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Location of the Source and Shallow Velocity Model Deduced from the Explosion Quakes Recorded by Two Seismic Antennas at Stromboli Volcano

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Abstract. The seismic wavefield associated to the ongoing eruptive activity at Stromboli volcano (Italy) is investigated using data from two small-aperture, short-period seismic arrays deployed on the northern and western flanks, located at about 1.7 km from the active craters. Two distinct approaches are used to analyze the recorded signals:
1) the zero-lag cross-correlation method is used to analyze the explosion quakes data, to estimate slowness and backazimuth as a function of lapse time;
2) multiple filter technique and phase matched filtering are used to estimate Rayleigh wave dispersion, to obtain a shallow velocity model of the two sites.

Estimates of slowness vectors at the two different array sites show a primary (volcanic) source located at shallow depth beneath the crater region. Secondary sources associated with path effects are located in close proximity of the sector graben of Sciara del Fuoco and of the old parasitic cone of Timpone del Fuoco. The shallow velocity structure derived for the western flank depicts striking resemblance with that previously inferred for the northern flank of the volcano.

1 Introduction

Stromboli volcano shows a typical activity characterized by mild explosions during which jets of gases laden with molten lava fragments burst in short eruptions at a typical rate of 5-10 events per hour. Explosions take place in an approximately 350-m-long by 150-m-wide crater terrace, located at an altitude of about 800 m above the sea level. Seismic activity at Stromboli is characterized by spindle-shaped signals associated with summit explosions, superimposed on a background of sustained tremor.

Many efforts have been devoted over the past 20 years to characterize the physical properties of the explosive source from the observed signals (Del Pezzo et al. 1974; Dietel et al., 1994; Chouet et al.1997). In this context the main goal is to constrain location and spatial extent of the primary and secondary sources of seismic energy. To achieve this result, a large-scale seismic experiment has been carried out during September 1997, when two dense small aperture seismic arrays were deployed near the northern and western shores of the island (Fig. 1, Del Pezzo et al, 1998). The first aim of this experiment was the explosion quakes source location. To obtain the best source location the two arrays should be deployed at an angle of 90 degrees with the source. Our sites choice was determined by the best compromise with the complex topography of the island, resulting in a 110 degrees angle with the source area. This array geometry allows to obtain contemporary estimates of slowness vector at different source-to-receiver azimuths, in order to constrain location and extent of the source of the primary phases as well as to individuate the source(s) of the secondary phases. Chouet et al. (1997) in fact suggest that the sector graben of the Sciara del Fuoco is a scatterer producing secondary phases.

The second aim of the experiment was to infer a velocity model of the shallow portion of Timpone del Fuoco where one of the two arrays was deployed.

In the following sections we first describe the arrays setup and data collection procedures, and after we show the results obtained from analysis of array data using the zero-lag cross-correlation technique (Del Pezzo et al., 1997). Finally, we apply a technique developed by Herrmann (1987) to infer the shallow velocity structures beneath the two sites using Rayleigh wave dispersion data.

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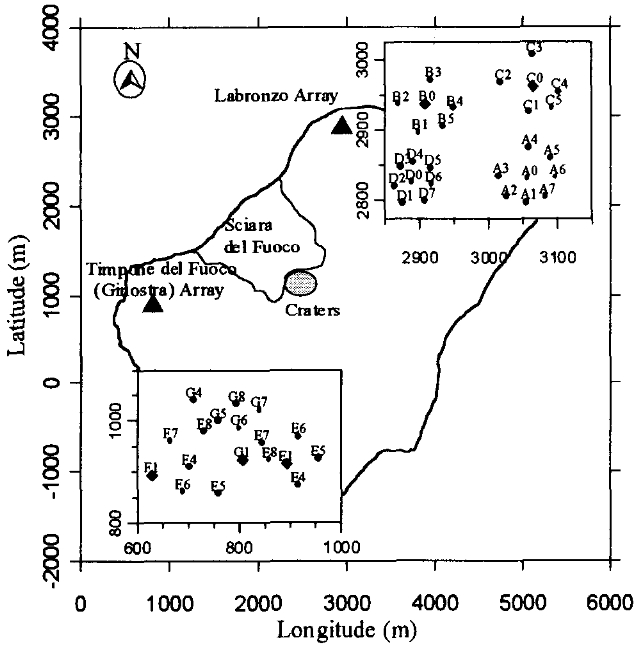

Fig. 1. Map of Stromboli Island with array locations at Semaforo Labronzo and Ginostra sites (triangles) and array configurations shown in foreground (circles are associated to vertical component and rhombs to three component seismometers). Borders of the sector graben of Sciara del Fuoco are also shown. The circle surrounds the crater area. The reference system is: Lat. 38° 47' North, Long. 15° 11' East.

