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Statistical analysis of intermittent volcanic tremor associated with the September 1989 summit explosive eruptions at Mount Etna, Sicily

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Abstract

The pattern of volcanic tremor accompanying the 1989 September eruption at the south-east summit crater of Mount Etna is studied. In specific, sixteen episodes of lava fountaining, which occurred in the first phase of the eruption, are analysed. Their periodic behaviour, also evidenced by autocorrelation, allows us to define the related tremor amplitude increases as intermittent volcanic tremor episodes. Focusing on the regular intermittent behaviour found for both lava fountains and intermittent volcanic tremors, we tried an a posteriori forecast using simple statistical methods based on linear regression and the Student' *t*-test. We performed the retrospective statistical forecast, and found that several eruptions would have been successfully forecast. In order to focus on the source mechanism of tremor linked to lava fountains, we investigated the relationship between volcanic and seismic parameters. A mechanism based on a shallow magma batch 'regularly' refilled from depth is suggested.

Keywords: Mount Etna; lava fountain eruption; volcanic tremor; statistical a posteriori forecast

1. Introduction

Mount Etna, located in Eastern Sicily (Fig. 1), is one of the most active volcanoes in the world. Its activity may be roughly divided into (i) persistent activity at the summit craters and (ii) lateral eruptions. The latter develop from fractures that open on the slopes of the volcano, giving rise to lava fields up to several square kilometres. These eruptions have duration spanning from days to years. The former includes several levels of emission of products, from quiet degassing to lava fountains (i.e. Cristofolini et al., 1988).

Volcanic tremor is a phenomenon characteristic of most volcanoes, which is generally correlated with their activity (e.g. Dibble, 1974; Aki et al., 1977; Fehler and Chouet, 1982; Hofstetter and Malone, 1986; McNutt, 1994; Chouet et al., 1987; Koyanagi et al., 1987; Julian, 1994; Beniot and McNutt, 1997). It is also present at Mount Etna, where it has been studied for decades. These studies focused on either the source (e.g. Schick and Riuscetti, 1973; Riuscetti et al., 1977; Seidl et

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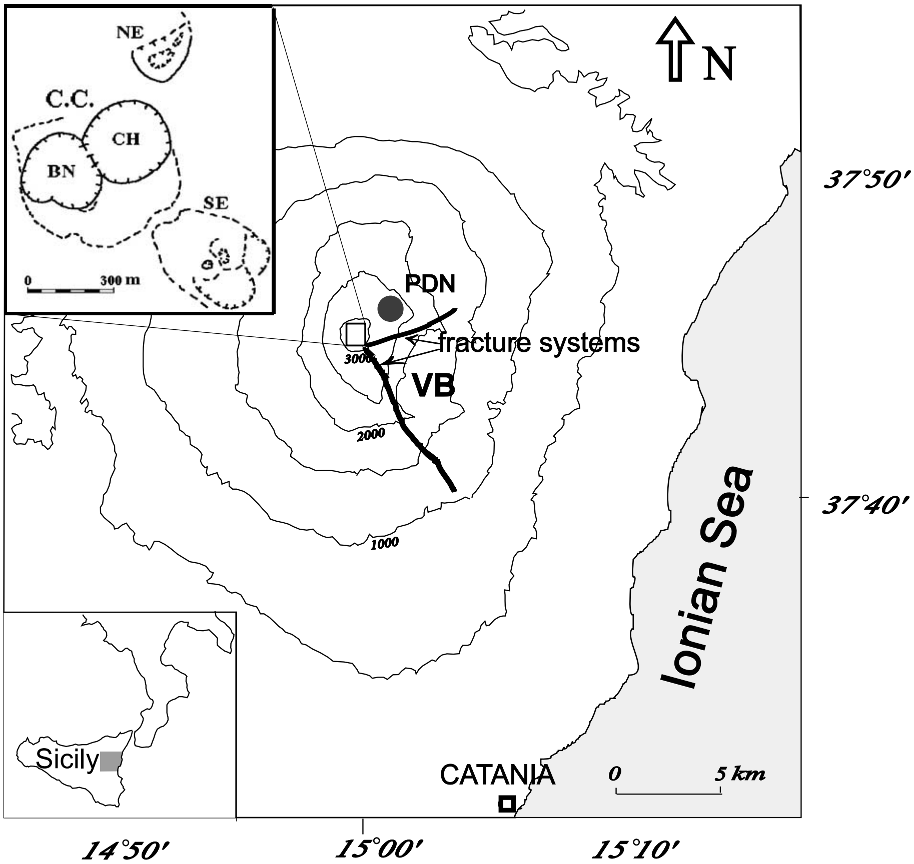

Fig. 1. Sketch map of Mount Etna with location of the seismic station (dot) used in this work and of the two fracture systems opened in September 1989 (see text for details). VB is the 'Valle del Bove' caldera. In the upper left corner insert the detail of the summit craters is shown; SE = South-east Crater, NE = North-east Crater, C.C. = Central Craters (in details CH = Chasm and BN = Bocca Nuova).

al., 1981; Schick et al., 1982; Ferrucci et al., 1990; Del Pezzo et al., 1993) or the relationship with volcanic activity (e.g. Tanguy and Patanè, 1984; Cosentino et al., 1989; Gresta et al., 1991, 1996a,b; Falsaperla et al., 1994).

