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Features of seismic events and volcanic tremor during the preliminary stages of the 1991-1993 eruption of Mt. Etna

Giuseppe Lombardo, Giuseppe Coco, Mauro Corrao and Stefano Gresta
Istituto di Geologia e Geofisica, Università di Catania, Italy

Abstract
The study of the spectral features of volcanic tremor and low frequency events (l.f.e.) recorded before and during the preliminary phases of the powerful 1991-1993 eruption of Mt. Etna is briefly described. Significant modifications were observed in the spectral signature of l.f.e. before the onset of the eruptive event, as well as in the temporal distribution of the volcanic tremor dominant frequencies. We interpret both l.f.e. and tremor changes in terms of a spatial modification of the source, as the paroxysmal eruptive activity is approaching. Such findings also appear quite interesting for the identification of markers of the modifications which some seismic events of the volcano undergo in the early stages heading the occurrence of an eruption.

Key words *Mt. Etna – eruption – volcanic tremor – low frequency events*

1. Introduction

The eruption of December 1991 – March 1993 was a remarkable event in the recent eruptive history of Mt. Etna, considering both its duration (473 days) and the great amount of emitted products (about 250×10^6 m^3). This activity took place in the southern flank of the volcano, following the SE Crater eruption of September-October 1989 (fig. 1).

On December 14th, at about 2:00 a.m. (l.t.), two radial fractures opened on the flanks of the SE Crater, accompanied by a swarm of earthquakes. Soon after, paroxysmal activity, characterized by the ejection of bombs and lava fountains up to 300 m high, occurred. A fracture system trending SSE propagated downslope, crossing the rim of the Valle del Bove on the evening of December 14th. During the early morning of December 15th the lava started to flow from the lower segment of the fracture accompanied by violent degassing and strombolian activity. Further details on the features of this eruption are given in Calvari *et al.* (1994).

In this paper the features of the low frequency events (l.f.e. hereafter) and the volcanic tremor recorded before and during the preliminary stages of the eruption are analysed. Our attention is focused, in particular, on the variation of the spectral signature of both the l.f.e. and the tremor in order to investigate some seismic features of such an eruptive event.

The source of volcanic tremor has been modeled (Seidl *et al.*, 1981) as linked to pressure fluctuations in the magma mixture filling the volcanic ducts which are forced to resonate. According to this model, dominant spectral peaks can be interpreted as the result of eigenvibrations in the main feeding dykes of the volcano, so that changes in the frequency values should be related to variations in the geometrical constraints of the ducts. In other words, and without taking into account path effects, high values for the frequency could be generally related to small sources while lower values could be related to bigger sources.

Ferrucci *et al.* (1990) postulated, studying the volcanic tremor during the 1989 eruption,