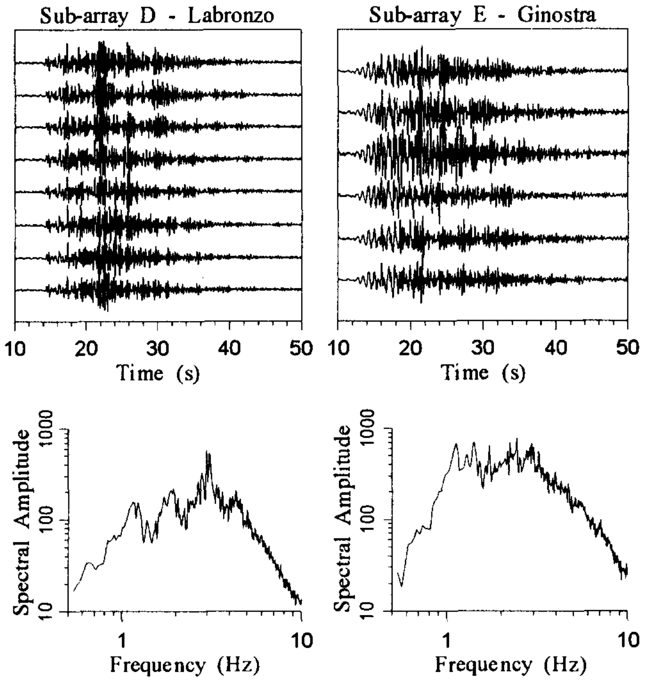

Fig. 2. An example of data recorded at Labronzo and Ginostra sites (top), with their corresponding sub-array averaged spectra (bottom). This event, named 2580141, was recorded on September 15, 1997.

2 Field Instruments

The first array was located in proximity of Semaforo Labronzo, a former military ligthhouse near the northern shore of the island (Fig. 1). It consisted of 26 vertical-component and 2 three-component Mark L15 sensors having a natural frequency of 4.5 Hz and electronically extended to 1 Hz. The array located at Ginostra-Timpone del Fuoco (Fig. 1) consisted of 15 vertical-component and 3 three-component MARK L4-C seismometers having natural frequency of 1 Hz. Seismic data were recorded using non commercial digital recorders consisting of a portable PC equipped with a 8-channel, 16-bit AD card and storing data at 200 samples/s/channel. Absolute timing at all the recorders was achieved by synchronizing the PC internal clock with the GPS time signal. The location of the sensors was measured using differential GPS positioning, obtaining a precision of less than 10 cm in absolute sensor coordinates. Although both the arrays were deployed on the volcano flanks, the average slopes were less than 10 degrees. For this reason in the following we consider a planar geometry approximation.

During 10 days of operation in trigger mode, the two arrays recorded about 500 explosion quakes, 150 of them were recorded by all of the sensors (roughly amounting to 1.5 Gigabytes of digital information).

3 Data analysis and preliminary results

3.1 Slowness analysis

Explosion quakes signals contemporary observed by all the recorders of the two arrays are analyzed using the zero-lag cross-correlation technique (Del Pezzo et al., 1997). It is adopted because it allows the use of short signal windows without any loss of resolution, thus being more appropriate for the analysis of rapidly time-varying signals like the Strombolian explosion quakes.

We first evaluate the spectral content of a selected number of explosion quakes by deriving array-averaged amplitude spectra at the vertical components of arrays D and E. The spectra show striking resemblance among all the analyzed events, further demonstrating the stationarity of the explosive source over time intervals spanning a few days (Dietel et al. 1994). An example of array-averaged spectral estimates of one explosion quake at two sub-arrays of Labronzo and Ginostra is shown in Figure 2. The two spectra are similar for frequency above 3 Hz. The decay of the spectral shape of Labronzo spectra with decreasing frequency between 3 and 1 Hz is determined by the instrument response curve, which is a factor 3 lower than the response curve of Ginostra instruments at 1 Hz.

