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Low frequency events at Mt. Etna: some problems and open questions

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Abstract
A short period seismic array setting at Mt. Etna symmetrically in regard to the fracture of the 1991-1993 eruption allowed an analysis of low frequency events which occurred in the first phase of the mentioned eruption. We recorded about 50 events, 19 of them belong to a family. They show very low amplitude values and spectral peaks ranging 0.5-4.5 Hz. The evidence of this family of events shows how the process driving the dynamics of the fluid in the volcano is often the same.

Key words *Mt. Etna – low frequency volcanic events – earthquake family – polarization*

1. Introduction

The so-called low frequency events (l.f.e.) are a type of volcanic earthquakes, and their observation is common in active volcanoes worldwide. Minakami (1960) defined B-type events as seismic signals with emergent *P*-wave onset, no clear *S*-wave, and a frequency content mainly ranging from 1 to 5 Hz. Several authors (Blot, 1971; Latter, 1971; Del Pezzo and Martini, 1981) have interpreted such events at Vulcano as due to gas pressure variation phenomena occurring in the upper structures of the volcano. The monochromatic character of these events was attributed (Blot, 1971; Latter, 1971) to resonance effects inside the gas-driving conduits. St. Lawrence and Qamar (1979) noted the similarity between so called low frequency events (or B-type events) occurring on volcanoes and l.f. icequakes; they postulated that the two types of events may be linked to fluid transients in fluid-filled conduits under volcanoes and glaciers. Fehler and Chouet (1982) noted that these events, at Mt. St. Helens, appeared correlated with the incoming eruptive activity; the waveform of l.f.e. was due to the excitation of some fixed cavity under the volcano. Bame and Fehler (1986) found evidence that the first seismic events occurring in the hydraulic fracturing of virgin rock are l.f.e.. McNutt (1986) showed that the l.f.e. at Pavlof volcano presented lacking clear *S* phases, and that they were located at very shallow depth. The energy input to the system is related to flow. Koyanagi *et al.* (1987) showed that l.f.e. at Kilauea are linked with magmatic activity. The l.f.e. show a dominant long-period of motion that can be quite stable, independent of event magnitude (Chouet, 1988). To explain the l.f.e., he supported a model of the resonance of a fluid-driven crack induced by an impulsive pressure transient. Godano and Vilardo (1991) suggested that the l.f.e. at Vulcano are driven by excess of pressure within a crack filled by a mixture of brine, steam and magmatic gases. At Galeras volcano (Colombia), sudden gas emissions and l.f.e. have been simultaneously observed (Gomez *et al.*, 1993).

The l.f.e. spectra generally peak in the range 1-5 Hz (Lo Bascio *et al.*, 1973; Capaldi *et al.*, 1978; Latter, 1981; Malone, 1983), which coincides with the observed frequency range of the harmonic volcanic tremor. This feature suggests that the volcanic tremor itself could be composed of a large number of low frequency transients (Malone, 1983; Chouet, 1985). In fact, a sudden onset of tremor episode and a l.f.e. have sometimes similar initial waveforms, indicating that they originate from a similar physical process and approximately in the same place (Fehler, 1983).

Frequently, and not only in volcanic areas, earthquakes have been observed to occur in cluster events with almost identical signal character. Tsujiura (1983) analysed in great detail many clusters of similar seismic events and called them earthquakes families.

A family of l.f.e. accompanied the first phases of the eruption 1991-1993 at Mt. Etna volcano. Aim of this paper is to analyse acquired data and raise some open questions on the wave composition of l.f.e..