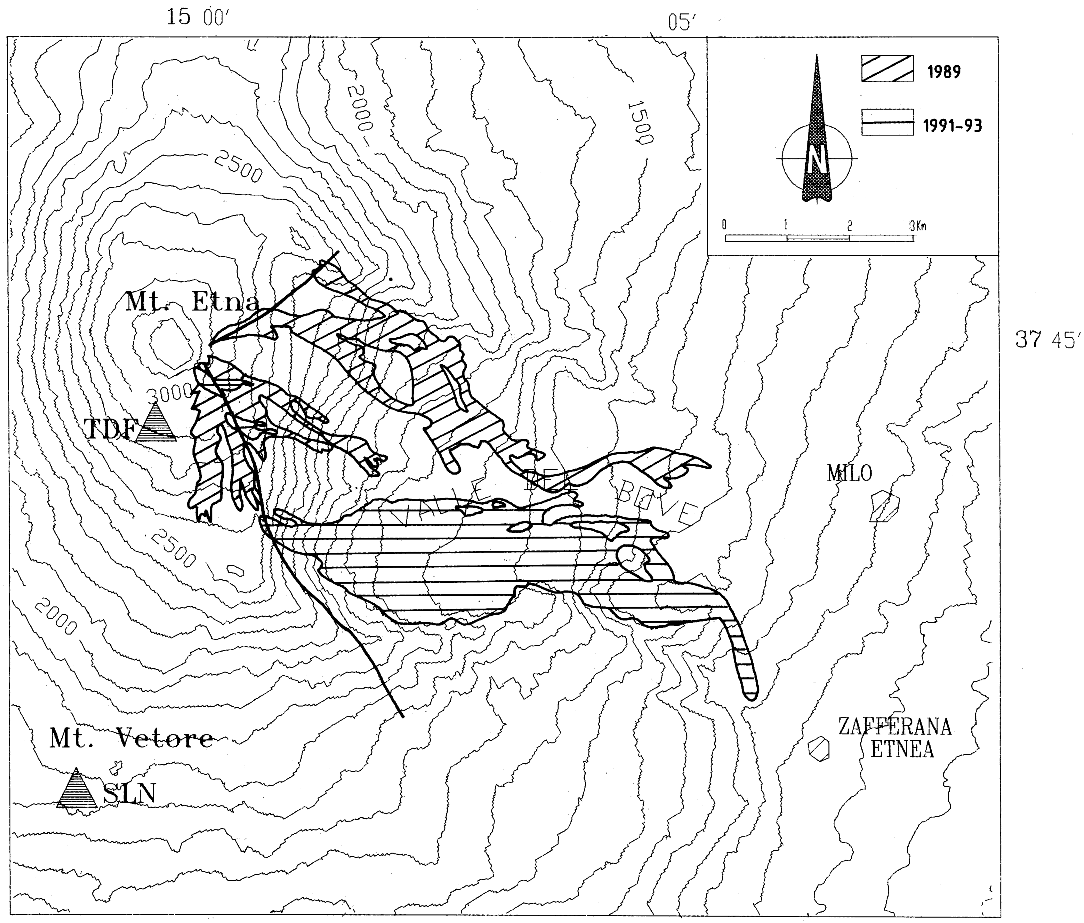

Fig. 1. Sketch map of the upper eastern flank of Mt. Etna showing the location of seismic stations (SLN, TDF), the 1989 and 1991-1993 eruptive fracture systems and the related lava flows (redrawn from Azzaro and Neri, 1992).

the existence of an elongated subvertical source, while Del Pezzo *et al.*, (1993) found a source located in the summit area, during non eruptive periods. Moreover, Napoli *et al.* (1994) observed significant variations in the linearity coefficient and in the direction of polarization of tremor recorded before and during the preliminary stage of the 1991-1993 eruption. Volcanic tremor can therefore be considered a suitable indicator of ongoing volcanic activity.

2. Data analysis

The seismic signals analysed in the present paper were recorded by the monocomponent stations of SLN and TDF which are located on the southern flank of the volcano at an elevation of 1735 m and 2915 m respectively (see fig. 1). Moreover, the records of a broadband seismometer (Wielandt Strekeisen) that is operating at SLN were used. The stations have a continuous analogical record, so that it is possible to follow any variation occurring in the seismic signal associated with the evolution of the eruptive activity.

Figure 2a,b shows the daily number of shocks recorded at SLN station in the time interval November 1st 1991 - January 15th 1992. Based on the characteristics of the signature of the shocks and adopting the morphological criteria described in Falsaperla and Lombardo (1989), all detectable shocks interpreted as due to shear fractures (fig. 2b), were distinguished from the total number of events (fig. 2a). The distinction of seismic events linked to fracturing from those connected to fluid-dynamic processes of the volcano (l.f.e.), allow us to emphasize the swarm which accompanied the opening of the eruptive fissures.

