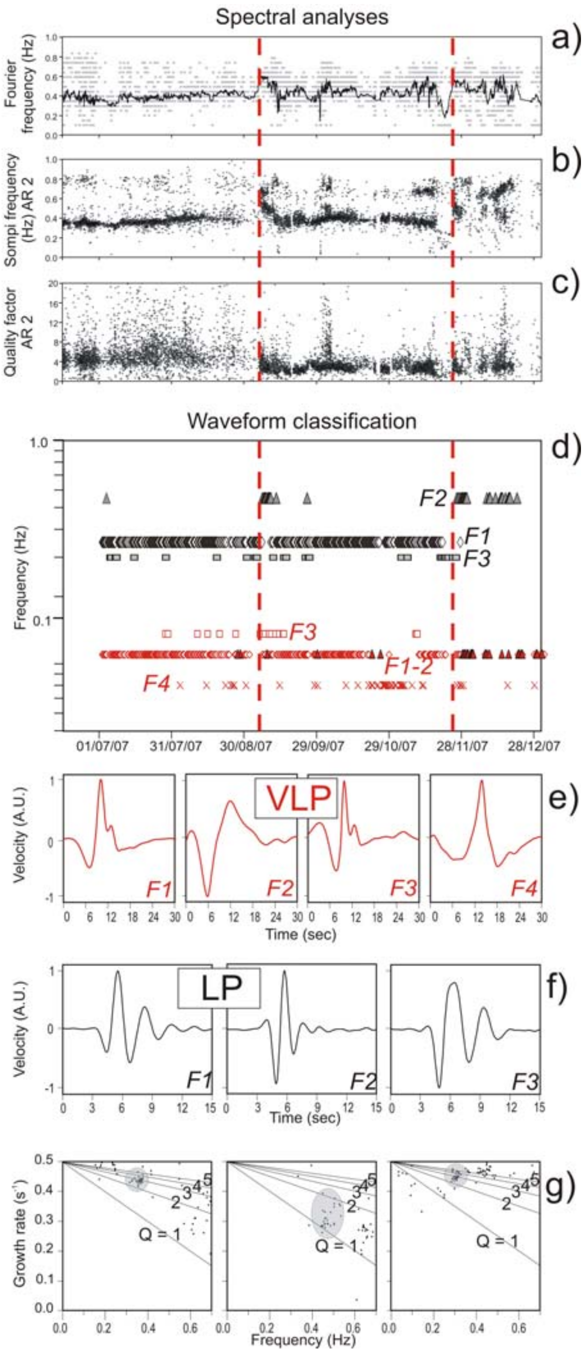


Figure 2 - ....

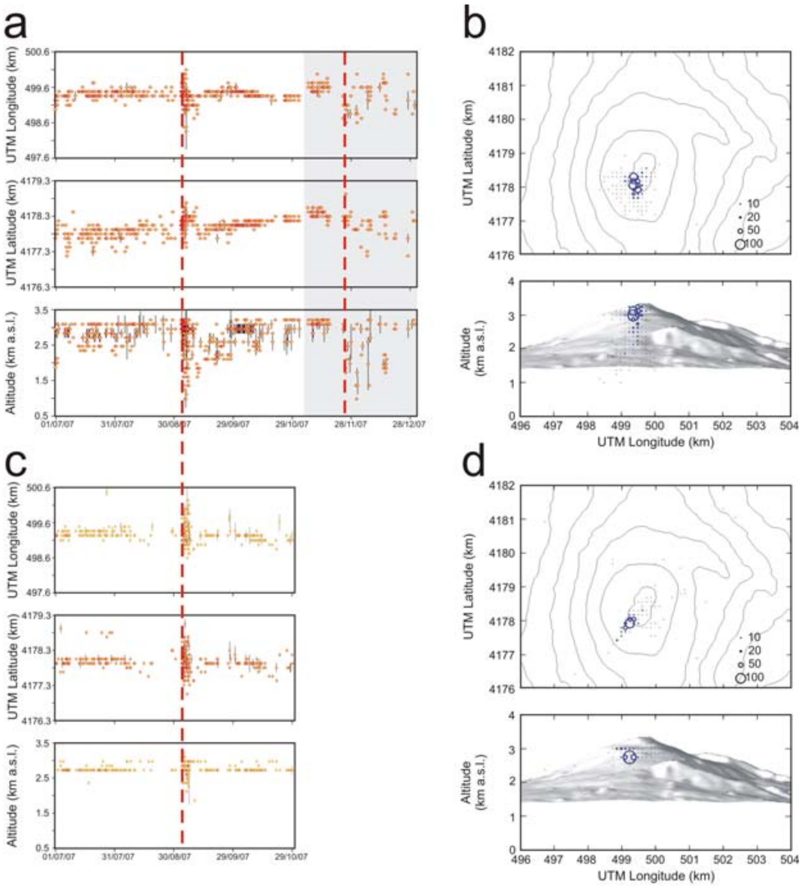
2006 period of quiescence. Such joint analyses allow to investigate the internal dynamic of a volcano and to improve the confidence of volcanic hazard assessment.