In detail, Schick and Riuscetti (1973) proposed that tremor energy is correlated with the velocity of gases escaping through the summit crater conduits. The observed steadiness of the frequency peaks can be related to at least one oscillator, excited by gas bubbles uprising in the magma (Riuscetti et al., 1977). A physical model for the source was then proposed (Seidl et al., 1981), and oscillators have been identified with the pipes along which magma rises. Schick et al. (1982) distinguished two different sources, one of which originated in a flat magma chamber, located ca 2 km beneath the Central Craters, while a second was associated with the upper portion of the active vents.

Moreover, investigations performed during moderate degassing activity showed that the tremor source is confined to the shallowest upper part of the volcano. The signals, recorded at a distance of few hundreds of metres from the craters, appear as an almost continuous vibration mainly due to surface waves (Del Pezzo et al., 1993), while polarisation analysis on the seismic wavefield recorded at only 50 m from the summit craters indicated the presence of P-waves during vigorous strombolian activity. Specifically, it was generated by the superposition of small shallow

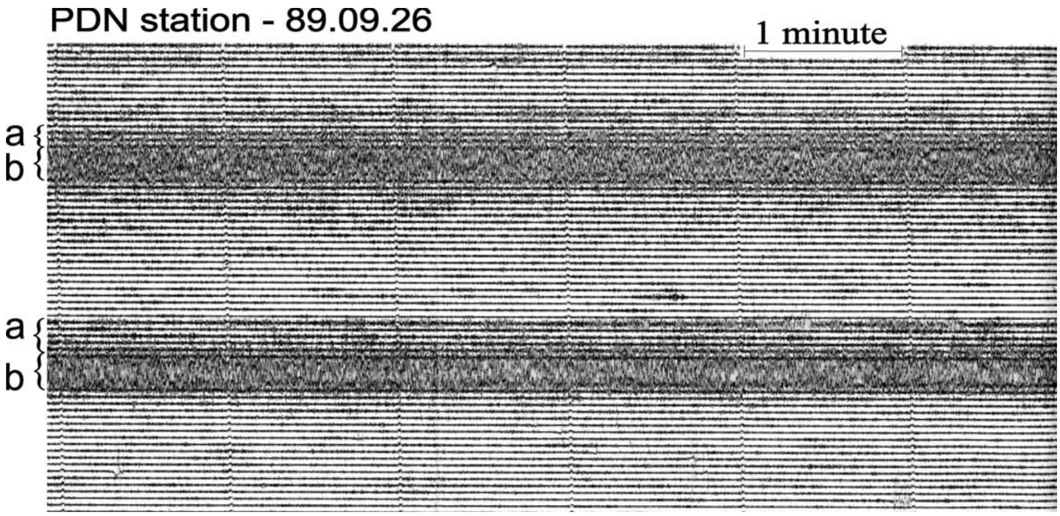

Fig. 2. Seismogram showing two typical periods of IVTs occurring in coincidence with two lava fountain episodes at the Southeast Crater. For each IVT episode a and b represent the onset and the paroxysmal phases, respectively.

point sources, acting at intervals of ∼2 s, as a consequence of degassing at the top of the magma column (Ripepe et al., 2001). Conversely, body waves radiated by an extended source had characterised the wavefield recorded some kilometres away from the summit craters during the lava fountain eruptions studied here (Ferrucci et al., 1990).

Looking at the relationships between tremor amplitude and volcanic activity, a general behaviour was evident from previous studies: a higher tremor amplitude corresponds to more energetic explosive activity at the summit craters, or to the onset of lateral eruptions (e.g. Gresta et al., 1991). This happened both on long (months–years) time periods (e.g. Tanguy and Patanè, 1984; Cosentino et al., 1989) and on short (hours–days) time spans relating to single eruptions (e.g. Gresta et al., 1996a; Falsaperla et al., 1994). Only one case was observed where significant increases in tremor amplitude did not correspond to increases in what was clearly magmatic volcanic activity. This happened in April 1987 when two moderate sudden phreatic eruptions occurred at summit craters, preceded by strong periodic increases of tremor amplitude with no observable volcanic activity (Gresta et al., 1996b). A boiling mechanism was invoked where magma had played a passive role as heat source, generating a geyser mechanism (Kieffer, 1984). Also on other volcanoes, such as Karkar (McKee et al., 1981) and Nevado del Ruiz (Martinelli, 1990), the occurrence of phreatic and/or phreato-magmatic explosions was accompanied by a regular increase and decrease of tremor amplitude. In such cases the term 'banded tremor' was used (McNutt, 1992), coming from the signature on drum records forming evident stripes on seismograms (see Fig. 2). Obviously, this feature of the signal depends on the drum revolution time, therefore the definition intermittent volcanic tremor (IVT) has been suggested (Gresta et al., 1996b).

The literature reports analyses considering 'intermittent' or 'recurrent' phenomena both for tectonic (e.g. Bakun and McEvilly, 1984; Shimazaki and Nakata, 1980) and volcanic (e.g. Page et al., 1994) earthquakes. The latter authors observed a quasi-regular pattern in dome growth and destruction during the last phases of the 1989–1990 Redoubt eruption. They analysed the precursory swarms of long period events statistically and one dome failure was successfully forecast. After the end of the eruption, Page et al. (1994) performed the retrospective statistical forecast over the whole eruption sequence using hindcasting analysis. Several eruptions would have been successfully forecast.