The l.f.e. are used in this study to investigate the relationships between seismic events and the occurrence of eruptive activities. At Mt. Etna, l.f.e. are seismic signals given by a series of low frequency (f $\leq$ 5 Hz) oscillations, emergent onset and duration ranging between fifteen seconds and about one minute. From a genetic point of view (Chouet, 1992), the l.f.e. can be considered simple tremor processes and can be interpreted as the impulsive responses of the tremor generated by the system. They therefore share the same source as the volcanic tremor since they have similar spectral features.

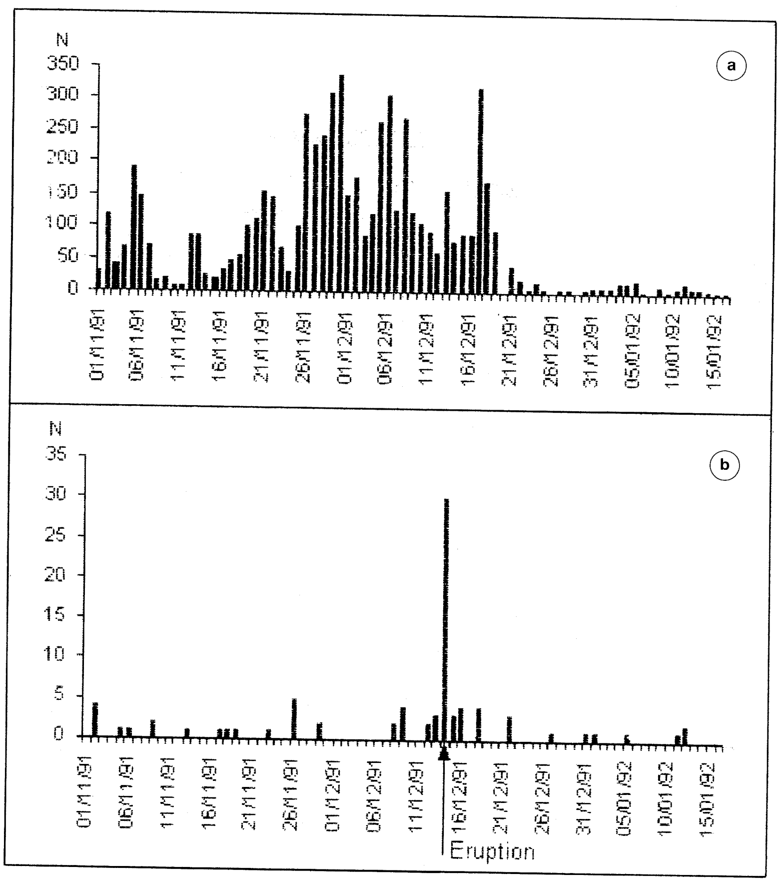

Fig. 2a,b. Daily number of shocks in the time interval November 1991-January 1992. a) Total number of events; b) earthquakes due to fracturing.

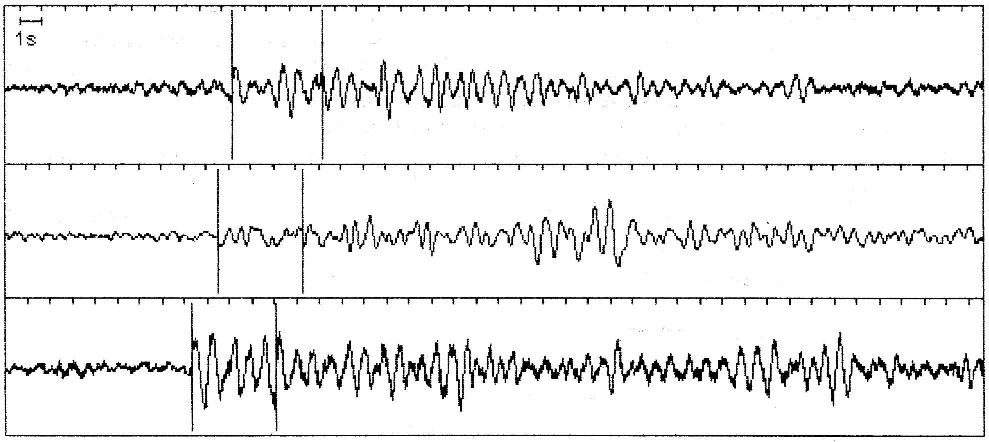

Fig. 3. Examples of low frequency events analysed in the present work. Same arbitrary units for the vertical scale of all the three plots.

