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A comparative study of low-frequency seismic signals recorded at Stromboli volcano, Italy, and at Yasur volcano, Vanuatu

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Abstract The explosive activities of the volcanoes Stromboli (Aeolian Islands, Italy) and Yasur (Tanna Island, Vanuatu) produce low-frequency seismic signals. Several types of such signals were identified both on Stromboli (Types Is and IIs) and on Yasur (Types Iy, IIy, and IIIy). The dominant frequencies of these signals fall generally between 1 and 3 Hz although sometimes frequencies in the range 3–6 Hz also exist. The two volcanoes display similar seismic characteristics: the seismic signal associated with the strombolian explosion is accompanied by a forerunner signal that occurs several seconds before eruption and which corresponds to the time separating the formation of the gas pocket at different levels in the magmatic column and its reaching the surface.

The similar spectral characteristics of the volcanic background seismic noise and the discrete signals suggest a common source.

Keywords seismology; volcanology; Yasur; volcanic earthquakes; low-frequency seismic events; explosion earthquakes; Stromboli; Italy; Vanuatu

INTRODUCTION

Low-frequency seismic signals recorded on active volcanoes are usually interpreted as a direct consequence of underground magmatic activity. Whatever volcanic activity, their spectral content is dominated by one or several frequencies between 1 and 10 Hz (e.g., Kilauea, Aki & Koyanagi 1981; Mt St Helens, Fehler 1983; Merapi, Seidl et al. 1990; Pavlof, McNutt 1986; Tolbachick, Gordeev 1992; Etna, Del Pezzo et al. 1993).

Provided that the low-frequency events are recorded near their source (i.e. within a distance less than one wavelength) their characteristics are mostly due to the properties of the source rather than to propagation path (Aki & Koyanagi 1981; Chouet 1988). The processes which generate these signals are often linked to the excitation of the volcanic conduit by some triggering mechanism. The volcanic structures involved are magmatic pipes, chambers, or cracks (Aki et al. 1977; Ferrick et al. 1982; Schick et al. 1982; Chouet 1985, 1986, 1988; Crosson & Bame 1985; Hurst 1992). One plausible mechanism is the exsolution of gases from the fluid phase in a magmatic column. Apart from actual eruptions, the permanent volcanic activity can produce a continuous volcanic background noise whose origin may be the same as that of the low-frequency seismic signals.

Stromboli and Yasur are particularly interesting for the comparison of low-frequency seismic activity because they have similar eruption dynamics, characterised by regular strombolian explosions. The objective of collecting seismic data on these volcanoes is to provide temporal and spectral information of low-frequency signals and volcanic noise. In this study we shall present the different types of low-frequency events recorded on each volcano, and their relationship with the observed volcanic noise and the eruptive activities.

DESCRIPTION OF THE VOLCANOES AND PREVIOUS STUDIES

Stromboli

Stromboli volcano is located in the Aeolian Islands, north of Sicily (Italy), at a latitude of 38.8°N and a longitude of 15°E. It extends 920 m above sea level, and 3000 m above the ocean floor. It is a regular cone which has three craters, named C1, C2, and C3, at its summit (Fig. 1).

Stromboli has been continuously active over the last 2000 years. Its present activity is characterised by regularly spaced explosions (approx. every 20 min). During our observations, crater C3 was the most active and produced the liveliest explosions, ejecting incandescent rocks and lapilli. Crater C1 was less active, emitting ash and lapilli-rich plug material in the form of small plumes. At crater C2, the activity was limited to the production of smoke and gas.

At the Stromboli volcano, the existence of a seismic signal preceding the explosions was mentioned by Sieberg (1914) and later confirmed by others (Peterschmitt & Tazieff 1962; Schick & Riuscetti 1973; Fadeli 1984). Peterschmitt and Tazieff attributed the differences observed in the time lag between signal and explosion (from 15 to 40 s) to changes in level in the magmatic column. This peculiarity of Stromboli's explosions was ignored by the majority of the other researchers, who focused their attention on the seismic signals generated by the actual explosions (which they called "volcanic shocks" or "explosion quakes"). These studies (Lo Bascio et al. 1973; Fadeli 1984; Cardaci & Lombardo 1988; Falsaperla et al. 1989; Ntepe & Dorel 1990; Dreier et al. 1994; Carniel & Iacop 1996) resulted in several

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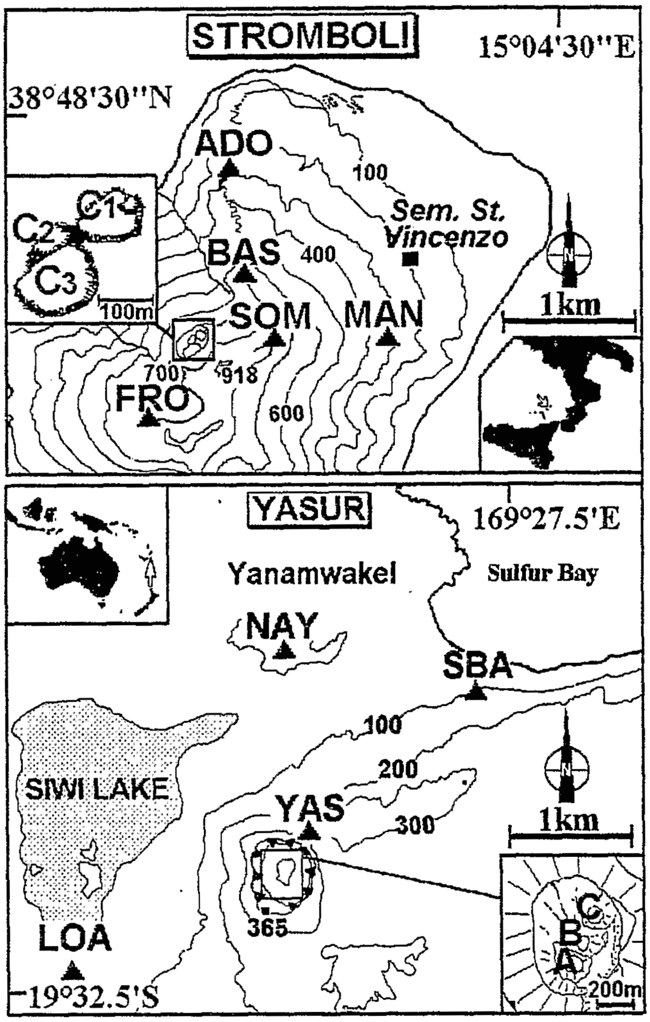

Fig. 1 Map of Stromboli and Yasur volcanoes showing the location of seismic stations (▲). Sromboli and Yasur's active vents (C1, C2, C3 and A, B, C) are shown in the insets.

classification schemes which differentiated usually between three and five types of signal issuing from the different craters.