2. Data analysis

An array of 5 portable digital seismic stations (fig. 1), equipped with three-component 1 Hz geophones was operating at Mt. Etna volcano during the first stages of the 1991-

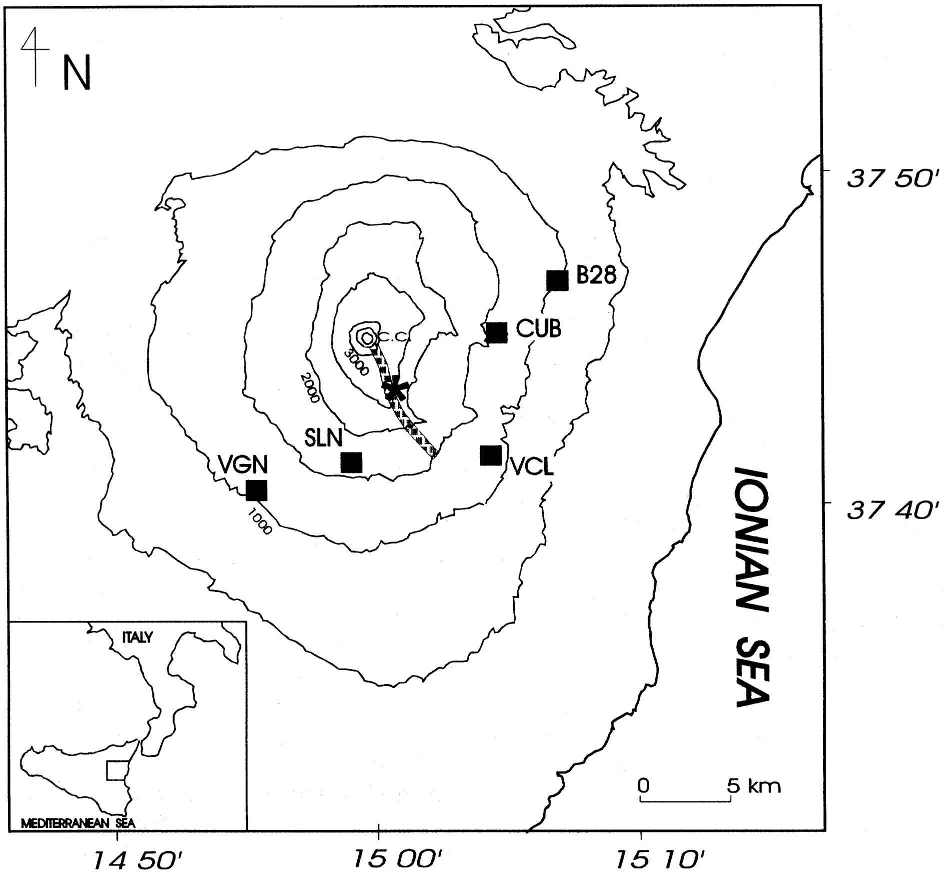

Fig. 1. Sketch map of Mt. Etna: CC indicates the Central Craters; asterisk the 1991-1993 eruptive boccas; dashed area the 1989 NNW-SSE fracture system reactivated during the 1991-1993 eruption; squares the three-component digital seismic stations.