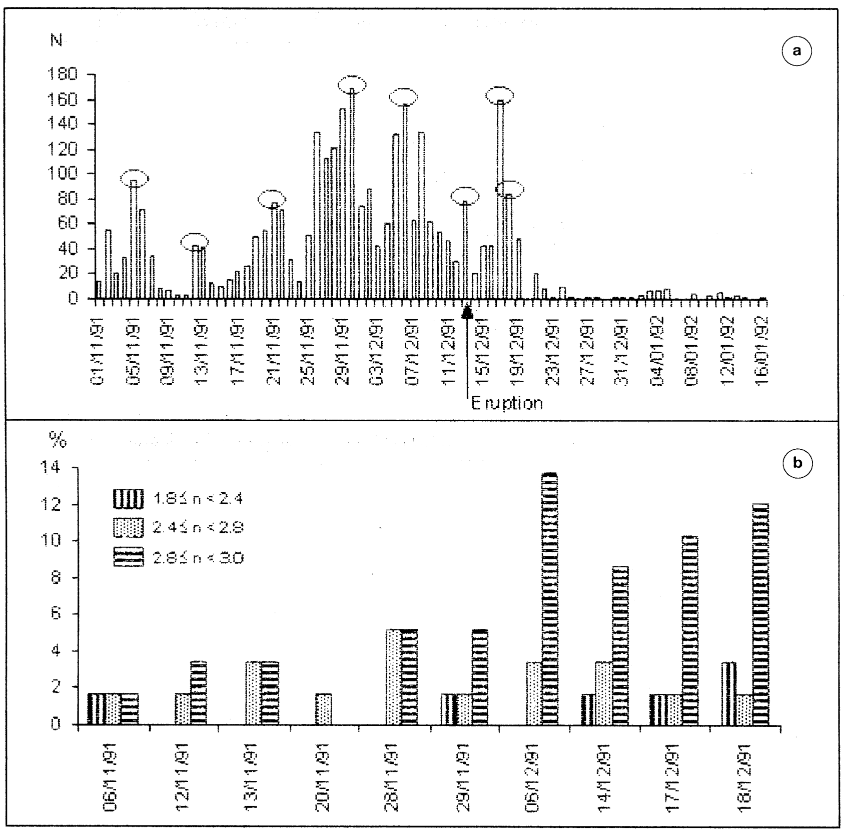

Fig. 4a,b. a) Time distribution of studied events (circles indicate the days of shock sampling); b) percentage of events with different values of the amplitude decay coefficient «*n*»

Figure 3 shows some examples of the recorded low frequency events. The studied events were randomly sampled among such shocks, according to the distribution shown in fig. 4a. The selected events were digitized by an A/D converter LeCroy 8013A and displacement spectra were obtained by processing the first three seconds of the signal (see examples in fig. 5). Since only records of SLN station were used, and a relative comparison of recorded signals was made, the spectra were not corrected for the site response.

The inspection of the obtained spectra showed significant differences especially in the decay of spectral amplitudes at frequency values greater than 2 Hz.

An exponential fitting procedure was adopted which evidenced significant changes in the slope (coefficient «n»). This allowed us to distinguish three classes of spectra as shown in fig. 5. The changes in the values of «n», appear time dependent, they range between 1.8 and 3.0 in the time interval preceding the eruptive event while, since the first week of December and during the early stages of the eruption, the percentage of shocks having values of «n» in the range 2.8-3.0 increase significantly (fig. 4b).

