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The spatial amplitude distribution of volcanic tremor at Stromboli volcano (Italy)

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Abstract
A portable seismic station consisting of a three-component seismometer in conjunction with a spectral analyzer was deployed in May and June 1994 to record volcanic tremor in a wide area on Stromboli. For the reduction of path effects, tremor spectra were averaged over 164 observation points. They illustrate smooth and broadband spectral lobes in the frequency range between 1-12 Hz. It is suggestive that these overall spectra represent in a first approximation the spectral radiation caused by source processes. Identical and significant maxima at 2.65 Hz and 3.65 Hz are found in all components. No systematic distinction is found in the amplitude values and spectral forms for either horizontal component. The amplitude of the vertical component presents approximately one third that of the horizontal components. A subclassification of the data according to geological strata shows frequency dependent amplitude amplifications. Thick ash and lapilli beds reach a factor of four within frequencies from 4-6 Hz. The influence of these site effects seems minor below 2 Hz. The paper presents maps for each of the three components showing the distribution of the tremor amplitudes averaged over areas of 150 m by 150 m. Model curves derived from fluid-flow acoustics are compared with the tremor spectra.

Key words *Stromboli – volcanic tremor – volcanic seismicity*

1. Introduction

A common observation in examining volcanic tremor are sharp spectral peaks in the frequency range between approximately 1 to 10 Hz. Although there exist cases where the extreme high Q-factor of the spectral peaks (Hurst and Sherburn, 1993) or the consistent center frequencies of the peaks on different site conditions clearly imply that source effects produce the resonances, the spectral content with volcanic tremor is still discussed controversially in regard to the influence of source or path effects (Correig and Vila, 1993). In comparison with the typical narrow-band spectra of volcanic tremor as observed on Semeru (Schlindwein *et al.*, 1995), Arenal (Alvarado, 1988) or Ruapehu (Hurst and Sherburn, 1993), the spectral form of volcanic tremor at Stromboli is characterized by a broad lobe of several Hertz half-bandwith with varying emergent peaks (Falsaperla and Schick, 1993). Falsaperla *et al.* (1989) studied the change of amplitudes and mean frequencies of such peaks with time and tried to correlate the data to a different dynamical state of Strombolian activity. These and comparable studies by other authors are based on data from one single seismic station. Providing the observed spectral peaks are dominantly caused by path effects (*e.g.*, due to resonant scattering as studied by Correig and Vila, 1993) and less by source effects, small variations in the location of the tremor sources might be associated with a frequency shift of the spectral peaks. This would mean a serious deterioration in the significance of correlating the spectral form of volcanic tremor to the kind of dynamic processes acting on volcanoes.

The aim of the present study is to establish whether an observation of the volcanic tremor on Stromboli over a wide area will result in a better discrimination between source and path resonances. As a simultaneous operation of a few hundred stations distributed on the flanks of the volcano is not feasible, consecutive measurements in time using one station were performed.

2. Methods of registration

The field measurements were carried out from the 4th-30th May, 1994. The essential part of the recording equipment consisted of one three-component seismometer with output proportional to ground velocity (Type Le3D,

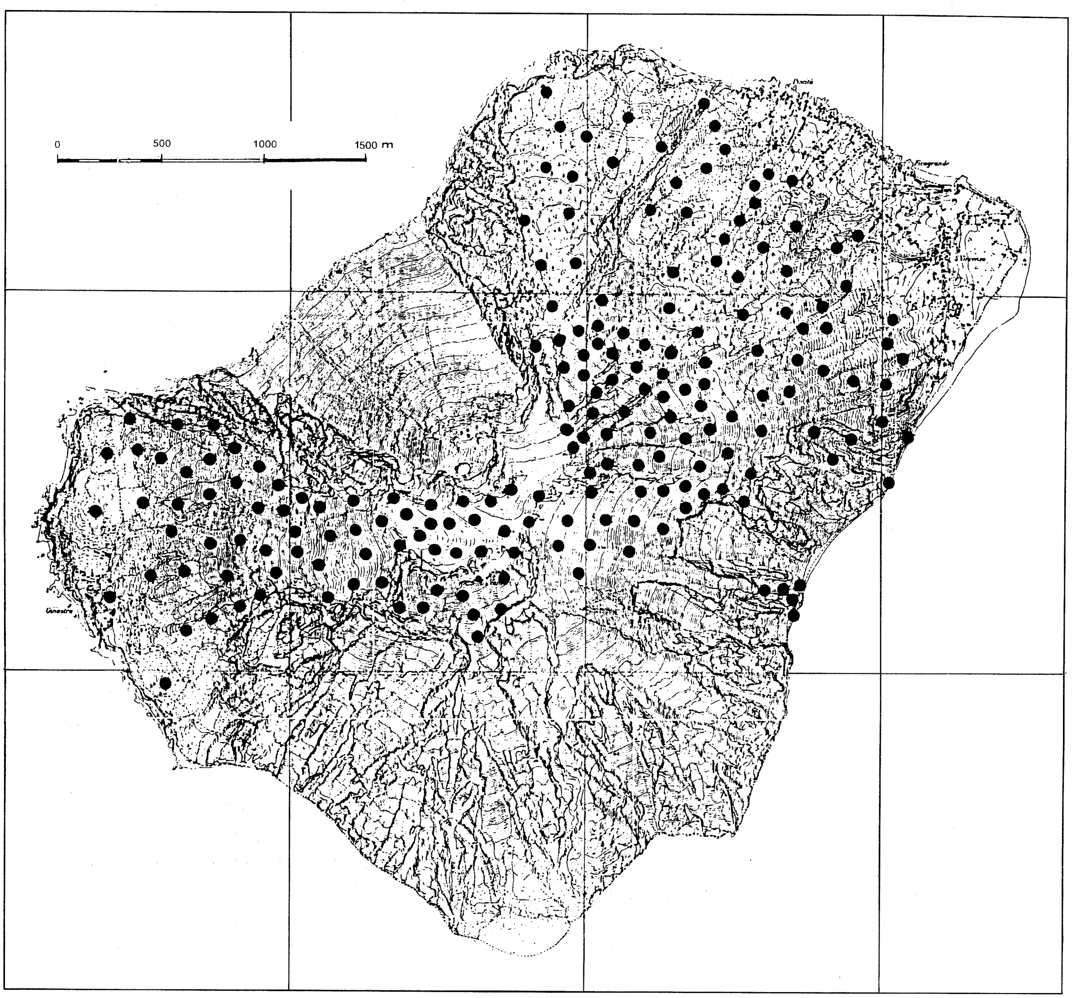


Fig. 1. Map of Stromboli with the distribution of 164 observation points on the volcano.

