The use of seismic arrays to study the seismo-volcanic source. The example of Mt Etna and Stromboli Volcano

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Abstract

The properties of volcanic tremor wavefields at Mt Etna Volcano, Italy, are investigated using data from two dense, small aperture arrays of short-period seismometers deployed on the North and South flank of the volcano. Spectral analysis shows that most of the seismic energy is associated with several, narrow spectral peaks spanning the 1–5 Hz frequency band. Analysis of simultaneous recordings indicates that most of these peaks are common to different sites, thus suggesting a source effect as the origin of this energy. Frequency-slowness analyses show a complex wavefield, where body- and surface-waves alternatively dominate depending on the frequency band and the component of motion taken into account. Using a probabilistic approach, we invert slowness data measured at two dense arrays for retrieving source location and extent. The joint inversion of slowness data from the two arrays points to different source locations. This observation is interpreted in terms of ray bending associated with lateral heterogeneity and/or strong topographic effects on wave propagation. Once the propagation effects are taken into account, the most probable source location is a shallow region encompassing the summit craters and the eruptive fissures active at the time of the experiment. Data from two dense arrays of short-period seismometers are used to retrieve source locations of the explosion quakes at Stromboli volcano. Slowness vectors estimated at both arrays with the zero-lag cross-correlation technique constitute the experimental data set. A probabilistic approach based on a grid search spanning the volcano interior is used to calculate the probability of the source location. Results show a shallow source, located beneath the crater area, at depths not greater than 500 m below the surface.

Introduction

Volcanic tremor is one of the most difficult signals to interpret for seismologists. The lack of clear body-wave phase arrivals, and the rapid loss of signal coherence with increasing station spacing, makes it impossible to retrieve source location by means of the hypocenter determination techniques adopted in classical seismology. Moreover, the complexity and heterogeneity of volcanic structures affect volcanic seismic signals to a large extent, thus making the separation of source, path or recording site a challenging effort. Notwithstanding these obstacles, the widely acknowledged links among tremor and eruptive dynamics has prompted several efforts to quantitatively assess tremor source and its associated elastic wavefield (e.g. Almendros et al., 1997, 2000, 2007; Chouet., 2003; Ibáñez et al., 2000).

Volcanic tremor source at Etna volcano

Data used in this study were recorded during a large-scale seismic experiment jointly conducted by Italian and Spanish research groups. The experiment consisted of the deployment of two dense, small-aperture (300 m) semicircular antennas, and a linear profile of length 600 m. The first semicircular array was located in close proximity to the Pizzi Deneri volcanological observatory, and the second close to the Cisternazza lateral pit crater (see figure 1) in Torre del Filosofo area. The duration of the experiment was of 2 weeks.

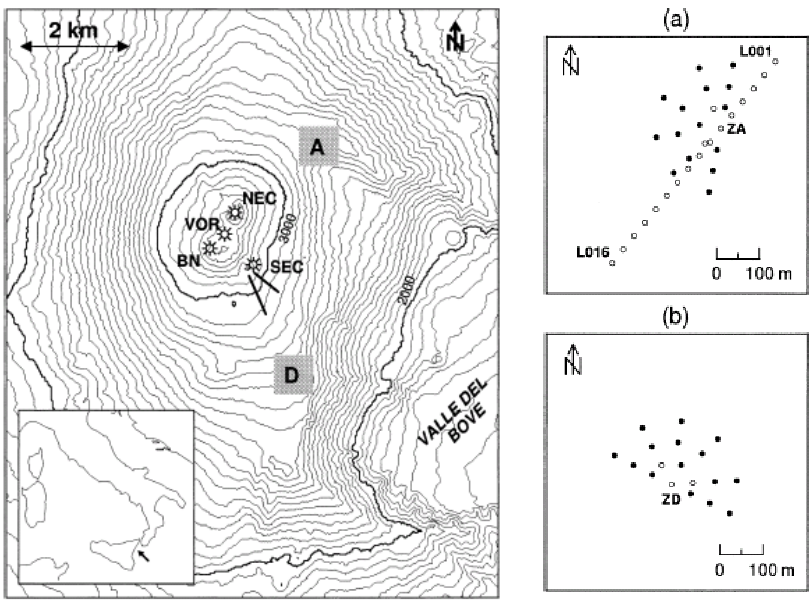

Figure 1. Left figure. Map of the summit Etna Volcano showing location of the A and D sites (gray-shaded boxes) where dense arrays were deployed . Spoked circles mark the summit craters (BN: Bocca Nuova; VOR: Voragine; SEC: South-East Crater; NEC: North-East Crater). The two bold lines south of the South-East Crater indicate the eruptive fissures active at the time of the experiment. The inset shows the position of

Etna with respect to Sicily and Italian peninsula. Right figures. (a) Map of the semicircular A array and linear profile L deployed in proximity of the Pizzi De Neri volcanological observatory. Filled and empty circles mark vertical and three-component stations, respectively. (b) The same as in (a), but for array D.