Slowness spectra are derived separately at the two arrays using 1.5-s-long windows spanning 15- to 20-s-long interval of signals with 0.3 s of increment. At each window position, the average zero-lag cross-correlation is calculated over a regular square grid spanning the -2 ÷ 2

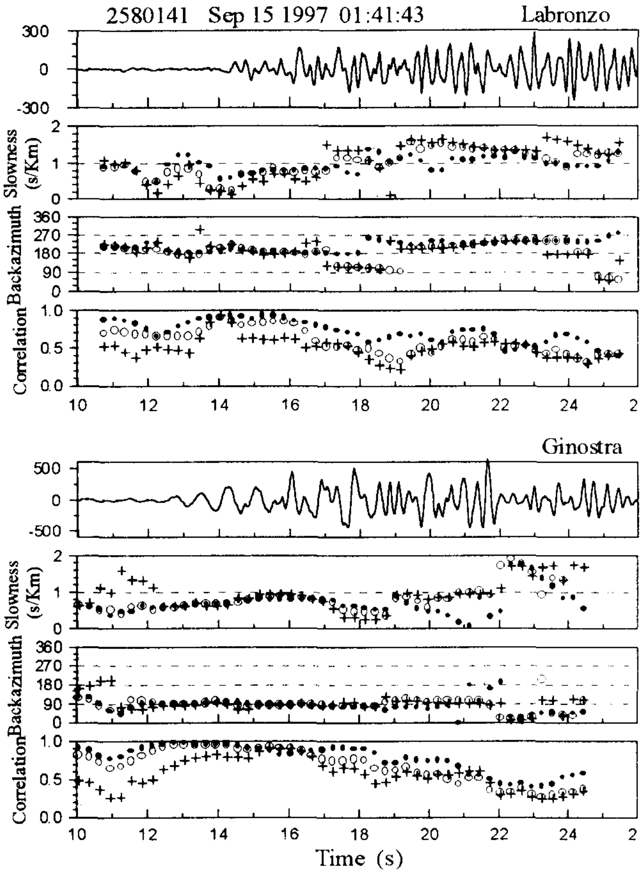

Fig. 3. An example of zero-lag cross-correlation analysis for Labronzo and Ginostra array. The full circles, empty circles and crosses represent solutions obtained for the 1-2 Hz, 1.5-2.5 Hz and 2-3 Hz frequency bands respectively.

s/Km range with a constant step of 0.05 s/Km. From the position of the correlation peak in the slowness plane we estimate backazimuth (measured positive clockwise from North) and ray parameter associated to each plane wave crossing the array. Apparent velocity (corresponding to the inverse of ray parameter) and backazimuth are estimated separately over three 1-Hz-wide frequency bands spanning the 1-3 Hz frequency interval (namely: 1-2 Hz, 1.5-2.5 Hz, 2-3 Hz). The analyses are carried out over 15-s-long records starting a few seconds before the initial phases of the explosion quakes.

The analyzed explosion quakes are characterized by similar wave forms, with an emergent onset dominated by a frequency of about 1-2 Hz, while the spectral content of the successive phases is characterized by higher frequencies (up to 5-7 Hz). Due to the different transfer functions of the instruments used for the two arrays, the low-frequency onset of the explosion quakes is clearer in the recordings obtained at the Ginostra array than in those obtained at the Labronzo array. Moreover, the distance of Labronzo site from the presumed source is slightly greater than that of Ginostra site and this may result in a different signal attenuation. For example at 3 Hz, using a Q = 10 as found by Del Pezzo (1988) for Stromboli, the amplitude at Labronzo decreases of a factor 1.4 compared to Ginostra.

The results obtained at different frequencies are very similar. The first phase of the explosion quakes is characterized by high values (about 0.9) of the averaged zero-lag cross-correlation coefficient, ray parameter of about 0.6 s/Km and backazimuth close to the crater–to-receiver direction (Fig. 3). Backazimuth observed in the first 5 - 6 seconds of signal is almost constant, while slowness shows an increasing trend from about 0.6 s/Km to about 1 s/Km. This is due to the presence of surface waves crossing the arrays immediately after the first phase. Late arrivals are characterized by lower values of the averaged zero-lag cross-correlation coefficient, higher ray parameter and backazimuth scattered over a wide angular interval. In fig. 3, third panel – Labronzo – some jumps in the backazimuth pattern can be recognized at 17, 18, 22 and 25 seconds. The same kind of jumps can be observed for Ginostra after about 21 seconds. They indicate that some coherent wave packets come to the array from backazimuths which are completely different from those of the source. The corresponding high slownesses are compatible with a composition of surface waves, so these phases can be interpreted as surface waves scattered at surface.

