ANNALI DI GEOFISICA, VOL. XXXIX, N. 2, March 1996

Analysis of the intermittent volcanic tremor observed at Mt. Etna, Sicily during March-May 1987

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Abstract
Volcanic activity at the summit craters of Mt. Etna includes phreatic eruptions which jeopardize tourists and other people who sporadically approach the top of the volcano. To date no appreciable precursors of this kind of activity are known. Solely intermittent volcanic tremor might be considered a short-term seismic forerunner. The pattern of volcanic tremor amplitude at Mt. Etna during springtime 1987 was investigated and revealed significant periodicities before both phreatic explosions occurring at the summit craters during that time span. Results are in agreement with a boiling mechanism as the source of intermittent volcanic tremor, even if the lack of data on the ground water table in the upper part of the volcano did not allow the formulation of quantitative models.

Key words *Mt. Etna – intermittent volcanic tremor – phreatic eruptions*

1. Introduction

Volcanic tremor is a seismic signal observed in coincidence with eruptions and continuously in open conduit volcanoes characterized by persistent activity. Tremor was investigated by means of analyses in time, frequency and space domains, and many papers report features of this seismic signal at volcanoes throughout the world (*e.g.*, Dibble, 1974; Aki *et al.*, 1977; Fehler and Chouet, 1982; Fehler 1983, Hofstetter and Malone, 1986; McNutt, 1986, 1987; Chouet *et al.*, 1987; Koyanagi *et al.*, 1987; Schick, 1988; Ferrazzini *et al.*, 1991; Power *et al.*, 1994), including Mt. Etna (*e.g.*, Schick and Riuscetti, 1973; Guerra *et al.*, 1976; Riuscetti *et al.*, 1977; Seidl *et al.*, 1981; Cosentino *et al.*, 1989; Ferrucci *et al.*, 1990; Gresta *et al.*, 1991; Del Pezzo *et al.*, 1993; Falsaperla *et al.*, 1994; Napoli *et al.*, 1994). All results evidenced a relationship between tremor and eruptions.

At present, several aspects of volcanic tremor are substantially unknown and detailed studies need to achieve an exhaustive characterization of its physical characteristics.

The literature reports intermittent phenomena in tremor amplitude increase and decrease for some volcanoes and several geysers (*cf.*, McNutt, 1992, 1994). They are characterized by many transient episodes of increased tremor amplitude, followed by quiescent periods. It is interesting that records collected worldwide often look very similar, despite the different geology, petrology and tectonic environments. Volcanic tremor assumes a very regular and rhythmic pattern, so that a two phase cycle characterized by an almost constant period can be recognized. The term «banded tremor» is often used (*i.e.*, Barberi *et al.*, 1992; McKee *et al.*, 1981; Kieffer, 1984; McNutt, 1992; 1994) to identify this phenomenon and comes from