These arrays are referred hereinafter as deployments A and D, respectively. Linear array L was located in close proximity to site A, and oriented radially with respect to the summit craters. Arrays A and D consisted of 15 vertical-component and three 3-component receivers deployed in a semicircular spoke pattern, with a station spacing of 50 m along the spokes and angular spacing of 30º or 60º between spokes. These arrays were equipped with MARK Products, L4C-1 Hz sensors connected via cable to three 8-channel data loggers. The electronic characteristics of this equipment are described in Saccorotti et al. (2004). The linear array consisted of 16 3-component 4.5 Hz sensors, electronically extended to 1 Hz, deployed along a line trending approximately N45°E, with a station spacing of 40 m. Each seismometer was connected via cable to a Lennartz MARS LITE data logger with a dynamic range of 20 bits, storing data over Magneto-Optical disks at a sampling rate of 125 samples/s/channel. Timing at each data logger was provided by synchronization to the GPS time code. For our analysis, we selected a 13-h-long interval of tremor

Recorded tremor signal is characterized by a sustained ground vibration with characteristic frequencies spanning the 1–5 Hz frequency band, and a different distribution of dominant spectral peaks depending on the component of motion taken into account. This background signal is superimposed by frequent bursts of energy, characterized by wider frequency content. Correlation analyses for seismograms filtered over subsequent, narrow frequency bands demonstrated that significant wave coherency throughout the different array elements was maintained up to frequencies of about 3 Hz.

The results obtained from frequency-slowness analysis of tremor data at Mt Etna indicates a complex wavefield composed of a mix of body and surface waves, whose propagation and polarization parameters are severely affected by path effects. Inversion of slowness data for source location shows at least two sources (Saccorotti et al, 2004).