A preliminary estimate of source location is gained by selecting backazimuth obtained from contemporary time windows of signal analyzed at the two arrays. For each pair of windows, the corresponding backazimuths define in fact two vectors whose intersection gives an estimate of the source of seismic energy. This analysis is carried out over windows corresponding to the low-frequency onset of a selected number of explosion quakes; the results, displayed in Figure 6, indicate an extended source distributed in close proximity of the crater region.

3.2 Velocity model

The study of surface wave dispersion is carried out using Multiple Filter Technique (MFT, Dziewonski et al., 1969; Herrmann, 1973, 1987) and Phase Matched Filter (PMF, Herrin and Goforth, 1977). We analyze Rayleigh waves in the wavefield generated by Strombolian explosion quakes, to obtain group and phase velocity dispersion curves. Through the inversion of these curves we are able to infer the velocity model to a depth of about 200 m for both Labronzo (Petrosino et al., 1998; Petrosino, 1997) and Ginostra sites.

Labronzo data were recorded by a linear array deployed in 1992 by U.S. Geological Survey, Università dell'Aquila and Osservatorio Vesuviano (Dietel et al., 1994). As typical Rayleigh wave particle motion patterns were clearly visible in the seismograms, we apply the MFT analysis to 14 events recorded by one vertical component sensor belonging to the array. Signals are first narrow band-pass filtered around a series of center frequencies (from 2 to 8 Hz), then group velocity is computed by measuring the arrival time of the maximum amplitude of the filtered signals envelope. For each event we plotted the maximum

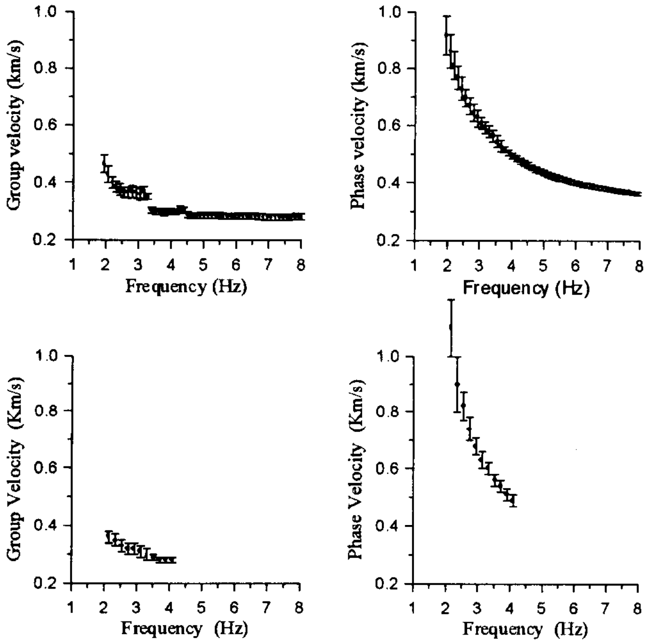

Fig.4. Stack of 42 group velocity dispersion curves obtained from 14 seismograms recorded at Labronzo linear array (top on the left) and analyzed by Del Pezzo et al. (1998). Error bars are 2σ widht. The plot on the right is the same for phase velocity. At the bottom, stack of 20 group velocity and phase velocity dispersion curves obtained from 20 seismograms recorded at stations F1, Ginostra.

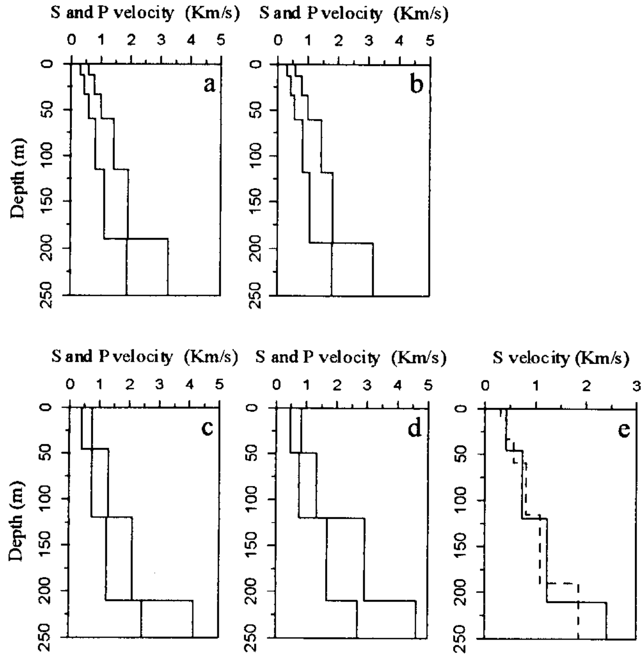

Fig. 5. Velocity models inferred by inversion of:
a) group velocity dispersion for Labronzo;
b) phase velocity dispersion for Labronzo;
c) group velocity dispersion for Ginostra;
d) phase velocity dispersion for Ginostra.
Plot e shows comparison between S wave velocity models at Ginostra and Labronzo (dashed line).

