Bull Volcanol (1998) 60: 75–88

ORIGINAL PAPER

S. Falsaperla · H. Langer · S. Spampinato

Statistical analyses and characteristics of volcanic tremor on Stromboli Volcano (Italy)

Received: 15 December 1996 / Accepted: 31 March 1998

Abstract A study of volcanic tremor on Stromboli is carried out on the basis of data recorded daily between 1993 and 1995 by a permanent seismic station (STR) located 1.8 km away from the active craters. We also consider the signal of a second station (TF1), which operated for a shorter time span. Changes in the spectral tremor characteristics can be related to modifications in volcanic activity, particularly to lava effusions and explosive sequences. Statistical analyses were carried out on a set of spectra calculated daily from seismic signals where explosion quakes were present or excluded. Principal component analysis and cluster analysis were applied to identify different classes of spectra. Three clusters of spectra are associated with two different states of volcanic activity. One cluster corresponds to a state of low to moderate activity, whereas the two other clusters are present during phases with a high magma column as inferred from the occurrence of lava fountains or effusions. We therefore conclude that variations in volcanic activity at Stromboli are usually linked to changes in the spectral characteristics of volcanic tremor. Site effects are evident when comparing the spectra calculated from signals synchronously recorded at STR and TF1. However, some major spectral peaks at both stations may reflect source properties. Statistical considerations and polarization analysis are in favor of a prevailing presence of P-waves in the tremor signal along with a position of the source northwest of the craters and at shallow depth.

Editorial responsibility: J.-F. Lénat

S. Falsaperla (✉) · S. Spampinato
Istituto Internazionale di Vulcanologia, C.N.R., Piazza Roma 2, I-95123 Catania, Italy
Fax: +39 95 435801
e-mail: susanna@iiv.ct.cnr.it

H. Langer
Dipartimento Elettrico, Elettronico e Sistemistico, Univ. di Catania, V.le Andrea Doria, 6, I-95122 Catania, Italy

Key words Stromboli · Volcanic tremor · Statistical analysis

Introduction

Stromboli Volcano belongs to a chain of volcanic islands that form the Aeolian Archipelago in the southern Tyrrhenian Sea. Its activity has been persistent for at least 2000 years and consists of continuous degassing as well as Strombolian explosions with ejection of ash, lapilli, and lava bombs. Periodically eruptive crises occur, with occasional lava effusions and/or more violent explosions. Hot avalanches and tsunami were also reported during the effusions in 1930 and 1944 (Imbò 1928; Cavallaro 1955). The lava emissions are usually of short duration, e.g., days or weeks (Washington 1917; Capaldi et al. 1978; Barberi et al. 1993), with the only exception in this century being the 1985 eruption, which started on 6 December 1985 and lasted 141 days (De Fino et al. 1988).

A particular kind of eruptive activity consists of sequences of Strombolian explosions characterized by powerful ejection of old and/or juvenile material with variable dimensions (up to several meters). The spatter can be thrown 200–250 m high and often falls out across the entire summit area (Bonaccorso et al. 1996). These violent explosions (hereafter called explosive sequences) occur in rapid succession, within a few tens of seconds of one another. They represent paroxysmal phases and are not unusual for Stromboli Volcano (on average two per year), even if associated with a higher energy release.

On seismic records Strombolian explosions are generally associated with signals called explosion quakes, which usually appear with an emergent onset, lack a clear S phase, have a relatively long duration with respect to their amplitude, and have a frequency content mainly concentrated below 5 Hz (Minakami 1974). Apart from numerous explosion quakes (more than 200 per day on average), the main seismic feature is volcanic tremor, the origin of which is related to the dynamics of the fluids inside the feeding conduits (e.g., Schick 1981; Chouet 1988). Studies of this signal demonstrate a strict link between changes in its spectral characteristics and variations in volcanic activity (Falsaperla et al. 1994 a). A statistical analysis of spectral variations in tremor radiation was carried out on the basis of data from seismic station STR (Fig. 1) covering a time span of several years (Langer and Falsaperla 1996). This analysis was performed with the aim of finding temporal relationships with episodes of explosive activity, the occurrence of powerful explosive sequences, and lava flows. The results highlighted the importance of tremor as a key to follow different states of volcanic activity. These states may be related to cycles of loading and unloading in the feeding volcanic system, i.e., to variations in the height of the magma column (Falsaperla et al. 1994 a). Such cycles may last from a few weeks to years (Falsaperla et al. 1989; Langer and Falsaperla 1996). Similar observations are reported by McNutt (1992), who summarizes the data recorded at hundreds of other volcanic areas worldwide.

The background signal on Stromboli is persistent and contains variations in amplitude and spectral shape developing over several weeks or months. These features lead us to distinguish Stromboli from other volcanoes that are characterized by storms of tremor, such as those observed during phases of lava-dome building for Merapi (Seidl et al. 1990), as well as by swarms of long-period events that merge into sustained tremor, as recorded before the reawakening of Redoubt Volcano in 1989 (Chouet et al. 1994).

The dominant spectral peaks in Stromboli tremor are in the range between 1 and 5.5 Hz (e.g., Schick 1981; Del Pezzo et al. 1988; Falsaperla et al. 1989). This observation holds for signals acquired by means of conventional data-acquisition systems equipped with short period seismometers. This system has a flat response between 1 and approximately 20 Hz. Digital broadband stations, which operated for a short time on the island, provided data where low-frequency (<1 Hz) spectral peaks were present (e.g., Dreier et al. 1994; Falsaperla et al. 1994b; Neuberg et al. 1994; Wasserman 1997). In addition, Falsaperla et al. (1994b) report high-frequency peaks at 35, 65, and 82 Hz, which were found in the signal recorded by a Q-Flex accelerometer by Sunstrand Co., USA. Since in this paper only data of short-period seismometers (1 s) are considered, we do not further discuss these new data and restrict ourselves to the frequency interval of conventional observations, i.e., between 1 and 20 Hz.

The data we present here were recorded in the framework of the seismic monitoring of Stromboli Volcano. Our interest in the persistent background signal on Stromboli focuses on the evolution of energy radiation over long time spans, such as months or years. This permits the study of changes of the spectral shape of tremor and their relation to volcanic activity with the aim of recognizing long-term precursors of potentially hazardous eruptions. The existence of a relation between the frequency content of tremor and volcanic activity has been claimed by various authors. Gordeev et al. (1990) analyzed temporal and spatial characteristics of the tremor-wave field at Klyuchevskoy Volcano to collect information on the tremor source. In particular, Gordeev et al. (1990) evaluated tremor power in three different frequency bands, which were selected on the basis of the main spectral peaks, to explore the problem

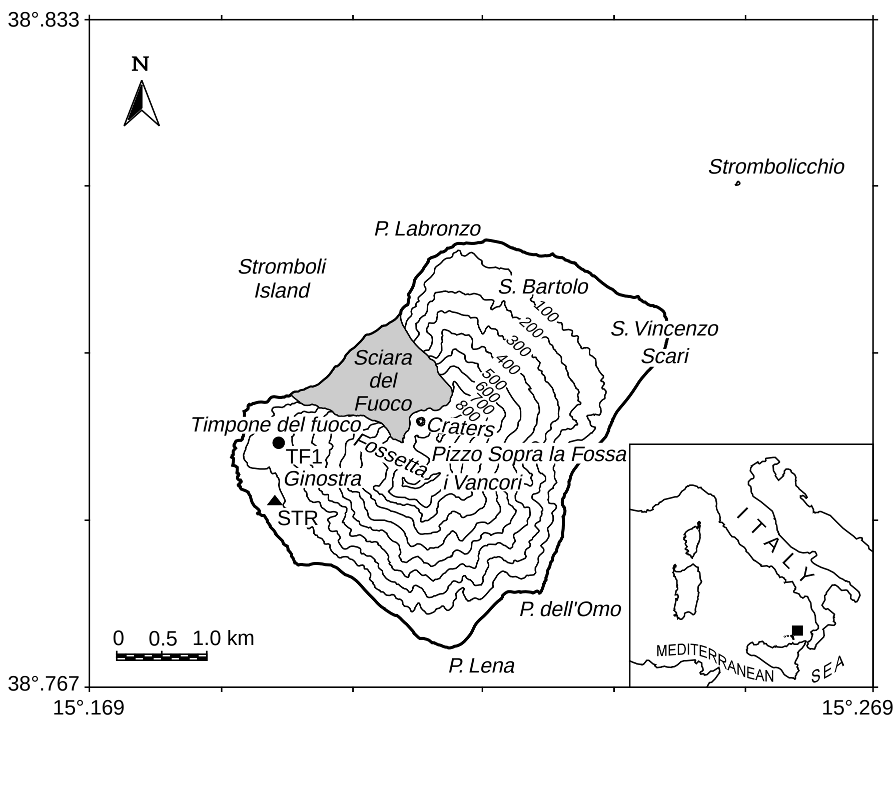


Fig. 1 Map of the island of Stromboli. Locations of seismic stations STR and TF1 are depicted with a *triangle* and a *circle*, respectively, for the three component and the vertical component

of spectral variability depending on tremor intensity. They reported a shift in tremor spectra toward lower frequency with increasing level of volcanic activity and tremor radiation. Similarly, Langer and Falsaperla (1996) considered the problem of energy contribution at Stromboli in 1990–1993. They applied cluster analysis to five frequency bands in which the most recurrent dominant peaks in the spectrum of the vertical component of the station STR were present. Inside of each frequency band Langer and Falsaperla (1996) picked the maximum amplitude instead of calculating RMS values of the bands. In so doing they could include the spectra from 1990 to March 1991 for which only hard copies were available. They observed a shift in tremor spectra toward higher frequencies during periods where the magma column was high and tremor amplitude increased. Their selection of the frequency bands, however, has some uncertainty since only potentially dominant peaks were considered, whereas minima, being as important as peaks (maxima) for the featuring of a spectrum, were neglected. To improve their study, we analyzed the problem of energy contribution in defined intervals of frequency by using spectra of the same seismic station that were acquired in digital form. This allowed us to evaluate RMS amplitude values for specific frequency bands without any a priori selection of the spectral peaks, apart from the definition of the width for each interval. Because our data set was limited to just one station for the major part of the time span discussed here, no physical model could be constrained in a meaningful way. We therefore restrict ourselves to a statistical description of the spectral changes and try to relate them to relevant volcanic phenomena that could be observed at the surface. We investigated the time span from 1993 to 1995, when three-component records are also available.