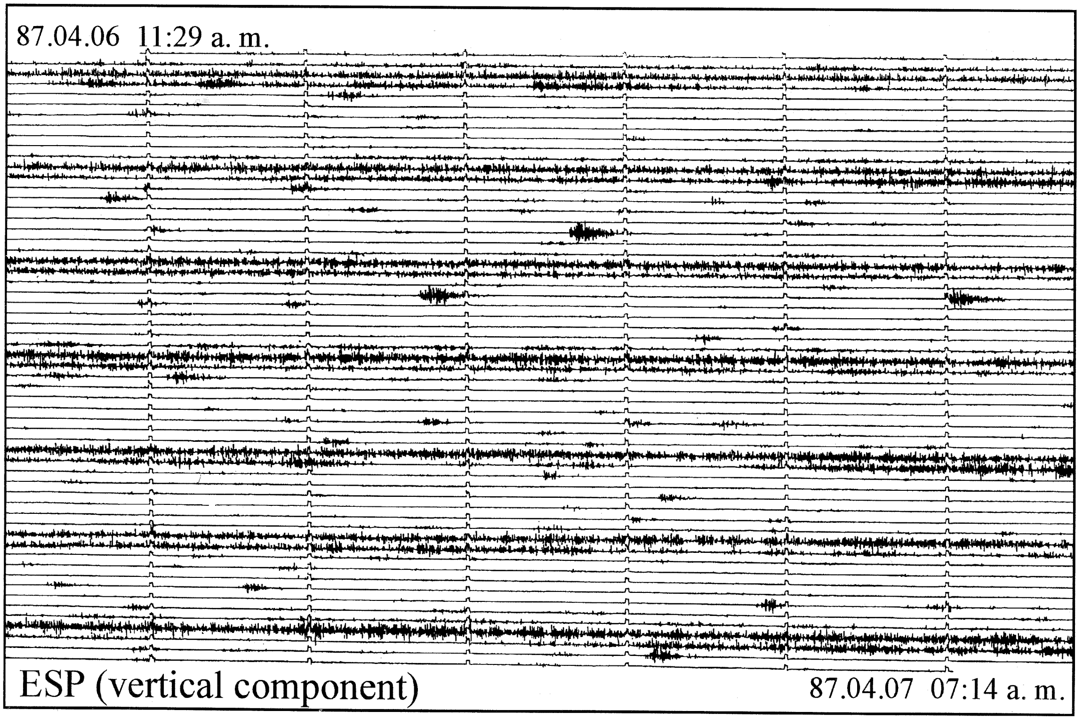

Fig. 1. Example of IVT recorded by the ESP seismic station. Spacing between seismogram lines is 20 min, between time marks 1 min.

the seismic signature on seismograph drum records forming evident stripes on seismograms. Figure 1 shows an example recorded at Mt. Etna during the time span investigated in this paper. Obviously, the apparent banded features of the signal depend on the drum revolution time, and are not related to the intermittence (and/or periodicity) of the signal. Therefore the definition Intermittent Volcanic Tremor (IVT) might be more appropriate.

During IVT episodes observed on other volcanoes, time durations of bursts (increased tremor amplitude) vary from 1 min (Ulawun and Galeras) to about 2 h (Klyuchevskoy), while periods between the end of a burst and the onset of the next one range from 3 min at Kilauea to about 6 h at Klyuchevskoy (McNutt, 1992, 1994). As many IVT episodes occurred during periods of hydrothermal activity, marked analogy between IVT source mechanisms and those ruling a geyser system was postulated. The appropriate study by Kieffer (1984) is very impressive; IVT phenomena which occurred (McKee *et al.*, 1981) during a fatal hydro-eruption of Karkar volcano (Papua, New Guinea) were very similar to signals recorded near the Old Faithful Geyser (Yellowstone, Wyoming). At Nevado del Ruiz, IVT episodes were observed before phreatic eruptions (Martinelli, 1990) and their shallowness was explained by a hydrothermal boiling mechanism (Gil Cruz *et al.*, 1987). McNutt (1994) gives a complete list of worldwide observed IVT, and related volcanic activity. At Mt. Etna some IVT episodes were previously reported and associated with paroxysmal magmatic eruptions (Privitera *et al.*, 1989).

This paper focuses on springtime 1987 when two main phreatic explosions occurred at the summit craters of Mt. Etna in coincidence with apparently regular and periodic bursts of tremor (Lombardo *et al.*, 1987). We analyzed a three month time series of volcanic tremor amplitude in order to understand its evolution and reveal any relationships between volcanic tremor and summit crater activity.

2. Data analysis

The analysis was performed in the period March 1-May 31, using data recorded at Serra Pizzuta Calvarina station (ESP, fig. 2a). This station was equipped with a three component short period (1 s) seismometer and analogic radio link with Istituto Internazionale di Vulcanologia in Catania where signals were recorded on paper by a drum with a revolution speed of 1 mm/s. This station was chosen because it was the nearest to the summit area that ran almost continuously throughout the analyzed period. Unfortunately, no magnetic records are available for stations operating on Mt. Etna at that time, and this hinders the application of more refined techniques of analysis.

