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Characteristics of volcanic tremor accompanying the September 24th, 1986 explosive eruption of Mt. Etna (Italy)

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Abstract
Features of the volcanic tremor recorded before, during and after the eruptive event which occurred at Mt. Etna on September 24th 1986, are described. The whole eruption was particularly short in time (about eight hours) and characterized by an extremely violent explosive activity with lava fountains a few hundred meters high. As the complete record of the seismic signals generated during the whole eruptive episode was available, a detailed spectral analysis of the volcanic tremor recorded at four stations, located at increasing distance from the summit of the volcano, was carried out. Fourier analysis, that was performed using temporal windows of about 11 min in duration, pointed to some large fluctuations of the overall spectral amplitude, as well as some frequency variations of the dominant spectral peaks. The ratio of the overall spectral amplitude recorded at the highest station and at the peripheral ones, was calculated in the two spectral bands 1.0-2.5 and 2.6-6.0 Hz, respectively. The significant contribution of energy at low frequency values supports the hypothesis of a subvertical planar source, which was active during the paroxysmal stage of the eruption. Such results are also supported by the analysis of the attenuation function of the spectral amplitude.

Key words *Mt. Etna – summit paroxysmal eruption – volcanic tremor*

1. Introduction

The volcanic activity of Mt. Etna may be divided into persistent activity at the summit craters and flank eruptions. The latter usually involve higher effusion rates and show different styles (*e.g.*, Cristofolini *et al.*, 1988), whereas the former occurs as lava filling within the main conduits, with a low effusion rate (less than 1 m^3/s), or strombolian explosions.

In recent times, the summit craters of Mt. Etna have shown either effusive or explosive activity, spanning from quiet and continuous degassing to violent paroxysmal phases, with lava fountaining and aboundant emission of tephra. A violent explosion occurred on September 24th 1986 in the afternoon, at the NE Crater (fig. 1). The explosion produced a relevant amount of tephra which was spread over a large area in Southeastern Sicily. This event evolved through various phases from a phreatic and phreatomagmatic nature to a frankly magmatic one, thus proving to be a peculiar event in the recent history of Etna.

Volcanic tremor is a common feature of many volcanoes, which has been studied by several authors in the past decades (Kubotera, 1974; Steinberg and Steinberg, 1975; Aki *et al.*, 1977; Seidl *et al.*, 1981; Ferrick *et al.*, 1982; Schick, 1988; Chouet, 1992). Tremor usually shows a non impulsive character, a very shallow source, and mainly occurs on basaltic volcanoes. Moreover, tremor energy usually changes according to volcanic activity.

From an instrumental point of view, a typical feature of tremor is the peaked shape of its