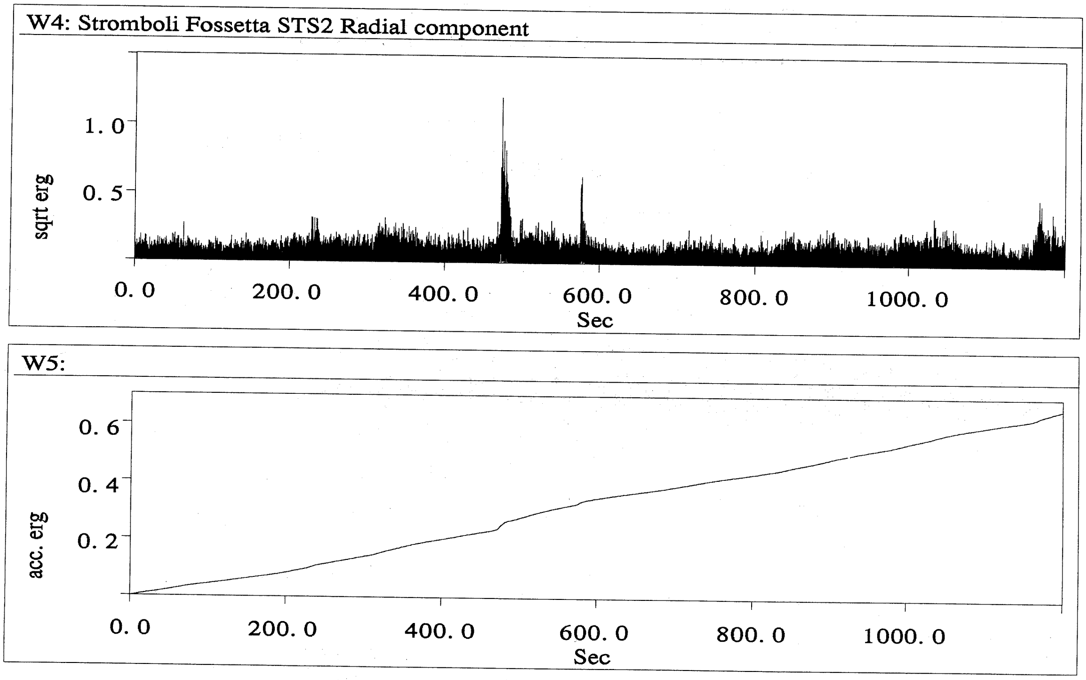


Fig. 2. Square root of seismic energy flux recorded in the Fossetta on Stromboli; the pronounced peaks correspond to explosions (above). Integrated square root of seismic energy flux exhibiting the long-term dominance of tremor energy *vs* Strombolian explosions (below).

1 s, Lennartz-Electronics, Tuebingen) and one portable two-channel spectral analyzer (Type SD222, Spectral Dynamics Corp., San Diego). The portable equipment was housed in a small aluminum suitcase and powered by batteries.

Since all measuring points on Stromboli volcano can only be reached on foot, the limited weight of one day-pack did not exceed 10 kg. At each observation site, the stacked amplitude spectra of the tremor were stored in the analyzer. This naturally involves a loss of information against the recording of time series. On the other hand, the on-line calculation and display of the spectra on the screen of the analyzer permitted quick decisions concerning the necessary measuring density of the stations relative to a certain area. The spectra were calculated in the frequency range between 0-25 Hz, with a frequency interval of 0.125 Hz. The spectral average over 29 spectra was stored in the memory of the analyzer. The components of the Le3D were oriented vertically, radially and transversally with respect to the active crater region. Since the spectral analyzer permitted only a two channel analysis, the recordings were divided into simultaneous observations of vertical and radial components and radial and transversal components. One observational point lasted approximately 30 min including packing and attending equipment.

Figure 1 illustrates the locations of 164 observation points on a map of Stromboli. For safety reasons, the Sciara del Fuoco and the steep flanks and gorges in the southern regions of the island were excluded from measurements.

The on-line updating of the spectra could be observed on the display of the spectral analyzer. As can be seen in fig. 2, the integrated energy within the observation time is primarily associated with the volcanic tremor. Energy