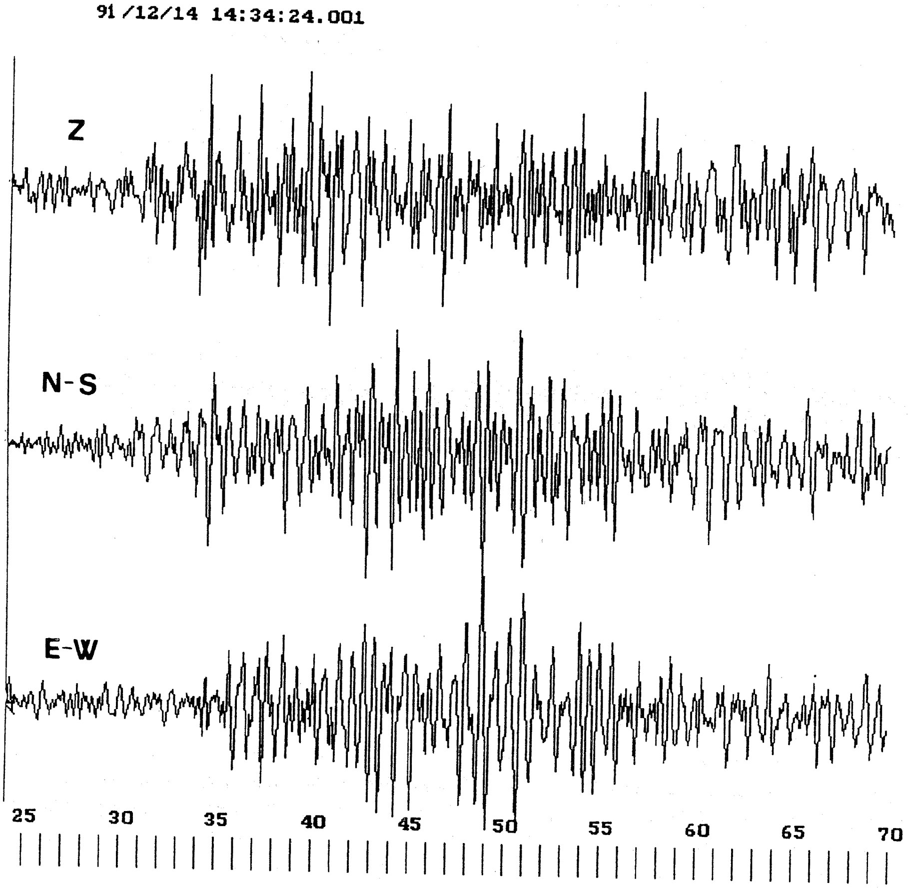

Fig. 2. An example of l.f.e. recording at the three-component VGN station.

1993 eruption. Seismic stations were signal-triggered on short-term/long-term signal averages comparison, a procedure used worldwide for portable equipment; the sampling rate was held constant at 125 Hz.

The beginning of the eruption was heralded by a seismic swarm consisting of more than 1000 events exceeding magnitude 1 (*i.e.* Patanè *et al.*, 1993). Seismic activity, after two major earthquake sequences which occurred on December 14 and 15 ($M_{\max} = 4.5$), abruptly decreased in a few days and was seldom observed during the eruption, remaining at low levels (Ferrucci and Patanè, 1993). During the first phase of the eruption a feeding fracture system developed, originating from the SE subterminal crater and closely matching the SSE branch of the fracture system formed during the 1989 eruptive event (Barberi and Villari, 1994).

The main data set consists of about 50 l.f.e., about 40 of them occurred on December 14, 1991, from 13:27 to 20:18 GMT, the others on the 15th and the 16th. Among these events only 3 were detected simultaneously by three stations, 8 events by a couple of stations, while most of them (29) were detected by the station SLN only.

The l.f.e. recordings have very peculiar seismograms with a spindle-shaped amplitude envelope (see fig. 2), often with an emergent on-