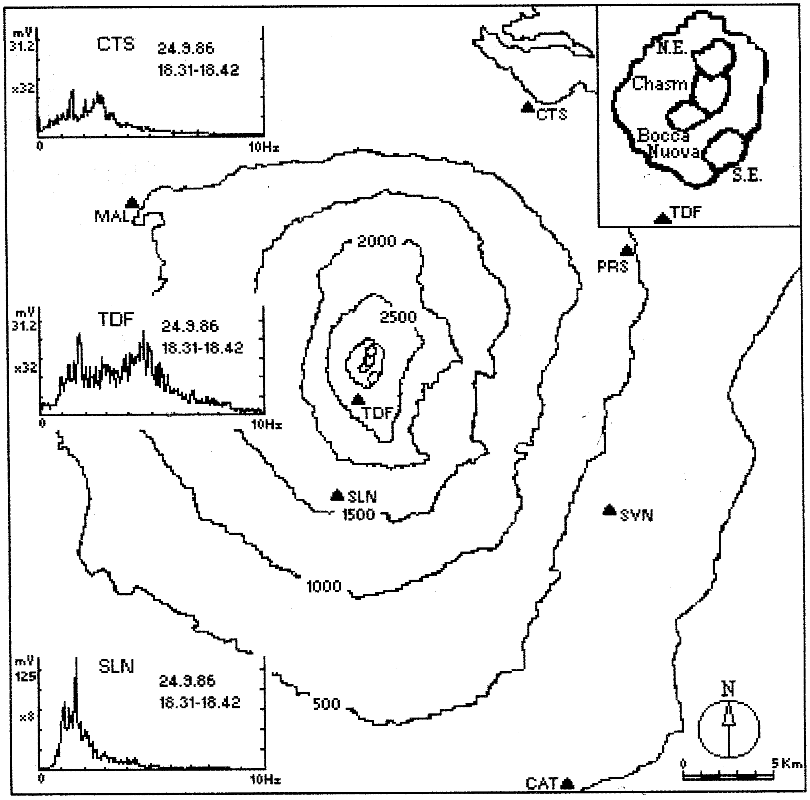

Fig. 1. Sketch of the seismic network at Mt. Etna and examples of tremor spectra simultaneously obtained at the topmost (TDF), intermediate (SLN) and a peripheral (CTS) stations; a map of the summit crater area is sketched in the upper right corner.

spectra. The frequency of dominant spectral peaks sometimes changes in short time intervals (Aki *et al.*, 1977), whereas in other instances, as at Mt. Etna, it remains stable over long time intervals (Riuscetti *et al.*, 1977; Schick *et al.*, 1982).

The main features of tremor at Mt. Etna volcano are its low energy content, the limited frequency range, as well as the stability of the signal during phases of low volcanic activity. The estimated yearly tremor energy release ranges from 10^{12} to 10^{13} Joules (Distefano and Gresta, 1991). Frequency changes of the dominant spectral peaks, prior to flank eruptions have been observed for the majority of recent events (Cosentino *et al.*, 1989).

A physical model for the source of volcanic tremor at Mt. Etna, was proposed by Seidl *et al.* (1981). Turbulent motions in the magma mixture filling the volcanic ducts induce the pipes to behave as oscillators whose frequency of resonance is mainly dependent on geometrical constraints. An analysis of the amplitude attenuation along several profiles, allowed Schick *et al.* (1982) to suggest the existence of two different sources. The former source, characterized by low frequency contents ($f < 1.5$ Hz), should have its origin in a flat magmatic body, located at about 2 km beneath the Central Crater, and a horizontal extent of about 4 km; the latter one, characterized by higher frequencies ($1.0 < f < 6.0$ Hz), is associated with the upper ducts of the active vents (Schick *et al.*, 1982). This source model for tremor is in good agreement with the present features of Etna's volcanic activity during quiet stages of degassing.

On the grounds of the above mentioned model of a hydraulic origin of tremor, some simplified sketch models of Mt. Etna's feeding conduits were proposed (Schick *et al.*, 1982; Cosentino *et al.*, 1989; Gresta *et al.*, 1991).

Furthermore, Ferrucci *et al.* (1990) suggested the existence of an elongated source having a horizontal projection trending north-south and radiating mainly *P*-waves, by studying both amplitude and polarization patterns for tremor episodes during the 1989 eruption. Conversely, Del Pezzo *et al.* (1993) found a high content of surface waves originated by a source located in the summit crater area, using cross-correlation techniques on data collected at a small seismic array during non-eruptive stages.

In the present paper we present a detailed spectral analysis of the volcanic tremor recorded at four different stations during the explosive eruption of September 24th 1986, since the complete record of seismic signals generated during the whole eruption is available.

The relationship between spectral tremor parameters and the time evolution of the eruption will then be treated in order to obtain information on the eruptive dynamics and the features of the feeding system.

2. Chronicle of the September 24th 1986 eruption

The September 24th 1986 was a peculiar summit eruption, since it was very powerful and characterized by a particularly short duration. During September 1986 the NE Crater (see fig. 1) showed a mild strombolian and effusive activity until the 24th, when in the early morning, both a small inner cone and some parts of the internal sides of the crater collapsed into the conduit, obstructing it and leaving a steaming pit about 50 m deep. At the same time a tensional fracture system, 1.5 m wide and trending NNE-SSW, gradually opened on the northern rim of the Bocca Nuova Crater.

Around noon (all reported times are local, GMT + 2 h), some white steam explosions started, with intermittent emission of reddish ash. This activity evolved in a few hours to short periods (around ten minutes long) of quiet emission of brown ash alternating with the expulsion of black ash-laden clouds characterized by cypressoid and columnar shape, which rose up to 200-300 m over the crater.

At about 3:00 p.m. two columns were clearly visible which rose from the crater, one gradually growing white column of steam rising from the south flank of the crater, while a darker brown-reddish plume emerged from a place located some tens of meters further north. Both columns rose many hundred meters above the summit of the crater and were driven southwards by a northerly wind.