envelope as a function of group velocity and frequency, obtaining a group velocity dispersion curve. To clean the plots by contamination of body waves and higher modes, we phase-matched the seismograms using a trial dispersion curve resulting by the stacking of the 14 dispersion curves deduced by the MFT analysis. The PMF was applied to 42 signals (14 events recorded by three stations) to get 42 group and phase velocity dispersion curves (Petrosino et al., 1998). These curves were stacked to infer the final dispersion relation of the fundamental mode (Fig. 4).

This kind of analysis was also performed on some events recorded at Ginostra during the Twin Array Experiment of September 1997. We chose 20 explosion quakes recorded at station F1 and we applied the MFT to each event, obtaining 20 group velocity dispersion curves. The curves were stacked to get the trial dispersion curve for the PMF. We phase-matched filtered the 20 seismograms, getting the improved group and phase velocity dispersion curves which were finally stacked to obtain the final dispersion (Fig. 4).

To infer the velocity model for both Ginostra and Labronzo site, we inverted group and phase velocity dispersion curve. We used a surface wave inversion program (Herrmann, 1987) which inverts iteratively observed group (or phase) velocity dispersion for plane-layered shear-wave velocity earth structure, using singular value decomposition. We chose as starting model the velocity model obtained by Chouet et al. (1998) for Labronzo site from a study of the volcanic tremor and we inverted the dispersion curve until the fit between observed and predicted data was good. The inversion of group and phase velocity dispersion curves obtained for Labronzo and Ginostra led to the velocity models shown in Figure 5, where we also show a comparison between the two S-wave models at the two sites.

4 Discussion and Conclusions

The preliminary results described in the present paper show that the twin array configuration can be usefully applied for the space location of the source of Stromboli activity. Results from a limited subset of events show an almost constant wave vector for the first 10 seconds of lapse time. This result indicates a persistent source located close to the crater area. Volcanic tremor preceding the explosions is coherent, showing the same source of the explosion quakes. Wave vectors, evaluated along the wave packet, show in the late coda some abrupt changes in backazimuth and apparent velocity (Fig. 3), possibly corresponding to phases produced by the interaction of the primary waves with strong scatterers. In this case the intersection between the two backazimuth lines obtained at the two arrays does not necessarily match the scatterers position. In fact they could be produced by two different sources. On the contrary the intersection of the backazimuth lines obtained for the first P wave at both arrays shows that the location of the primary source is close to the crater area, even though some solutions are

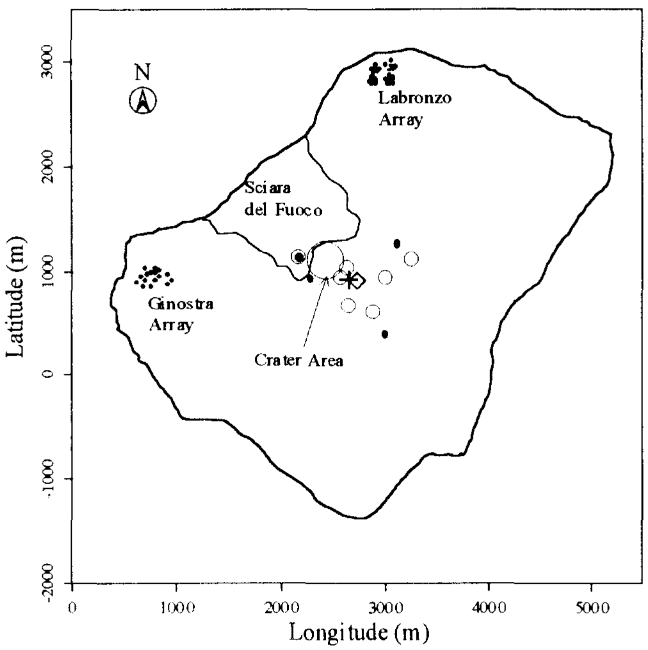

Fig. 6. Source locations obtained by the intersection of wave vectors derived at Ginostra and Labronzo sites. The full and empty circles represent solutions obtained for 1-2 Hz and 1.5-2.5 Hz frequency bands respectively. The cross and the rhomb represent the corresponding average solutions.

hundreds of meters away (Fig. 6). This effect could be produced by the approximate procedure we have used to put in phase the two time windows. A more careful analysis based on an objective estimate of the phase delay should reduce the spreading of these solutions around the crater area.