Yasur

Yasur volcano is located on the island of Tanna (Vanuatu), at a latitude of 19.5°S and a longitude of 169.5°E in the Southwest Pacific. It has a cone 365 m high; and its summit consists of a crater within which, at a depth of 150 m, are three eruptive vents called A, B, and C (Fig. 1).

During our measurements, the volcanic activity consisted of violent strombolian explosions coming mainly from crater A. These explosions ejected volcanic bombs to a height greater than that of the main crater rim. Unfortunately, bad weather reduced greatly the extent of our observations and measurements.

At Yasur volcano, Blot & Tazieff (1961) showed the existence of discrete events generated by surface explosions. Later, Nairn et al. (1988) and Lardy & Willy (1989) were able to show the existence of two types of explosion quakes: the first, with a dominant frequency of 2–2.5 Hz, was associated with the volcanic activity at crater B; the second, characterised by dominant frequencies between 2 and 4 Hz and the presence of a sound wave, was linked to gas explosions within the three craters. Unlike the observations made by Blot and Tazieff, the volcanic noise recorded by Nairn et al. (1988) at two different sites was relatively constant in amplitude and dominant frequency (between 2 and 4 Hz). They attributed its origin to continuous gas emission at crater B.

DATA ACQUISITION

Recordings were made at Stromboli from 6 to 18 June 1991, and at Yasur from 1 to 7 April 1992. Figure 1 shows the location of the recording stations at Stromboli (SOM, FRO, BAS, ADO, MAN), and at Yasur (YAS, NAY, SBA, LOA). At Stromboli, stations SOM, BAS, and FRO where located 300 m from the crater, whereas stations ADO and MAN were positioned 1500 m from the crater. At Yasur, the four stations were located at 300 m (YAS), 1600 m (NAY), 1900 m (LOA), and 2000 m (SBA) from the crater.

Two types of stations were used: Lennartz and Ceis-Espace. The Lennartz stations (SOM, ADO, and MAN at Stromboli; YAS, SBA, and NAY at Yasur) consisted of an encoder and a three-component seismometer. The encoder (PCM 5800) features 120 dB dynamics and converts the pre-amplified analog signals into digital data. The sampling frequency was 125 Hz. The seismometers are Mark-Product 1 Hz for Stromboli and 2 Hz for Yasur. Furthermore, a seismometer of 0.2 Hz frequency was installed temporarily at Stromboli's MAN station. The two horizontal components were oriented radially (R) and transversally (T) with respect to the craters.

The Ceis-Espace stations (FRO, BAS at Stromboli; LOA at Yasur) consisted of a self-contained digital recording unit (sampling at 50 Hz) and a Mark-Product 1 Hz single-component (vertical) seismometer.

The responses in frequency of our instruments are given in Fig. 2.

DATA ANALYSIS

Volcanic background seismic noise (volcanic noise)

The volcanic noise was sampled for about a week and the data were analysed for their spectral content. We used the maximum entropy method, by 0.05 Hz increments, because it provides a very good frequency resolution even for short signal samples, and is well suited to showing the frequency peaks present in a sample.

An average of the spectra was then assembled, based on a large number of recording "windows", and corrected for instrument response. Each window, of 6 s duration, shows one dominant frequency. The whole of the frequencies thus obtained were plotted as a histogram representing the whole of the windows. This histogram is superimposed on the average spectrum. Hence, the stability of dominant frequency is shown.

Figure 3 shows an example of volcanic noise recorded on the two volcanoes: the high-frequency content is greater at Yasur than at Stromboli. In both records, the amplitude of the signal was always greater for the horizontal components than for the vertical, often by a factor of two. The average noise level is slightly higher at Yasur than Stromboli.

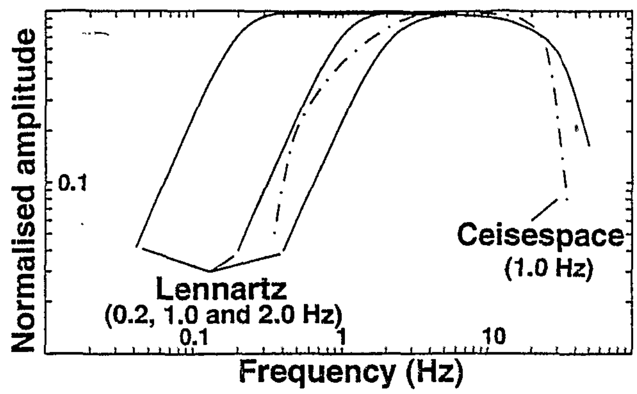

Fig. 2 Velocity response of the different types of instruments used during the experiments.

Stromboli

The spectral analysis was performed on 1000 windows. The averaged spectra and the corresponding histograms (Fig. 3) show a predominance of frequencies between 1 and 3 Hz for all three stations. Fluctuations of the dominant frequency were less pronounced for the station located close to the crater rim (SOM) than for the more distant ones. At station SOM, frequencies between 2 and 3 Hz were dominant for the vertical component, while the 1–2 Hz range dominated the horizontal components. For the stations farther away from the craters, the spectrum is broader, and the dominant frequencies are less distinct. This observation is probably due to propagation effects. This also suggests that the origin of volcanic seismic noise might be in the vicinity of the craters. One may also note an increase of frequencies in the 4–7 Hz range in the horizontal components at station MAN.