Volcanic tremor, LP and VLP events during June-December 2007

Since the frequency and damping of a resonant system is strongly influenced by the nature of liquid and gas content (Chouet, 2003), the study of the spectral evolution of seismic signals in volcanic areas provides useful information for monitoring purposes. In order to assess the time evolution of fluid-driven sources during the studied period, two different spectral analyses are performed on about 13000 LP events.

We compute the highest peak frequency for each event using the Fast Fourier Transform (FFT). Furthermore, in order to obtain information about the damping features of the LP source, we use the Sompi analysis (Kumazawa et al., 1990), based on a low order (2-10) Auto-Regressive (AR) model. Both analyses highlight spectral time variations, most of which are related to the volcanic activity. The frequency values decrease before the lava fountain episodes on September 4-5 and November 23-24 and then increase again. The decrease before the first episode is lower than the second one. The quality factor decreases from about 5 to 2-3 after the first episode of lava fountain on September 4-5 (Fig. 2c).

We recognize different LP and VLP clusters, implying the same source mechanism and location, on the basis of the waveform similarity. On the basis of such considerations we follow the Green and Neuberg's procedure (Green and Neuberg, 2006), that allows to identify gradual waveform variations. Two datasets of 980 LP and 700 VLP events, characterized by high signal to noise ratio and uniformly distributed in time, are selected. Using a correlation matrix, we obtain three main families of LP events and four families of VLP (Fig. 2f), that comprise about 90% of all the considered events, suggesting the repetitive excitation of stationary sources and a non-destructive process. The main variations of the waveforms occur at the same time as the lava fountains (Fig. 2d).



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Location of tremor, LP and VLP sources is a basic information for monitoring of volcanoes. In order to constrain the volcanic tremor source locations at Mt. Etna, we use the spatial distribution of tremor amplitudes at the network stations, assuming the propagation in a homogenous medium and a seismic amplitude decaying with the distance (Di Grazia et al., 2006; Patanè et al., 2008). Figure 1 depicts the 3D source centroids of tremor locations computed for the period between August 20 and September 15 in the frequency range 0.5-5.0 Hz. These locations reveal, for the first time, the geometry of the shallow central feeding system. The imaged conduit consists of two connected resonating dike-like bodies, extending from sea level to the surface. The deeper dike is located below 1 km a.s.l., striking in the NNW-SSE direction and crossing the central craters (black dots in Fig. 1 a-c), while the shallower one is rotated in the NW-SE direction toward the South-East crater (orange and red dots in Fig. 1a-c).

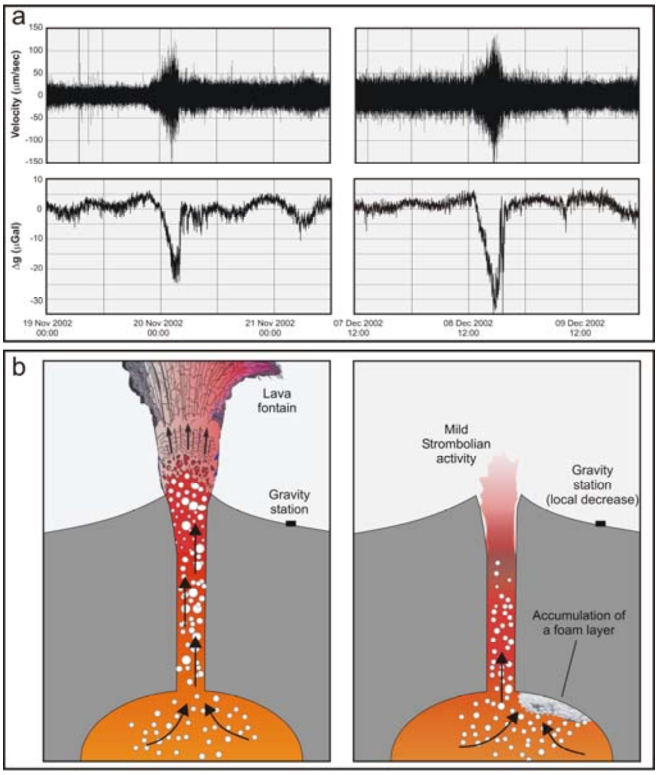
LP locations during the investigated period are retrieved through the semblance technique (Patanè et al., 2008). The results, summarized in Fig. 3a,b are suggestive of a shallow LP source located below the summit craters. The LP source shows striking time variations and a deepening from 3 to 1 km a.s.l., after the two lava fountain episodes. In addition, the LP source gradually shifts northward from September to November.