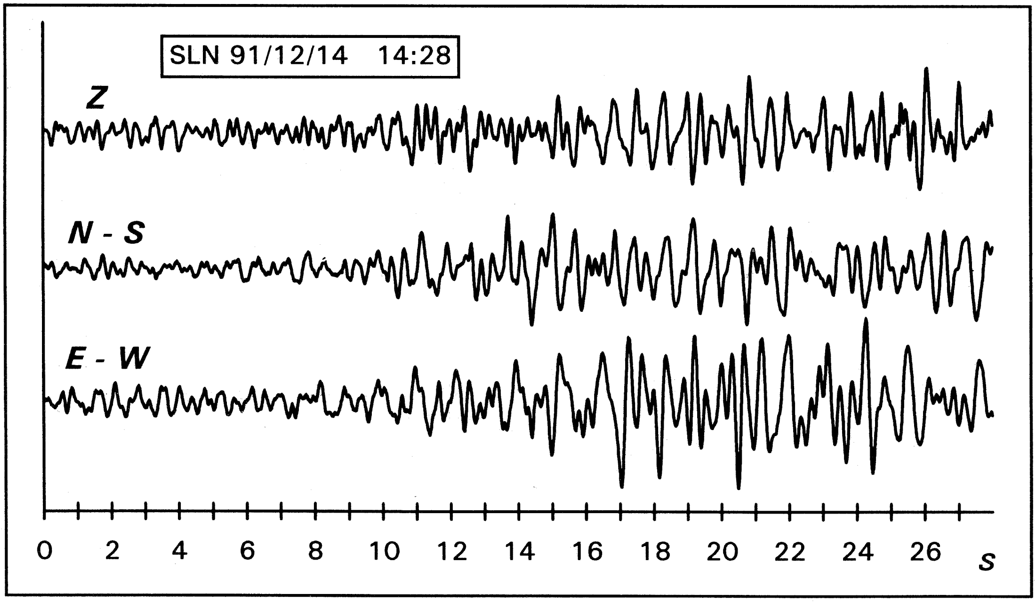

Fig. 3. Typical seismogram for an l.f.e. recorded at SLN station. Note the lacking of clear *P*- and *S*-wave first-arrivals.

set. They show low amplitude values, making it difficult to measure the onset of the events which are barred in the tremor level. In fact, the first *P*-wave arrivals are not always evident (fig. 3) because the low signal/noise ratio.

On December 14, 1991 (from 14:09 to 20:18 GMT) 19 events were detected having very similar waveforms, only two among them were detected by three stations. The high degree of similarity in the waveforms (see fig. 4) suggests that the underlying process is repetitive. Therefore, these events must belong to the same source mechanism.

2.1. *Particle motion*

In order to understand the general features of the ground motion, a particle motion analysis was carried out on the whole signal. From such analysis the onset of the events was inferred to be quite similar to the tremor and increasing in energy only. Impulsive *P*-waves were observed on a few events only and evidence of *S*-waves was rare, suggesting that shear fracturing sources are not proposable. Figure 5 shows an example of particle motion analysis carried out on time-intervals scattered along the signal. Note the irregular motion with abrupt inversions in the direction, inflexion points and intersections. The remarkable result is the finding of very regular and well developed Rayleigh waves, with evident elliptical motion on the vertical plane (*g*-phase of fig. 5). In all events the polarization of the first *P*-waves arrival is not constant: this behaviour is probably due to interference effects with noise.

2.2. *Spectral composition*

The spectral content of the signals was investigated by use of the classical FFT method over two time windows covering the first 4 s and the following 4 s of each signal, respectively. The average spectrum of all the events recorded at station SLN is reported in fig. 6 (all spectra have been normalised separately to emphasize the spectral shape for each component). A very high spectral stability can be found. In fact, the variance is very low for both horizontal and vertical components and the spectral peaks mainly range 0.5-4.5 Hz. Figure 7a-c shows spectra of an event simultaneously recorded at three stations. The most interesting features are: i) the power spectrum peaks at different frequencies for different components (see, for example, SLN-a); ii) the change in frequency of the highest peak between the first and the second window at B28 station recordings; this is not observed on the VCL station. These differing features are probably due to either path or site effects, only the 3.5 Hz peak observed in all spectra might be characteristic of the source of the events.

Finally, spectra of tremor samples collected just before the onset of each event generally show the same behaviour as the l.f.e. (fig. 7a,c). This supports the hypothesis that harmonic tremor and l.f.e. have a common source.