Yasur

Sixty windows with a length of 6 s were selected during the recording period. The average spectra (Fig. 3) show that the frequencies between 4 and 7 Hz dominate, mainly at station YAS. Lower frequencies are present at the other stations. A 3 Hz peak is present at all three stations. Fluctuations of the dominant and sub-dominant frequencies are less pronounced at station YAS than at the other stations.

While the amplitude is of the same order of magnitude for both volcanoes, maximum seismic noise occurs at different frequencies. At Stromboli, frequencies between 1 and 3 Hz dominate, while at Yasur we observed a predominance of frequencies between 4 and 7 Hz, although some energy exists in a lower band (2–3 Hz).

Low-frequency seismic signals

Low-frequency seismic signals recorded at both Stromboli and Yasur were mostly related to the strombolian explosions

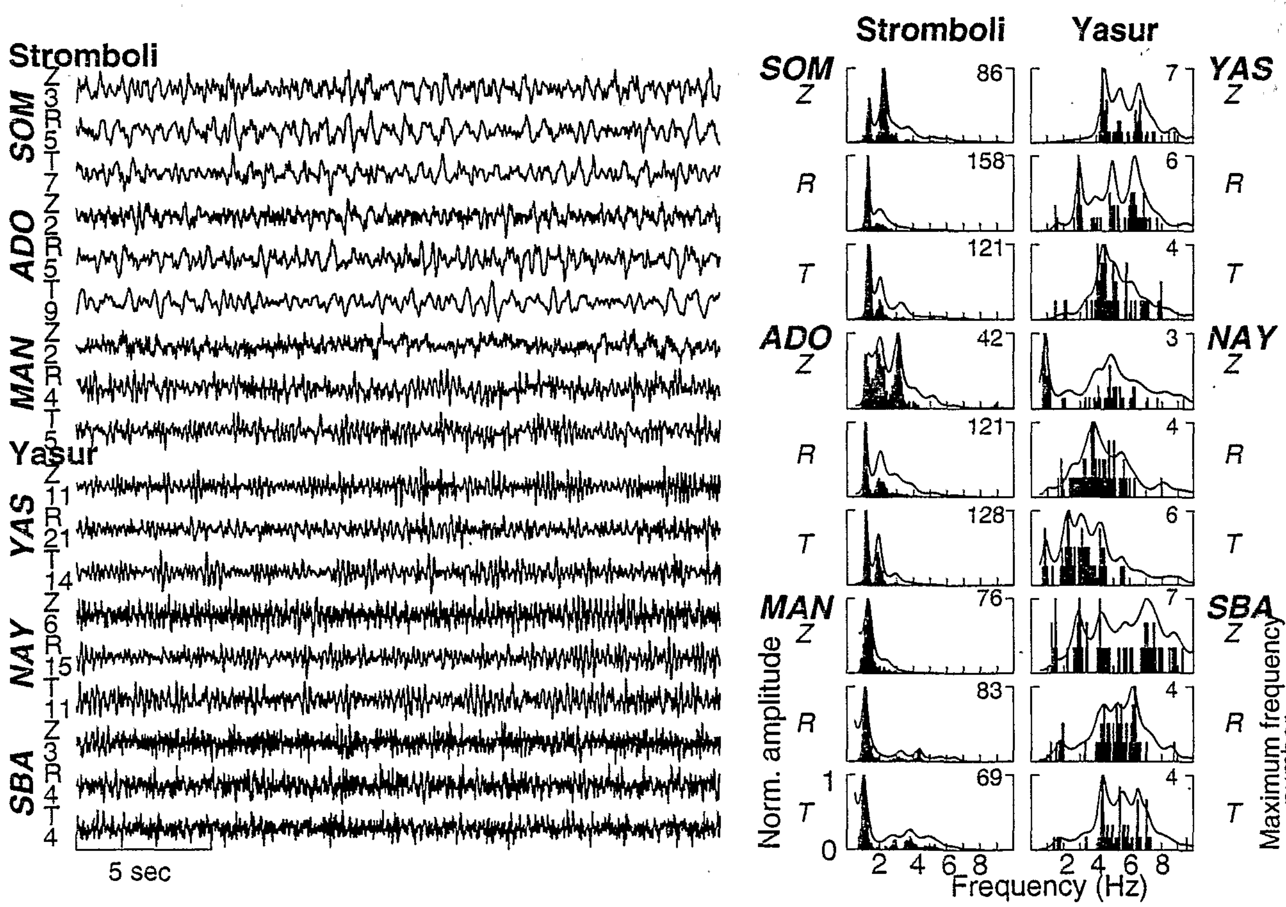

Fig. 3 *Left*: Recordings of volcanic background seismic noise at the three stations on Stromboli and Yasur volcanoes. Peak trace amplitude (μ/s) is indicated under the name of each component (Z, R, T). *Right*: Normalised average spectra with the histograms of the dominant frequency. The right scale is the number of dominant frequency observed for each interval of 0.05 Hz.