Data

The data analyzed here refer to seismic signals recorded on Stromboli by means of the permanent station STR (Fig. 1), which has been used for the seismic surveillance of the island since 1985. STR is a 1-Hz three-component station located 1.8 km southwest of the active craters. The signals were transmitted by radio telemetry to Lipari, another of the islands of the Aeolian Archipelago, and from there retransmitted to Catania by telephone link. Here, the signals were converted into digital form by means of a 12-bit A/D converter with a sample rate of 100 Hz and stored on a personal computer. We analyzed samples of volcanic tremor data in the frequency domain. Spectra were computed for each component over time windows of different lengths. The spectra were daily calculated on-line from the analog seismic signal by means of a two-channel spectrum analyzer. This computes a Fast Fourier Transform (FFT) using 400 spectral lines with a frequency resolution of 0.05 Hz, after an A/D conversion with a sample rate of 19.5 ms. The range covered by the spectral analysis spans from 0.05 to 20 Hz. Spectra obtained are power spectra, which were calculated by averaging over 64 or 350 successive single spectra, each performed over a time window with a length of 20 s. In this way, the spectra correspond to time series of approximately 20 min and 2 h, respectively, to guarantee a high degree of statistical stability (Randall 1977). The spectral analyses were carried out both for signals not including explosion quakes and for temporal intervals where explosion quakes occurred. These different modes of processing were adopted with the aim of examining the modifications in the spectral features of time series with various lengths, and of analyzing the contribution of explosion quakes to the frequency content. The removal of the explosion quakes was automatically carried out by interrupting the sampling when they occurred following an STA/LTA criterion.

For the vertical and E–W components, we collected averaged spectra over approximately 20 min of signal without explosion quakes (shsample), and over 2 h including explosion quakes (2hsample). Moreover, averaged spectra were performed over temporal windows of 20 min of signal including explosion quakes (64sample) for both N–S and E–W components.

The period of study January 1993 to August 1995, was characterized by different levels of volcanic activity that, according to observations carried out regularly by volcanologists of the Istituto Internazionale di Vulcanologia in the framework of the volcano monitoring program (M. Coltelli, pers. commun.), evolved from very intense to low. In particular, powerful Strombolian activity took place in the first 7 months in 1993 (Bonaccorso et al. 1996). The climax was reached on 16 and 18 May 1993 with two aa lava flows 300 m long and 20 m wide (Bonaccorso et al. 1996). From August 1993, volcanic activity decreased considerably. After a temporary renewal of activity in the first months in 1994, volcanic activity was low until the end of 1995 (Coltelli and Cardaci 1994; GVN 1995; Falsaperla and Cardaci, 1998). Besides the usual Strombolian activity, several powerful sequences of explosions occurred, such as those on 10 February, 16 and 30 October, and 4 November 1993. In 1994–1995 the major sequences were observed on 4 June 1994, 5 March 1995, and 10 May 1995 (Bonaccorso et al. 1996; Coltelli and Cardaci 1994; Falsaperla and Cardaci, 1998). On seismograms the sequences look like rapid successions of a variable number of explosion quakes that are associated with a temporary increase in tremor amplitude (Fig. 2). The tremor amplitude remains elevated for several minutes, fading gradually. The total duration of these seismic sequences is usually from three to tens of minutes (Falsaperla et al. 1989). Drops of tremor amplitude are usually observed immediately after the sequences.

The different intensity of volcanic activity in 1993–1995 offers a good opportunity to study the long-term changes in the spectral energy of tremor radiation. Unfortunately, our data set is not complete through

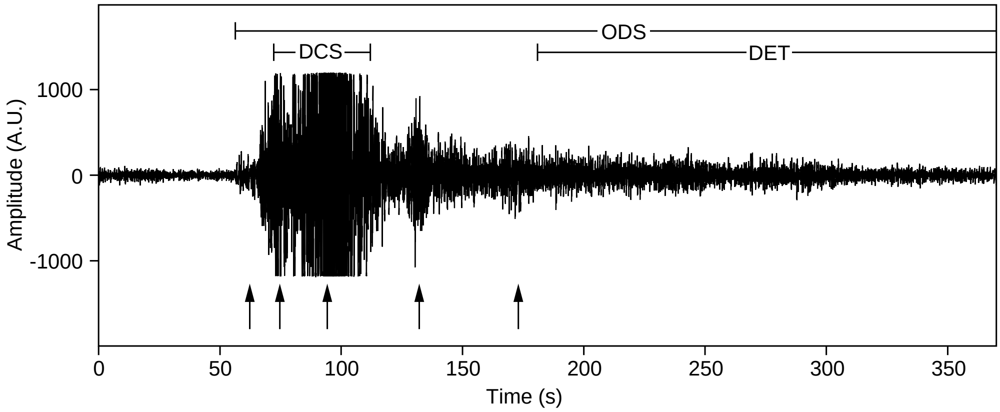


Fig. 2 Example of seismogram of an explosive sequence. *ODS, DCS,* and *DET* are the same as in Table 1. The *arrows* indicate the distinguishable seismic explosion quakes

those years. We rejected the spectra from January to September 1994, which were not reliable. In particular, several spectra had to be discarded as strongly affected by bad weather conditions, since we noted their influence even in the spectral band of interest. This aspect can be crucial during the rainy and windy periods of the year, as pointed out by Braun et al. (1996).

From June 1995 onward synchronous digital data acquisition at STR and TF1 was available (Fig. 1). TF1 was set up at Timpone del Fuoco approximately 800 m distant from STR, and equipped with a 1 s vertical seismometer. Spectra of time series having a duration of approximately 80 s were computed from 14 June to 24 August 1995, by averaging successive spectra using an FFT over a window consisting of 4096 points. The resolution obtained is 0.024 Hz. This analysis was carried out for the vertical components of STR and TF1, allowing a comparison of the signals recorded synchronously at the two different sites.

Analyses and results

Development of tremor spectra as a function of time

For purposes of data reduction and for the convenience of representation, we subdivided the spectra into intervals of 0.5 Hz and calculated the RMS spectral amplitudes for each frequency band. This restricted frequency resolution is thought to be sufficient to represent most important spectral features. By recognizing that the spectral energy is essentially concentrated in the range below 5.5 Hz and neglecting lower frequencies below 1 Hz, we obtain nine frequency classes representing the spectral range from 1.0 to 5.5 Hz. Because of the different levels of both seismic and volcanic activity, we divided the set into two subsets, one for 1993 and the other for October 1994 to August 1995. Due to instrumental problems related to the gain of the station, the absolute amplitude values of the two subsets cannot be compared directly.

The variations of the RMS values in all frequency intervals were found to be coherent, although the changes are scaled differently in the various frequency classes (see Figs. 3, 4). This observation holds for the vertical component spectra as well as the horizontal components in 1994–1995, regardless of the duration of sampling or whether explosion quakes were present. The variations of spectra including explosion quakes were generally higher, both in absolute and relative values, than those without explosion quakes (Figs. 3, 4a–d). In 1993 the shape of the vertical spectra underwent considerable variations. Several weeks before and after the lava effusions on 16–18 May 1993 the frequency content above 2.5 Hz dominated, whereas toward the end of the year lower frequencies prevailed. Throughout the whole period from October 1994 to August 1995, the low-frequency contribution below 2.5 Hz on the vertical component was dominant. The energy content of the horizontal component spectra in the period from October 1994 to August 1995 was concentrated essentially between 1 and 3 Hz.

On the basis of the temporal evolution of amplitudes, the most significant changes occurred in May 1993, when the largest amplitudes of the whole study period were reached (Fig. 3). In August a period of decreasing amplitude started, during which three explosive sequences were recorded on 16 and 30 October and 4 November (Fig. 3). In Table 1 we provide some empirical criteria that allowed us to characterize the explosive sequences with respect to their intensity from a seismic viewpoint. With these criteria it was also possi-

Table 1 General features of the explosive sequences in 1993–1995

Date		ODS	DCS	NDE	DET
February 10, 1993	16:10	360	85	5	240
October 16, 1993	01:07	620	155	5	>420
October 30, 1993	00:53	80	0	3	30
November 4, 1993	23:50	105	0	6	< 10
June 4, 1994	00:15	482	0	10	147
March 5, 1995	17:43	290	40	4	150
May 10, 1995	22:41	498	5	3	400

ODS = Overall duration of sequence in seconds
DCS = Duration of clipped signal in seconds
NDE = Minimum number of distinguishable explosion quakes
DET = Duration of enhanced tremor amplitude in seconds