The results of the spectral analysis show remarkable similarities between the features of the studied events and that of the volcanic tremor. Several authors (Chouet, 1992; Crosson and Bame, 1985; Fehler and Chouet, 1982; McNutt, 1986) have pointed out that both the tremor and the l.f.e. share the same source mechanism. Alparone and Gresta (1996), analyzing a set of l.f.e. recorded at Mt. Etna by three component seismic stations in the same time interval, found, similarly to what has been found for the volcanic tremor, a lack of body waves in the particle motion plots. Chouet *et al.* (1994), studying a set of l.f.e. recorded during the 1991-1993 eruption, found similarities between the spectral features of l.f.e. and the ones of volcanic tremor, so that they postulated a common source, linked to the presence of the dyke feeding the eruptive activity. Such considerations led us to analyze spectral features and possible variations in the volcanic tremor recorded in the same period,

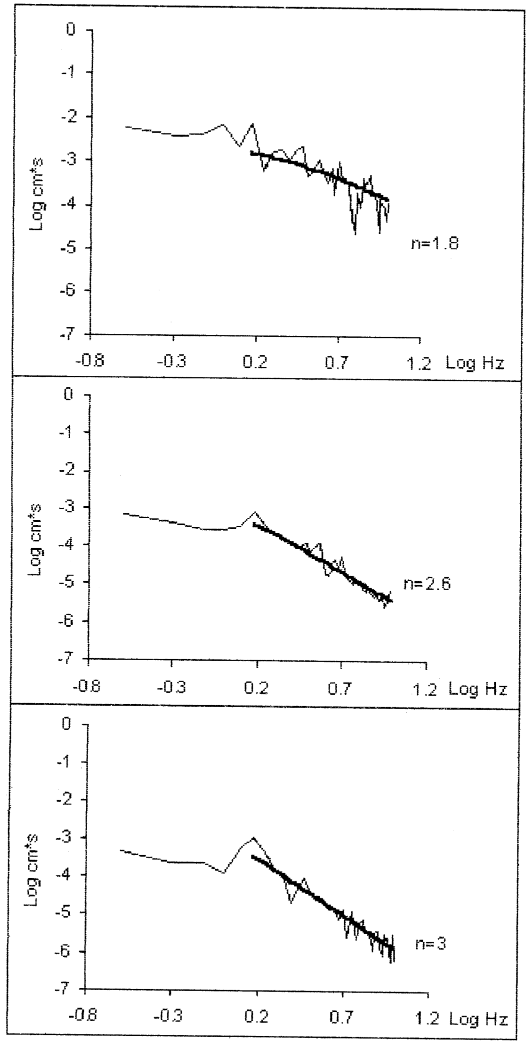

Fig. 5. Examples of displacement spectra showing different values of the exponential decay «n».

trying to extend the same considerations to the source of the low frequency events. The spectral features of the volcanic tremor recorded at the stations of Torre del Filosofo (TDF) and Serra la Nave (SLN) were analysed and, in particular, the trend of the dominant spectral peaks as well as the overall spectral amplitude were plotted (fig. 6a-e), trying to evidence any