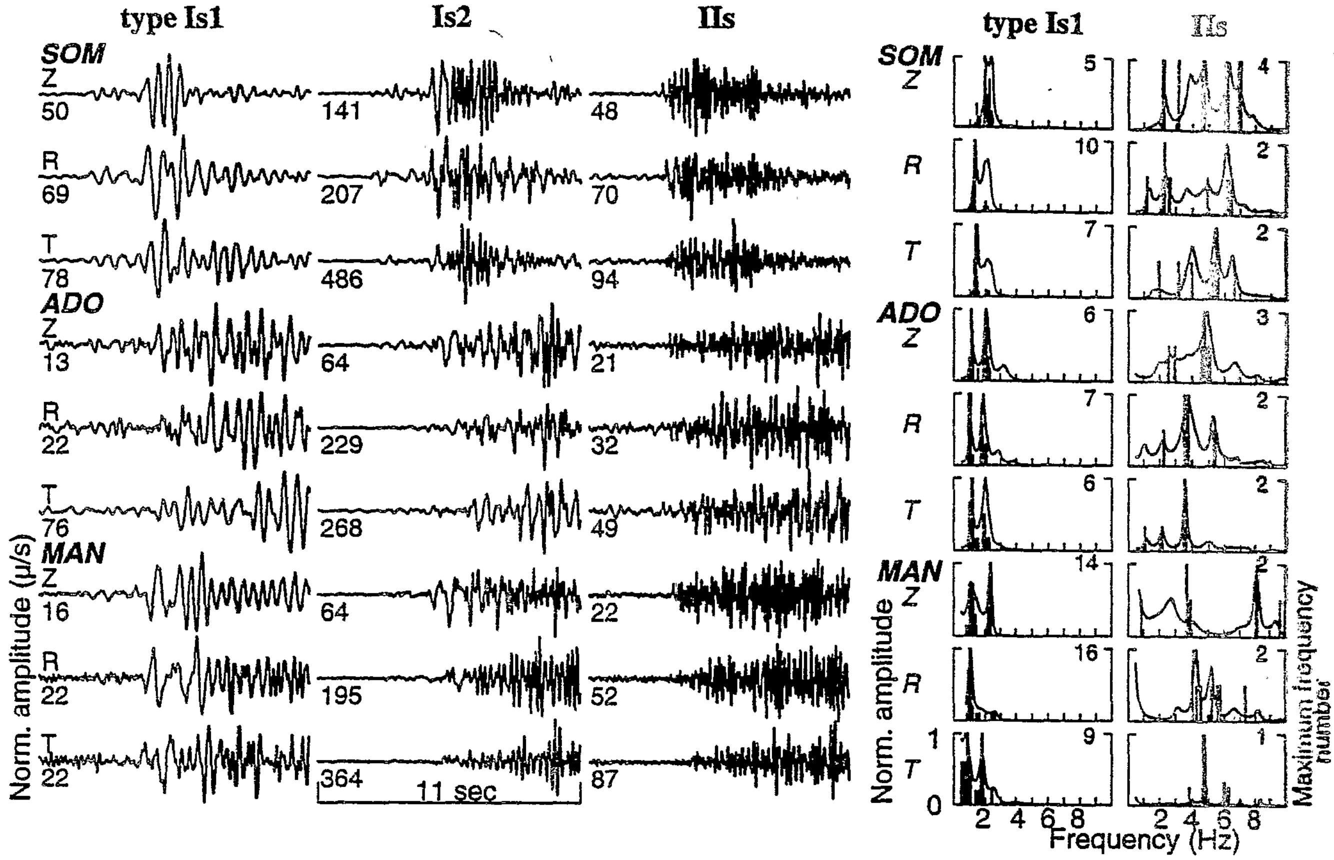

Fig. 4 *Left*: Example of the three types of low-frequency events observed at the three stations on Stromboli volcano recorded on the three components Z, R, T. The maximum amplitude (µ/s) is indicated on the left and under each trace. *Right*: Averaged spectra and the histograms of the dominant frequency for the type I_{S1} and II_S.

which are characteristic of the dynamics of these two volcanoes. Because of the large number of explosions, we obtained a good sampling of seismic events. The repetition of these signals and observations of the shape of the waveforms show that the signals can be grouped by a limited number of types. We establish below a classification of these signals for each volcano based on their overall aspect and spectral content, and attempt to correlate the types with observable surface events (gas emission, explosions).

Stromboli

Almost every recorded signal (c. 200 per day) was linked to explosive activity at craters C3 and C1. Figure 4 shows the most often observed and most repetitive signal types (I_{S1}, I_{S2}, and II_S)

Types I_{S1} and I_{S2}: These two signal types are grouped together under the same classification (I_S), and differ only in their high-frequency content, which may vary from one signal and another. Within these signals, we may distinguish several phases (b, c, and d) as indicated in Fig. 5.

The c phase has always a distinctly greater amplitude than the forerunner phase b. These two phases have practically the same spectral characteristics, namely dominant frequencies between 1 and 3 Hz (Fig. 5). The spectrum of the background noise which can be recorded before the onset of the signal (part a on Fig. 5) is similar to the b and c phases with the same dominant frequencies. The average spectrum and histogram for b and c phases show that the vertical components are dominated by a frequency between 2 and 3 Hz, while frequencies between 1 and 2 Hz are most heavily represented in the horizontal components (Fig. 5). However, sometimes all the energy is concentrated in the 1–2 Hz band for all three components. Time fluctuations of these dominant frequencies are less pronounced than for the volcanic noise. The recordings of the same signals at stations ADO and MAN show that the spectrum remains unchanged whatever the location of the recording stations (Fig. 4). Therefore, the dominant frequencies of the signal are independent of the propagation path. However, the waveform, and especially its duration, vary as a function of distance.

The time interval (Δt_I) between the onsets of b and c phases fluctuates between 2 and 20 s (Fig. 6). Longer intervals have been observed.

The distinction between types I_{S1} and I_{S2} is based on the relative magnitude of the d phase, whose frequencies range from 3 to 6 Hz. The beginning of this phase, which is emergent, is simultaneous with the onset of phase c (Fig. 4). As this latter has a large amplitude, the onset of the phase d is partially hidden. Type I_{S1} corresponds to a signal nearly lacking a d phase, whereas type I_{S2} shows a well-developed d phase.