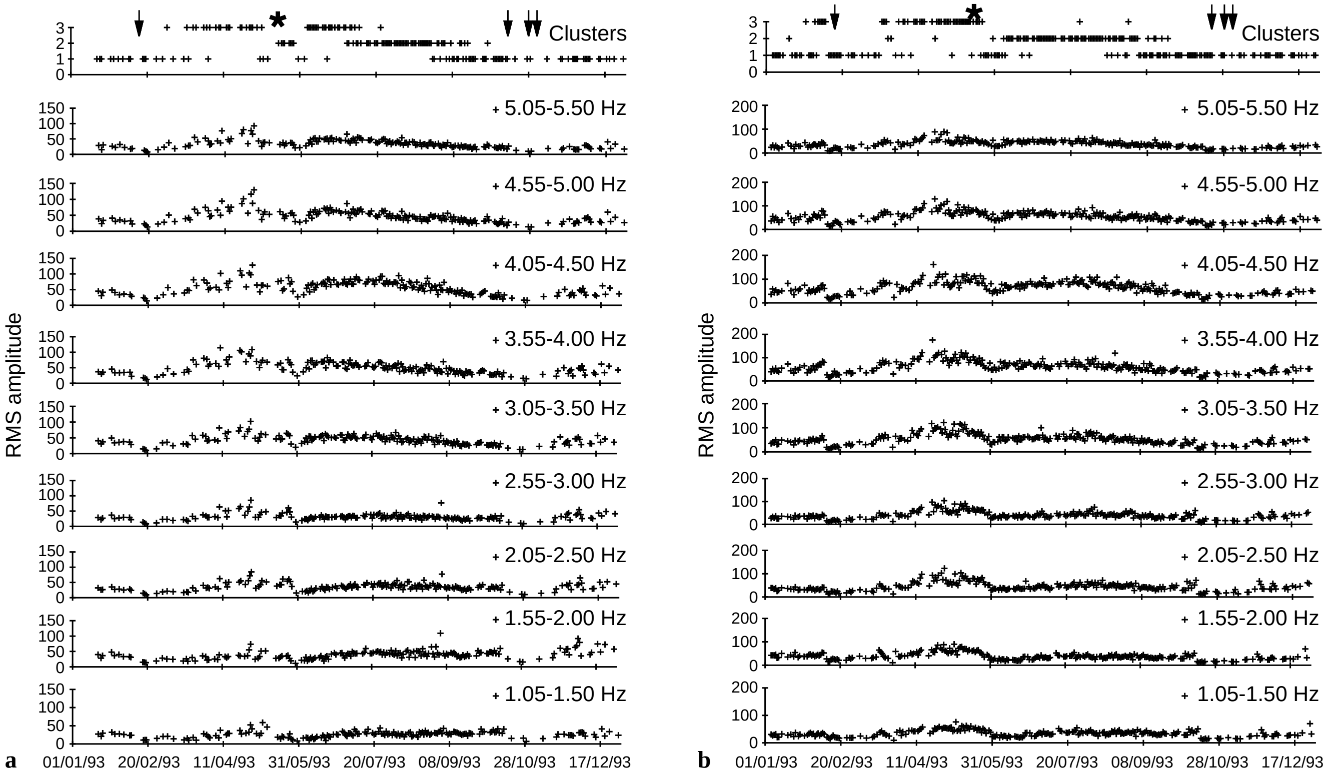


Fig. 3 Development of spectral amplitudes in nine selected frequency classes using the vertical component of the station STR in 1993 for **a** 20-min samplings, and **b** 2-h samplings. The uppermost trace refers to the results of the cluster analysis. The *arrows* and the *asterisk* indicate explosive sequences and lava effusions, respectively

ble to describe those explosive sequences for which only hard-copy records were available. Interestingly, a sudden amplitude reduction was observed especially in the intervals from 1 to 3.5 Hz in correspondence to the occurrence of the powerful explosive sequence of 16 October. According to our criteria, the sequences of 30 October and 4 November had a minor energy release, and no corresponding variation of tremor amplitude is visible. Another evident reduction in amplitude occurred together with a strong explosive sequence on 10 February 1993. In this case, the variation can be observed in all intervals, although it is larger in the frequency range above 2.5 Hz (Fig. 3).

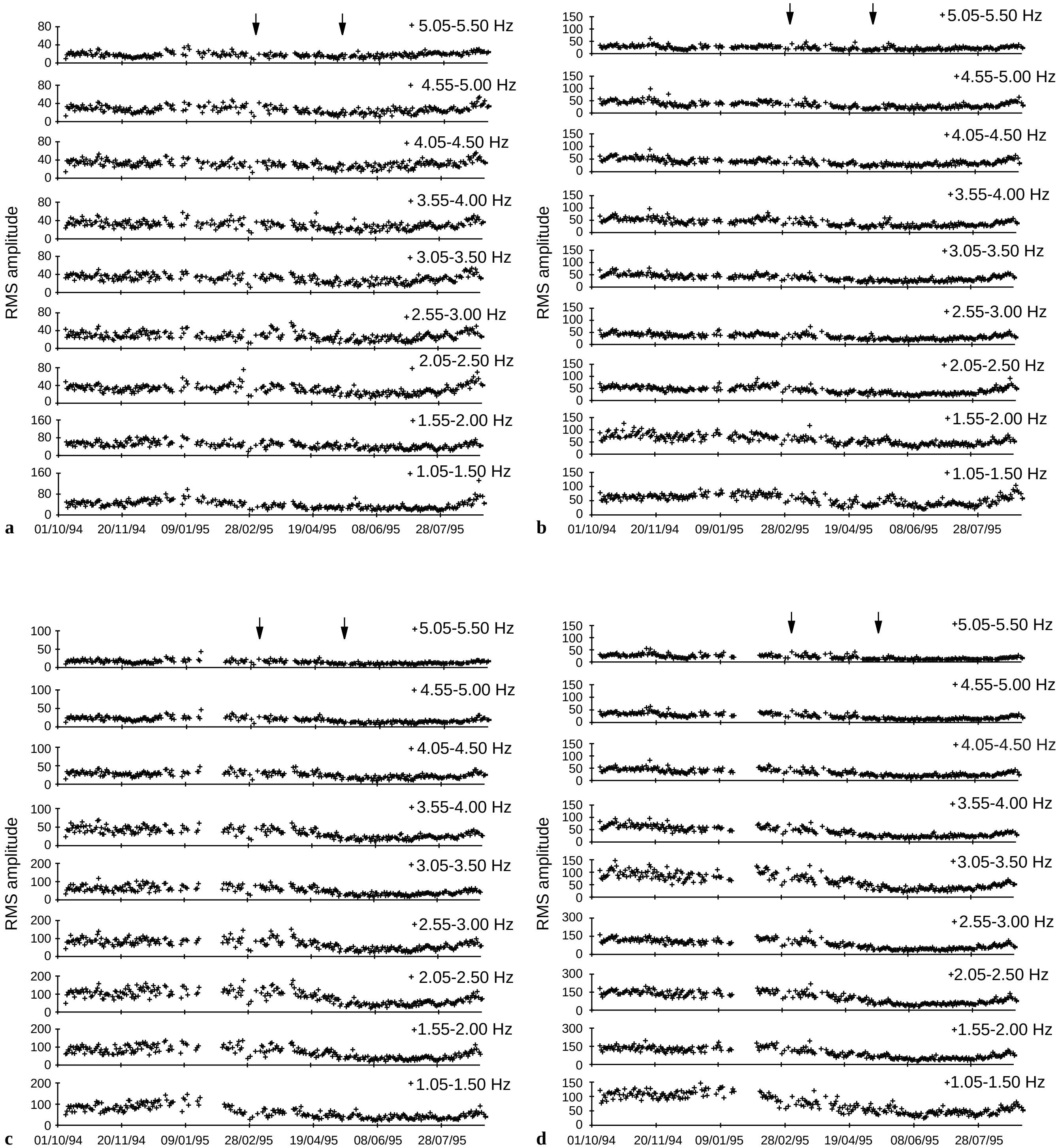
From October 1994 onward the data of all spectra delineated a decreasing amplitude trend during which two other explosive sequences occurred on 5 March and 10 May 1995. Despite their intensity, these two sequences are not evidenced by a visible amplitude reduction, since the level of tremor radiation was already very low (Fig. 4). A modest increment in amplitude was recorded from June to the end of August 1995. The increase was stronger in the vertical and in the N–S components, especially in the interval of the lowest frequencies (1.05–1.5 Hz; Fig. 4a, b, f).

To extract the main features of the spectra, a stack was carried out for each component, separating the period 1993 from 1994–1995. The temporal separation was justified by the different levels of activity during these years, which could correspond to dissimilarities in the general shape of the spectra. Indeed, a substantial difference exists between the spectra of the vertical component throughout these periods, for which data are available with and without explosion quakes. In the stack for 1993, there are several dominant spectral peaks in the high-frequency part (3–5 Hz; Fig. 5a, b). Particularly in the stack for spectra without explosion quakes this feature is even more evident, with the presence of the first dominant peak at 4.25 Hz (Fig. 5a). In the following years the average spectra looked more narrowly banded, with larger amplitudes in the intervals at lower frequency (1–2 Hz). A well-defined minimum at a frequency around 2.5 Hz is common to all stacks of the vertical component (Fig. 5a–d). This minimum is also reported by Langer and Falsaperla (1996), who considered different time intervals. Spectra of the horizontal components are typically narrowly banded, the energy being concentrated mainly in the frequency range between 1 and 3.5 Hz (Fig. 5e, f). Particularly the N–S component, for which only 20-min samplings with explosion quakes are available, presents dominant peaks between 1 and 2.5 Hz.