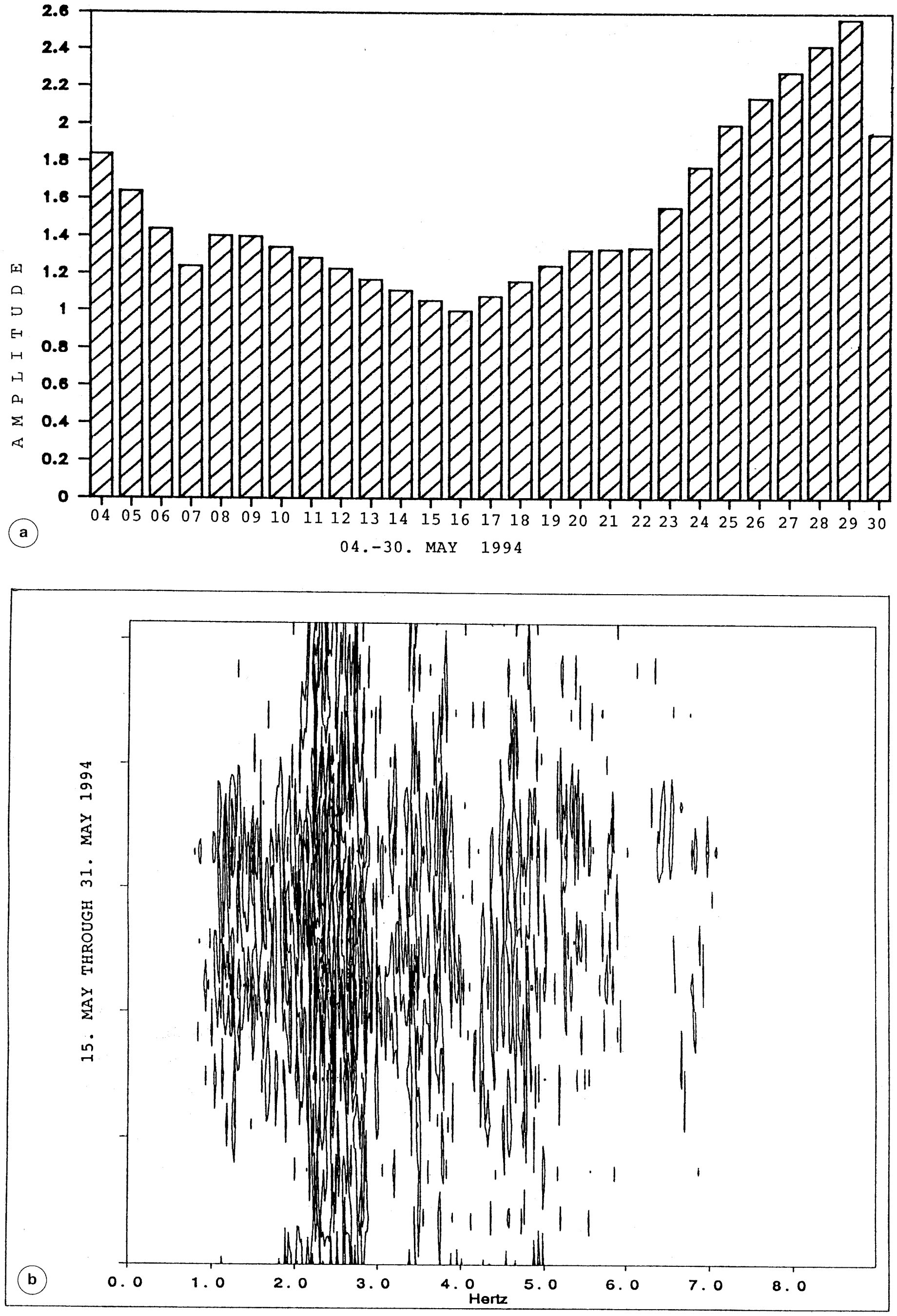


Fig. 3a,b. a) Variation of the average tremor amplitude (radial component) during the measurement period; b) contour plot illustrating the fluctuations of tremor amplitude *vs* frequency during part of the observation time.

contributed by the majority of the explosions is negligible for the total amount of seismic energy. Figure 2 presents time series of the square root of the energy flux (upper diagram) and the corresponding integrated energy (lower diagram). In case of exceptionally strong Strombolian explosions during the time of measurements or disturbances from non-volcanic signals, *e.g.*, from hydrofoil boats, the measurements were restarted.

3. Tremor spectra corrections

During our observations on Stromboli, the rms values of the volcanic tremor averaged over the selected recording windows varied slowly within measuring increments. Our corrections for temporal changes in the amplitudes and in the spectral composition of the tremor source relied on:

i) a remigrated (loop) analysis using a combination of repetitive measurements in the same region;

ii) a base station where samples in hourly intervals of the tremor were recorded. The station is located in the area of Bastimento and is operated by the Istituto di Scienze della Terra, Università di Udine (Carniel, 1994).

Figure 3a presents the mean daily tremor amplitude variation which was applied to the spectral corrections. The plot is based on digital data already published by Carniel (1994) and a loop analysis using the recorded observation points. Figure 3b shows in a contour plot a spectrogram during part of the recording period. Because of the sufficient temporal stability noted in spectral composition of the tremor, the correction factor was assumed as independent from frequency.

The amplitude spectra were neither normalized nor were they corrected for different crater distances.

4. Presentation and analysis of data

Figure 4 shows amplitude spectra for the radial (R), transversal (T) and vertical (Z) component averaged over all the available observation points. No corrections other than temporal were applied to the spectra from the individual recording sites before calculating the average. The abscissae extend from 1 Hz to 12 Hz in frequency increments of 0.125 Hz. The ordinates represent the spectral amplitude of the ground velocity. The amplitude scales are in arbitrary units but comparable between components R, T and Z. Values for absolute maxima for both horizontal components are nearly identical. The maximum of the vertical component is approximately one third relative to both horizontal components. Within the frequency resolution of 0.125 Hz, the maximum amplitudes of all three components are at the same frequency of 2.65 Hz. A less pronounced maximum is seen in all components at 3.65 Hz. The vertical component shows a third maximum at 5.1 Hz which may faintly be seen in the horizontal components again.

The normalized statistical error of the spectral estimates can be calculated by taking the inverse square root of the number of independent sample spectra. With an average of over 29 spectra for each component and each observation site and 164 observation sites for R, T and Z, one obtains an amplitude error of 1.5%.

Figure 5 distinguishes between observation points located on different geological ground:

i) consolidated and hard lava rock (I) with 39 observation points;

ii) thin ash or lapilli beds above lava rock (II) with 74 observation points;

iii) ash or lapilli beds of large, unknown thickness (III) with 51 observation points.

A further differentiation is illustrated in fig. 6 and fig. 7 where the spectra were obtained from an average over all observation points below and above an altitude of 600 m, respectively. This height was selected as it seems to mark a remarkable change in the amplitude gradient between crater region and sea level. Although all spectral amplitude scales are in relative units, they can still be compared with one-another.

The spatial distribution of mean tremor amplitude in the spectral windows from 1-12 Hz is illustrated for the radial, transversal and vertical components in figs. 8a-c. The numbers