The results achieved in the present work about the velocity model are in agreement with those obtained by Chouet et al. (1998) for Labronzo site using Aki's correlation method (Aki, 1957). However the MFT approach is easier and faster than Aki's approach because of the lower number of stations used for the analysis. The velocity models derived for Labronzo and Ginostra sites are in agreement with the geological knowledge which show a superposition of sand and pyroclastic materials over deeper layers composed by consolidated lava flows. Besides, the two velocity models do not show significant differences, confirming the geological similarities of the two sites.

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References

Aki, K., Space and time spectra of stationary stochastic waves, with special reference to microtremors. *Bull. Earth. Res. Inst.* Tokio Univ. 25, 415-457, 1957.

Chouet, B., Saccorotti, G., Martini, M., Dawson, P., De Luca, G., Milana, G., Scarpa, R., Source and path effects in the wave fields of tremor and explosions at Stromboli Volcano, Italy. *Journ. Geophys. Res.*, 102, B7, 15129-15150, 1997.

Chouet, B., De Luca, G., Dawson, P., Milana, G., Martini, M., Scarpa, R., Shallow velocity structure of Stromboli volcano, Italy, derived from small-aperture array measurements of Strombolian tremor. *Bull. Seism. Soc. Am.*, 88, 3, 653 – 666, 1998.

Del Pezzo, E., Guerra, I., Lo Bascio, A., Luongo, G., Nappi, G., Scarpa, R., Microtremors and volcanic explosions at Stromboli, part 2. *Bull Volcanol.*, 38, 1023-1036, 1974.

Del Pezzo, E., Attenuazione dei segnali sismici di terremoti vulcanici; *Atti del 7° Convegno Annuale del Gruppo Nazionale di Geofisica della Terra Solida*, 1988.

Del Pezzo, E., La Rocca, M., Ibanez, J., Observation of high frequency scattered waves at at Teide Volcano, *Bull. Seism. Soc. Am.*, 87, 6, 1637 - 1647, December 1997.

Del Pezzo, E., La Rocca, M., Petrosino, S., Grozea, B., Maritato, L., Saccorotti, G., Simini, M., Ibanez, J., Alguacil, G., Carmona, E., Abril, M., Almendros, J., Ortiz, R., Garcia, A., Pingue, F., Esposito, T., Twin digital short period seismic Array Experiment at Stromboli Volcano (September 1997). Open file report n. 1, Osservatorio Vesuviano, 1998.

Dietel, C., Chouet, B., Kleinman, J., De Luca, G., Martini, M., Milana, G., Power, J., Harlow, D., Scarpa, R., Array tracking tremor sources at Stromboli volcano, Italy. *US Geol. Surv. Open-File rep.* 94-142, 1-86, 1994.

Dziewonski, A., Bloch, S., Landisman, M., A technique for the analysis of transient seismic signals. *Bull. Seism. Soc. Am.*, 59, 427-444, 1969.

Herrmann, R. B., Some aspects of band-pass filtering of surface waves. *Bull. Seism. Soc Am.*, 63, 663-671, 1973.

Herrmann, R. B., *Computer programs in seismology, User manual.* vol 1, 2, 3, 4 - Univ. of St Louis, Missouri, 1987.

Herrin, E. and Goforth, T., Phase-matched filters: application to the study of Rayleigh waves. *Bull. Seism. Soc Am.*, 67, 1259-1275, 1977.

Petrosino, S., Del Pezzo, E., La Rocca M., Shallow velocity model of the Northern Flank of Stromboli Volcano, deduced by high frequency surface wave dispersion. *Journ. of Seism.*, (in press), 1998.

Petrosino, S., Modello di velocità di Stromboli dedotto dallo studio delle onde superficiali, MD thesis, Univ.di Salerno, 1997.

Saccorotti G., Studio del campo d'onda sismico a corto periodo (T<2 s) associato all'attività dello Stromboli. PhD thesis, Univ. di Napoli, 1997.