After the end (February 27, 1987) of a four month subterminal eruption from SE Crater (see fig. 2b), weak activity (gas and steam emission) was observed at the summit craters throughout March. The amplitude of volcanic tremor showed a stationary low level during the same time interval.

IVT commenced as from April 1 and the increase in volcanic tremor amplitude lasted about one hour (fig. 1), and was repeated 43 times until April 7. In the first two days the time interval between two bursts gradually decreased from *ca.* 8 to *ca.* 3 h, remaining almost stationary at 3 h for the following six days. Subsequently IVT vanished in concomitance with a phreatic explosion at the Bocca Nuova Crater (fig. 2b). IVT renewed on April 13, even if the time lapse between two cycles ranged between *ca.* 2 and *ca.* 11 h. The phenomenon ended on April 21 and 24 bursts were observed. On April 17 a phreatic eruption occurred at the SE Crater (fig. 2b) killing two people and injuring seven others about 500 m from the crater. Visual inspection of seismograms clearly showed the independence of the

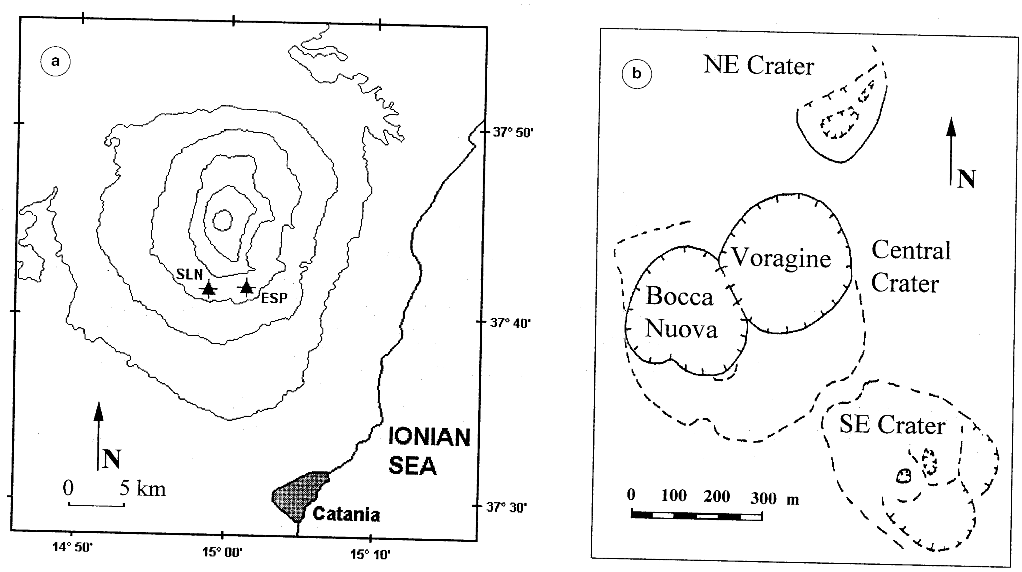

Fig. 2a,b. a) Sketch map of Mt. Etna (contour lines each 500 m) with seismic stations used in the present analysis; b) topography of the summit craters area in 1988 (redrawn from Calvari *et al.*, 1989).

IVT cycle duration respect to the amplitude of the signal. It is noteworthy that both periods (April 1 to 7, and 13 to 21) presented almost the same overall IVT duration (*ca.* 168 h), in spite of the different patterns and the different craters where phreatic eruptions occurred.

No regular tremor amplitude patterns were recognized until May 1, when weak, discontinuous strombolian activity was observed simultaneously at both the Bocca Nuova and SE Craters. In May, volcanic tremor amplitude showed a stationary pattern, while weak activity occurred at SE Crater (a detailed description of the volcanic activity occurring during this time span was given by Calvari *et al.*, 1989).