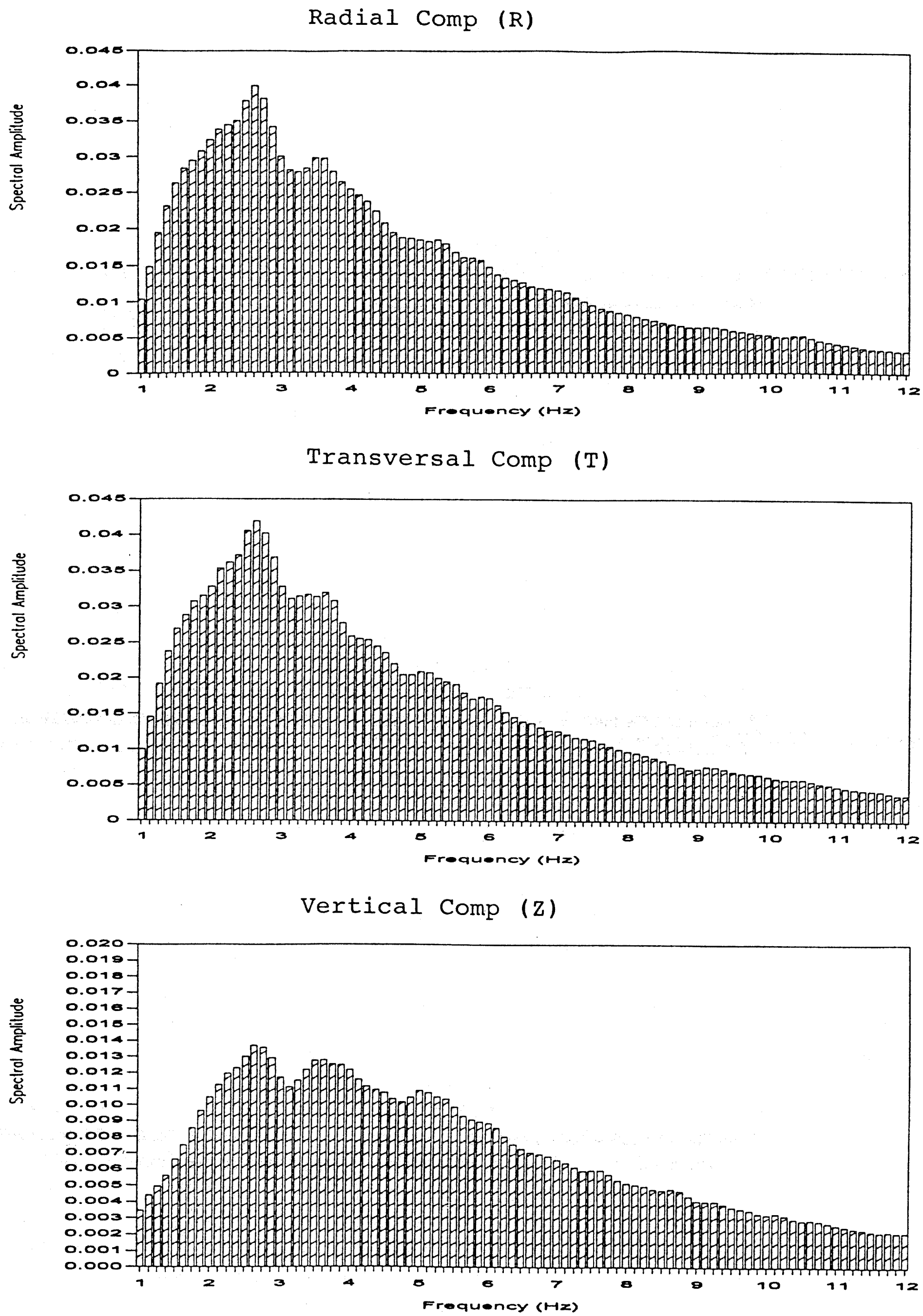


Fig. 4. Amplitude spectra for the radial, transversal and vertical components averaged over all 164 observation points.

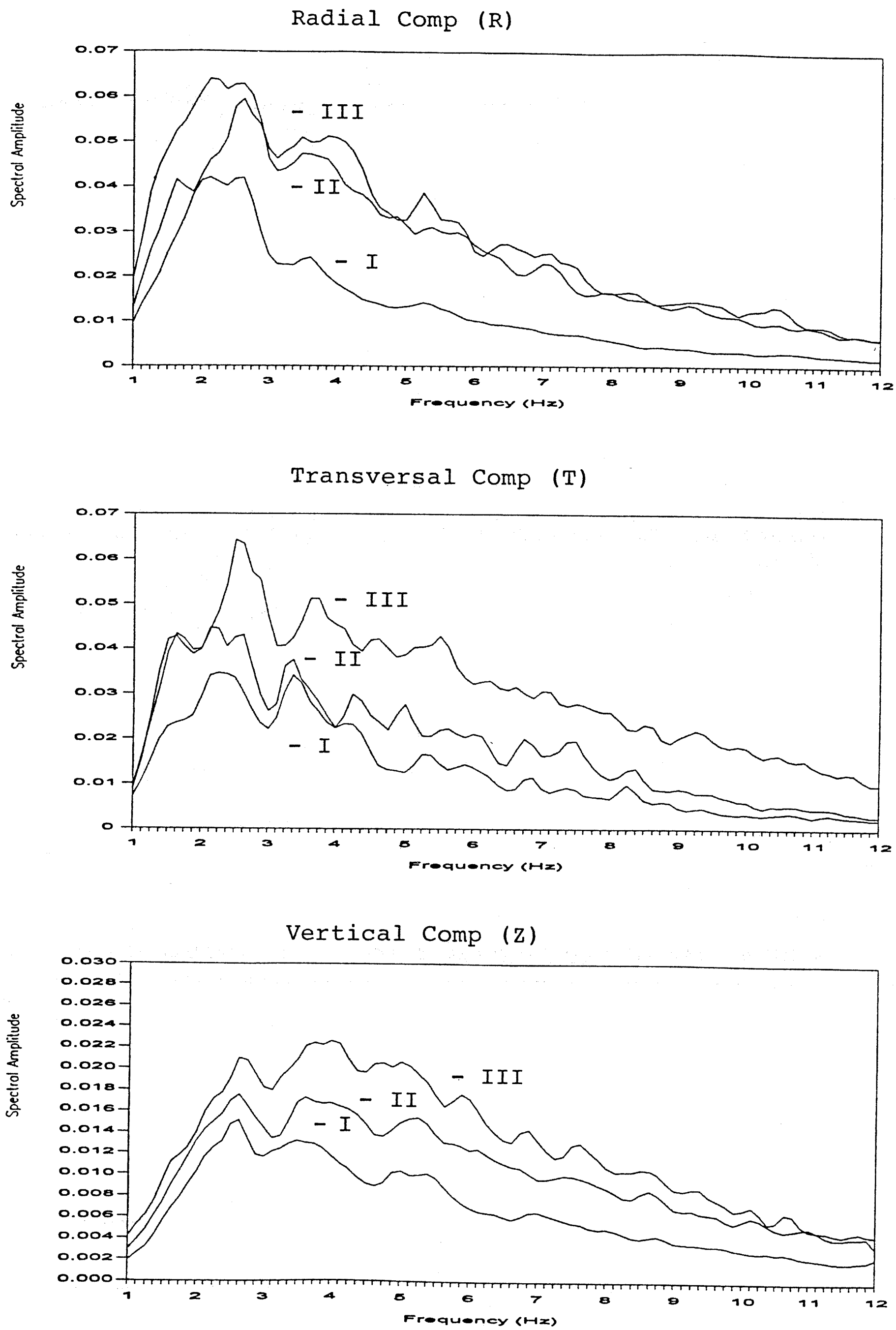


Fig. 5. Corresponding to fig. 4 with amplitude spectra subclassified for the three ground types: hard lava rock (I), thin ash beds (II), thick ash beds (III).