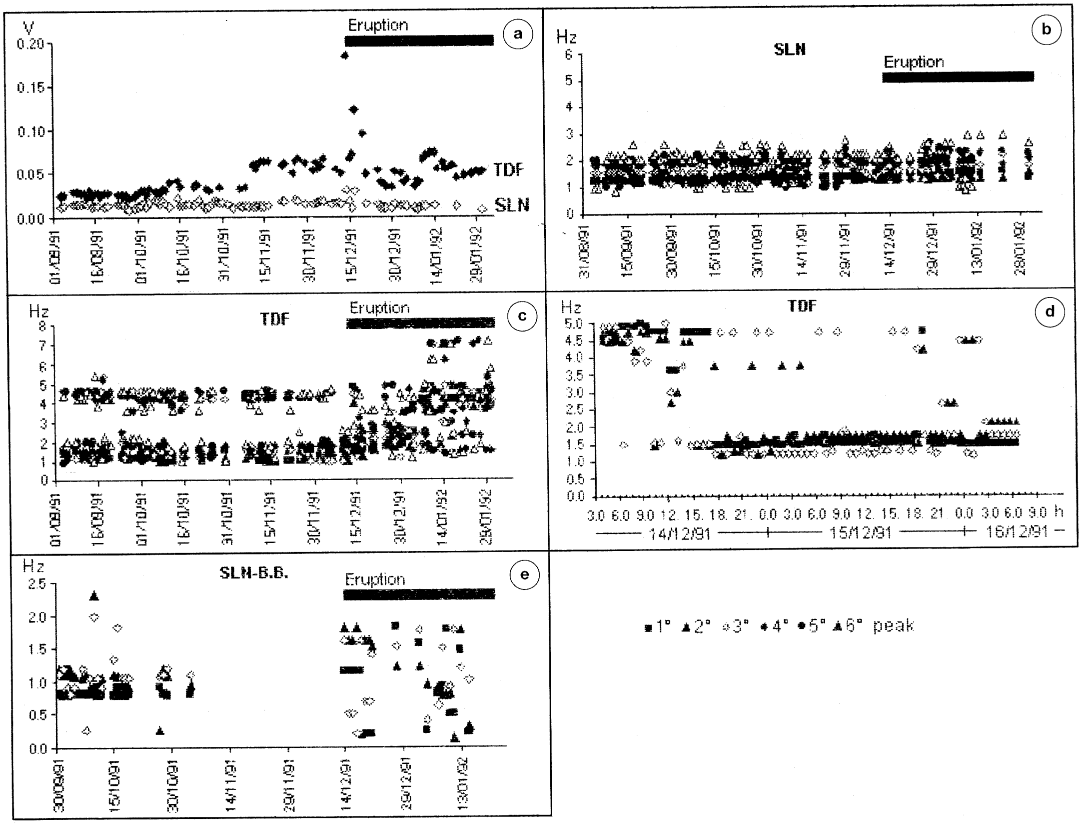

Fig. 6a-e. Plots of spectral features of volcanic tremor in the time interval September 1991-January 1992. a) Overall spectral amplitude at TDF and SLN stations; b) dominant spectral peaks at SLN and c) TDF; d) hourly variations of dominant spectral peaks at TDF during December 14th; e) dominant spectral peaks at SLN, recorded with a broadband seismometer.

significant temporal variation which could be related to the evolution of the volcanic phenomena.

Concerning the overall spectral amplitude (fig. 6a), no particular changes can be observed, with the exception of a sharp variation, more pronounced at TDF, coinciding with the onset of the eruptive event.

Figures 6b and 6c, show the trend of the first six dominant spectral peaks at SLN and TDF stations respectively. It is interesting to point out the lack of significant changes in the SLN diagram, while significant variations in the time distribution of dominant spectral peaks can be observed in the data recorded at TDF station. Two trends with frequency values at 1.0-2.0 Hz and 3.5-4.5 Hz respectively, can be observed in the pre-eruptive period. The approaching of the eruption onset is accompanied by the progressive disappearance of the two distinct trends. Such behaviour is observed from the end of November until December 14th when the two distinct trends can no longer be detected.

Moreover, magnetic recordings at TDF station during the 14th, 15th, and 16th of December were used in order to follow in detail the time evolution of the phenomenon. The spectra, obtained using time windows of 45 min, showed that the spectral dominant peaks at relatively high frequency, detected in the spectra of December 14th, remain at values of about 4.5-5.0 Hz until the afternoon (about 4:30-5:00 p.m.), when lower values (around 1.5 Hz) become dominant (fig. 6d).