During September 1989 several IVT episodes were observed at Mount Etna volcano accompanying an intense magmatic eruptive sequence. Sixteen lava fountain eruptions occurred at the South-east Crater, one-to-one related to recorded IVT episodes (Fig. 2). The aim of this work is to study those IVT episodes in order to investigate their apparently regular occurrence in time and to suggest a possible source mechanism for the eruptions.

In our case, the onset of volcanic tremor and the beginning of eruptive activity are almost simultaneous, so we will not be able to provide a seismic forecast of the eruptions. Nevertheless, lava fountain eruptions give rise to large ash clouds hazardous to both airline traffic and road traffic when ashes fall down. Then, the one-to-one relations between IVT and lava fountains represent a very powerful tool for the study of the time evolution of eruptive activity, especially when weather conditions do not allow direct sight of the top of the volcano. This condition occurs on Mount Etna ca 100 days/year. In fact, during September 1998 the lava fountain activity at the South-east Crater of Mount Etna volcano resumed, with more than 100 episodes until July 2001. The empirical threshold of tremor reduced displacement (R.D.) that will be shown in the present paper has been routinely and successfully used for issuing warnings to the civil defence and air traffic authorities since April 2000.

2. The data

After the end of the October 1986–February 1987 flank eruption, Mount Etna experienced a long time span characterised only by quiet degassing activity at the summit craters. A renewal of explosive activity was observed in the period April–August 1988, when moderate strombolian activity to 'small' lava fountaining was observed at the Bocca Nuova and Chasm Craters (Calvari et al., 1989). In October 1988 strombolian activity started at the South-east Crater also, and a gradual increase of the eruptive energy was observed until the second part of November. Explosive activity carried on until September 1989 with different levels of energy at the three mentioned summit craters (Fig. 1), whereas the NE Crater showed only gas emission. A remarkable increase of the activity was marked by the occurrence of lava fountains and overflows at the South-east Crater, starting on September 11, 1989. Sixteen lava fountain episodes occurred until September 27, when two fracture systems opened on the eastern flank of the volcano (Fig. 1). The eruptive one was trending N60°E, and lava outpouring gave rise to a lava field in the Valle del Bove. The eruption stopped on October 9 by which time about 38×10^6 m^3 of lava had erupted (Calvari et al., 1989). The second fracture, trending N140°E and propagating downslope for about 7 km in a few days, was a dry fracture system.

In this paper we perform the analysis over a time period (August 22–October 15, 1989) encompassing the eruption. Both volcanological and seismic data are used. A summary of the volcanic activity that occurred at summit craters during the investigated period is reported in Table 1. Volcanological data derive from visual observations and sporadic field surveys. Unfortunately no systematic video recordings are available and we estimate that lava fountain parameters reported here may be affected by uncertainty of ca 10–20%.

Lava fountains reached up to 800 m in height, forming a sustained column, while the ejected bombs covered an area of few square kilometres. They were accompanied by strong increases of the tremor amplitude, with a one-to-one relationship. Details on the timing and height of lava fountains, as well as duration of IVT episodes, are reported in Table 2.

Seismic data refer to tremor recorded at the Pizzi Deneri (PDN) station, located ca 2250 m from the South-east Crater (see Fig. 1). The station was equipped with a vertical short period seismometer (1 s); data were radiolink transmitted to Catania and there recorded only on paper drums with a revolution speed of 1 mm/s (see Fig. 2). Peak-to-peak amplitude of seismograms was sampled every 10 min for the whole period, for a total of 7866 samples; it was used to compute R.D., a means of quantifying tremor intensity (Fehler, 1983).

Using the observed dominant frequency spec-

Table 1
Summary of the volcanic activity observed at the summit craters of Mount Etna for the investigated time period

<table>
<tr><th>MONTH/DAY</th><th>SE-CRATER</th><th>BOCCA NUOVA</th><th>CHASM</th><th>NE-CRATER</th></tr>
<tr><td>AUG. 29, 31</td><td rowspan="2">INCREASE OF STROMBOLIAN ACTIVITY</td><td rowspan="2">SPORADIC STROMBOLIAN ACTIVITY</td><td>EXPLOSIVE ERUPTION WITH LAVA FOUNTAINING TO 700-800 m AND 500 m HEIGHT, RESPECTIVELY. AT THE END CRATER OBSTRUCTED</td><td rowspan="5">SPORADIC GAS EMISSIONS</td></tr>
<tr><td>SEP. 10</td><td>LAVA FOUNTAINS ACTIVITY TO 500 m HEIGHT</td></tr>
<tr><td>SEP. 11</td><td>RESUMPITION OF STROMBOLIAN ACTIVITY WITH LAVA FOUNTAINS, OVERFLOWS FROM THE CRATER RIM</td><td rowspan="2">INTENSE STEAM EMISSION AND ASH EJECTIONS</td><td rowspan="2">INTENSE STEAM EMISSION AND ASH EJECTIONS</td></tr>
<tr><td>SEP. 11 - 13</td><td>6 EVENTS OF LAVA FOUNTAINS</td></tr>
<tr><td>SEP. 19</td><td>LAVA FOUNTAINS</td><td rowspan="3">DEGASSING ACTIVITY</td><td rowspan="7">OBSTRUCTED</td></tr>
<tr><td>SEP. 22 -27</td><td>9 EVENTS OF LAVA FOUNTAINS</td><td rowspan="3">INTENSE DEGASSING</td></tr>
<tr><td>SEP. 25</td><td>OPENING OF TWO RADIAL FRACTURES SYSTEMS</td></tr>
<tr><td>SEP. 27</td><td>OPENING OF A NEW ERUPTIVE FRACTURE IN VALLE DEL LEONE</td><td>SMALL ASH AND STEAM COLUMN</td></tr>
<tr><td>OCT. 03 - 04</td><td>INTENSE EXPLOSIVE ACTIVITY. ASH EMISSION OF INCREASING INTENSITY</td><td rowspan="2">CONTINUOUS GAS EMISSIONS</td><td rowspan="3">GAS EMISSION AT HIGHT TEMPERATURE</td></tr>
<tr><td>OCT. 06</td><td>STROMBOLIAN ACTIVITY</td></tr>
<tr><td>OCT. 11</td><td>OBSTRUCTED BY THE COLLAPSED PRODUCTS</td><td>WEAK EXPLOSIVE ACTIVITY WITH ASH EMISSION</td></tr>
</table>