At 4:00 p.m. (Lowenstern, personal communication) the ejection of ashes and blocks began at regular intervals from the vent emitting the darker plume. This activity became more and more violent and frequent at about 4:45 p.m., with increasing amounts of expelled blocks, consisting of portions of the collapsed small cone and crater walls.

At roughly 6:00 p.m. the first emission of glowing material was observed, and in about 40 min continuous lava fountains developed amidst a wide column of dark ash rising up to about 600 m above the crater rim. At this time turbulent yellow-brown surges formed at the southern base of the convective steam and ash column, probably due to its collapse and derived from the vent widening (SEAN Bulletin, 1986).

The activity slightly decreased at about 6:30 p.m. until 6:45 p.m., when suddenly the paroxysmal phase started, with lava fountains rising up to about 800-1000 m, and bombs directed south-west. Indeed, whereas till then bombs only fell as far as the external flank of the NE Crater cone, later on they reached an area as far as south-west of the Bocca Nuova Crater (see fig. 1). A dense and dark ash-laden cloud flowed into the Valle del Bove, and very soon the whole south-eastern flank of the volcano was blanketed by an air-fall deposit, with

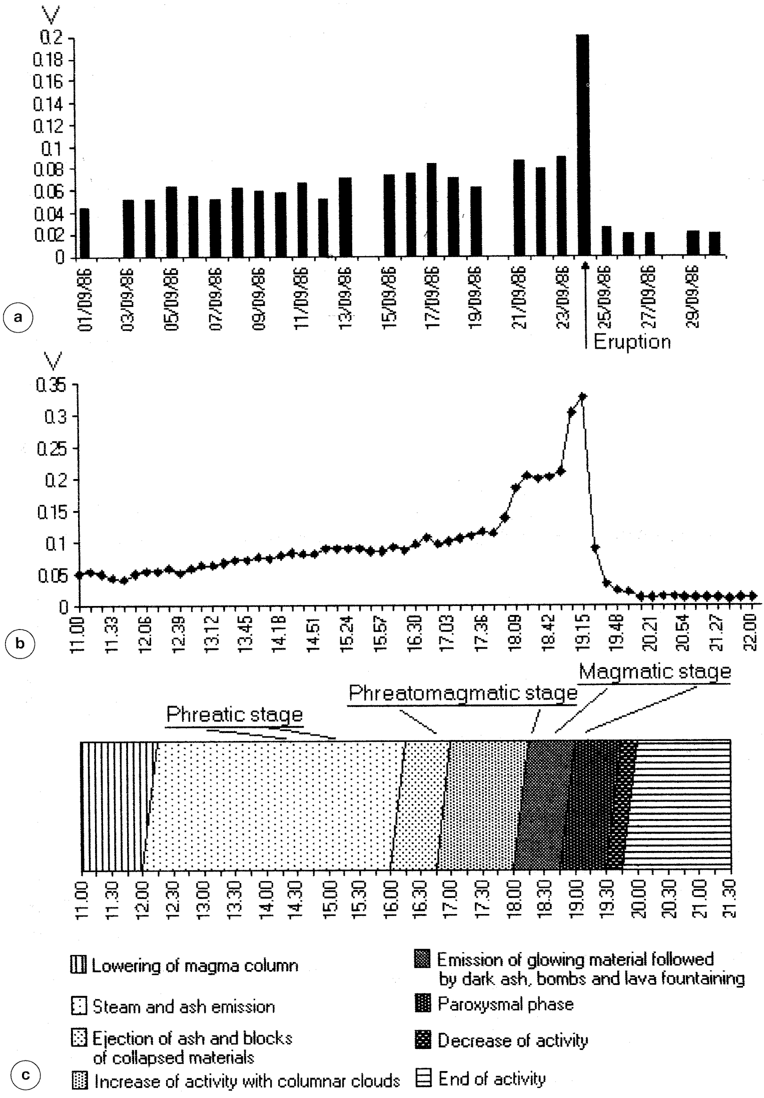

Fig. 2a-c. Trend of the overall spectral amplitude of tremor during September 1986 (a); time evolution of the overall spectral amplitude of tremor (b) and of the eruptive activity, (c) during September 24th.

thickness and grain-size distribution depending on wind direction and distance from the crater (SEAN Bulletin, 1986).