Finally, a comparison of the stacks of spectra of STR and TF1 (Fig. 6) was carried out for June to August 1995 with the aim of evaluating site effects. In contrast to the spectra previously discussed, which refer to long-time windows of analysis (each at least 20 min), each stack was evaluated on the basis of spectra of approximately 80 s. Keeping in mind this difference, we observe that spectra from TF1 are more narrowly banded than those of STR, with a frequency range from 1 to 3.5 Hz. The presence of a single peak with larger amplitude than the others is evident in the stack of STR. The minimum at 2.5 Hz is not clearly visible at TF1. The differences between the two stations should indicate the existence of site effects. However, some peaks of STR, which exceed one third of the maximum amplitude, are also found among peaks exceeding one third of the maximum in the spectrum of TF1. These common peaks may be related to source properties.

Statistical analysis

Various physical models for the seismic signals on volcanoes in general and Stromboli in particular are under discussion (e.g., Fadeli 1984; Chouet 1988; Neuberg and



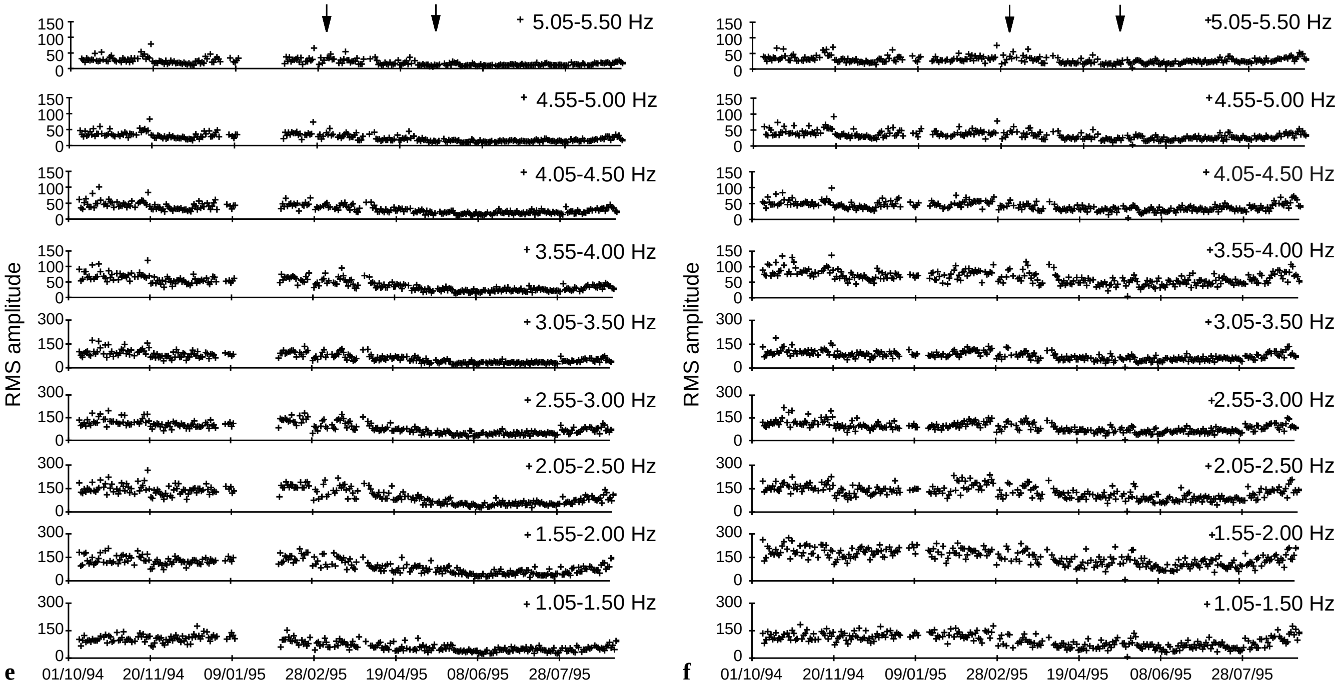


Fig. 4 Development of spectral amplitudes at station STR in nine selected frequency classes in 1994–1995: **a, b** refer, respectively, to 20-min samplings, without explosion quakes and 2-h samplings on the vertical component; **c, d** refer, respectively, to 20-min samplings without explosion quakes and 2-h samplings on the E–W component; **e, f** 20-min samplings on the E–W and N–S components, respectively. *Arrows* indicate the explosive sequences

Luckett 1996). Despite the numerous research efforts on Stromboli, the understanding of basic source parameters, such as their position, shape, and extent, is vague. Further difficulties for a quantitative description of source effects arise from the fact that the magma forms a multiphase system the behavior of which poses severe problems to feasible modeling of volcanic and seismic phenomena. The limitations of our data set leave little hope of constraining physical models for the seismic signals on Stromboli in a meaningful way, or of deciding whether one model is more suitable than a competing one. A further problem arises from wave-propagation effects, the influence of which becomes obvious from the comparison of the spectral peaks observed at different sites but which, given the complicated geologic structure of the volcanic edifice, add more difficulties to modeling the seismic waveforms, at least in the frequency range discussed here. In light of these difficulties, we limit ourselves mainly to a statistical description of the observations. The statistical analysis is carried out with the aim of extracting a limited number of parameters (e.g., averages, variances, etc.) from the data and relating them to relevant volcanologic phenomena as they are observed at the surface. This can be done without any a priori assumption of a physical model. The analysis presented here focuses particularly on the temporal variations of the frequency content rather than the shape of the spectra themselves, thus excluding site effects which are likely to be time invariant.

We base the analysis on daily representative power spectra averaged over time windows of 2 h or 20 min, respectively. The advantage of this type of monitoring compared with continuous recording is obvious; the amount of data accumulated even in years is limited, whereas the handling of continuously recorded time sequences over such a long time span is cumbersome from the viewpoints of storage and data processing. For the statistical treatment we consider the seismic spectra as an n-dimensional random variable X, with n being the number of frequency bands. The bands have been chosen as before, i.e., between 1.0 and 5.5 Hz with a bandwidth of 0.5 Hz. This choice matches both the requests of statistical stability of spectral estimates and the resolution of the characteristic features of the spectra. We thus obtained a nine-dimensional random variable X whose components correspond to the frequency bands 1–1.5, 1.55–2, 2.05–2.5, 2.55–3, 3.05–3.5, 3.55–4, 4.05–4.5, 4.55–5, and 5.05–5.5 Hz. The indices have been chosen in a way that the frequency band 1–1.5 Hz corresponds to the component x_1, and the uppermost frequency band 5.05–5-5 Hz corresponds to the component x_9. The interpretation of multivariate data sets poses particular problems, since the mere consideration of marginal distributions is not sufficient. We therefore calculated, for all data sets and components, average vectors as well as covariance and correlation matrices, and we performed a Principal Component Analysis (e.g., see Davis 1986) to calculate eigenvalues λ and eigenvectors e of the covariance matrix. Following common conventions, we give the λ's sorted with respect to

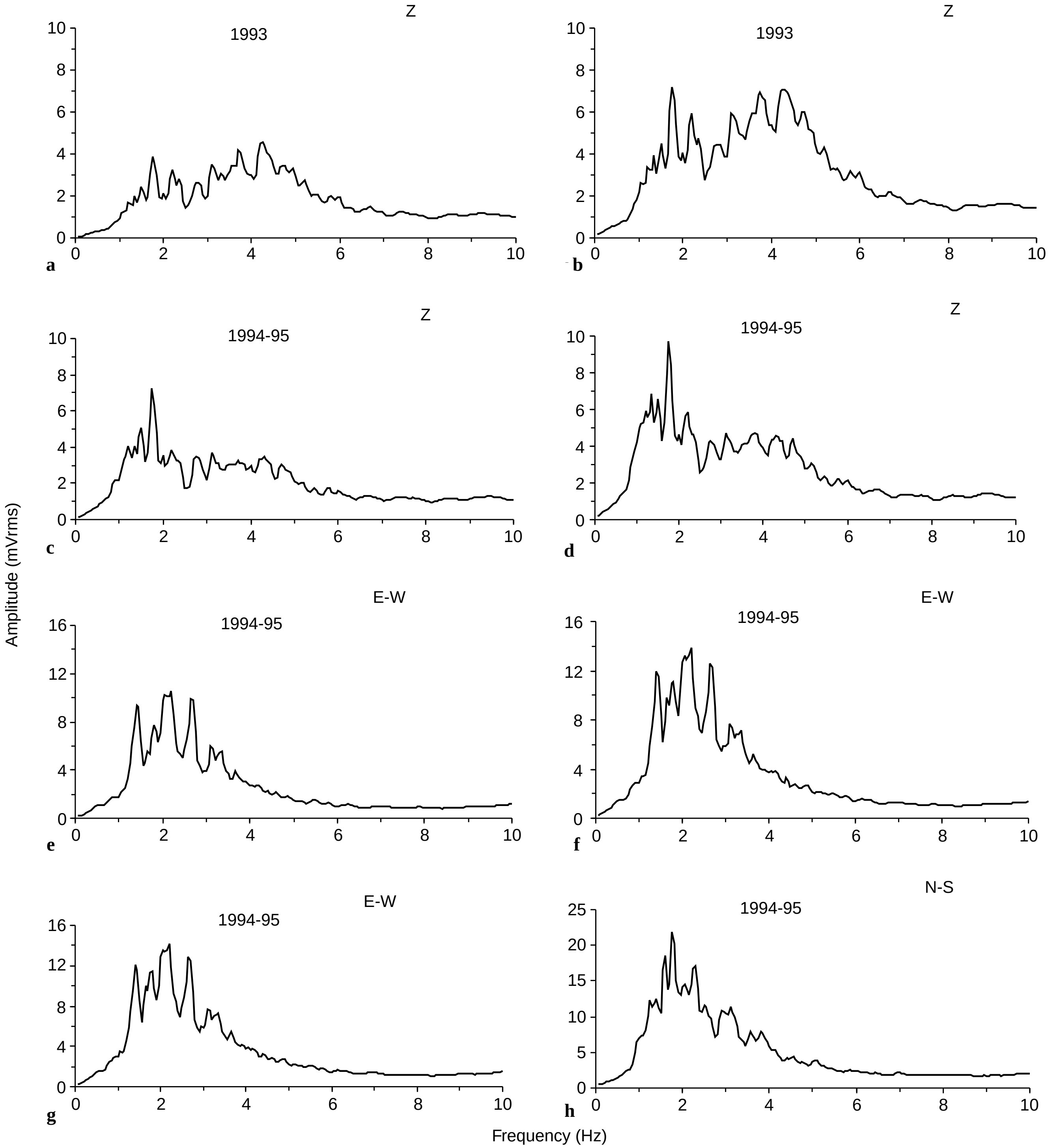


Fig. 5 Stacks of the spectra of station STR: **a, b** refer, respectively, to 20-min samplings without explosion quakes and 2-h samplings for the vertical component in 1993; **c, d** refer, respectively, to 20-min samplings without explosion quakes and 2-h samplings for the vertical component in 1994–1995; **e, f** refer, respectively, to 20-min samplings without explosion quakes and 2-h samplings for the E–W component in 1994–1995; **g, h** refer, respectively, to 20-min samplings on the E–W and N–S components in 1994–1995