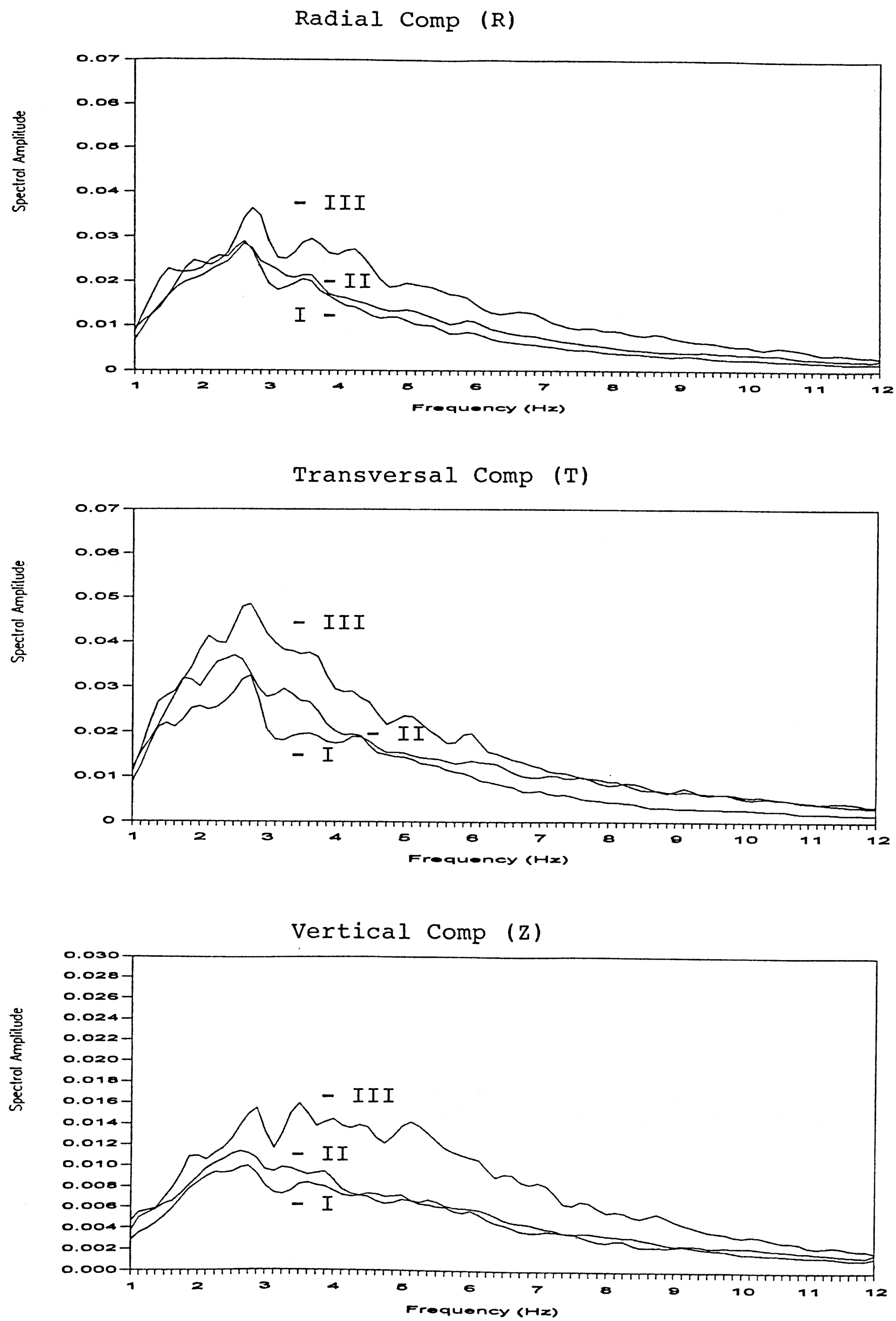


Fig. 6. Corresponding to fig. 5 classifying in observation sites below 600 m elevation a.s.l.

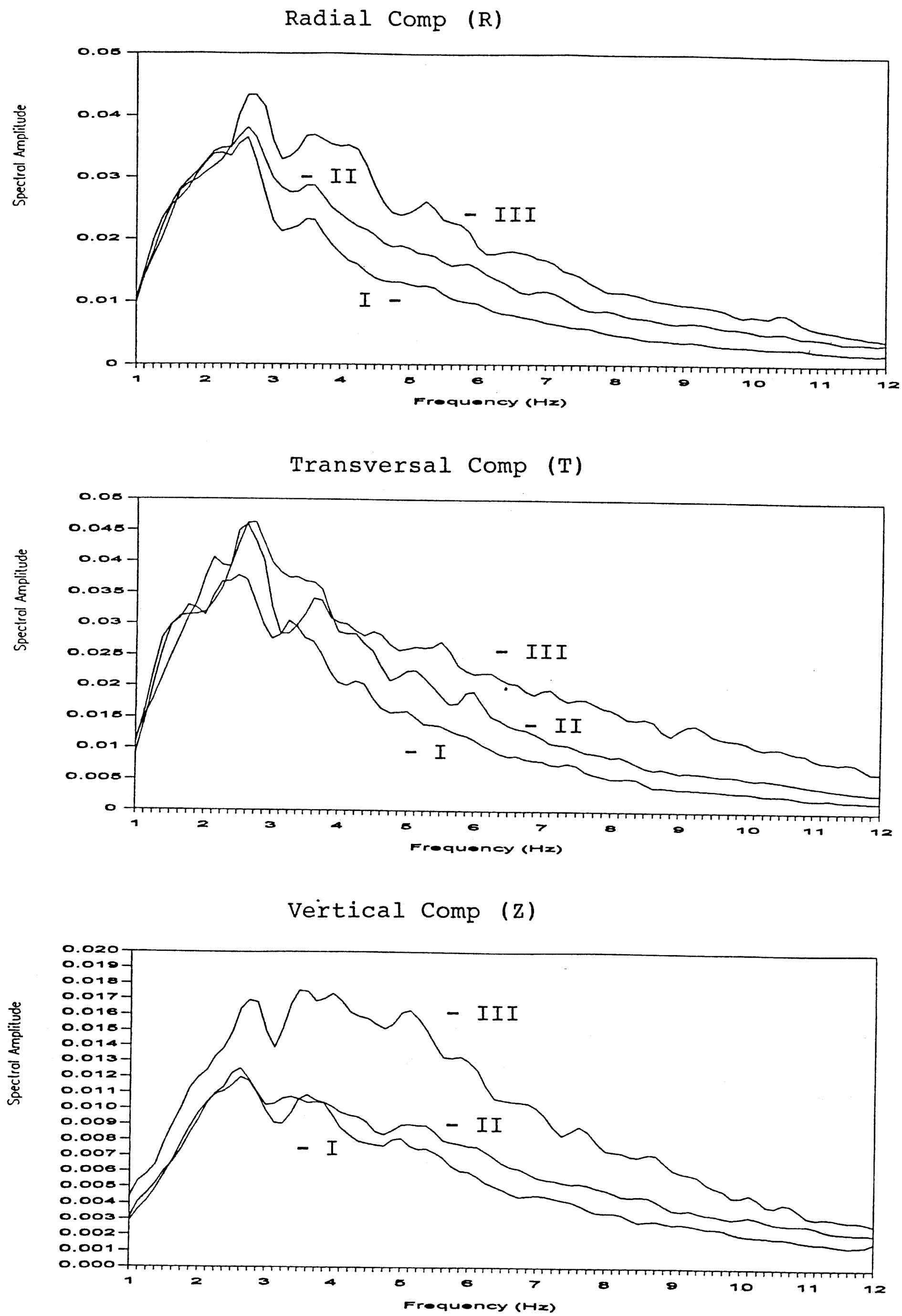
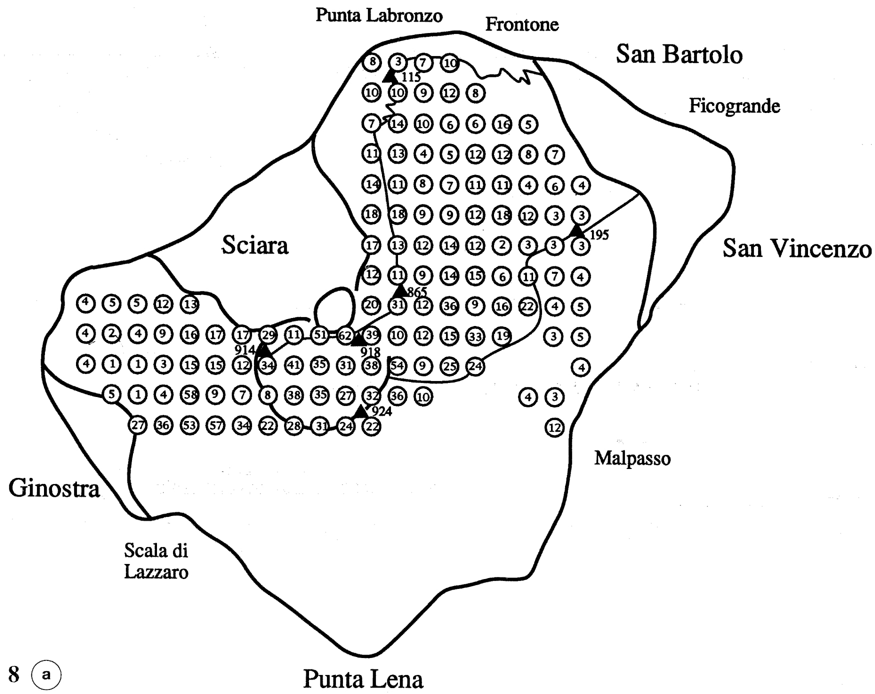