About 400 VLP events, occurring between July and October 2007, are located by the radial semblance method (Kawakatsu et al. 2000). The VLP locations, shown in Fig. 3c,d are also suggestive of shallow VLP sources located below the summit area. Unlike the LP ones, the VLP locations (Fig. 3c,d) remain steady for the whole period. A slight deepening can be observed after the lava fountain episode occurring on September 4-5.

Joint seismological-gravity studies at Mt. Etna volcano.

Integrating a wide range of geophysical and geochemical techniques to examine a complex volcano such as Etna can be very challenging since the same source process can simultaneously generate distinct physical processes, in turn producing different detectable signals.

The cross-analysis of volcanic tremor and other geophysical and geochemical observables might provide an important volcano monitoring and prediction tool. In particular, cross analysis performed between tremor and gravity sequences acquired simultaneously at Mt. Etna allowed to discover common



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anomalies on two occasions: during the 2002-03 eruption and during the December 2005-January 2006 period of quiescence.

During the course of the 2002-03 eruption, marked increases of the tremor amplitude (up to a factor of 4) occurred simultaneously with gravity decreases (10-30 microGal) observed at the only station working during that period (Fig. 4a). The concurrent gravity/tremor anomalies last 6 to 12 hours and terminate with rapid (up to 2 hours) changes, after which the signals return back to their original levels. Based on volcanological observations, encompassing the simultaneous anomalies, we infer that the accumulation of a gas cloud at some level in the conduit plexus feeding the active eruptive vent could have acted as a joint source (Carbone et al, 2006; Fig. 4b).

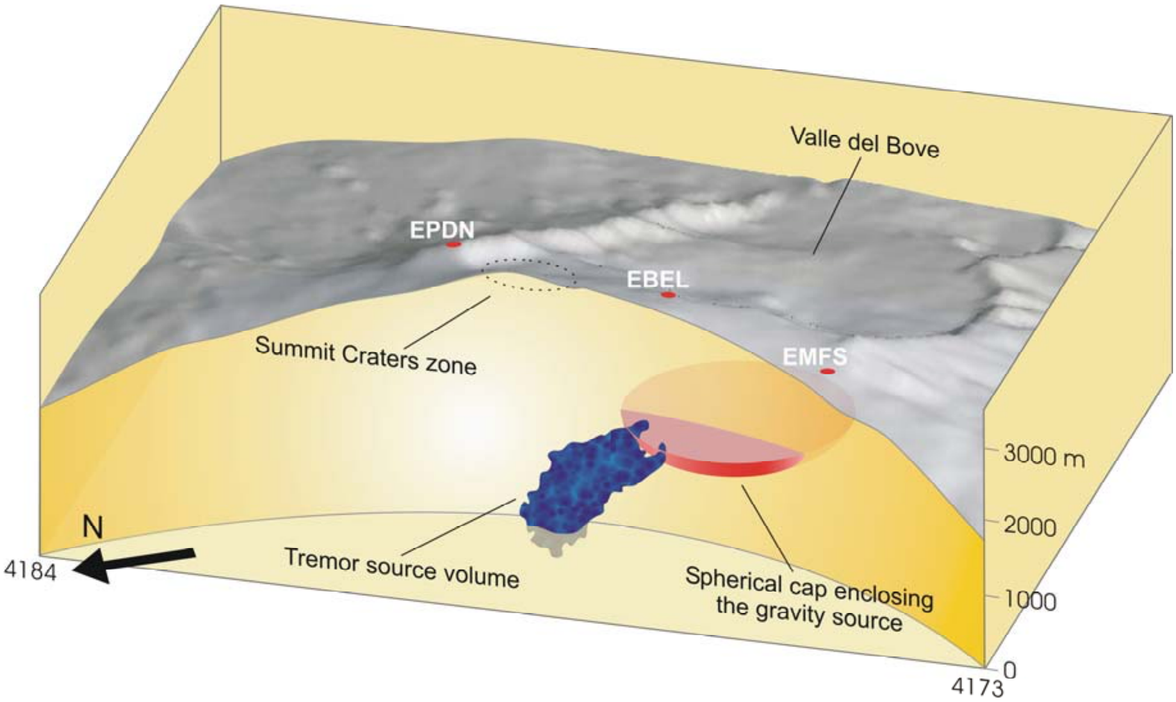

Figure. 5 - ....