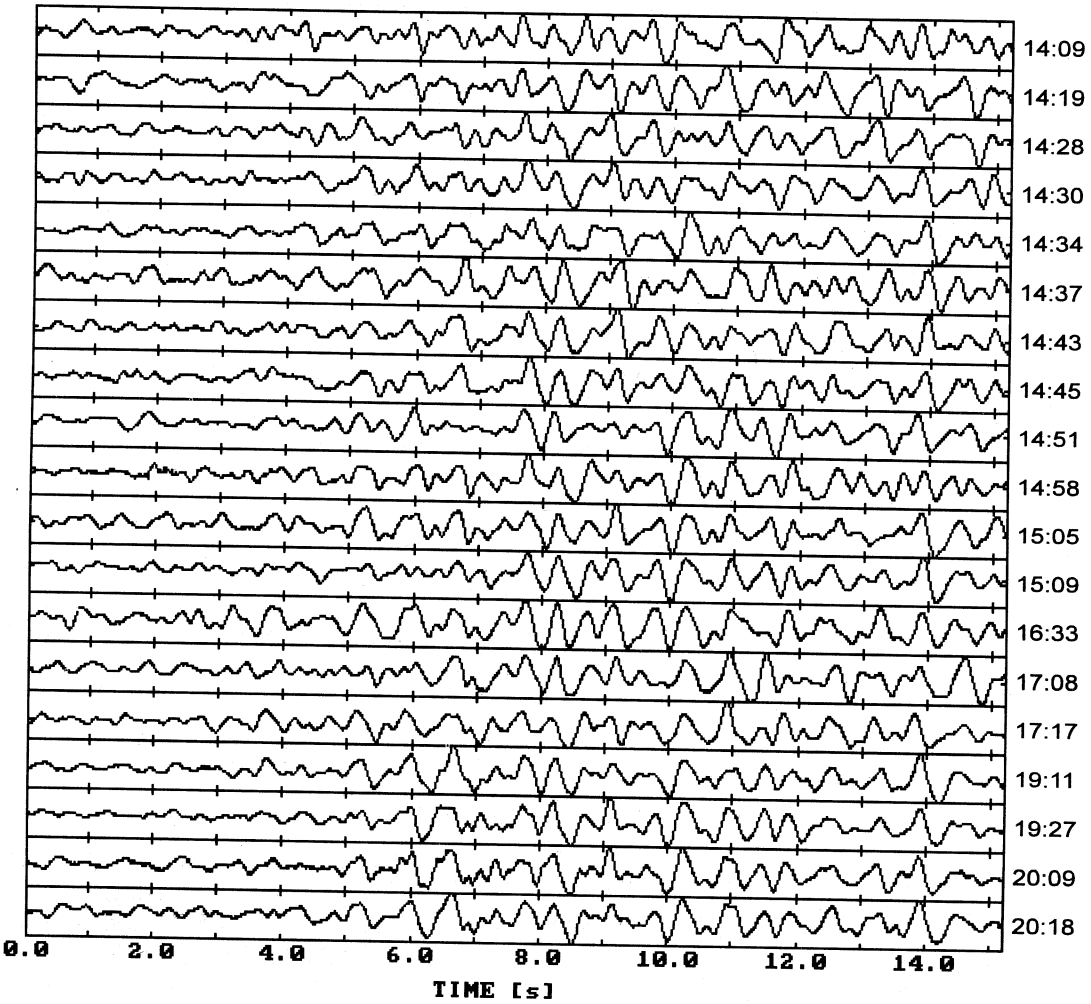

Fig. 4. Seismograms (N-S horizontal component at SLN station) for the 19 events of the family.