At this stage the sustained column was about 1000 m high and the convective plume rose almost vertical from 5 km up to a maximum of about 10 km above the Mt. Etna summit (Kieffer and Tanguy, 1987), being only slightly displaced by a mild northwesterly crosswind.

The explosive activity significantly decreased at about 7:30 p.m., being completely over 10 min later.

No activity was observed at the Central Crater from September 24th until September 29th, when it started degassing again in the morning.

The SE Crater activity remained unchanged with reference to the previous months, showing only low gas and vapour emission. A more detailed description of the eruption and of the tephra distribution is given by Amore *et al.* (1987).

Figure 2c summarizes the main phases of the eruptive activity which are plotted together with the trend of the overall spectral amplitude of tremor recorded at SLN station during September 1986 (a) and with a blow-up of the eruptive episode (b).

3. Data analysis

The instrumental study of the explosive activity of September 24th at the NE Crater was made by spectral analysis of volcanic tremor.

In the present work, data recorded by four seismic stations, equipped with short period ($T = 1$ s) vertical seismometers (Mark L4-C), and telemetered to Catania University, were used.

Figure 1 shows the location of the seismic stations together with three samples of tremor spectra obtained from the signals simultaneously recorded during the paroxysmal phase. The complete set of the seismic signals recorded before, during and after the eruptive

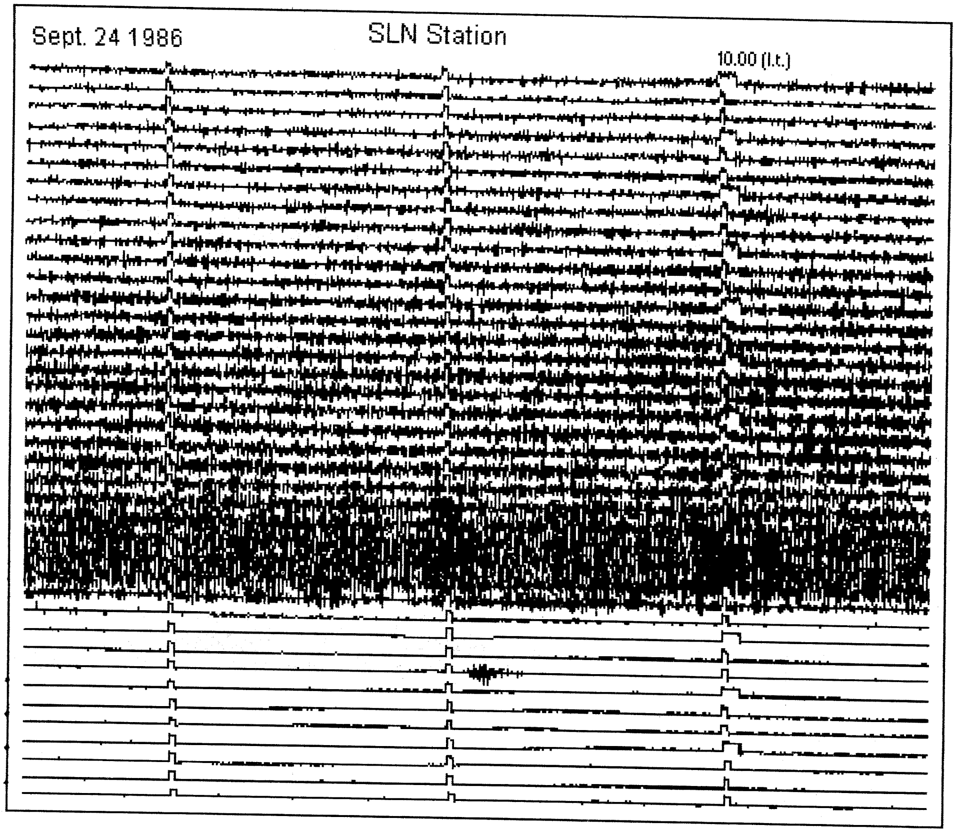

Fig. 3. Seismogram recorded on September 24th 1986 at SLN station, showing the seismic features of the complete eruptive phenomenon (spacing between seismogram lines is 20 min, and time marks at 60 s).

event (see, for example, fig. 3) was processed. Spectral analyses were performed by means of an FFT (Fast Fourier Transform) algorithm, using a spectrum analyzer having 400 resolution lines and a digital filter with Hanning windowing, which also gives the summation of the 400 line amplitudes (overall spectral amplitude).