Fig. 7. Corresponding to fig. 5 classifying in observation sites above 600 m elevation a.s.l.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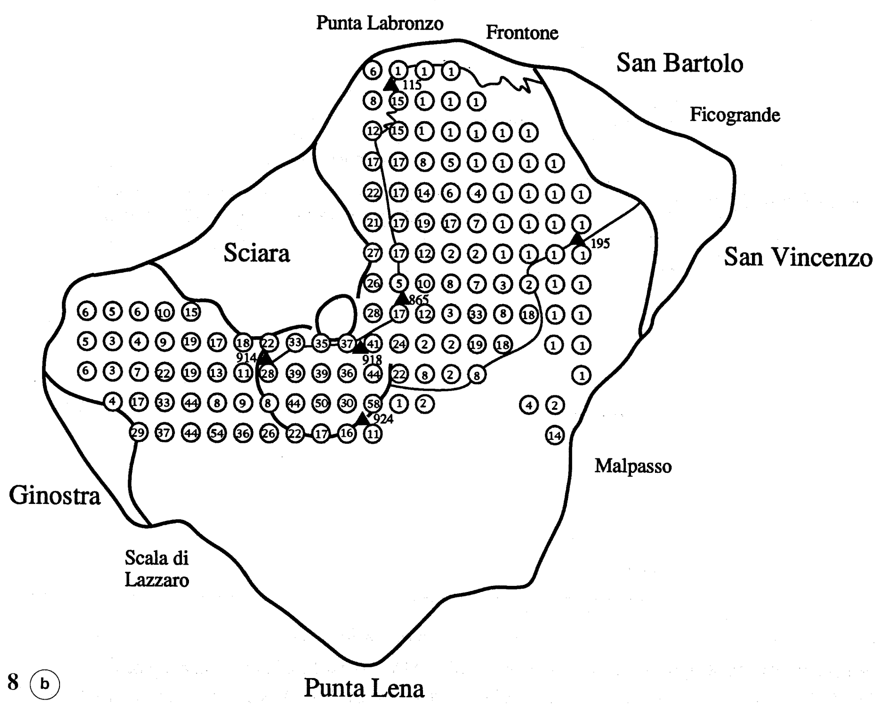
8 (a)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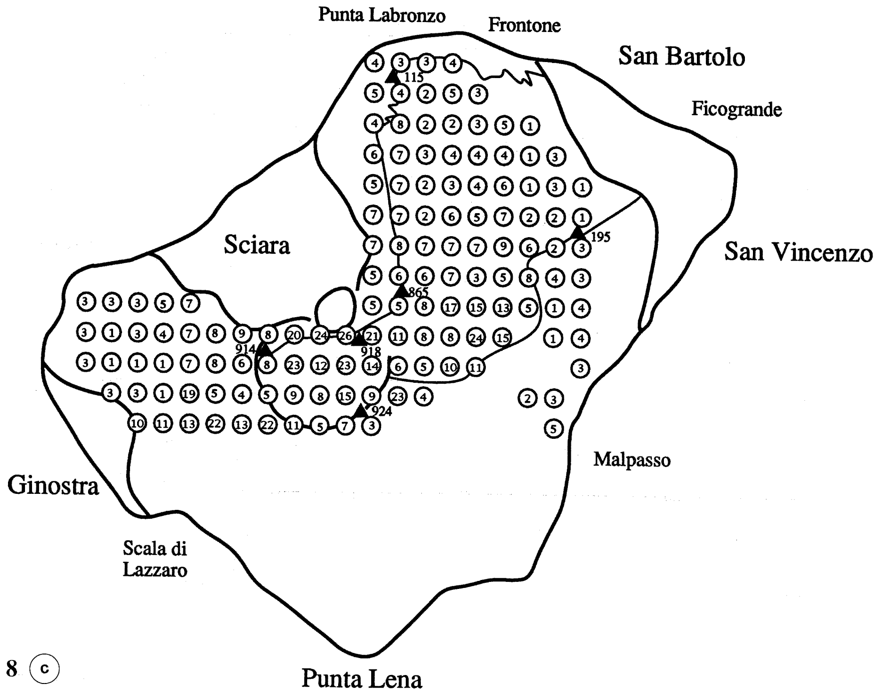

Fig. 8a-c. Maps of partitioned mean tremor amplitude. a) Radial component; b) transversal component; c) vertical component.

are averages over the recordings made within an area of 150 m × 150 m. The values are once again relative but comparable between the components. Cross-sections of the spatial amplitude distribution projected along the section A-B-C (fig. 9) are presented in fig. 10. It was preferred to plot the amplitude *vs* elevation a.s.l. and not *vs* crater distance because the elevation value associated with each observation point is unambiguous. Due to the location of craters on Stromboli within the summit area, these amplitude-elevation curves are similar to the frequently used amplitude-distance curves.