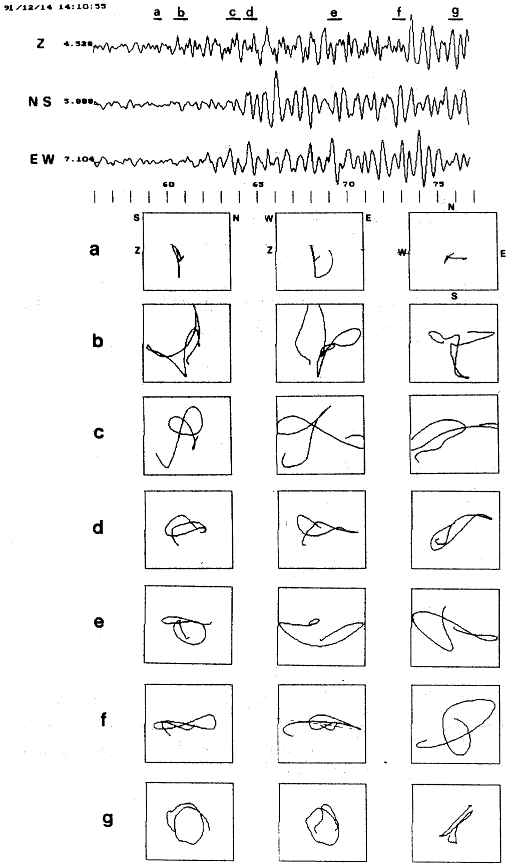

Fig. 5. Particle motion analysis carried out on a major part of the signal. The letters show the windows (0.7 s) of the analysed signal. (a) Points up the arrival of *P*-waves, while the other letters point up the absence of *S*-waves and the prevalence of surface waves.

2.3. *Rectilinearity filter*

In order to measure the rectilinearity (RCL) and the direction of particle motion, the method described in Montalbetti and Kanasevich (1970) was applied. It was already used on shocks at Stromboli (Del Pezzo *et al.*, 1991) and Vulcano (Godano and Vilardo, 1991), and on volcanic tremor at Mt. Etna (Ferrucci *et al.*, 1990; Napoli *et al.*, 1994). The method is based on the evaluation of the covariance matrix in a set of points of the signal (in our case $N = 1000$, corresponding to a window of 8 s of signal):

$$C = \begin{Bmatrix} \mathrm{var}(X) & \mathrm{cov}(X, Y) & \mathrm{cov}(X, Z) \\ \mathrm{cov}(Y, X) & \mathrm{var}(Y) & \mathrm{cov}(Y, Z) \\ \mathrm{cov}(Z, X) & \mathrm{cov}(Z, Y) & \mathrm{var}(Z) \end{Bmatrix}$$

where X, Y and Z are respectively the N-S, the E-W and the vertical components. Each second of the three-component signal at each station can be considered a single «event» and separately processed by diagonalizing the covariance matrix. C is the matrix of coefficients for a quadratic form of the polarization ellipsoid; the eigenvector associated with the largest eigenvalue λ_1, indicates the polarization direction. If λ_2 is the second-largest eigenvalue of the covariance matrix, then a coefficient of the form:

$$\mathrm{RCL} = 1 - \lambda_2/\lambda_1$$

would be close to unity for a high rectilinearity ($\lambda_1 \gg \lambda_2$, near-linear polarization), and close to zero when the two principal axes approach one another in magnitude ($\lambda_1 = \lambda_2$, circular polarization). This implies that body waves and Love waves will display high values of RCL (typically larger than 0.7-0.8), whereas Rayleigh waves will provide linearity values close to zero (typically less than 0.5). Besides, it is possible to determine the direction of wave polarization: the eigenvector associated with the largest eigenvalue (λ_1) indicates the polarization azimuth.

In polarization analysis the orientation of the horizontal geophones couple were considered with respect to hypothetical source. The horizontal seismogram components were then rotated to obtain the radial and tangential components of the oscillation with respect to wave front propagation. Two analyses have been carried out considering the source coincident with eruptive boccas and SE crater, respectively. Figure 8 shows the results of the analysis over the two most powerful events of the family.