Analyses were made in the frequency range 0.5-10 Hz, with a frequency resolution of 0.025 Hz. Time series with a length varying from about 11 min to about 3 h were used so that a number of independent spectra ranging from 16 to 256 were averaged in order to obtain the final spectrum. The time series having a length of about 11 min proved to be a good compromise between the stability of the signal and the possibility to analyze in detail the time evolution of the eruptive phenomenon.

In fig. 4a,b, the values of the overall spectral amplitude and the frequencies of the first three dominant spectral peaks of the tremor recorded at the considered stations, are plotted versus time. Significant fluctuations can be ob-

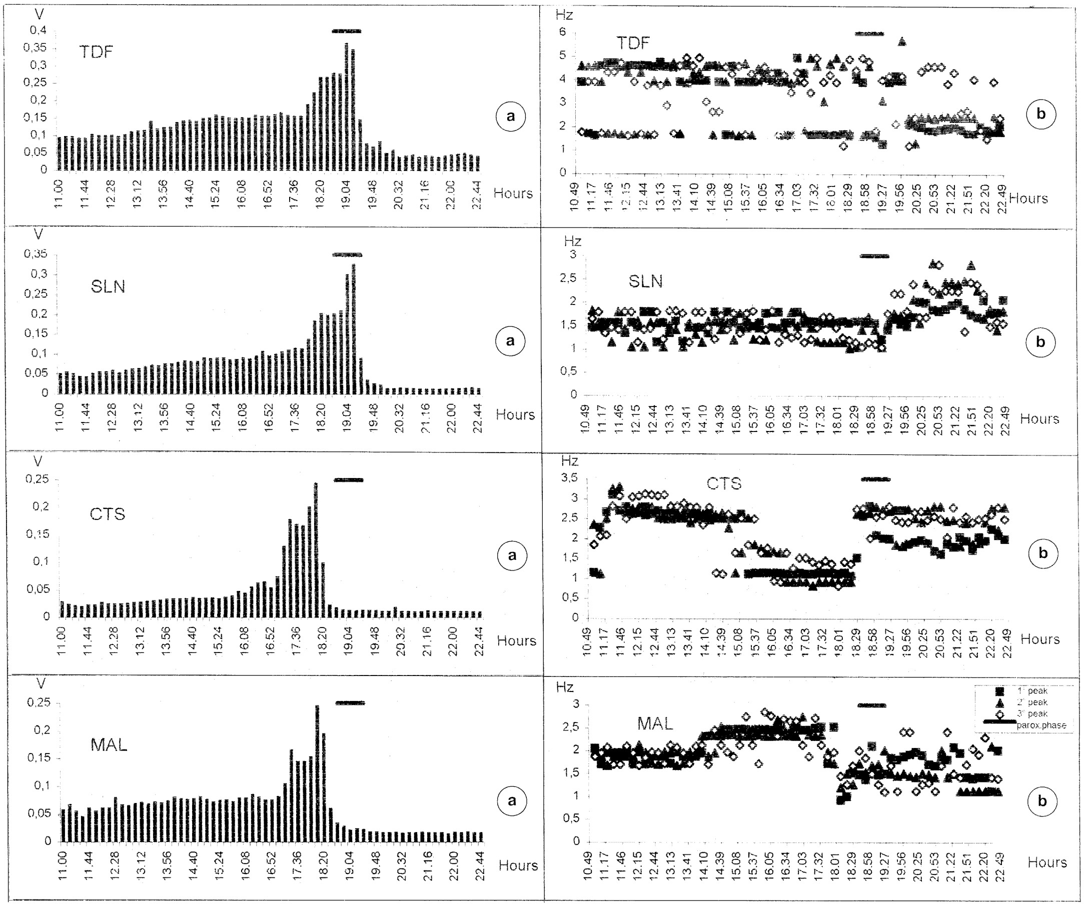

Fig. 4a,b. Overall spectral amplitude (a) and dominant spectral peaks (b) in the tremor signal recorded at four stations during the eruption. The horizontal bar marks the occurrence of the paroxysmal phase.