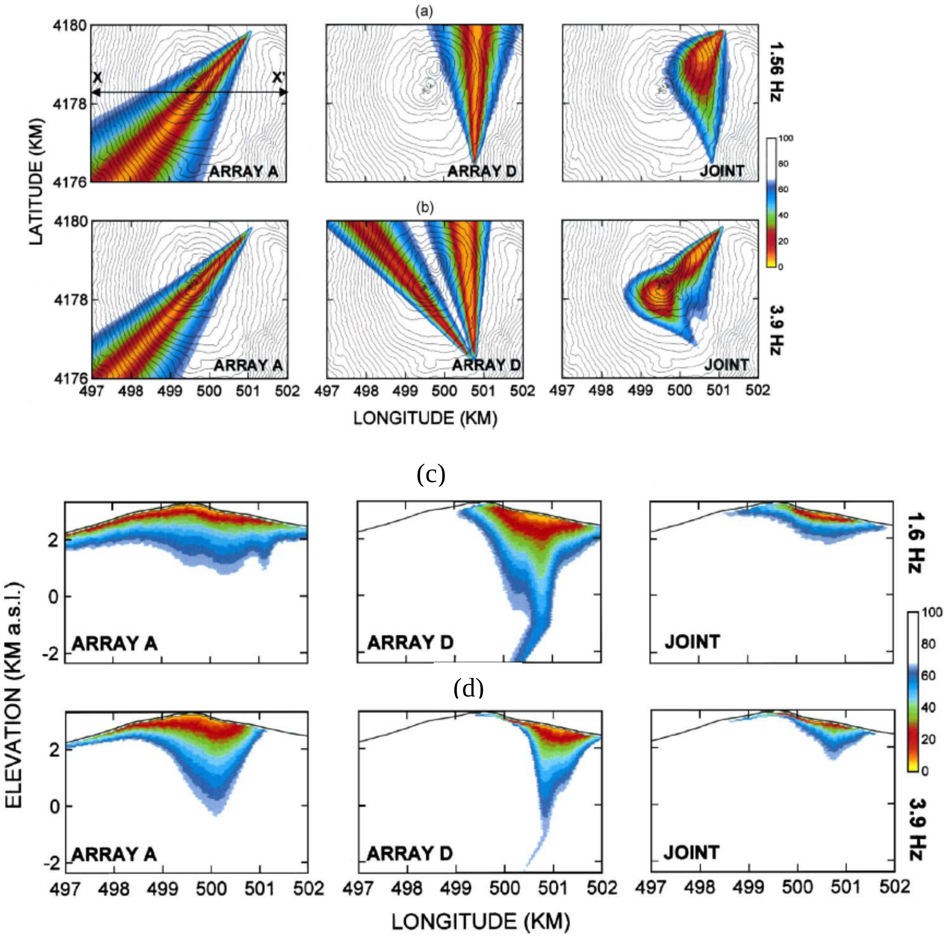

Figure 2 Top two rows: Azimuthal wedges and corresponding joint probabilities defining the source regions compatible with slowness measurements at arrays A and D for the sample frequencies of 1.6 Hz (a) and 3.9 Hz (b). X-X’ marks the trace of the vertical section displayed in the bottom section. Colours bound the different confidence regions for source location, according to the scale shown at the right. Bottom two rows: EW vertical section of the summit of Mount Etna passing through the craters depicting the confidence regions obtained from projection of the slowness vectors measured at A and D arrays at the sample frequencies of 1.6 Hz (c) and 3.9 Hz (d).

The first source is observed over the whole-investigated frequency interval, and radiates both body and surface waves. The two arrays image this source at different back-azimuths (see figure 2), which represents one of the most puzzling observations derived from our study. A working hypothesis for interpreting these results involves the influence of topography and/or medium heterogeneity on wave propagation. Considering that array D offered the sharper image of the source, we could assume that tremor originates from a volume located at shallow depth east of the SE crater, and extending down a few hundred meters below the topography. This location, figure 2, would coincide with the vent systems, where vigorous degassing and mild Strombolian activity was concentrated at different times during the 1999 eruption. Elastic waves radiated from this source could follow a non-straight path as they propagate to array A. As the seismic beams are distorted and defocused as they interact with the concave topography of the summit cone and with the sharp topographic discontinuity bordering the NW edge of the Valle del Bove. Testing this hypothesis would require a simulation of wave propagation in 3D heterogeneous media including Mt Etna topography.

The second source is associated with higher frequency (3–4 Hz) surface waves. For this source, back-azimuths estimated at the two arrays point to a region compatible with the Bocca Nuova crater (figure 2). This second source could be associated with the vigorous magma degassing occurring at the summit craters during our measurements (Saccorotti et al., 2004). Interestingly, no back-azimuth anomaly are observed for this source, confirming the idea that the main complication in wave propagation occurs in the case of body waves impinging the complex topography of the E–NE sector of the summit cone. The results gained in this work thus confirm the complexity of tremor wavefields at Mt Etna, in turn suggesting the need of further studies to better elucidate the spatial setting and dynamic processes of the tremor sources acting during either quiescent or eruptive periods. The propagation of elastic waves through the complex volcanic terrain is severely affected by complications associated with the medium heterogeneity and the rough topography, as already observed in some recent studies (e.g. Almendros et al., 2001a, b, 2002; Saccorotti et al 2001a, b).

Source location of explosion-quakes at Stromboli volcano

Two small-aperture, short period seismic arrays were installed on the North and West flanks of Stromboli Island, at Labronzo and Ginostra sites respectively. Ginostra array included 15 vertical-component and three 3-component Mark Products L4C seismometers, which have a natural frequency of 1 Hz. Labronzo array included 26 vertical-component and two 3-component Mark Products L15B seismometers with a natural frequency of 4.5 Hz (see figure 3). The electronic characteristics are described in La Rocca et al. (2004). In this work we use a set of 32 explosion quakes recorded at all the data loggers for both arrays.

The explosive signals observed at frequencies greater than 0.5 Hz have emergent onset and are spindle-shaped, with a duration which rarely exceeds 1 min. The first 2-3 s of the signal are dominated by frequencies between 0.5 and 2 Hz, while the successive phases show a broader frequency content.

Our approach for determining source location is essentially probabilistic, in the sense that we searched for the points of a gridded model space for which the misfit among the observed and predicted slownesses are minimized. The method describes the probability for source location as the difference between the measured and theoretical slowness vector. The compound probability is weighted for the array-averaged correlation coefficient. The grid search approach allows a complete mapping of the error function over the whole volume investigated, thus permitting the detection of either the principal or secondary maxima of the probability pattern.

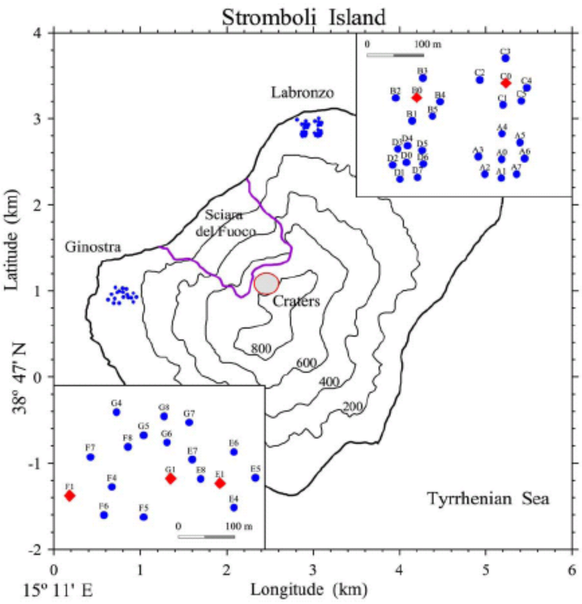

Figure 3 Topography of Stromboli Island showing the position of the two arrays and the crater area. The two insets show the details of array configurations, in which full circles and diamonds indicate vertical-component and three-component stations, respectively. The bold line bounds the sector graben named Sciara del Fuoco.