their size, and the eigenvectors e are written in their transpose form e^T. This type of analysis is appropriate in multivariate data sets, since eigenvalues and eigenvectors give a rough geometrical idea about form and position of a data cloud. The data set has an elongated shape if one eigenvalue is much larger than the others, whereas it looks like a sphere (or hypersphere) if the eigenvalues are of the same order. The components of the eigenvectors correspond to the direction cosines of the axes. They are close to 1 or –1 if the data set has an

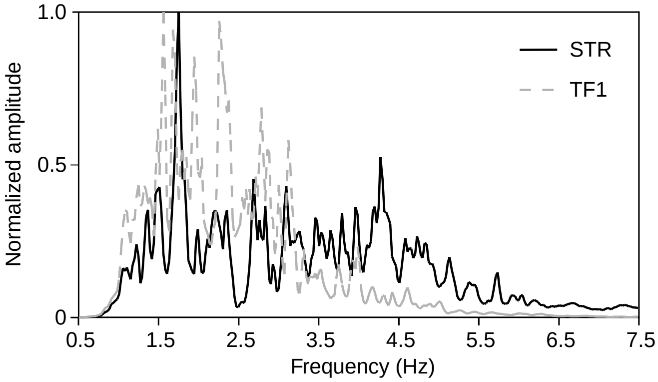


Fig. 6 Comparison of the stacks of the spectra at stations STR and TF1 from 14 June to 24 August 1995. The spectral analysis was carried out on time series of 80-s duration, and by averaging successive spectra, each performed by using an FFT over a window consisting of 4096 points

orientation quasi-parallel to the corresponding axis, and they become 0 if the orientation is perpendicular to the axis. In our specific case, where we observe mainly elongated data clouds, the largest eigenvalue explains a major part of the total variance. We therefore can base our discussion essentially on a few parameters, such as the average vector μ, the first eigenvalue, and the corresponding eigenvector, rather than enter a tedious analysis of the covariance matrices themselves.

Firstly, we considered the vertical component spectra of the year 1993 (Table 2). For the 2hsample of the vertical component (including explosion quakes), we observed relatively large amplitudes in the high-frequency range (i.e., above 2.5 Hz), a first eigenvalue λ explaining 87% of the total variance, and the corresponding eigenvector having its major components in the frequency range between 3 and 5 Hz (Table 2a). Essentially, the same holds for the shsample (explosion quakes excluded), where the first eigenvalue explains 80% of the total variance and the major coefficients of the corresponding eigenvector occur in the range above 3 Hz (Table 2b). In other words, we observe high amplitudes in the frequency range above 2.5 Hz and, at the same time, a greater fluctuation of the amplitudes in these frequency classes. The average amplitudes of the frequencies below 2.5 Hz are considerably lower, as are the amplitude fluctuations in this range. The differences of the samples with and without explosion quakes are minor from a statistical point of view; hence, the conclusions drawn from the 2hsample should not be affected by the presence of the explosion quakes. This facilitates the task of continuous seismic surveillance, since one can speed up the extraction of useful information from the data as they are, without any processing to exclude the explosion quakes. On the other hand, it supports the hypothesis surmised by Del Pezzo et al. (1988), who claimed that explosion quakes and volcanic tremor on Stromboli were related to the same source.

Cluster analysis represents an unsupervised classification method with limited use of a priori information, concerning essentially the measure of compactness of the classes. We applied this method to data of the vertical component in 1993, first considering the 2hsample,

Table 2a Statistics of vertical 2 hour spectra in 1993

x	μ	Covariance matrix									λ	Eigenvectors e^T								
1.00–1.5	34.1	136	154	185	157	189	189	192	148	102	2844	0.17	0.22	0.31	0.29	0.39	0.45	0.44	0.36	0.25
1.55–2.0	38.1		222	232	201	247	265	242	202	131	231	0.39	0.48	0.47	0.28	0.05	−0.20	−0.36	−0.30	−0.24
2.05–2.5	44.7			344	292	350	369	356	280	197	56	0.30	0.65	−0.41	−0.41	−0.20	0.04	−0.06	0.31	0.09
2.55–3.0	40.0				273	329	356	341	269	185	46	−0.33	0.05	−0.12	0.11	0.20	0.55	−0.68	0.17	−0.13
3.05–3.5	52.7					455	497	485	391	270	31	−0.05	0.19	0.32	0.02	0.08	0.38	0.40	−0.53	−0.52
3.55–4.0	61.7						602	569	466	319	18	−0.14	0.04	0.38	0.01	−0.82	0.39	0.08	0.07	0.07
4.05–4.5	64.5							618	465	331	14	0.74	−0.47	−0.07	−0.02	−0.03	0.36	−0.17	−0.15	0.09
4.55–5.0	54.3								403	275	10	−0.21	0.13	0.36	−0.66	0.26	0.14	−0.04	−0.41	0.34
5.05–5.5	37.6									204	7	−0.05	0.15	−0.34	0.44	−0.12	0.04	−0.08	−0.43	0.67

Table 2b Statistics of vertical 20 min spectra in 1993 – explosion quakes excluded

x	μ	Covariance matrix									λ	Eigenvectors e^T								
1.00–1.5	26.2	69	86	66	51	49	45	55	42	35	1604	0.08	0.12	0.23	0.23	0.35	0.45	0.5	0.44	0.33
1.55–2.0	39.6		198	122	94	72	48	74	36	30	304	0.33	0.73	0.41	0.28	0.04	−0.16	−0.11	−0.22	−0.17
2.05–2.5	35.6			149	125	132	141	168	127	94	58	−0.04	−0.22	0.15	0.42	−0.09	0.41	−0.73	0.20	−0.11
2.55–3.0	31.3				124	132	155	159	139	100	44	−0.48	−0.29	0.40	0.30	0.15	0.06	0.33	−0.42	−0.36
3.05–3.5	43.2					206	253	279	239	178	25	0.55	−0.54	0.42	0.14	−0.17	−0.38	0.05	0.07	0.18
3.55–4.0	49.2						350	352	324	238	21	−0.57	0.17	0.17	0.21	−0.22	−0.49	−0.09	0.44	0.29
4.05–4.5	56.0							449	347	271	9	−0.01	0.07	0.12	0.05	−0.87	0.43	0.17	−0.01	−0.05
4.55–5.0	46.1								339	248	7	−0.08	0.01	−0.13	0.25	−0.01	0.09	−0.10	−0.58	0.75
5.05–5.5	34.2									196	5	−0.16	0.02	0.60	−0.69	0.08	0.17	−0.22	−0.08	0.21

then the shsample. As described above, a variety of volcanic phenomena was observed in this period, and the fluctuation of the tremor signal was considerable. As in the Principal Component Analysis, we used the nine-dimensional data vectors given by the RMS values in the intervals from 1.0 to 5.5 Hz. The task of cluster analysis is to find a partition with groups having an optimum homogeneity. As a measure of homogeneity we used the distances

$$d^2ik=(x_{ik}-x_k)^T\ G_k\ (x_{ik}-x_k),$$

where $G_k=det(S_k)^{(1/r)}S_k^{-1}$, S_k is the dispersion matrix of the kth cluster, and r is the rank of the dispersion matrix (Späth 1983). The optimum partition has been found by minimizing

$$D=\sum_i\sum_k d_{ik}{}^2=\sum_i\sum_k (\mathrm{x}_{ik}-\mathrm{x}_k)^T\ G_k\ (x_{ik}-x_k)$$

This measure of homogeneity of clusters is known as the "adaptive determinant criterion." The application of the adaptive determinant criterion also accounts for groups of data with different directions of their principal axes. We address the interested reader to textbooks of cluster analysis by Anderberg (1973) or Späth (1983). Choosing a partition with three clusters according to Langer and Falsaperla (1996), the cluster analysis for the 2hsample identifies a cluster 3 with high values in all frequencies during the lava effusions on 16 and 18 May (Fig. 3b). An intermediate cluster 2 with high-amplitude values in the high-frequency range (above 2.5 Hz) occurred from June to September 1993. A third cluster (cluster 1) representing low amplitudes occurred shortly after the effusions and from September to the end of the year. Contrary to clusters 2 and 3, in cluster 1 the low-frequency part of the spectra below 2.5 Hz prevails over higher frequencies (i.e., above 2.5 Hz). Similar results are obtained for the shsample spectra (Fig. 3a). Slight differences were observed in May, where cluster 3 of the shsample corresponded to cluster 2 in the set of the 2hsample, and vice versa in June. These general trends have been reported by Langer and Falsaperla (1996) for the period 1990–1993, even though the results turn out more clearly from the present analysis, which is due to the increased number of components available here (nine instead of five in the paper cited above). The stability of the results is improved by calculating RMS amplitudes instead of reading maximum values within predefined spectral intervals. In fact, the heterogeneity between the clusters we found here is more pronounced than in Langer and Falsaperla (1996), since periods where clusters alternate rapidly are limited.