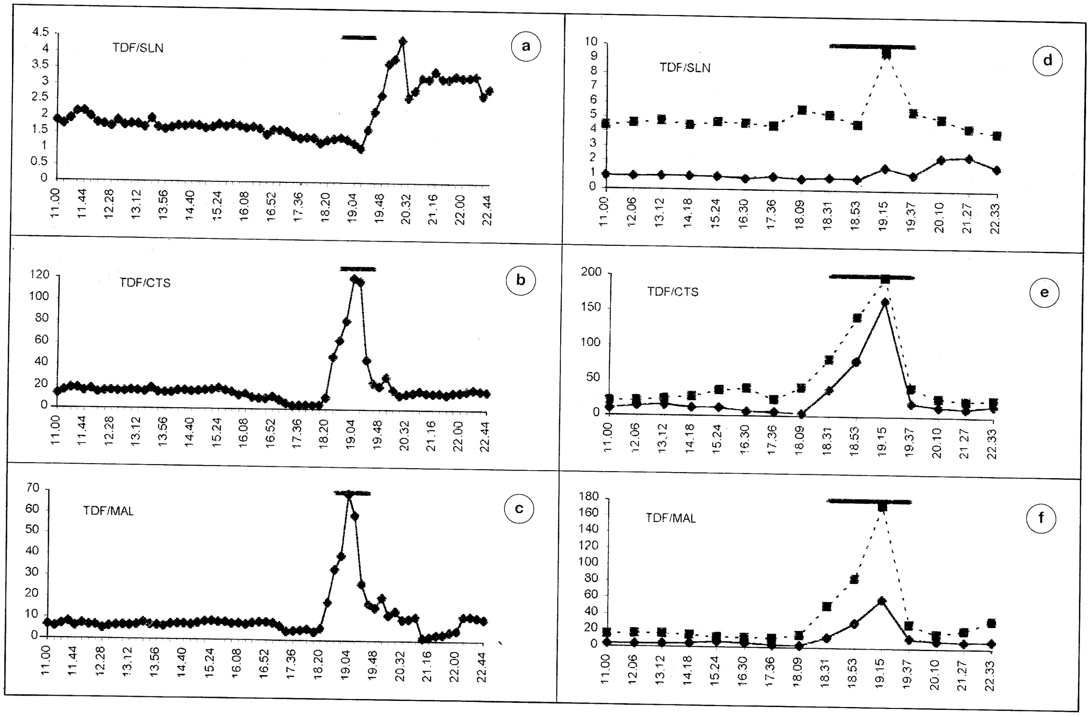

Fig. 5a-f. Ratio of the overall spectral amplitude at the topmost station (TDF) with respect to other ones; (a-c) in the whole spectral band, and (d-f) in the two frequency bands 1.0-2.5 Hz (continuous line) and 2.5-6.0 Hz (dashed line). The horizontal bar marks the occurrence of the paroxysmal phase. For figures d-f the time scale was expanded in the interval 18:00-20:00.

served at all stations, and it is worth noting that the wider fluctuations are more evident in the peripheral ones (CTS and MAL). Moreover, both the increase in the overall amplitude and fluctuations in the spectral dominant peaks occurred at the peripheral stations almost one hour before that the same variations were observed at the stations located closer to the summit area. We are not able to give a reasonable interpretation of this observation.

In the latter couple of stations (SLN and TDF), such variations practically coincide in time with the occurrence of the paroxysmal stage of the eruption (6:30-6:45 p.m.). This observation is also shown in fig. 5a-c, where the ratio of the overall spectral amplitude at the highest station (TDF) with respect to the other ones is plotted versus time. The ratio calculated both in the spectral area ranging from 1.0 to 2.5 Hz and 2.6-6.0 Hz is particularly interesting (see fig. 5d-f). High frequency values are typically observed at the station TDF, which is closer to the NE Crater, and their contribution is less evident at distant stations. It is remarkable that when the paroxysmal stage is reached, the ratio associated with the higher frequencies increases in all stations (fig. 5d-f), except the TDF/SLN ratio. Indeed, such values are almost constantly around 1, due to an anomalously high amplitude at SLN station. We suggest the activation of a source contributing to lower frequency values, close to such station, during the paroxysmal eruptive phase. This hypothesis is also supported by the time evolution of the overall amplitude decay at increasing distance from the NE Crater.