Peak-to-peak amplitude of the seismogram was sampled every ten minutes for the whole 3 month period, and 13248 samples were collected. The zero level corresponds to the trace amplitude (0.5 mm) during periods characterized by nil tremor; the resolution is 0.5 mm. The few gaps in data collection (ranging from 1 to 14 h) were filled with records from Serra la Nave station (SLN, fig. 2a). Data collected at the two stations were normalized taking into account their amplitude ratio and gain levels.

Daily FFT spectra were performed in order to investigate significant periodicities. They were found only during the time interval April 4-18 (see table I). In detail, a periodicity of around 180 min was found on April 4, 5 and 6, confirm-

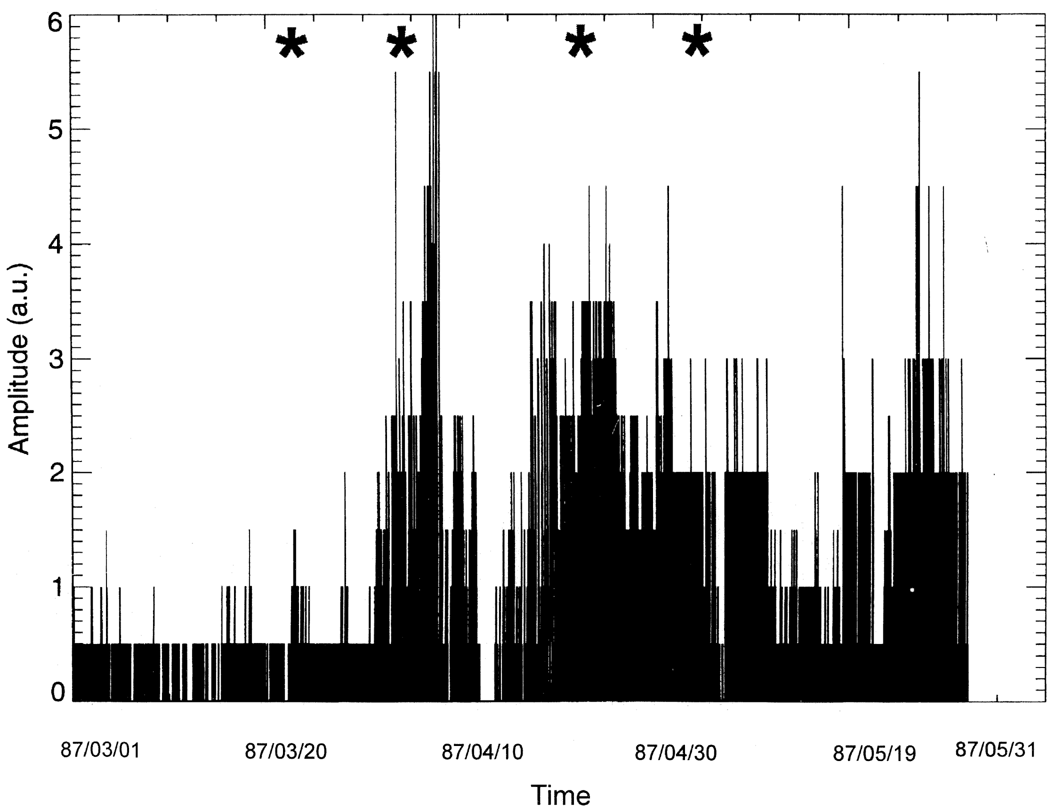

Fig. 3. Volcanic tremor amplitude at ESP station during the period March 1-May 31, 1987. Asterisks indicate the change points of the whole time series (see text).

Table I. Values of significant (s.l. < 0.0001) periodicity peaks observed on daily tremor amplitude spectra for the whole period March-May 1987.

April 04	200
April 05	170
April 06	160
April 10	480
April 13	480
April 14	480
April 15	480
April 16	200-360-480
April 17	480
April 18	170-360

ing the above results of the visual inspection for the first IVT. Since April 10 the 480 min periodicity appeared to be very stable, until April 18.