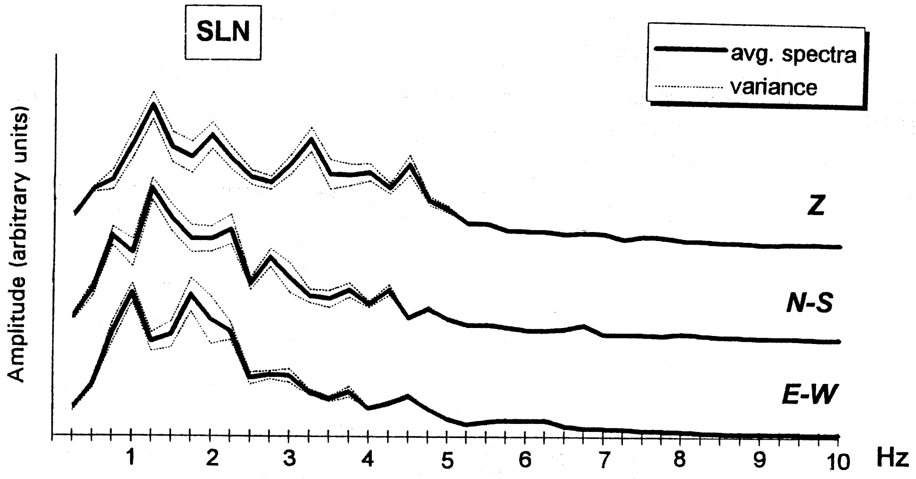

Fig. 6. Average spectra of whole 19 l.f.e. of the family at SLN station. The thick line indicates the average spectra; the dashed line the variance.

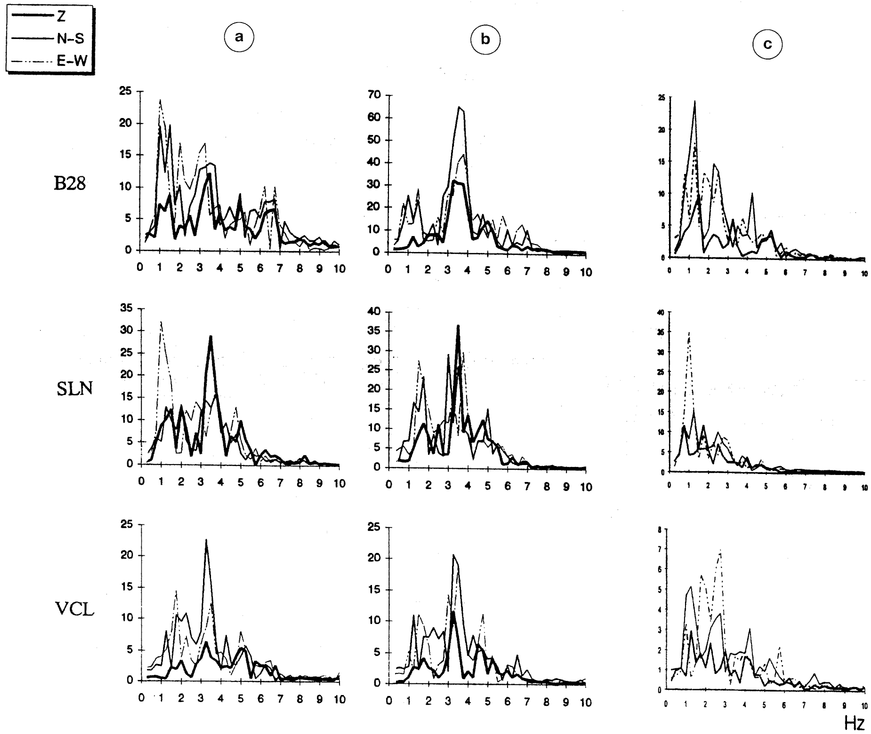

Fig. 7a-c. Amplitude spectra for the event occurred on the December 14, 1991 at 20:17 GMT recorded at three stations. Spectra performed on the first 4 s of signal (a), on the following 4 s (b) and on the tremor just before the event (c).