Interesting observations were also made by analysing the tremor recorded by the wide-band seismometer in SLN. In fig. 6e, a tendency towards changes in the values of dominant spectral peaks can be observed. Although the lack of continuity in the acquisition of the signal, did not allow the monitoring during the days preceding the onset of the eruption, variations in the spectral dominant peaks, which change from values of 0.8-0.9 Hz, during the pre-eruptive period, to values of 1.2 and 0.2 Hz in the preliminary stages of the eruption (from the 14th to the 16th of December) are quite evident.

3. Discussion

The results so far described, confirm that on Mt. Etna the transition from a pre-eruptive stage to a paroxysmal one is marked by significant modifications in the spectral features of the volcanic tremor. Similar evidence has been found by several authors (Cosentino *et al.*, 1989; Gresta *et al.*, 1991; Cardaci *et al.*, 1993; Montalto *et al.*, 1995). In particular, both the overall spectral amplitude and the spectral dominant peaks undergo significant changes.

Falsaperla *et al.* (1994), processing the seismic signals recorded during the 1991-1993 eruption, found appreciable variations in the temporal distribution of spectral dominant peaks. They observed that higher values of frequencies become dominant soon after the beginning of the eruption, and they explained such a behaviour in terms of «spatial variations of the source».

Our study confirms that besides the changes in the spectral parameters of the tremor, the spectral features of l.f.e. also seem to be modified in relation to the modifications of the volcanic activity. Although no reliable location of such shocks was possible, following Chouet *et al.* (1994), their source is probably confined in the uppermost part of the main feeding dykes.

The observed variation in the decay of the spectral amplitude is not easy to interpret. It can be explained either as due to a change in the location of the source (so that different paths were covered by waves propagating from the source to the recording station), or as a consequence of a variation in the source mechanism of the shocks, or to both the causes. Similarly, the existence of more than one source can be invoked. Unfortunately, the available data do not allow any reliable location of the source and, therefore, it is not possible to point out any hypothetical migration of it. Moreover, we have no evidence that a change in the source mechanism occurred.

As the comparison with spectral features of the tremor points out that changes in the geometry of the source occurred since the end of November 1991, it seems possible that the observed variations in the values of the exponential decay (n) could be related to variations in the geometrical constraints of the source.

All the changes observed in the tremor spectra, indicate a transition from higher to lower values of spectral dominant frequencies as the onset of the eruptive phenomenon was approaching, or in its preliminary stages. This could be interpreted in terms of a «bigger» source that becomes active shortly before and in the early stages of the eruption. We interpret the observed variations in the spectral features of the volcanic tremor as due to the presence of an elongated source that becomes active during the eruptive event. Since volcanic tremor and l.f.e. share the same source, the changes observed in the spectral parameters of l.f.e. could be interpreted in terms of modifications of the source geometry.

4. Concluding remarks

The following brief considerations can be drawn:

1) The start of the 1991-1993 eruption of Mt. Etna was characterized by variations of both the rate of seismicity and the type of shocks. The daily number of low frequency

events, which are linked to the fluid-dynamic processes, did not change sharply before the beginning of the eruption, even though they showed an increase in the occurrence rate in the period preceding the eruption onset. On the other hand, the sudden increment of the rate of shocks linked to shear fracturing marked the opening of the eruptive fractures.

2) Spectral features of l.f.e., and in particular the amplitude decay coefficient (n), appear to be time dependent, showing significant changes as the beginning of the eruption was approaching. We observed that since the first week of December and at the beginning of the eruptive activity, the shocks having values of (n) close to 3.0 became prevalent.

3) The approaching and the early stages of the eruption were characterized by marked variations in the spectral dominant peaks of tremor. Changes from high values of frequency to lower values have been observed, suggesting that an elongated source could be active during the paroxysmal activity of the volcano. The observed changes in the spectral features of both tremor and l.f.e. can then be explained in terms of spatial variation of the source.

Finally, it is important to stress that the use of broadband seismometers and the monitoring of l.f.e. by small arrays of stations located in the topmost parts of the volcano are necessary for a reliable location of the source.

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