From October 1994 to August 1995 tremor radiation on the vertical component is characterized by spectra with a dominant low-frequency part (Table 3a). In the 2hsample the first eigenvalue corresponds to 85% of the total variance, and its eigenvector has major components in the low-frequency bands. In other words, the signal is dominated by low frequencies, and the fluctuations of spectral amplitudes are mainly limited to this range. Spectral shape and statistical properties resemble cluster 1 of 1993, i.e., with low frequencies below 2.5 Hz prevailing. As for the spectra in 1993, the exclusion of the explosion quakes (shsample) from the

Table 3a Statistics of vertical 2 hour spectra in 1994/95

x	μ	Covariance matrix									λ	Eigenvectors e^T								
1.00–1.5	60.0	353	212	165	184	210	169	171	90	55	1157	0.50	0.37	0.29	0.34	0.39	0.32	0.33	0.18	0.11
1.55–2.0	42.1		188	129	141	161	125	130	67	38	97	−0.71	−0.20	−0.02	0.11	0.27	0.31	0.36	0.30	0.22
2.05–2.5	33.8			117	120	130	107	106	57	36	47	0.49	−0.67	−0.33	−0.22	−0.06	0.11	0.21	0.25	0.20
2.55–3.0	37.7				144	154	131	127	67	43	25	−0.10	0.52	−0.41	−0.51	0.17	−0.33	0.25	0.30	0.09
3.05–3.5	40.4					198	151	156	89	53	17	−0.00	−0.10	−0.44	0.10	0.71	0.07	−0.25	−0.26	−0.38
3.55–4.0	38.3						139	133	74	47	13	−0.00	−0.24	0.51	−0.11	0.45	−0.54	−0.27	0.25	0.21
4.05–4.5	33.6							148	83	52	7	−0.01	−0.18	0.26	−0.18	0.08	−0.26	0.69	−0.42	−0.37
4.55–5.0	23.9								57	35	5	0.01	−0.02	−0.34	0.69	−0.09	−0.06	0.20	−0.03	0.21
5.05–5.5	19.0									27	3	−0.04	0.06	−0.03	−0.17	0.15	0.09	−0.00	−0.64	0.72

Table 3b Statistics of vertical 20 min spectra in 1994/95 – explosion quakes excluded

x	μ	Covariance matrix									λ	Eigenvectors e^T								
1.00–1.5	47.0	207	92	88	87	78	59	52	22	14	465	0.59	0.36	0.34	0.35	0.34	0.27	0.26	0.14	0.09
1.55–2.0	30.5		77	57	57	55	39	42	20	12	82	−0.67	−0.01	0.02	0.1	0.28	0.35	0.40	0.34	0.25
2.05–2.5	27.3			73	59	51	42	36	21	15	28	0.42	−0.56	−0.54	−0.19	0.08	0.28	0.22	0.18	0.16
2.55–3.0	30.5				64	56	48	42	23	14	20	0.01	0.67	−0.61	−0.20	0.08	−0.20	0.27	0.01	−0.06
3.05–3.5	29.9					64	50	48	28	19	12	−0.12	−0.09	−0.28	0.44	0.23	0.34	−0.03	−0.41	−0.61
3.55–4.0	30.5						52	44	27	18	7	−0.03	0.02	−0.15	−0.01	0.69	−0.11	−0.63	−0.02	0.29
4.05–4.5	25.7							50	28	18	5	−0.00	−0.25	0.25	−0.31	0.50	−0.44	0.47	−0.28	−0.19
4.55–5.0	18.0								23	16	3	0.00	−0.19	−0.21	0.71	−0.06	−0.06	0.16	0.12	0.19
5.05–5.5	15.3									16	2	−0.03	0.04	−0.04	0.06	−0.1	0.16	0.14	−0.75	0.61

analysis does not alter the general picture (Table 4b). Indeed, the dominant radiation in this case also comes from the low-frequency part, the first eigenvalue corresponds to the major part of the contribution (75%), and the major components of the eigenvector are found in the low-frequency part of the spectrum. Nevertheless, we note that in 1993, as from October 1994 to August 1995, the significance of the first eigenvalue slightly increases for the vertical 2-h spectra where explosion quakes are not excluded, despite the general differences between the spectra observed in 1993 and in 1994–1995. One may conclude that the temporal development of spectra shows similar features both in the tremor and the explosion quakes but is even more pronounced in the latter ones.

The tremor amplitudes are higher on the horizontal components than on the vertical one by a factor of 2–3 (Table 4a–c). The spectra of the horizontal components are somewhat more narrowly banded than those of the vertical component. The prevalence of the low-frequency radiation over the higher frequencies is emphasized on the E–W component. Again, exclusion of the explosion quakes does not affect the general trends. In both cases the first eigenvalue of the covariance matrix explains over 90% of the total variance, and its eigenvector has almost the same orientation with its major contributions from the four lower-frequency classes.

Throughout the period from October 1994 to August 1995, the radiation of frequencies above 2.5 Hz was low in all components, including the vertical. This makes it difficult to decide whether the missing higher frequencies on the horizontal components reflect mainly source or wave-propagation effects. An inspection of the spectral shapes (Fig. 5) on both horizontal components reveals a more or less monotonously decreasing trend toward high frequencies, whereas on the vertical component there is a side maximum around 3.8 Hz. From the correlation matrices (Table 5), we find that the majority of the correlation coefficients are lower for the vertical component than for the E–W component.

Table 4a Statistics of E-W 2 hour spectra in 1994/95

x	μ	Covariance matrix									λ	Eigenvectors e^T								
1.00–1.5	96	1683	1793	1371	1080	713	455	394	288	232	6361	0.50	0.57	0.44	0.35	0.23	0.15	0.13	0.09	0.08
1.55–2.0	106		2085	1587	1258	824	524	448	331	264	163	−0.70	0.15	0.30	0.42	0.31	0.23	0.18	0.15	0.13
2.05–2.5	85			1300	1006	664	423	361	263	212	78	0.41	−0.48	−0.30	−0.08	0.23	0.30	0.36	0.37	0.33
2.55–3.0	65				846	546	348	293	214	170	48	−0.31	0.63	−0.39	−0.31	−0.08	0.09	0.19	0.35	0.29
3.05–3.5	43					376	238	203	150	120	41	−0.02	−0.14	0.69	−0.62	−0.18	−0.08	0.14	0.17	0.21
3.55–4.0	32						163	137	103	84	13	0.03	−0.08	0.05	0.47	−0.73	−0.26	0.04	0.25	0.31
4.05–4.5	25							124	95	77	6	0.00	−0.03	0.12	−0.02	0.46	−0.80	−0.14	0.20	0.29
4.55–5.0	20								80	65	3	0.02	−0.02	0.02	−0.01	0.04	0.34	−0.78	−0.02	0.51
5.05–5.5	16									57	2	−0.01	0.03	−0.04	0.00	0.00	−0.05	0.35	−0.76	0.54

Table 4b Statistics of E-W 20 min spectra in 1994/95 – explosion quakes excluded

x	μ	Covariance matrix									λ	Eigenvectors e^T								
1.00–1.5	69	912	1049	727	578	349	184	156	96	77	3494	0.49	0.61	0.44	0.34	0.21	0.11	0.09	0.06	0.05
1.55–2.0	84		1320	915	724	438	236	196	121	98	111	−0.62	−0.23	0.58	0.29	0.23	0.20	0.12	0.11	0.12
2.05–2.5	69			736	538	332	182	145	91	76	46	0.08	−0.08	0.62	−0.33	−0.23	−0.27	−0.39	−0.36	−0.31
2.55–3.0	52				456	262	142	117	73	60	40	0.58	−0.68	0.19	−0.12	0.15	0.14	0.17	0.18	0.18
3.05–3.5	34					171	92	76	50	41	34	−0.13	0.32	0.15	−0.80	0.05	0.20	0.24	0.24	0.24
3.55–4.0	25						60	47	32	26	9	0.02	0.02	0.15	0.18	−0.87	−0.05	0.14	0.25	0.33
4.05–4.5	19							45	31	26	6	−0.04	0.02	0.04	0.00	0.27	−0.85	−0.01	0.20	0.40
4.55–5.0	15								24	21	2	0.01	0.02	−0.05	0.01	0.06	0.29	−0.78	0.02	0.54
5.05–5.5	12									20	1	0.00		−0.01			0.03	0.32	−0.81	0.48

Table 4c Statistics of E-W 20 min spectra in 1994/95

x	μ	Covariance matrix									λ	Eigenvectors e^T								
1.00–1.5	96	1941	2002	1454	1147	763	502	430	352	284	7082	0.50	0.58	0.44	0.35	0.23	0.15	0.13	0.10	0.09
1.55–2.0	106		2446	1760	1389	902	590	493	407	339	302	−0.75	−0.1	0.37	0.44	0.23	0.18	0.01	0.08	0.08
2.05–2.5	85			1452	1105	707	467	383	212	256	160	0.04	−0.58	−0.24	0.18	0.31	0.32	0.32	0.31	0.23
2.55–3.0	65				970	598	400	316	257	209	106	−0.29	0.53	−0.47	−0.27	0.09	0.14	0.26	0.34	0.35
3.05–3.5	43					421	273	224	183	149	76	0.01	−0.18	0.63	−0.62	−0.14	−0.02	0.20	0.27	0.26
3.55–4.0	32						202	157	133	108	28	0.04	−0.03	−0.03	0.44	−0.76	−0.21	0.08	0.29	0.31
4.05–4.5	25							147	133	108	14	0.00	−0.04	−0.02	0.08	0.41	−0.87	0.11	0.08	0.19
4.55–5.0	20								116	95	8	0.04	−0.04	0.02	−0.08	0.15	0.08	−0.85	0.19	0.47
5.05–5.5	17									86	3	0.02	−0.02	−0.02	0.00	−0.03	0.07	0.18	−0.75	0.63