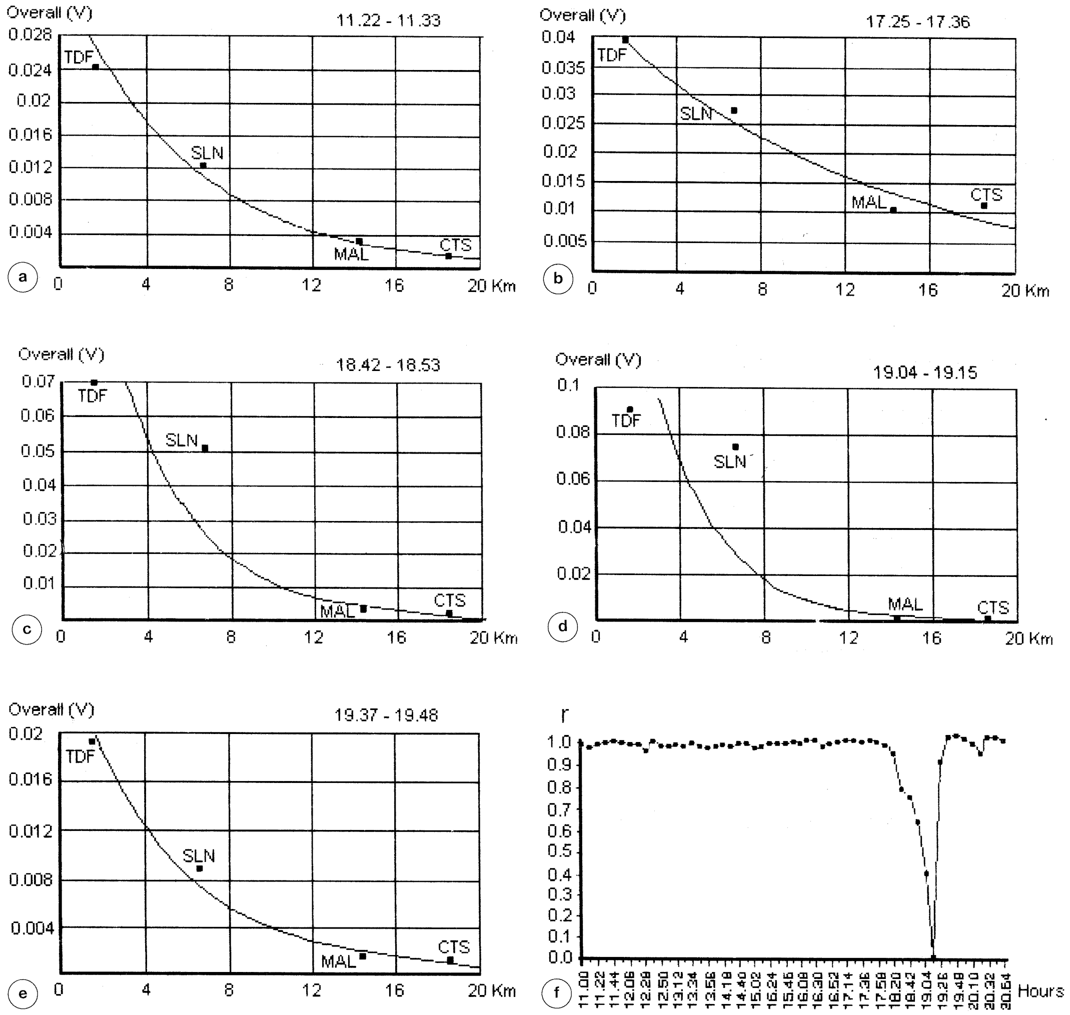

Fig. 6a-f. Overall spectral amplitude *vs.* distance NE Crater-seismic stations. Examples in the time interval before (a,b), during (c,d) and after (e) the paroxysmal phase of the eruption, and corresponding time variation (f) of the fit correlation coefficient *r* (see text for details).

Figure 6a-e gives some examples during the evolution of the eruptive activity. It can be observed that the fit with a negative exponential curve is quite good, except during the paroxysmal phase (fig. 6c,d). During this stage, the previously mentioned anomalous behaviour at SLN station strongly affects the correlation coefficient *r* which, therefore, dramatically drops (fig. 6f).