In order to objectively identify different patterns of the whole time series, Kolmogorov-Smirnov two sample-statistics (*i.e.*, Mulargia *et al.*, 1987) was used. This method, when it is applied in consecutive steps, first identifies the main change point (CHPT), and then all the others. Four CHPTs (March 21, April 1, April 18 and May 1) were identified in our data set, dividing the whole time series into five intervals (see fig. 3) with different characteristics.

The third identified period (April 2-18) includes: i) the occurrence of the two phreatic eruptions (see fig. 4), ii) the two observed IVT

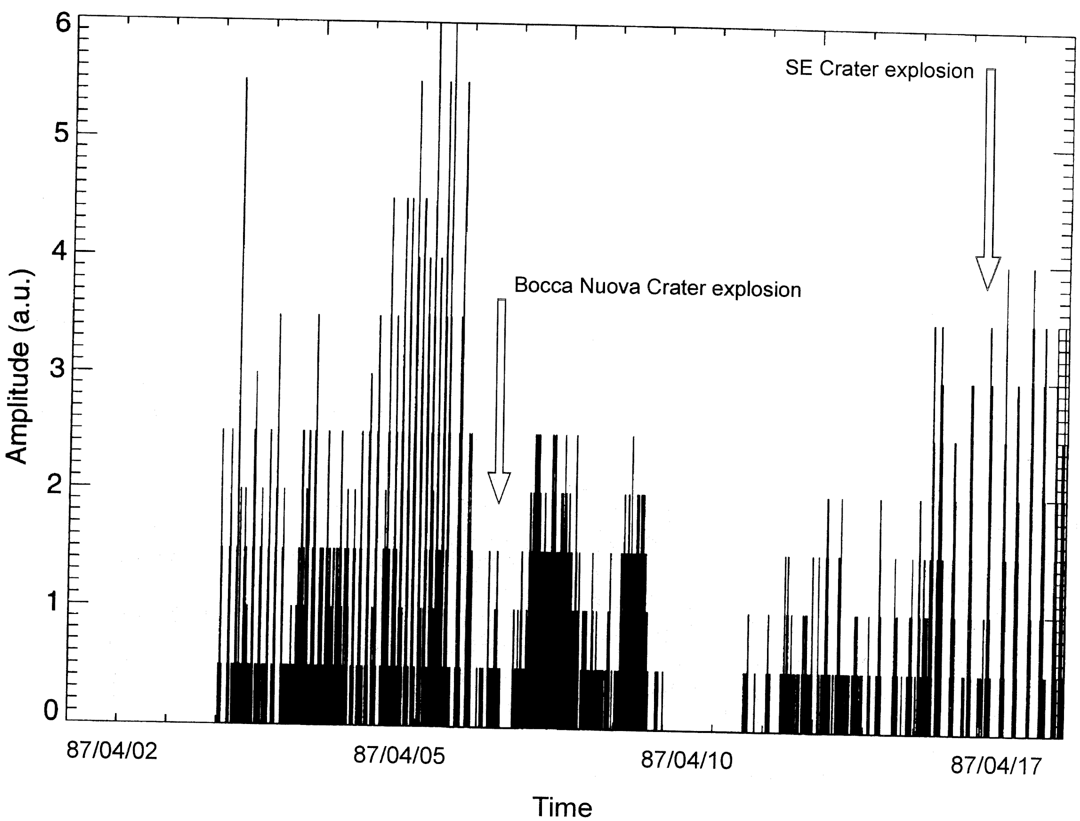

Fig. 4. Detail of fig. 3 for the time period April 1-20. Arrows indicate the occurrence of phreatic explosions.

Table II. Values (in minutes) of the autocorrelation and FFT significant (s.l. < 0.0001) peaks for the five time intervals identified by CHPT analysis (see text for details).