The multiple array source location technique applied in the present work is well suited to transient signals with emergent first arrivals, like the explosion quakes recorded at Stromboli at a distance of approximately 1.7 km from the source. The main problems in its application were twofold: The first is the complete ignorance of the velocity model at depths greater than 300 m below the surface. The second is related to the presence of well correlated noise added to the explosion quake signal (the volcanic tremor), which produces uncertainty in signal synchronization at the two arrays. The problems related to the ignorance of the velocity models were partially solved generating a suite of reasonable models on the basis of what has been observed on other volcanoes. The problems related to the presence of the volcanic tremor were overcome using considerations based on the results of the array analysis applied to the pre-event signal. We used the changes in the pattern of correlation coefficient as a function of time to pick the event onset at both arrays, and were able to identify the beginning of the events utilized for source location.

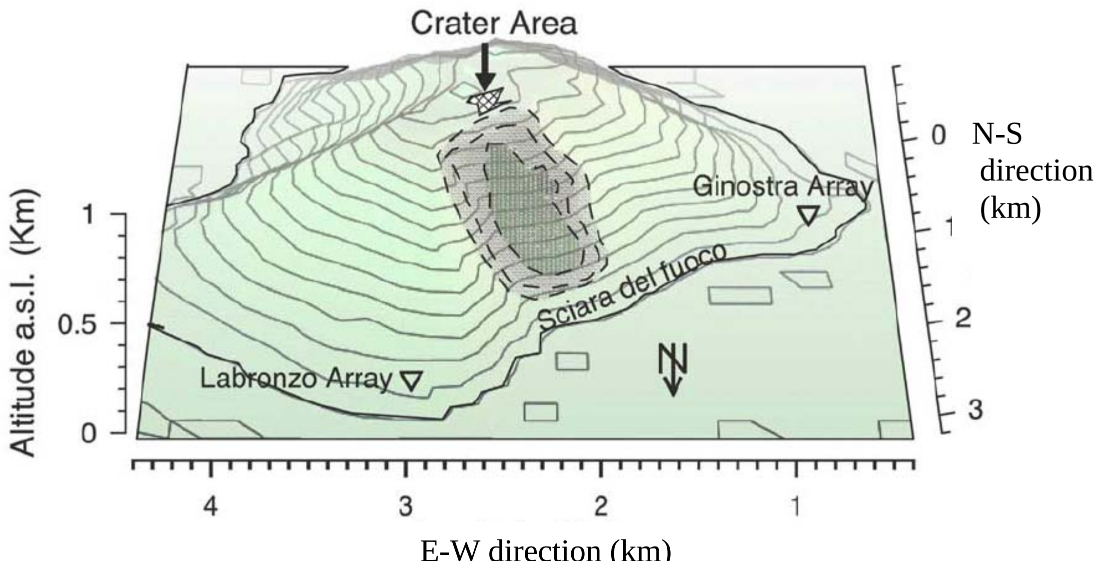

Figure 4 Map of Stromboli Island (view from the north), with the representation of the source located using 0.5-1.5 Hz results. The array positions and crater area are also indicated.

Despite the above-mentioned limitations, the method gives results characterized by high resolution and by a reasonably short computing time. From the different velocity models used, we selected a medium velocity model (La Rocca et al., 2004) since it has the highest maximum value of the probability function for each individual event. In contrast, models with higher velocity values have a large number of solutions located at the free surface and have low probability values. Results indicate that the volume containing the source of the explosion quakes at Stromboli volcano is located beneath the crater area, and extends to depths not greater than 700 m below the surface (see figure 4). The horizontal extension, estimated at 80% probability, is between 0.5 and 1 km. It is also noteworthy that locations obtained at 1 and 2 Hz are different. The multiple solutions we obtained at frequency 2 Hz may be attributed to the process of magma ejection at the free surface, or to the action of near-source scatterers. These two latter hypotheses are not alternative, and both of them may concur in producing the complex pattern.

Acknowledgements

This study was in part financed by the following research projects: VOLUME, UE, FP6-2004-Global-3-018471, SISVOLTEDEC CGL2005-05789-C03-02/ANT and HISS CGL2008-01660.

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