5. Discussion and conclusions

The spectra averaged over the 164 registration points show a rather smooth and broad amplitude form (fig. 4) for which small statistical errors involved in calculating spectral amplitudes are necessary preconditions. The amplitudes of the tremor with the horizontal components are each larger than the vertical component by a factor of nearly three. The radial and transversal components are quite similar in amplitude and spectral form. It is remarkable that in examining all three components, the maximum spectral amplitude is, within the spectral resolution of 0.125 Hz, at an identical frequency of 2.65 Hz. There is one second significant maximum at 3.65 Hz.

The classification from observations recorded on different geological strata (figs. 5 to 7) show interesting variations. Below approximately 2 Hz the influence of different ground conditions on the spectral amplitude is minor. At higher frequencies, there exists a pronounced ground or soil amplification factor. The factor is higher for less dense material and it seems to have a maximum at frequencies of 4-6 Hz. This observation is not surprising because an estimation of eigenresonances of ash or lapilli beds with a thickness of some 10 m leads to similar values.

The classification from observation points below and above an elevation of 600 m illustrates no essential differences in the spectral form. The plots are less smooth which is possibly due to the smaller number of samples as the subclassification becomes more and more refined. The tremor amplitudes decrease at smaller elevations, implying a larger distance to the sources generating the tremor. However, there is no significant shift in frequency with the broad spectral amplitude maxima. This effect was already noticed with measurements made in 1974 (Falsaperla and Schick, 1993). The past study reflected a maximum at 2.3 Hz instead of 2.65 Hz as noticed in the present study. As expected, the mean amplitude of the tremor in the frequency range from 1-12 Hz shows that the highest values occur in a region closest to the Fossa encompassing the active craters (figs. 8a-c). The amplitude distribution around the crater region is highly asymmetric, with generally higher amplitudes on the WSW side towards the village of Ginostra. A cluster of unusually high amplitudes is found in the upper part of the Vallone di Rina.

The cross-section of mean tremor amplitudes for all three components (fig. 10) along A-B-C as illustrated in fig. 9 shows an interesting behaviour of the amplitudes. Surprisingly symmetrical to the craters, strongly enhanced values can be found in all components at elevations between 200 m to 500 m. This phenomenon was found before by Del Pezzo *et al.* (1974), Ntepe and Dorel (1990) and Falsaperla *et al.* (1992). All previously studied tremor amplitude-crater distance functions (respective to elevation) suffer from few observation points along profiles from the crater region down to sealevel. Therefore, these zones were

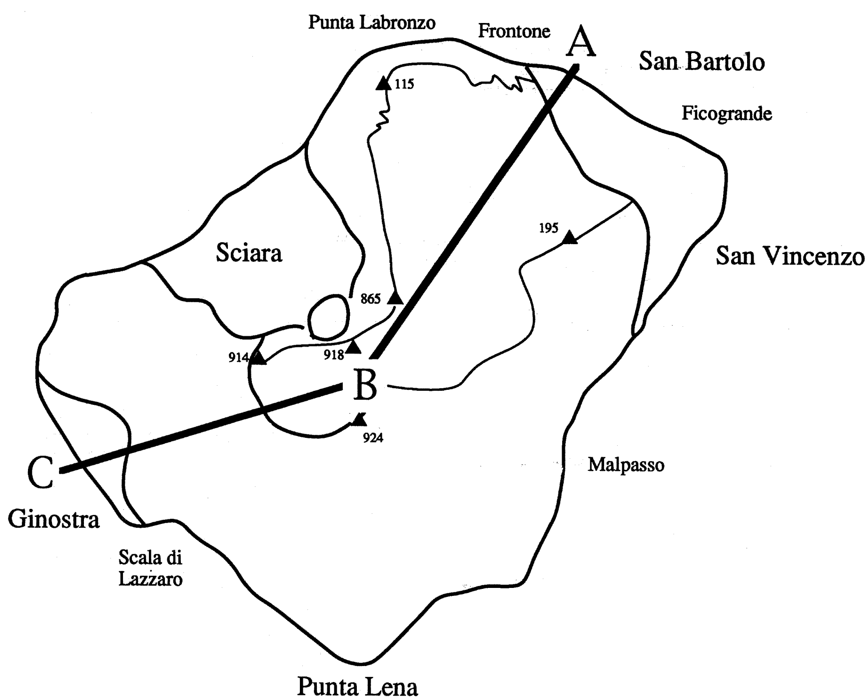

Fig. 9. Map showing A-B-C cross-section for the amplitude profiles shown in fig. 10.

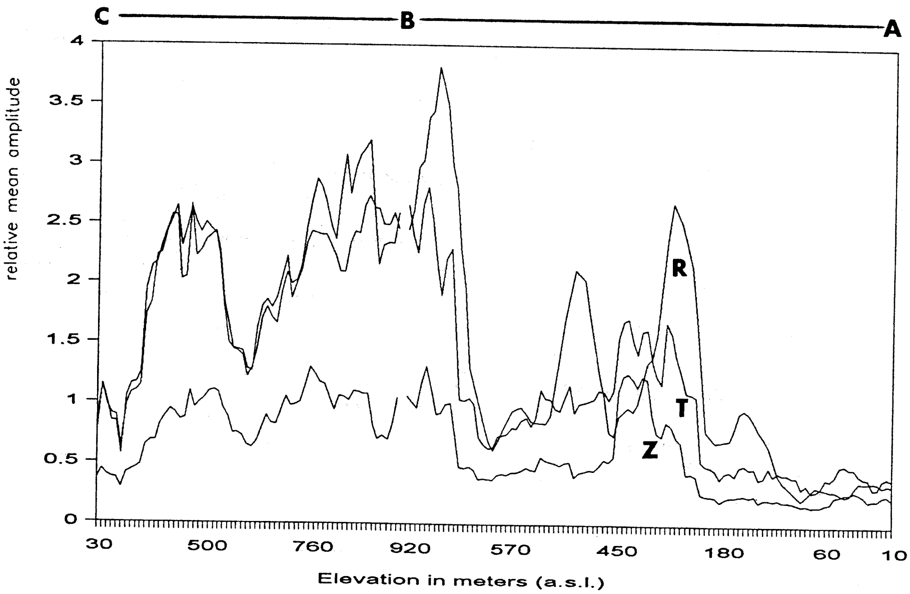

Fig. 10. Tremor amplitude profile along the cross-section A-B-C.