Type II_S: These signals are rare. They are characterised by a significant high-frequency (3–7 Hz) spectral content, giving the signals a distinctly different aspect from the I_S type (Fig. 4). However, they always contain a weak

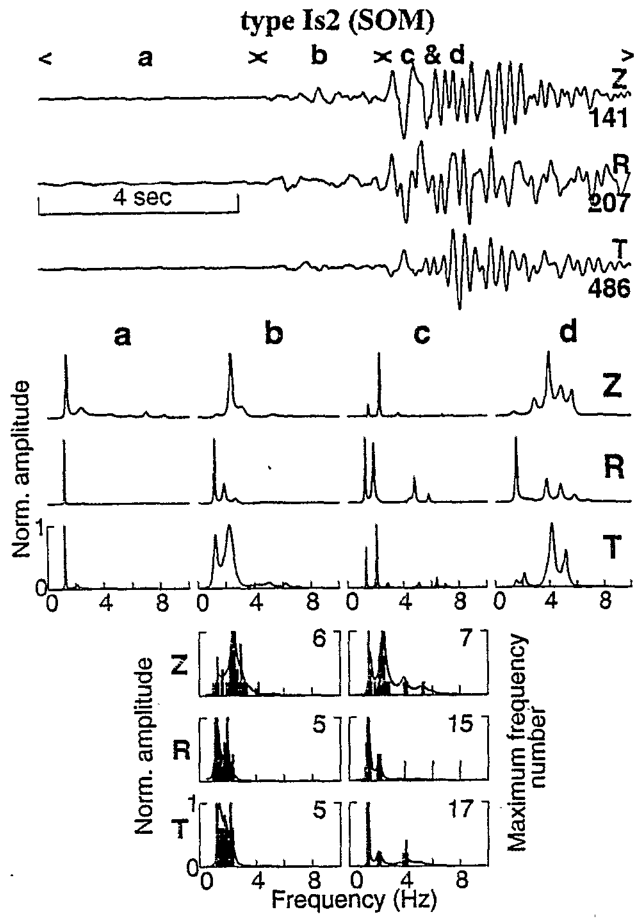

Fig. 5 *Top to bottom*: The type I_{S2} signal recorded on Stromboli at station SOM showing the three phases b, c, d (*top*); the corresponding spectra (*middle*); and the average spectrum (50 events) of b and c phases for the three components (*bottom*). The part a of the signal is the seismic noise before the onset of the event.

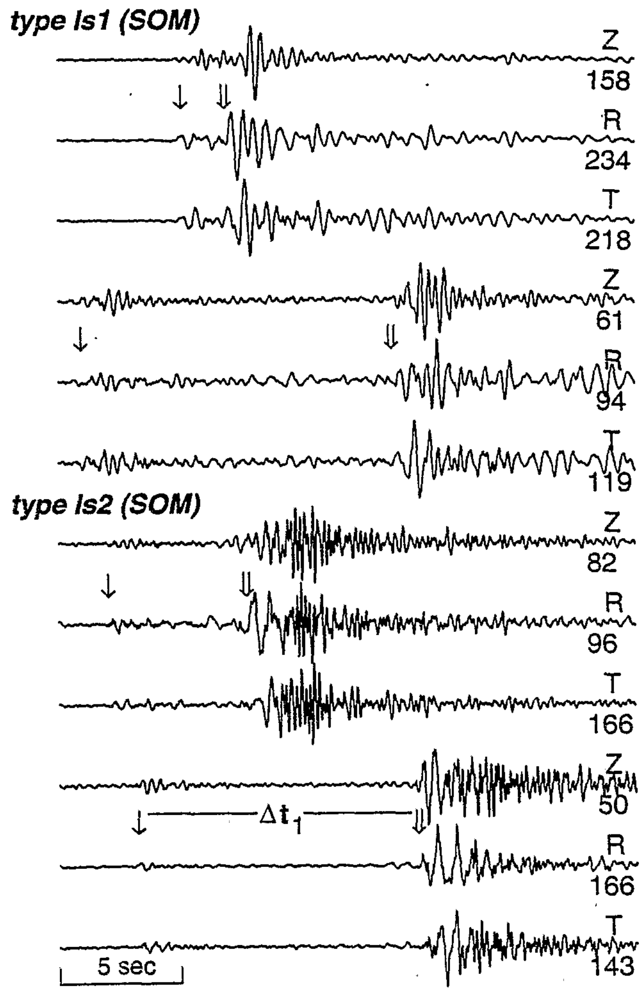

Fig. 6 Two examples of type I_{S1} (*top*) and type I_{S2} (*bottom*) signal recorded at SOM station of Stromboli, showing the different time intervals (Δt_1) between b (arrow) and c (double arrow) phases. The maximum amplitude (μ/s) of each compoments (Z, R, T) is given in the lower right of each trace.

low-frequency (1–3 Hz) component (phase c). The dominant frequencies are highly variable, without any particular frequency emerging as most common. These signals differ also from the previous type by the absence of phase b.

Simultaneously with the seismic recording, we recorded images of the surface events, such as gas emissions and explosions, with a video camera. The movies show that the recorded signals were nearly always associated with surface explosions; type I_S was associated with crater C3 and type II_S with crater C1. These explosions were either accompanied by ejection of solid material, or were simply gas explosions. A second conclusion brought about by the visual observation was that the phase c which we had identified in the signals is linked to the strombolian surface explosion, while phase b, which appears several seconds before, can be explained as a kind of forerunner of the explosion.

A study of particle motion for these two phases shows a rectilinear horizontal movement which is nearly the same for both phases (Fig. 7). Because they also have a nearly identical spectral content, we suggest that the two phases have the same origin.

Phase d is related to the nature of the explosion. In a powerful explosion with projection of solid matter, this phase is well developed (type I_{S2}), while a simple gas explosion tends to yield signals of type I_{S1} (i.e. no d phase).

Type II_S signals were associated with crater C1, whose activity was characterised by powerful ash and lapilli explosions, but without incandescent blocks (by contrast with the activity at crater C3). This would explain the difference in the high frequencies observed in the spectrum of these signals.

Yasur

The observed signals were classified under three types: I_Y, II_Y, and III_Y (Fig. 8).