Table 4d Statistics of N-S 20 min spectra in 1994/95

x	μ	Covariance matrix									λ	Eigenvectors e^T								
1.00–1.5	149	2383	1651	1151	944	712	437	419	293	222	5550	0.61	0.52	0.38	0.31	0.24	0.14	0.13	0.1	0.08
1.55–2.0	124		1675	1099	888	673	397	362	267	211	533	−0.75	0.17	0.40	0.31	0.28	0.15	0.12	0.13	0.12
2.05–2.5	88			980	722	559	319	291	223	178	239	0.22	−0.78	0.10	0.20	0.26	0.22	0.28	0.25	0.20
2.55–3.0	77				655	468	280	255	192	146	133	−0.77	0.31	−0.66	−0.11	0.09	0.23	0.37	0.37	0.34
3.05–3.5	65					411	232	214	162	120	77	0.01	0.02	0.48	−0.66	−0.24	−0.10	0.12	0.27	0.42
3.55–4.0	41						161	140	109	83	47	0.00	−0.02	0.00	0.56	−0.73	−0.19	−0.01	0.15	0.32
4.05–4.5	33							154	118	95	17	0.02	−0.01	−0.11	0.10	0.43	−0.83	−0.11	0.11	0.28
4.55–5.0	29								111	87	11	0.03	−0.02	−0.07	0.02	0.12	0.35	−0.74	−0.11	0.55
5.05–5.5	22									89	9	−0.01	−0.01	−0.01	0.02	−0.01	0.43	−0.80	0.41	0.43

Table 5 Correlation matrices for spectra in 1994/95 – vertical (2 h), E-W (20 min), N-S (20 min)

1.	0.82	0.81	0.81	0.79	0.76	0.75	0.64	0.56
	1.	0.87	0.86	0.84	0.77	0.78	0.65	0.54
		1.	0.92	0.85	0.84	0.81	0.70	0.65
			1.	0.91	0.93	0.87	0.75	0.68
				1.	0.91	0.91	0.85	0.74
					1.0	0.93	0.84	0.77
						1.	0.90	0.83
							1.0	0.89
								1.0

1.	0.92	0.87	0.84	0.84	0.80	0.81	0.74	0.69
	1.	0.93	0.90	0.89	0.84	0.82	0.76	0.74
		1.	0.93	0.90	0.86	0.83	0.76	0.73
			1.	0.94	0.90	0.84	0.77	0.72
				1.	0.94	0.90	0.83	0.78
					1.	0.91	0.87	0.82
						1.	0.94	0.90
							1.	0.96
								1.

1.	0.83	0.76	0.76	0.72	0.71	0.69	0.57	0.48
	1.	0.86	0.84	0.81	0.77	0.71	0.62	0.55
		1.	0.90	0.88	0.80	0.75	0.67	0.60
			1.	0.90	0.86	0.80	0.71	0.60
				1.	0.90	0.85	0.76	0.63
					1.	0.89	0.82	0.70
						1.	0.90	0.81
							1.	0.88
								1.

For the N–S component we have spectra sampled only at 20 min, with tremor and explosion quakes together. Their statistical behavior resembles that of the vertical component with weaker correlation between high and low frequencies than for the E–W spectra, sampled over both 2 h and 20 min. From a statistical point of view, the differences between the two horizontal components are more pronounced than the differences between the vertical component and the N–S component. One could speculate that, due to the properties of the radiation pattern of the sources, certain wave types are dominant on the E–W component, whereas other wave types that are linked to each other on the N–S and vertical components prevail. An example from classical earthquake seismology may help to explain what is meant. There can be a situation in which one horizontal component corresponds to the transverse one with prevailing SH- (Love-) waves, whereas P-SV waves (or Rayleigh waves) are present both on the vertical and radial components. In this case, both wave-propagation effects and radiation patterns are more complicated for the P-SV waves than for the SH waves, giving minor correlation for the P-SV part.

The polarization analysis, carried out for a few time series of August 1995 (Fig. 7), confirms the speculation about wave types based on statistical considerations. It reveals an essentially north/south-directed particle motion with subhorizontal incidence. Assuming a similar location for the source of tremor and the explosion quakes, i.e., somewhat northwest of the craters (e.g., see Del Pezzo et al. 1988; Neuberg et al. 1994), the dominant N–S component should indicate a prevailing radial particle motion, whereas the E–W component should correspond to a transverse orientation. The shallow incidence is easily explained if we assume a source close to the surface and if the volcanic tremor represents essentially P waves.

Discussion and conclusion

According to our results, variations in volcanic activity at Stromboli are usually preceded and/or accompanied by changes in the spectral characteristics of volcanic tremor. These changes are clearly observed in the frequency interval between 1 and 5.5 Hz.

Cluster analysis highlights the existence of at least two states of activity, which typically last from weeks to several months. A state of low to moderate activity can be associated with cluster 1, i.e., spectra with generally low amplitudes and frequencies below 2.5 Hz. A state of strong activity, such as the lava effusions in May 1993, can be related to clusters 2 and 3, where the frequencies above 2.5 Hz are dominant. Although we cannot directly compare amplitudes in 1993 with those of 1994–1995, the statistical analysis as well as the stacked spectra reveal that the 1994-1995 tremor essentially corresponded to cluster 1, whereas in 1993 all kinds of clusters were present because of the larger variety of volcanic phenomena.

We suggest that on Stromboli the amplitudes as well as the shape of the spectra depend on the height of the magma column. Independent evidence of this correlation was provided by witnesses, such as volcanologists and Alpine guides, who periodically reported on visual observations at the craters (M. Coltelli and A. Zerilli, pers. commun.). A high position of the column, which may lead to paroxysmal phases such as lava fountains or effusions, is typically accompanied by large spectral amplitudes, and prevailing high frequencies (i.e., >2.5 Hz on the vertical component at STR). Examples

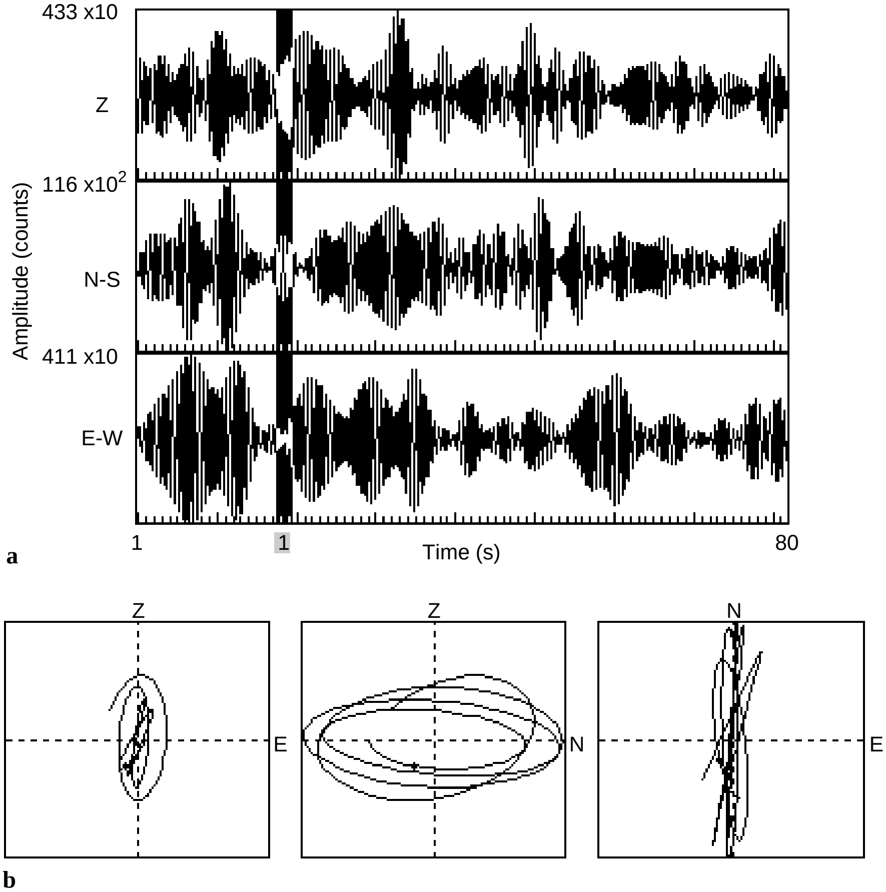


Fig. 7a, b Example of particle-motion analysis on a time series of tremor recorded in 1995 at station STR. The sampling frequency of signal is 100 Hz. **a** Signals of the three component record filtered with a Butterworth bandpass between 1.55 and 2 Hz; **b** particle motion. The frequency interval considered here represents the band with the highest spectral amplitude. The results for the other frequency bands discussed in the text are essentially the same

of these phenomena are the lava effusions in October 1990 and May 1993 (Langer and Falsaperla 1996). A low position of the magma column is characterized by low amplitudes and a spectral shape where the lower frequencies prevail. Explosive sequences usually occur during periods characterized by decreasing values of tremor amplitude (Falsaperla et al. 1994a). These sequences are typically accompanied by an additional sudden reduction in tremor amplitudes. This amplitude drop depends on the features of the sequence, e.g., the number of explosion quakes, duration of the phase with enhancement of tremor amplitudes, etc. (see Table 1). During the explosive sequence of 10 May 1995, the background signal was already low. Therefore, the amplitude drop is hardly visible, although this sequence was strong according to the criteria reported in Table 1.