not identified as anomalous high amplitude regions, but instead were assumed to be a consequence of wave propagation resulting in a shadow zone at *ca.* 600 m elevation. Only speculations are possible about this origin of the increased amplitudes in larger crater distances. However, the form of these amplitude-elevation curves do not favour the idea of a shadow zone but suggests a more proximal tremor source.

It is certainly remarkable that for all altitudes of the volcano, the vertical component of the tremor reflects minimal amplitudes. Usually, the location of tremor source is assumed in a depth of about 200-300 m below the eruptive vents, corresponding to 400-500 m height a.s.l. It seems likely that the radial components of compressional waves show strong amplitudes in these elevations. However, fig. 10 demonstrates that close to the summit region of Stromboli, above the assumed tremor sources, the amplitude ratio of horizontal to vertical components reaches a maximum. A possible explanation might be found reading Imbò (1954). In his opinion, it is the hammering of the magma flow on the vertically orientated walls of the feeding conduits which cause horizontal excitation forces. These forces lead to ground vibrations which are observed as volcanic tremor. As Stromboli volcano is presumably penetrated by a criss-cross pattern of vertically oriented and horizontally extended feeding conduits, it is not surprising that both horizontal components of the tremor do not permit an azimuthal distinction with respect to radial and transversal amplitudes.

The present study does not support the idea that the origin of tremor on Stromboli is associated with oscillating processes of high-Q resonators. The spectral peaks with small bandwidths, which are found in the analysis of tremor, might have their origin in propagation effects between the source and the recording station. Except for local site effects, plane layer resonances in the heterogeneous volcanic medium can be neglected so that other kinds of selective interferences must be taken into account. For instance, Correig and Vila (1993) emphasize the strong selective filtering which is involved in resonant scattering.

Certainly, one can think of numerous mechanical sources which produce that kind of spectral radiation. Morse and Ingard (1968) calculate the acoustic radiation from a region of violent fluid motion into unbounded space. Their equation has the general form (Seidl *et al*, 1981; Schick *et al.*, 1982):

$$A \sim \sum_i f^{N_i} \cdot \exp\left(-M_i \cdot f^K\right)$$

where:

A: spectral amplitude corresponding to ground velocity;

N: parameter ($N = 1$ for monopole source, $N = 2$ for dipole source);

M: spatial and time coherency factor for extended source;

K: $K = 2$ (for isotropic and randomly fluctuating source).

Seidl *et al.* (1981), as well as Vila *et al.* (1992), applied the Morse-Ingard equations to model tremor spectra. Figure 11 represents a best parameter fit of a model curve obtained with this equation to the tremor spectra shown in fig. 4 for the radial component. The main problem consists with the ambiguity in the assumption of the fluctuation parameters with the randomly moving fluid. However, it is notable that two additive terms are needed to fit the observations. The first term in the mathematical expression given in fig. 11 represents a

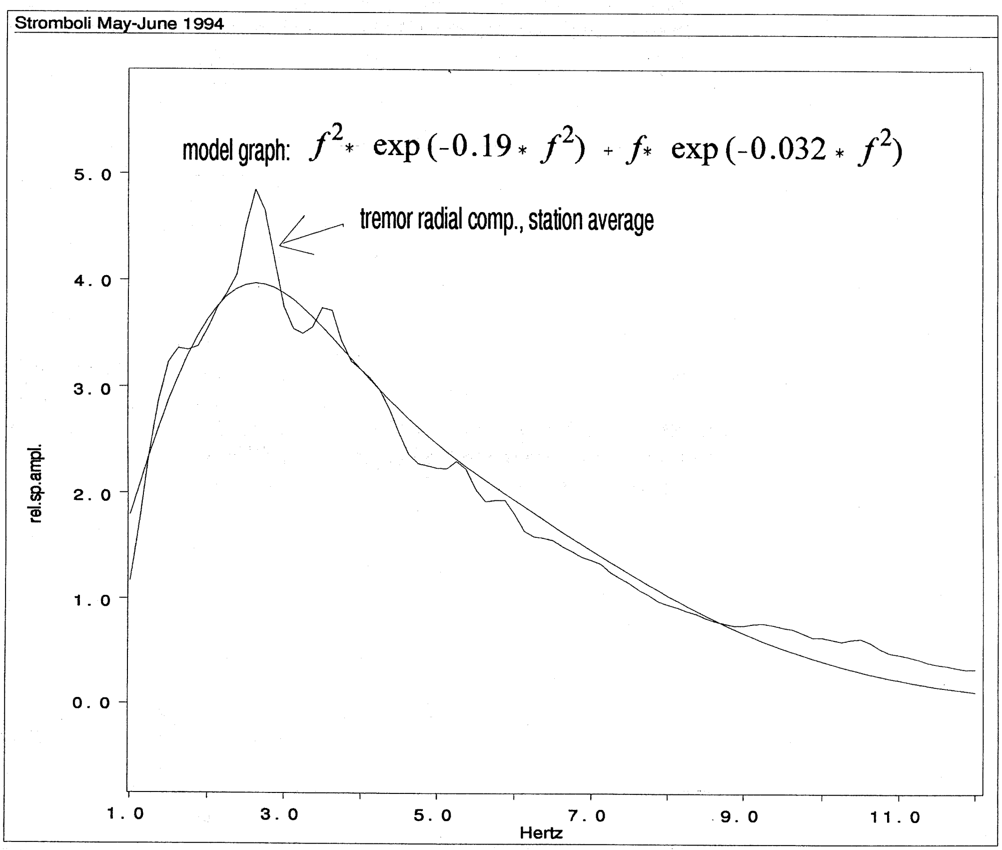

Fig. 11. Tremor spectrum and model graph.

dipole source ($N = 2$), the second term a monopole source ($N = 1$). A dipole source may be attributed to convective flow, a monopole source to unidirectional flow.

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