Type I_Y: This represented >70% of the signals recorded at Yasur. The type is characterised by short duration oscillations, with dominant frequencies lower than 2 Hz. The signals had a low-amplitude higher frequency component (4–6 Hz). The averaged spectra of these signals (Fig. 8) show dominant frequencies between 1 and 2 Hz over all three stations. Their amplitude, although highly variable (10–300 μ/s at YAS), was consistently higher for the horizontal than for the vertical components.

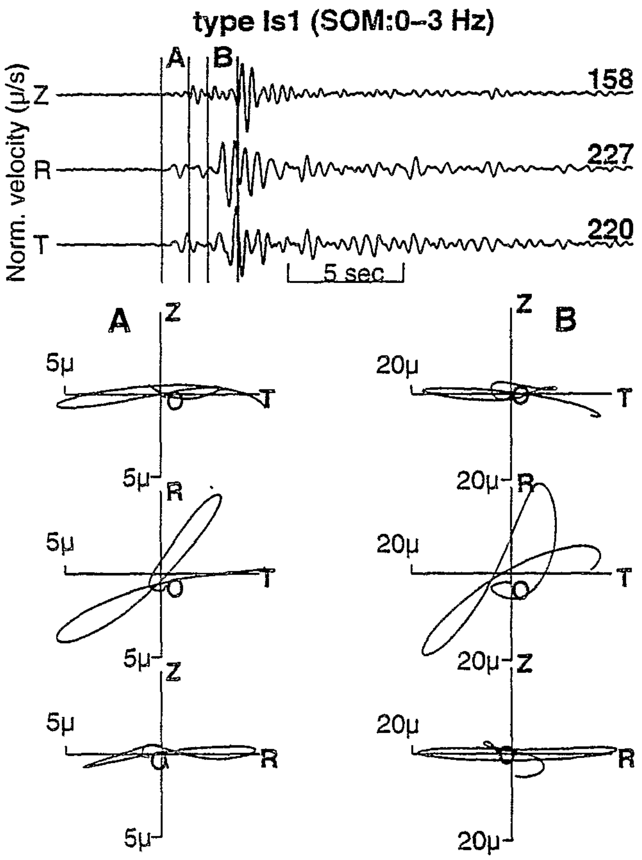

Fig. 7 Particle trajectories of the b phase (A), and the c phase (B), for the signal I_{S1} recorded at the SOM station of Stromboli. The signal filtered between 0 and 3 Hz shows the same rectilinear horizontal motion for both phases.

The time interval (Δt_2) between signal I_Y and the onset of the explosion wave varied between 4 and 13 s at station YAS (Fig. 9), located near the rim of the crater. This shows that type I_Y signals are generated well before the surface explosion.

Type II_Y: This type was less frequent than the previous type. The amplitude of the signals remained constant over time, and dominant frequencies were found between 2 and 3 Hz. Their averaged spectra showed two frequencies to be common to all three stations: the first, near 3 Hz, is distinct on the radial component at YAS; the second, close to 2 Hz, appeared on all components at the three stations (Fig. 8). Frequencies between 4 and 6 Hz were relatively significant at station YAS, and much fainter elsewhere; this may be accounted for by the fact that these frequencies are generated near the surface, and thus are quickly damped by distance. Spectra recorded at YASZ often show a predominance of peaks between 4 and 6 Hz. We observed that these signals were fairly often followed, a few seconds later, by type I_Y signals.

Both types of events described above show certain spectral similarities. Both feature significant frequencies at 2–3 Hz and at 4–6 Hz. Furthermore, their surface particle movement (Fig. 10), filtered between 1 and 2 Hz (for type I_Y) and between 2 and 3 Hz (for type II_Y), have similar characteristics, particularly a linear movement in the horizontal plane.

Type III_Y: This type was characterised by a dominant high-frequency (4–6 Hz) spectral content at all stations (Fig. 8). The signal duration was comparable to that of the other types. The amplitude was always much higher at station YAS than at the other two stations, and was higher than that of the other types of signal. This type of event appears, frequently, in association with type I_Y but also sometimes alone.

DISCUSSION

A survey of the data which we have just analysed shows that, for the seismic background noise as well as for the discrete signals, the dominant frequencies observed fluctuate within a fairly narrow band, as can be seen on histograms of these frequencies. Sometimes it is difficult to isolate a single dominant frequency. The volcanic noise at Yasur, for instance, has dominant frequencies varying between 4 and 7 Hz, although 4.45 Hz (±0.15 Hz) appears to be the most frequent. Farther away from the crater, the spread in frequency becomes much higher, as was observed at station NAY, and it is difficult to characterise the frequency of background noise.

For Stromboli, the dominant frequencies of the volcanic noise were better defined: frequencies of 1.3 Hz (±0.2 Hz) and 2.3 Hz (±0.25 Hz) were clearly apparent on the graphs of most stations, hence we use them to characterise the volcanic seismic noise.

For a given type, the discrete signals are much more stable over time, their spectra remain more constant, and their averages generally display a well-defined dominant frequency. The type I_S signals (Stromboli) present dominant frequencies at 2.3 Hz (±0.2 Hz) and 1.3 Hz (±0.1 Hz) in all the stations, showing that these frequencies are representative of the signal.

At Yasur, at all three stations, we find the same 1.3 Hz (±0.25 Hz) frequency for type I_Y signals. This constitutes a first analogy between low-frequency type I signals for the two volcanoes. This can not be a coincidence, and one must look for a type of mechanism that two volcanoes generating this 1.3 Hz frequency would have in common.

Types II_S (Stromboli) and type III_Y (Yasur) also show similarities: the spectra of both types of signal are characterised by dominant frequencies located between 3 and 7 Hz, and for neither type is there one particular single frequency which can be said to dominate.

Type II_Y shows dominant frequencies between 2 and 3 Hz, with little stability from station to station, which is close to one of the two frequencies observed for type I_S at Stromboli (2.3 Hz). Thus, we may say that both volcanoes produce signals with very close spectral characteristics. The following table shows the dominant frequencies observed for each type of event.