tral peak of 1.95 Hz, and the P-wave velocity of 1800 m/s, we calculate a wavelength at the PDN station of ca 920 m. By considering the distance between the South-east Crater and the PDN station (ca 2250 m), a formula was proposed to evaluate the R.D. from body waves in the near field (Aki and Koyanagi, 1981):

$$\mathrm{R.D.} = \frac{A_{\mathrm{P}} \cdot r}{2\sqrt{2}M}$$

where A_{P} is the peak-to-peak amplitude, r is the source–station distance and M is the instrument magnification. The $2\sqrt{2}$ term is correction for root mean square amplitude.

3. The analysis

Fig. 3 shows the R.D. pattern vs time during the period studied. Different values of volcanic tremor amplitude have been recorded during several different types of activity. The smallest values of R.D. are associated with quiet to more or less moderate degassing activity. During these spans,

Table 2
Volcanic and IVT parameters related to the 16 lava fountain episodes that occurred at the South-east Crater from 11 to 27 September 1989

Cumulative number	Date (Sept.)	Visual observation		Max. height	PDN			Max R.D.
		Start	End	(m)	Start	mean time	End	(cm^2)
1	11	07:40	08:30	400	06:30	08:05	09:40	57
2	11	19:00	20:00	300	18:30	19:20	20:10	57
3	12	NA	NA	NA	06:40	07:05	07:30	33
4	12	17:00	NA	NA	17:40	19:00	20:20	33
5	13	05:30	07:10	600	05:10	06:20	07:30	72*
6	13	20:00	22:00	300	19:50	21:55	24:00	72*
7	19	04:50	07:15	500	04:20	05:55	07:30	72*
8	22	06:00	10:00	500	06:30	08:20	10:10	72*
9	22	21:15	22:15	800	21:10	21:50	22:30	48
10	23	16:45	18:20	NA	16:40	17:50	19:00	72*
11	24	10:00	11:30	300	10:00	10:50	11:40	72*
12	25	04:30	07:00	300	04:30	06:00	07:30	62
13	25	18:00	19:10	300	17:50	18:35	19:20	72*
14	26	05:00	06:10	400	05:00	05:40	06:20	57
15	26	19:15	20:15	600	19:10	19:55	20:40	43
16	27	02:30	04:15	500	02:30	03:35	04:40	48

NA: not available.
Asterisks indicate R.D. values obtained from saturated seismograms.

the R.D. ranges from 3 to 9 cm^2. As the violence of the explosive activity increases, the amplitude becomes larger. Note the 16 increases of tremor amplitude which correspond to the 16 episodes of lava fountain that occurred on the South-east Crater during the period September 11–27. Other impulsive 'peaks' above a low level of noise appear. They are also associated with increases of explosive activity. Values slightly less than 30 cm^2 are observed in coincidence with lava fountains at the Chasm Crater (August 29 and 31, September 10) as well as during paroxysmal explosive phases of the fissure eruption (September 27–October 6). The threshold of 35 cm^2 was always exceeded coincident with lava fountains at the South-east Crater. Only once (October 3–4) was it reached during a very intense explosion with strong ash emission at the South-east Crater, but without lava fountains.

We focus our analyses on the 16 tremor amplitude increases (and the related lava fountain episodes). As shown in Fig. 3 the tremor increases associated with lava fountains appear 'intermittent'. On the basis of the apparent periodicity, they may be grouped in two 'families', comprised of six episodes from September 11 to 13, and nine episodes from September 22 to 27. The episode of lava fountaining on September 19 represents the dividing point of this subdivision.

The time occurrences of lava fountaining are shown in Fig. 4 and the regular behaviour of occurrence is evidenced. Again two well-defined 'families' are evident, separated by the sole episode of September 19. Moreover each 'family' shows a nearly linear trend. In fact a linear regression performed on the two families shows the following relation: $c.n. = 2.0t+1.0$; $R^2 = 0.99$ for the former family and $c.n. = 1.6t-9.6$; $R^2 = 0.99$ for the latter one, where c.n. is the cumulative number of each single episode, t is time (in days) and R is the correlation coefficient. Both R^2 values indicate a very good linear correlation.