4. Discussion and conclusions

From the data exposed above, some points look relevant for the discussion:

1) the mild strombolian and effusive activity at the NE Crater abruptly came to an end in the early morning of September 24th, and the upper part of the feeding system collapsed,

apparently because magma was suddenly drained off the conduits;

2) the weak activity at the Central Crater also ceased at the same time;

3) a small tensional fracture system gradually opened before and during the eruption, trending NNE-SSW to NE-SW on the northern rim of the Bocca Nuova Crater (see fig. 1);

4) the activity at the NE Crater gradually resumed, starting late in the morning of September 24th, and evolving from voluminous steam exhalation through increasingly violent steam-reach explosions ejecting only lithic fragments to more and more continuous lava fountains, that reached their climax late in the evening of the same day, and then suddenly stopped.

Both volcanological observations and tremor data indicate that this eruption developed into three stages: a phreatic activity involving steam from ground water and minor accessory ejecta (from about noon to 5:30 p.m.), a phreatomagmatic phase, until 6:00 p.m., characterized by the increase in tremor amplitude values and a magmatic one, marked by strong lava fountaining and the maximum tremor amplitude.

The observations and the results described so far show that magma within the central feeding system was suddenly drained off the conduits connected to the NE Crater. The magma was probably drained by the opening of NE-SW trending fissures, which intersected the craters. No significant earthquakes were recorded, probably because such fracture system was pre-existing and was only reactivated.

At the same time, the topmost part of the NE Crater conduit collapsed, probably due to the sudden lowering of the magma column, while phreatic water, existing within the volcanic edifice next to the aforementioned conduit, had access into the feeder fractures. The phreatic water poured into the obstructed conduit should have been suddenly heated and consequently vaporized. The steam, mixed to magmatic gases emanating from the fresh magma, should have given rise to an increasing pressure, that as soon as it overcame the strength of the obstructing plug, expelled it together with portions of the conduit walls, by repeated and violent explosions.

This phase of the eruption, characterized by an increasing occurrence rate of the explosions, was instrumentally marked by the progressive increase in the overall tremor amplitude. It may be considered of phreatic nature, because magma was not taking part in the explosive activity, as only the ejection of lithic material, derived from the collapse of the inner small cone and part of the NE Crater walls, was observed.

We suggest that the sudden reopening of the obstructed vent decreased the pressure and favoured the rising up of the magma column, that intercepting and vaporizing the infiltrated phreatic water, produced a significant increase in its total vapour pressure. The violent explosions which occurred from about 4:45 until 6:00 p.m., giving rise to cypressoid and columnar steam clouds loaded with pyroclastic products, are therefore attributed to a phreatomagmatic mechanism. During this second phase, both a sharp increase in the overall tremor amplitude and significant changes in the spectral dominant peaks were observed, unaccountably starting earlier at the peripheral stations.

The third stage of the eruption, the magmatic one, developed from about 6 p.m. when the first incandescent ejecta were observed and evolved towards the paroxysmal phase (6:45-7:00 p.m.), characterized by lava fountaining. The seismic signals show the highest values of the overall tremor amplitude and variations in the ratio of the tremor amplitude recorded at the topmost station and at the peripheral ones, as well as in its distribution among the various frequency bands. The ratio of spectral amplitude observed at TDF and SLN stations during this stage did not significantly change in the range 1.0-2.5 Hz. This leads us to hypothesize the existence of a significant energy contribution also by deeper sources, or in other words by a planar subvertical source.

Investigations performed using a small array of three component portable stations have shown that the source of volcanic tremor during quiet periods is confined to the shallowest upper part of the volcano (Del Pezzo *et al.*, 1993). Conversely, Ferrucci *et al.* (1990) proposed a deeper subvertical source, whose horizontal projection trends about N-S, as active during the paroxysmal eruptive episodes at the SE Crater in 1989.

Our results could be explained adopting a similar source model. It seems indeed quite resonable that a planar vertically extended source could be responsible for both the anomalous behaviour of the spectral amplitude decay at SLN station, and the significant energy contribution at low frequency values during the paroxysmal phase of the eruption.

Nevertheless, a recent study (Montalto *et al.*, 1995) showed that the spectral characteristics of volcanic tremor at Mt. Etna strongly depend on the physical properties of magma, as its density and degree of gas exsolution. These parameters were probably changing during the various stages of the studied eruption, suggesting that further detailed investigations are needed for a better understanding of the mechanisms of summit paroxysmal eruptions at Mt. Etna volcano.

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