	1.3 Hz	2.3 Hz	3–7 Hz
Is_1	X	X	
Is_2	X	X	X
II_S			X
I_Y	X		
II_Y		X	
III_Y			X

Although these two volcanoes display similar seismic characteristics, the sound wave produced by surface

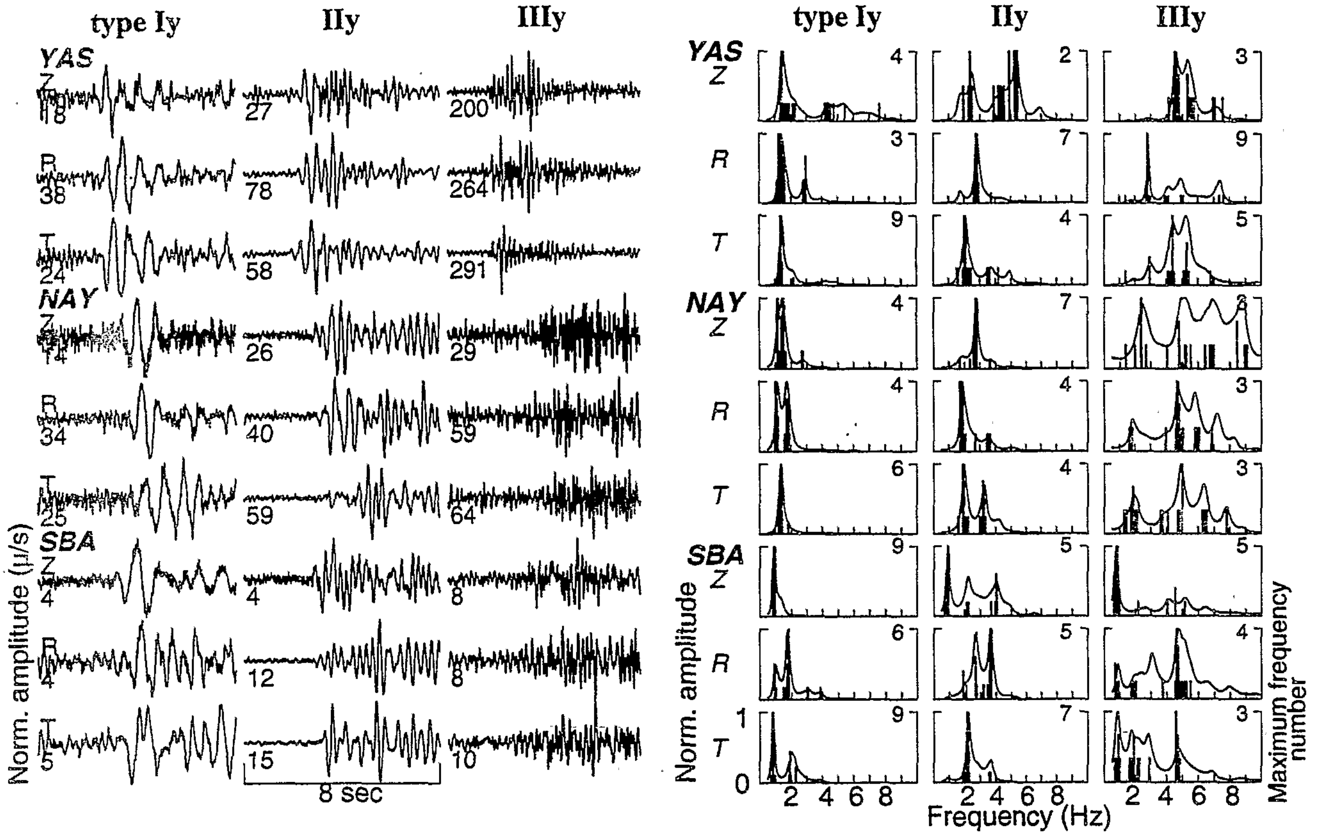

Fig. 8 *Left*: Example of the three types of low-frequency events observed at three stations of Yasur volcano recorded on the three components Z, R, T. The number on each trace is the peak amplitude in μ/s. *Right*: Averaged spectra and the histograms of the dominant frequency.

explosions is much stronger at Yasur than at Stromboli, because the explosions were far more violent at Yasur. The explosions generate two waves: a ground wave, that we call P explosion (Pex), which is a seismic wave due to the impact of the explosion on the walls of the crater, and a sound wave that propagates through the air.

Both waves are observed on Sromboli and Yasur (Fig. 11). The explosion phase (Pex) and the air waves have apparent velocities of 1.2 and 0.33 km/s, respectively. At Stromboli, the d phase corresponds to the phase Pex. In contrast to the situation at Yasur, where these two phases are the only ones accompanying the explosion of gas pockets, the explosions taking place in Stromboli's craters C1 and C3 generate a low-frequency c phase (1–2 Hz), with the same characteristics as the forerunner signal (phase b). These two signals share a common origin; only the trigger would be different.