We performed autocorrelation analyses of the two R.D. time series (September 11–13 and September 22–27). Figs. 5a,b shows autocorrelation functions relating to the two normalised time series and the associated standard deviation functions. The impression of periodic occurrence of IVT derived by a cursory examination of Table 2 and Figs. 3 and 4 is statistically confirmed for the former series (5760 min starting since September 11 h.00:00). A significant peak characterises

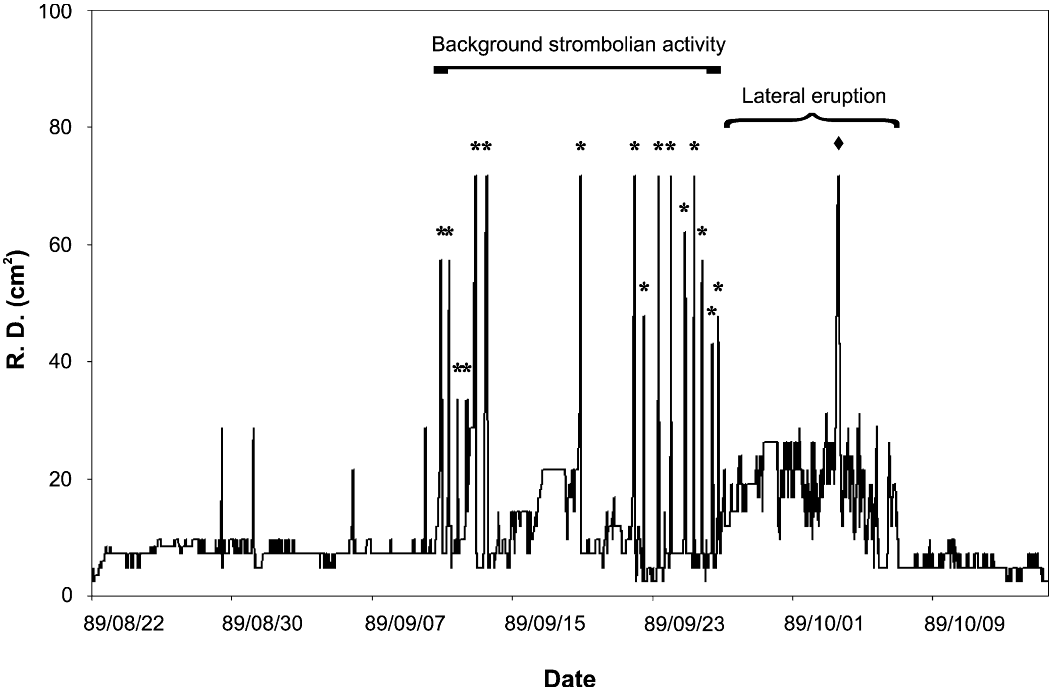

Fig. 3. Time series of the tremor R.D. at the PDN station for the time period August 22–October 15, 1989. Asterisks indicate the occurrence of lava fountain eruptions; the diamond marks the only time the empirical R.D. threshold was exceeded without lava fountaining.

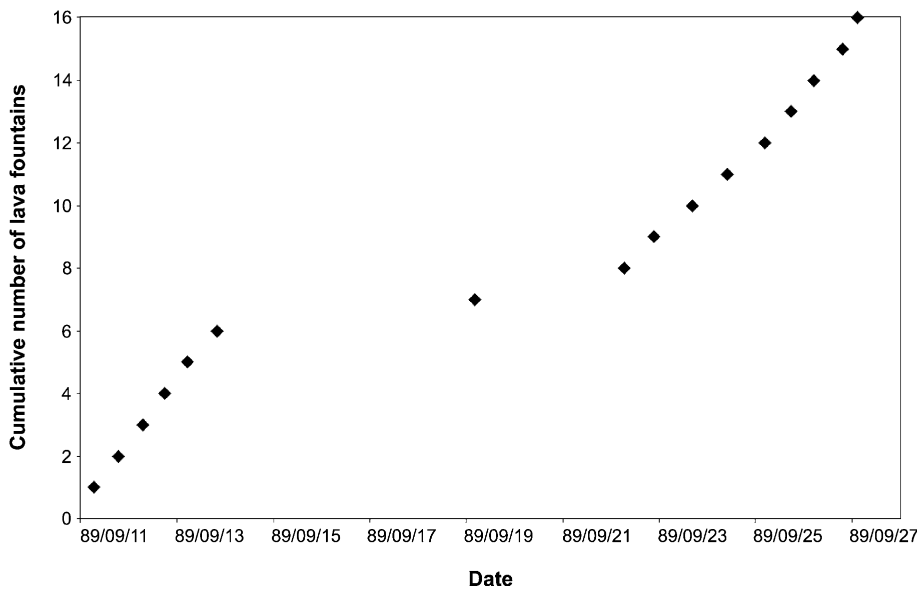

Fig. 4. Time sequences of lava fountains (and related IVTs) during September 1989.

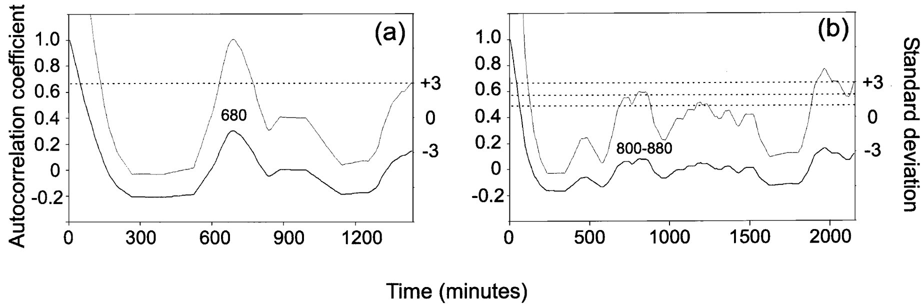

Fig. 5. Autocorrelation (bold line) and related standard deviation function (thin line) performed on the time series of the tremor R.D. at the PDN seismic station for: (a) September 11–13 and (b) September 22–27. Horizontal dashed lines indicate standard deviation thresholds.