During the December 2005-January 2006 non-eruptive period, the tremor amplitude at Etna markedly increased and negatively correlated with the gravity signal from one of the two summit stations, over 2- to 3-hour fluctuations. No correlation was found with the signal from the other gravity station. In this case, relying on the relative position of the two gravity stations, we can define the volume within which the gravity source must lie. During the period of marked anti-correlation, the tremor source, located by inverting the spatial distribution of seismic amplitudes, intersects this volume in a region located 1000 m S-SE of the summit craters and about 2000 m beneath the surface (Fig. 5). This finding suggests that the anti-correlation marks the activation of a joint source process, possibly related to the arrival of fresh, gas-rich magma and the consequent gas separation (Carbone et al., 2008).

Both the 2002-03 and the 2005-06 anti-correlated tremor/gravity anomalies are indicative of a quasi-closed system, becoming progressively enriched in volatiles. This occurrence may evolve to local accumulations of gas pockets, which in turn may climax with energetic, potentially dangerous paroxysms. Therefore, the ability to detect such accumulation processes is critical to any early identification of energetic eruptive episodes. In particular, during the 2005-06 period, sustained gas segregation did not lead to volcanic activity and thus it could be detected only on the grounds of the analysis of the available geophysical data. The above observations imply that joint seismological-gravity studies have the ability to detect “hidden” states of unrest at active volcanoes and thus are of considerable potential value for volcano monitoring.

Concluding remarks

We present results of (i) the analysis of tremor, LP and VLP events observed at Mt. Etna during June-December 2007, when two lava fountaining episodes occurred and (ii) the joint analysis of tremor and gravity data acquired during the 2002-03 eruption and the 2005-06 quiescent period. Through the analysis of the low-frequency seismic signals new insights are gained on the geometry of the shallow plumbing system feeding the lava fountaining activity . Moreover, quantitative hints are retrieved about the mechanisms preceding and accompanying paroxysmal volcanic events. The latter are especially important from the standpoint of risk assessment.

The cross-analysis of gravity and volcanic tremor allow to follow the evolution of gas accumulations within the plumbing system, and thus to discover states of unrest of the volcano, even when it does not display anomalous activity.

The cases of study presented here confirm the potential of the above analyses as tools to track the temporal evolution of volcanic sources and the ascent of gas-rich magma batches which could produce violent paroxysms.

Captions

Fig. 1 - (a) Map of the summit part of Mt. Etna volcano showing 3D source centroids of volcanic tremor locations, computed between August 20 and September 15, 2007. In the map, (i) historical eruptive fissures (red lines), (ii) time evolution of tremor locations (orange, red and black circles) and (iii) broad-band seismic stations (light blue triangles), are reported. EBEL, EPDN and ESLN are also gravity stations. Yellow dots indicate central craters (C.C.). The rose diagrams show the dyke structures directions as appearing at the surface through erosion processes in the southern and northern walls of Valle del Bove. (b, c) 3D images of the volcanic edifice reporting volcanic tremor locations.

Fig. 2 - (a) Peak frequency at the vertical component of ECPN station calculated by FFT (black line indicates the moving average over 25 samples). (b) Peak frequency and (c) quality factor at the vertical component of ECPN station obtained by Sompi method. d) Time distribution of the LP [Family 1 (black diamonds), 2 (black triangles) and 3 (black squares)] and VLP [Family 1 (red diamonds), 2 (red triangles), 3 (red squares) and 4 (red crosses)] events as a function of their average frequency content. (e, f) Average waveforms of the four VLP families and of the three LP families. (g) f-g diagrams of the average waveforms shown in (f). The black lines represent values of constant quality factor (Q). Clusters of points (encircled with grey ellipses) indicate a resolved dominant mode, scattered points represent noise. The red dashed lines in (a-d) indicate the occurrence of two lava fountain episodes.

Fig. 3 - (a,c) Time variation of the source location of about 900 LP and 400 VLP events, occurring between 1 July and 31 December 2007 and between 1 July and 31 October 2007, respectively. (b,d) Maps and vertical cross sections of summit area with the source locations of LP (b) and VLP (d) events (blue dots). The radii of the dots are roportional to the number of the locations.

Fig. 4 - During the course of the 2002-03 Etna eruption, gravity decreases, lasting a few hours, were observed simultaneously with increases in the amplitude of the volcanic tremor (a). The joint tremor/gravity anomalies took place during temporary switches from vigorous lava fountains to mild Strombolian activity (b). Carbone et al. (2006) interpreted these anomalies as due to accumulations of foam layers during periods when the gas flux along the upper part of the discharge system was inhibited.

Fig. 5 - 3-D view of Etna’s interior with location of the tremor source (blue surface) during the December 2005-January 2006 non-eruptive period. The red spherical cap bounds locations of possible sphere shaped gravity sources during the same period and was defined by the ratio between the gravity amplitudes observed at EBEL and EPDN stations (modified from Carbone et al., 2008).

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