Period	Autocorrelation	FFT
March 01 - 21	60 - 100 - 440	–
March 22 - April 01	110 - 150 - 420	–
April 02 - 18	110 - 180 - 280	160 - 190 - 420 - 520
April 19 - 30	180 - 380 - 450 - 630	–
May 01 - 31	30 - 270 - 300 - 370 - 690	–

episodes; iii) all days characterized by significant periodicities recognized by the daily FFT spectra (see table I). Finally, after removing trends from the whole time series, both autocorrelation and FFT analyses were performed for the five identified periods. Contrasting results were obtained (see table II), even if it is noteworthy that, in agreement with the above results from daily spectra, significant FFT peaks were found only for the period April 2-18.

3. Discussion and conclusions

During the time span March-May 1987 the volcanic activity of Mt. Etna was mainly characterized by weak strombolian explosions and gas emissions but two moderate phreatic eruptions occurred on April 8 and 17 at Bocca Nuova and SE Crater, respectively (fig. 2b). We have focused our attention on these two blasts, observing that they were accompanied by so-called «banded tremor», which we call Intermittent Volcanic Tremor (IVT). This finding agrees with data collected worldwide (Barberi *et al.*, 1992). Episodes of IVT are usually explained by the hydrothermal boiling mechanism (*i.e.*, McNutt, 1992) which requires the presence of magma in the upper part of the volcano playing only the passive role as heat source for shallow ground water. In fact, boiling occurs when the temperature of a parcel of water reaches the appropriate condition at a given pressure, so a two-phase liquid-vapor mixture is generated and convection starts within the aquifer. Under favorable conditions for the acoustic impedance between boiling water reservoir and surrounding rocks, mechanical energy can be transmitted as seismic waves, and tremor recognized (Kieffer, 1984). If the increased pressure in the aquifer is inadequately dissipated, the aquifer itself will behave like a pressure-cooker, continuously increasing both pressure and heat. This will induce the boiling to stop. If overpressure is discharged (as for example by the opening of local hydraulic fractures), boiling (and consequently tremor) resumes. Conversely, when the steam pressure exceeds the overburden of the top of the aquifer, a phreatic explosion will occur.

The CHPT analysis (Mulargia *et al.*, 1987) performed on the whole three month tremor amplitude time series evidenced five periods. The third one (April 2-18), was characterized by the occurrence of two phreatic eruptions and a couple of IVT episodes. Both autocorrelation and FFT analyses evidenced, during this time interval, enhanced significant periodicities (see tables I and II), confirming that the two observed IVT episodes were characterized by different features. A remarkable decrease in the periodicity trend occurring at the beginning of the first IVT (April 2-7) was followed by a constant periodicity of about 180 min. In contrast, the second IVT episode (April 13-18) did not show a regular trend, whereas periodicity ranged from 170 to 480 min (see also table I). This observation together with the different locations of the two phreatic eruptions, led us to postulate boiling mechanisms with different regimes between the two episodes.

The IVT phenomena which occurred at Mt. Etna volcano resemble those previously observed on several volcanoes, such as Karkar (McKee *et al.*, 1981) and Nevado del Ruiz (Martinelli, 1990); the related volcanic activity revealed the presence of great amounts of steam (phreatic and phreato-magmatic explosions). The postulated boiling mechanism requires both water and steam in the shallower summit part of the volcano. This may also be influenced by the melting of the snow in springtime and the consequent infiltration of water. In such a way, geyser mechanisms can be generated (*i.e.*, a confined water reservoir refilled at constant rate and/or particular settling in the conduit geometry requirements). Unfortunately, good-quality data on time variation of the water table level are not currently available, hindering quantitative approaches to the problem.

The end of IVT episodes was marked by a renewal of strombolian activity at the summit craters. We suggest that the uprising of the magma column in the summit plumbing complex may have modified the geometry and/or the thermal state in the shallow hydrothermal system, thus inhibiting further boiling mechanisms.

Acknowledgements

This work was supported by the Gruppo Nazionale per la Vulcanologia-CNR. We would like to thank Dr. Vincenza Longo for technical support in collecting data.

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