the autocorrelation function shown in Fig. 5a at 680 min, with the associated normalised standard deviation value being ca 7. Consequently, values of cumulative probability (taken from Hald, 1952) indicate a significance level much greater than 99.9% for this peak. Conversely, Fig. 5b shows the autocorrelation (and the associated standard deviation) relating to the latter normalised R.D. time series (8640 min starting since September 22 h.00:00). This autocorrelation function is more complex than the previous one. Many peaks are present, even if their standard deviation never exceeds the value of 3 (corresponding to a significance level of 99.9%), with the exception of a peak at 1960 min that is not considered because it has no meaning in the time series analysed and is probably due to a numerical instability. Only one wide peak at ca 800–880 min has a standard deviation value slightly greater than 2, implying a significance level of ca 98% (Hald, 1952).

In spite of the physical meaning of this statistical analysis, the comparison between the two au-

Table 3
Occurrence times, expected (average predicted) times and statistical forecast windows for the lava fountain episodes

Event	Occurred	Expected	95% forecast window		60% forecast window	
			Start	End	Start	End
1	11 08:05	–	–	–	–	–
2	11 19:20	–	–	–	–	–
3	12 07:05	–	–	–	–	–
4	12 19:00	12 18:30	**12 17:44**	**12 19:16**	12 18:19	12 18:41
5	13 06:20	13 06:30	**13 05:57**	**13 07:03**	**13 06:20**	**13 06:40**
6	13 21:55	13 18:01	13 17:37	13 18:25	13 17:53	13 18:09
7	19 05:55	14 10:40	14 04:05	14 17:15	14 09:02	14 12:18
8	22 08:20	21 10:58	–	–	**19 16:02**	**23 05:54**
9	22 21:50	25 08:08	–	–	24 06:12	26 10:04
10	23 17:50	25 03:57	–	–	24 04:41	26 03:13
11	24 10:50	24 09:30	**23 23:25**	**24 19:35**	**24 07:01**	**24 11:59**
12	25 06:00	25 04:35	**24 23:34**	**25 09:36**	**25 03:02**	**25 06:08**
13	25 18:35	25 23:58	25 20:27	26 03:29	25 22:46	26 01:10
14	26 05:40	26 10:10	**25 21:59**	**26 22:01**	26 07:02	26 12:58
15	26 19:55	26 19:48	**26 12:49**	**27 02:47**	**26 17:39**	**26 21:57**
16	27 03:35	27 08:36	27 04:06	27 13:06	27 07:05	27 10:07
17	No event	27 15:38	27 05:27	28 01:49	27 13:07	27 18:09

The a posteriori 'correct predictions' are reported in bold.

tocorrelations functions relating to the two series highlights a couple of differences. The first lava fountain family has shown a higher regularity than the latter one, while the dominant peaks of the two families are rather different, the second family having values greater (ca 800–880 min) than those observed for the former one (680 min).

Focusing again on the regular intermittent behaviour found in both lava fountain and volcanic tremor, we would like to determine if seismic data could be used to forecast the occurrence of a next eruptive episode. We tried an a posteriori forecast using simple statistical methods (linear regression and Student' t-test) on the tremor amplitude time series. We first used the onset time of each IVT in order to a posteriori forecast the onset of the next episode. Since these data did not take into account the different durations of single episodes, we used the mean time between onset and end of each episode. Using the mean time, we were able to reduce the influence of the duration of episodes on our statistical forecast. Results are shown in detail in Table 3 and Fig. 6. To evaluate the method we retrospectively calculated, for the two families separately and for a constant-rate process, the expected occurrence times and forecast windows (at 60% and 95% of the confidence level). Each forecast window is based on all the preceding events of the series; for instance the parameters for the fourth event are derived from the times of the preceding three events. Our calculation starts after three events have occurred. If an event occurs outside the forecast window, the forecast is considered a failure. So, we consider a new sequence based on the last three episodes. When the events in the time series are more regular, the windows are narrower.

This statistical method was applied on the whole sequence of lava fountain episodes. From September 11 to 13, six events had occurred in the sequence, the first five at remarkably regular intervals ranging from 11.2 to 11.9 h (computed from the column of mean time in Table 2). Only the interval between the last two episodes of the first family (15.5 h) is far from the previous ones. Based on these six events, the 95% forecast window for the fourth and the fifth events gave satisfactory results: both episodes could be statistically forecasted. In particular, for the fifth episode, even the 60% forecast window had success since the difference between the time of occurrence and expectance was only 10 min. The