The presence of explosion quakes affects absolute amplitude values of the spectra but leaves their general shape unchanged. The variations of spectral amplitudes are higher when explosion quakes are included (see Tables 2–4). On the other hand, the development with time of all types of spectra (i.e., spectra with and without explosion quakes, vertical and horizontal components) is essentially coherent (Figs. 3–5).

There is a considerable difference in the frequency content between vertical and horizontal components at STR. E–W and N–S components show a narrowly banded spectrum (between 1 and 3.5 Hz), and higher values of energy radiation with particular reference to the N–S component. Larger amplitudes for the horizontal components have been observed by Falsaperla et al. (1994b) close to the craters at Fossetta (Fig. 1), and are reported for other volcanoes such as Klyuchevskoy (Gordeev et al. 1990) and Etna (Ferrucci et al. 1990). Evidence of propagation of the tremor as surface waves is reported for several volcanoes such as Pavlof (McNutt 1986), Klyuchevskoy (Gordeev et al. 1990), and Mt. Etna (Del Pezzo et al. 1993). At Stromboli, Del Pezzo et al. (1988) deduce a shallow source of seismic activity in an area north of the crater terrace and find a prevailing contribution of P waves from the polarization analysis of a set of explosion quakes. The location of the source of the tremor is thought to be the same, since the shapes of spectra for tremor and explosion quakes are similar (Del Pezzo et al. 1988). Our speculations about wave types, based on statistical considerations as well as the polarization analysis carried out for several time series of tremor in August 1995, favor the conclusions of Del Pezzo et al. (1988).

Differences exist between the vertical components at STR and TF1. The comparison of the stacked spectra at the two stations highlights a broader spectrum of STR with respect to TF1. This observation indicates that site effects affect the signals. On the other hand, some dominant spectral peaks are found in the spectra of both

STR and TF1. These peaks may be related to source properties. In addition, the correlation matrices given in Table 5 indicate that the differences between the horizontal and vertical components at STR cannot be related solely to the influence of the propagation medium. Our results confirm previous studies (e.g., Langer and Falsaperla 1996), which found good correspondence between long-term modifications in volcanic activity and changes in the spectral features of tremor at STR, and demonstrate that this relationship is key to following the different states of the system. Therefore, we can surmise that source effects are responsible for these changes.

We consider the statistical analysis of the seismic signals to be a useful tool for monitoring purposes, since it can be carried out without any a priori information about physical models. Furthermore, it permits us to obtain useful indications about the status of Stromboli by using a very limited amount of information, i.e., the daily calculated RMS values of nine frequency bands. In doing so the amount of data can be drastically reduced in comparison with a continuous analysis of time series. We highly recommend a statistical analysis on other volcanoes with persistent seismic signals that make data compression desirable.

Acknowledgements We thank D. Seidl for critical reading of the manuscript and useful suggestions. We also appreciate comments and criticisms of two anonymous reviewers and J.F. Lénat. We are grateful to our colleagues P. Del Carlo and M. Coltelli for the information they provided on volcanic phenomena, and to D. Patanè and F. Ferrari for the use of their program for particle motion analysis. This work was supported financially by the "Gruppo Nazionale per la Vulcanologia".

References

Anderberg MR (1973) Cluster analysis for applications. Academic Press, New York, 359 pp

Barberi F, Rosi M, Sodi A (1993) Volcanic hazard assessment at Stromboli based on review of historical data. Acta Vulcanol 3:173–187

Bonaccorso A, Cardaci C, Coltelli M, Del Carlo P, Falsaperla S, Panucci S, Pompilio M, Villari L (1996) Volcanic activity on Stromboli in 1993. In: Annual Report of the World Volcanic Eruptions in 1993. Bull Volc Eruptions 33:7–13

Braun T, Neuberg J, Ripepe M (1996) On the origin of long-period tremor recorded at Stromboli Volcano (Italy). Ann Geofisica 39 (2): 311–326

Capaldi G, Guerra I, Lo Bascio A, Luongo G, Pece R, Rapolla A, Scarpa R, Del Pezzo E, Martini M, Ghiara MR, Lirer L, Munno E, La Volpe L (1978) Stromboli and its 1975 eruption. Bull Volcanol 41:259–285

Cavallaro C (1955) Attività dello Stromboli dal 1940 al 1953. Boll Accad Gioenia 3:525–532

Chouet BA (1988) Resonance of a fluid-driven crack: radiation properties and implications for the source of the long-period events and harmonic tremor. J Geophys Res 93:4375–4400

Chouet BA, Page RA, Stephens CD, Lahr JC, Power JA (1994) Precursory swarms of long-period events at Redoubt Volcano (1989–1990), Alaska: their origin and use as a forecasting tool. J Volcanol Geotherm Res 62:95–136

Coltelli M, Cardaci C (1994) Stromboli. Boll Geof Teorica ed Applicata Suppl 36, 141/144:679–683

Davis JC (1986) Statistics and data analysis in geology. Wiley, New York

De Fino M, La Volpe L, Falsaperla S, Frazzetta G, Neri G, Francalanci L, Rosi M, Sbrana A (1988) The Stromboli eruption of December 6 1985 to April 25 1986:volcanological, petrological and seismological data. Rendiconti Soc It Mineral Petrol 43:1021–1038

Del Pezzo E, Godano C, Gorini A, Martini M (1988) Explosion quakes at Stromboli Volcano: spectral composition and wave polarization. Rendiconti Soc It Mineral Petrol 43:1075–1085

Del Pezzo E, De Martino S, Gresta S, Martini M, Milana G, Patanè D, Sabbarese C (1993) Velocity and spectral characteristics of the volcanic tremor at Etna deduced by a small seismometer array. J Volcanol Geotherm Res 56:369–378

Dreier R, Widmer R, Schick R, Zürn W (1994) Stacking of broadband seismograms of shocks at Stromboli. Acta Vulcanol 5:173–178

Fadeli A (1984) A study of the eruption mechanism of volcano Stromboli (Italy). Institute of Geophysics, University of Stuttgart, Germany, 213:1–71

Falsaperla S, Cardaci C (1998) Main features of seismic activity on Stromboli between 1993 and 1995. Acta Vulcanol, 10:136–140

Falsaperla S, Montalto A, Spampinato S (1989) Analysis of seismic data concerning explosive sequences on Stromboli Volcano in 1989. Boll Gruppo Nazionale Vulcanol 1:249–258

Falsaperla S, Montalto A, Spampinato S (1994a) Seismic investigation on volcanic tremor at Stromboli Volcano (Italy). Acta Vulcanol 5:179–186

Falsaperla S, Langer H, Martinelli B, Schick R (1994b) Seismic measurements on Stromboli Volcano in a wide frequency range. Acta Vulcanol 5:173–178

Ferrucci F, Godano C, Pino NA (1990) Approach to the volcanic tremor by covariance analysis: an application to the eruption of Mt. Etna (Sicily). Geophys Res Lett 17:2425–2428

Gordeev EI, Saltykov VA, Sinitsyn VI, Chebrov VN (1990) Temporal and spatial characteristics of volcanic tremor wave fields. J Volcanol Geotherm Res 40:89–101

GVN Bulletin (1995) Stromboli. Smithsonian Institution Bulletin of the Global Volcanism Network 20 (11/12): 7–8

Imbò G (1928) Parossismo di Stromboli nel settembre 1930. Bull Volcanol 15–18:177–185

Langer H, Falsaperla S (1996) Long-term observation of volcanic tremor on Stromboli Volcano (Italy): a synopsis. Pageoph 147:1198–1223

McNutt SR (1986) Observations and analysis of B-type earthquakes, explosions, and volcanic tremor at Pavlof Volcano, Alaska. Bull Seismol Soc Am 76:153–175

McNutt SR (1992) Volcanic tremor. Encyclopedia of earth system science, vol 4. Academic Press, San Diego, pp 417–425

Minakami T (1974) Seismology of volcanoes in Japan. In: Civetta L, Gasparini P, Luongo G, Rapolla A (eds) Physical volcanology. Elsevier, Amsterdam, pp 1–27

Neuberg J, Lucket R (1996) Seismo-volcanic sources on Stromboli Volcano. Ann Geofisica 39 (2): 377–391

Neuberg J, Ripepe M, Braun T (1994) Highlights from a seismic broadband array on Stromboli Volcano. Geophys Res Lett 21:749–752

Randall RB (1977) Frequency analysis. Naeum Offset, Denmark

Schick R (1981) Source mechanism of volcanic tremor. Bull Volcanol 44:491–497

Seidl D, Kirbani SB, Brüstle W (1990) Maximum entropy spectral analysis of volcanic tremor using data from Etna (Sicily) and Merapi (central Java). Bull Volcanol 52:460–474

Späth H (1983) Cluster-Formation und Analyse, Theorie, FORTRAN-Programme, Beispiele. Oldenbourg, München

Washington HS (1917) Persistence of vents at Stromboli and its bearing on volcanic mechanism. Geol Soc Am Bull 28:248–278

Wasserman J (1997) Untersuchung seismicher Signale vulcanischen Ursprungs anhand von Breitband – Arrayregistrierungen an den Vulkanen Ätna und Stromboli. Berichte des Institutes für Geophysik der Universität Stuttgart, 10:1–172