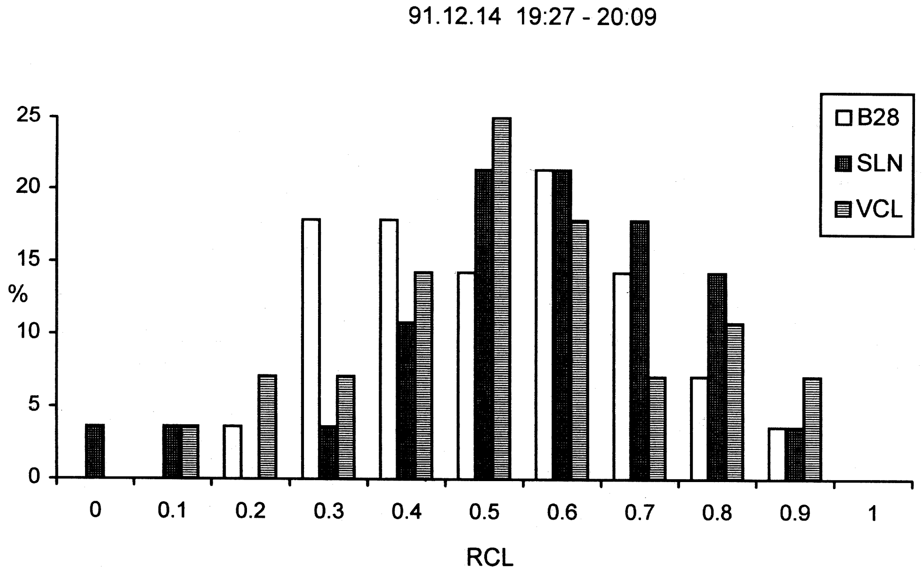

Fig. 8. Distribution of rectilinearity coefficient at three stations for a couple of events of the family.

RCL coefficients have average values ranging 0.5-0.6, showing the presence of different types of superimposed waves in the seismic signal. We assume such result valuable for the whole family of events considered, confirming the difficulties of a correct interpretation of this kind of seismic signals. From the azimuth distribution (fig. 9) it can be seen that the orientation is mainly tangential with respect to the location of the source. This leads to the hypothesis that the seismic signal may be mainly composed by surface-waves.

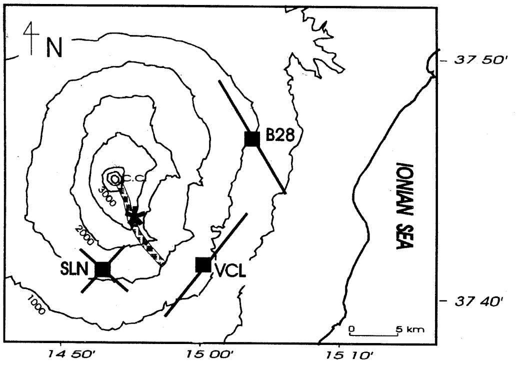

Fig. 9. Detail of fig. 1: line passing through station points indicate the polarization direction on the horizontal plane. If the source is assumed with eruptive boccas (asterisk), the polarization direction is tangential to them.

3. Concluding remarks

We have studied a family of l.f.e. which occurred during the first stage of the 1991-1993 eruption of Mt. Etna volcano. The analysis of the signal composition shows a high degree of complexity of the events. Their main features can be summarized as follows:

a) low energy-content with rare evidence of impulsive onset of both *P*- and *S*-waves;

b) power spectra peaked in the range 0.5-4.5 Hz;

c) signal mainly composed by surface-waves.

These features, observed during both the immediate pre-eruptive period and the first stages of the eruption, point to the hypothesis that l.f.e. are linked to the intrusion of magmatic-flow and/or to its fluctuations, as suggested by Chouet (1988). However, the dynamics of the system remain uncertain. Site responses and effects related to the source-station path have not been considered so far and should be studied in the future.

In the study of l.f.e. the main questions which remain are:

i) given the low energy content of most of the measured l.f.e. signals, how does the noise affect the results?

ii) how should the dispersion of body waves be considered?

iii) how to overcome difficulties in discriminating among phenomena generally producing low frequencies (l.f.e., gas-piston events and transients of tremor)?

iv) how can the use of bore-hole stations help in the identification of *S*- and *L*-waves?

v) what is the influence on the measured frequency of the seismic-array arrangement with respect to the source?

The latter arises from the strong attenuation in the upper layers of the crust, which is consistent with removal of energy at higher frequencies and may largely account for the «low-frequency» appearance of the B-type earthquakes. Usually, the corresponding waveforms contain little (or no) evidence of shear waves (Patanè *et al.*, 1994). In fact, taking into account the high frequency damping, the «usual» classification of the l.f.e. could be invalidated.

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