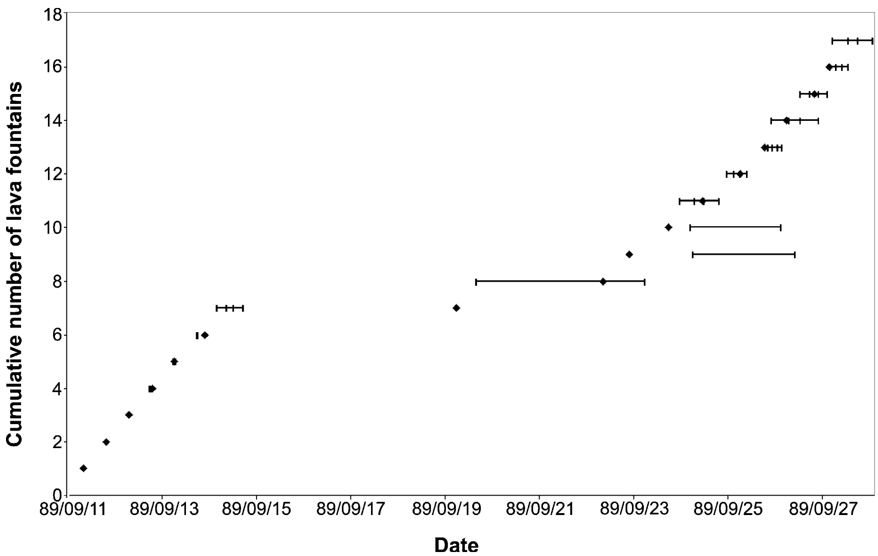

Fig. 6. Time sequence of lava fountain episodes (diamonds) and related statistical forecast windows. The forecast windows are indicated by horizontal bars (the longer ones define the 95% confidence intervals and the shorter ones refer to the 60% confidence intervals).

next forecast failed because the impressively regular 11.2–11.9 h interval between the increasing tremor amplitude (corresponding to the temporal gap between two consecutive episodes of lava fountaining) shifted to 15.5 h. The following forecast (seventh episode) failed because the underlying assumption of regular intermittent behaviour was violated (as demonstrated by the occurrence of the lone episode of September 19).

The lava fountains of the second family show a less regular interval of tremor amplitude increase than those of the first one, ranging from 7.5 to 20 h. This resulted in the computation of wider forecast windows. The forecasts failed when the duration of the interval between one event and the next one changed relative to the average interval (ca 15 h) between episodes of the second family of lava fountains. In total, six forecasts were made for the episodes of the second family, of which four were successful (the 11th, 12th, 14th and 15th episodes). The series finished in a failed forecast which consisted of a false-alarm failure (the 17th episode, which never occurred).

4. Discussion and conclusion

In this study we used the statistical method based on the time series of occurrence of lava fountain episodes to forecast the occurrence of the next one assuming a regular periodic fountaining process. Due to the one-to-one relation between IVT and lava fountains (Table 2), we used the IVT to statistically characterise the eruptive sequence. The results of our statistical analyses confirm the presence of two families of eruptive episodes: both are characterised by a nearly linear trend (Fig. 4), which means a periodic occurrence. The results of autocorrelation and forecast analysis both confirm the periodical occurrence of IVT episodes. In fact, the first six lava fountains repeated every ca 680 min (Fig. 5a) and, in the field of the statistical forecast, we calculated a mean interval between two consecutive episodes of the first family of ca 11.5 h. Conversely, the final nine eruptive episodes are slightly less regular. The mean peak of the autocorrelation function is rather poorly defined (from 800 to 880 min) and has a lower significance (see Fig. 5b). The forecast results had shown a mean time of occurrence ranging widely from ca 8–20 h.

However, a general result of the statistical method is that most of the episodes could be forecast using both the 95% and the 60% forecast windows.

Based on the regularity of intervals between episodes, we assumed a roughly constant-rate fountaining process. The false alarms occur when the behaviour of the volcano changes; such false alarms are inherent in the method. Therefore the statistical approach can be a useful complement to deterministic forecasting during times of metastable volcanic behaviour.

The remarkable periodicity verified for the two families of fountain episodes suggests that a persistent physical mechanism, during limited time spans, was controlling the eruptive behaviour. During these periods the statistical forecasts gave satisfying results. Moreover, factors able to break up the previous metastable state should recur. After such phases, a new metastable state begins, different from the previous one. As an example, the 64 episodes of lava fountaining that occurred at Mount Etna from January to June 2000 evidenced an initial ‘periodicity’ of ca 1 day, which then shifted to a half day, and finally to about 10 days. In conclusion, we are able to suppose limited time intervals during lava fountain episodes characterised by a more or less statistically linear behaviour of the feeding system. This result is independent of the assumed source model for both tremor and eruption. However, we suggest a conceptual model to explain the eruptive behaviour based on some constraints of the tremor source.

The most common source of mechanical energy is probably gas bubble formation, coalescence and collapse (Vergniolle and Jaupart, 1986). Because of the higher accelerations involved, bubble collapse is thought to be a more energetic process than bubble growth (Vergniolle and Jaupart, 1986). Nonetheless, bubble growth is the dominant process because gas expansion occurs and gases are released in the majority of open-conduit volcanoes and a larger amount of steam and other gases are liberated during eruptions. Gases ex-

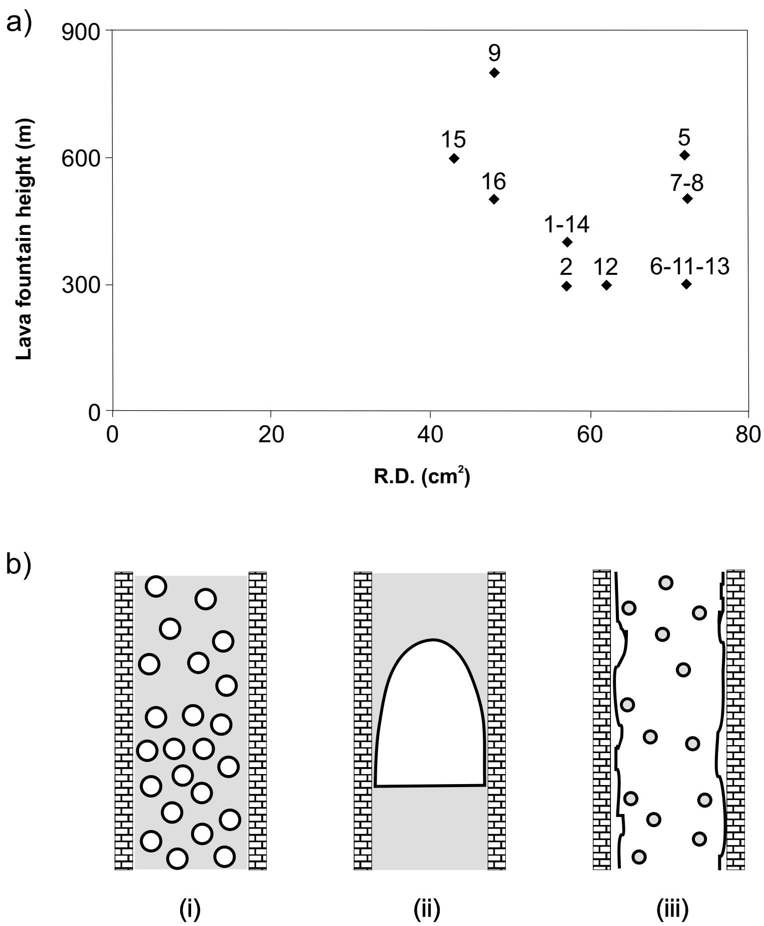

Fig. 7. (a) Lava fountain height vs tremor power (PDN station). (b) Sketch of three different regimes of bubble flow into the magma: (i) bubbly flow, (ii) intermittent slug flow, and (iii) annular flow (adapted from Vergniolle and Jaupart, 1986).

solve and expand when pressure decreases as magma moves toward the surface. Gas expansion and volcanic tremor occur in virtually all eruptions. It is noteworthy that the mechanical energy produced by gas bubbling into the conduit is transmitted through the shallow crust of the volcano to be recorded as tremor at a given seismic station. The amount of transmitted energy strongly depends on the coupling between the walls of the conduit and the magma inside it.

Taking into account the presence of gas bubbles as a source of mechanical energy, we suggest a simple model of a tremor source by considering the regimes of bubble flow into the magma. The essential physical features of the model are a shallow reservoir for the magma and a conduit linking the magma batch and the South-east Crater vent. The conduit also works as a buffer reservoir for magma. To explain the discharge of magma by 'cyclic' lava fountain episodes, we suggest the existence of a very shallow (some hundreds of metres) magma batch below the South-east Crater. This batch represents a temporary storage chamber that acts as a shallow reservoir for magma and it is directly connected, through the conduit, with the South-east Crater vent and with the feeding system from depth. Following La Delfa et al. (2001), we suppose different steps which involve this shallow feeding pocket and its invasion by magma from depth. When a critical level is reached the increasing magma pressure and the subsequent growth of bubbles causes the reopening of the crater conduit. The opening of the conduit triggers an explosive paroxysm, followed by a sudden pressure drop causing the end of the eruption. The process of filling and emptying the shallow magma reservoir occurs rapidly, as demonstrated by the relatively low degree of evolution of the products emitted during these summit eruptions (Armienti et al., 1989).

It is important to point out that eruptive system is strongly non-linear. Only sporadically and for short lapse times does the South-east Crater eruptive system shows a linear behaviour. It may be assumed to be a rare condition. For such a system there are one or more parameters that undertake values typical of a limit condition. Following this hypothesis small variations of a given parameter (such as the geometry of the feeding system, the gas content of magma, its density/viscosity) around the values typical of the limit condition should determine significant variations in the lava fountain parameters (i.e. duration, height, rest period). The statistical predictive model works 'well' only during the rare condition of linear behaviour. For observatory practice the use of an empirical threshold for tremor amplitude (and/or energy, R.D., etc.) will certainly give better results in terms of explosive eruption alerts. To reconstruct the source mechanism producing IVT episodes associated with the fountaining process, we considered the sketch from Vergniolle and Jaupart (1986) in which three different regimes of bubble flow into the magma were considered (bubbly flow, intermittent slug flow and annular flow). The three different regimes of bubble flow represent three different phases associated with different depths into the conduit. The location of the tremor source, in the condition of low volcanic activity, coincides with a reservoir filled by a mixture of magma and gases. A pressure increase, caused by the contribution of fresh magma (rich in gas) from depth, produces a coalescence process (regime of intermittent slug flow) and bigger bubbles begin to rise inside the conduit, causing the increase of volcanic tremor amplitude which reaches the highest values in coincidence with the lava fountain phase (regime of annular flow). This seems confirmed by the relationships among parameters reported in Table 2. In fact, Fig. 7a shows the height of fountains vs the maximum tremor R.D. Even considering the uncertainty in the lava fountain heights (about 100 m), and some clipped values of R.D. (due to saturated seismograms), a surprising inverse relation, with respect to the general features, may be observed. This behaviour could be explained by the characteristics of bubble flow occurring into the magma column (Fig. 7b). Probably, higher lava fountains are related to major annular flow, which is characterised by higher velocity of ejection, but also by significantly lower values of both the density of the liquid–gas mixture and the friction with the walls of the conduit. On the whole, the relatively scarce coupling of the magma flow with the conduit should produce lower tremor amplitude at the station closest to the summit craters.

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