Volcanic activity at both Stromboli and Yasur takes the form of short-duration intermittent strombolian explosions, between which we observe a rest phase where the only activity consists of "peaceful" gas and smoke emission. Nevertheless, there is no doubt that deep magmatic activity continues to take place during these "rest" periods (e.g., gas movements, magmatic convection). This activity is responsible for the volcanic background seismic noise of our observations. The release of gas by the magma consists of the production of gas bubbles; their upward progression in the magmatic pipe follows different two-phase flow processes (Wallis 1969; Butterworth & Hewitt 1977). A previous study has shown that each two-phase flow regime has a volcanic counterpart (Vergniolle & Jaupart 1986). In a first process, the liquid phase contains a few gas bubbles in suspension (bubbly flow); these may reach the volcanic vents without resulting in surface explosions. Magmatic movements linked to this form of gas-release generate a volcanic noise whose characteristics depend on the physical parameters of the phenomenon (e.g., size of the conduits, viscosity of the magma, gas content). A second gas-release process consists of the gas bubbles coalescing to form larger gas pockets with diameters of the same order as that of the magma pipe (slug flow). The sudden formation of such gas pockets would result in equally sudden pressure disturbance leading to an oscillation of the magma column, which in turn would generate the forerunner signals observed. The volume of gas and the ability of the bubble to coalesce are, among others, important parameters controlling the switch from one type of process to the other (Wallis 1969; Taitel et al. 1980; Weisman & Kang 1981). Thus, it is the variation in the rate at which gas is exsolved by the magma which determines the type of flow; this explains the intermittent character of strombolian explosions and the form and spectral content of the signals (Ripepe et al. 1993; Ripepe 1996). The accumulation of gas bubbles and their coalescing can take place at the top of the magmatic chamber (Jaupart & Vergniolle 1988, 1989) or at different levels within the pipe. The forerunner signal may be also linked to the gas pocket vibration in the uppermost 30 m of the magma column (Vergniolle et al. 1996). The Δt_1 and Δt_2 time lag

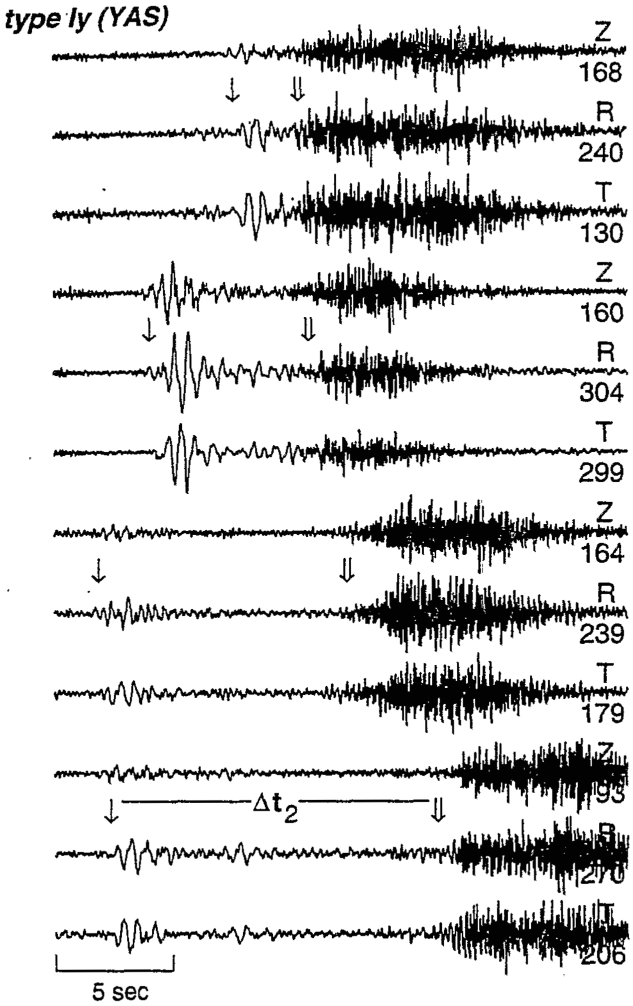

Fig. 9 Four examples of type I_Y signal recorded at YAS station on Yasur, showing the different time intervals (Δt_2) between type I_Y (arrow) and explosion onset (double arrow). The maximum amplitude (μ/s) of each components (Z, R, T) is given at right under the trace.

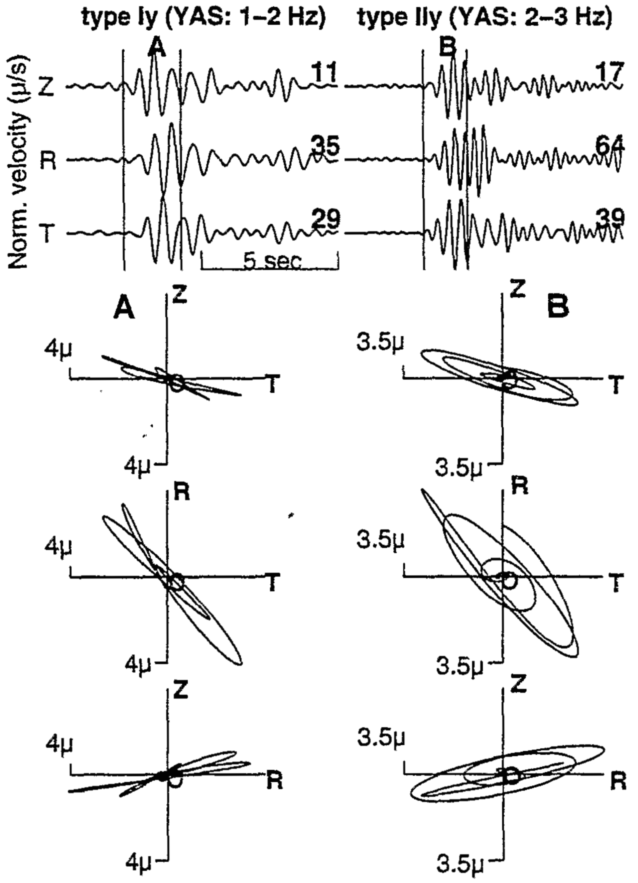

Fig. 10 Particle trajectories of type I_Y filtered between 1 and 2 Hz (A) and type II_Y filtered between 2 and 3 Hz (B) recorded at YAS station of Yasur. We observe the same linear motion in the horizontal plan for both signals.

would then correspond to the time separating the formation or vibration of the gas pocket and its reaching the surface (Fig. 12).

The upward velocity of large-scale gas pockets in cylindrical pipes, where melt viscosity and surface tension are negligible, is given by Wallis (1969) and Vergniolle & Jaupart (1990) as:

$v_s = K\,[gD]^{1/2}$ with $K = 0.345$

In this formula, the velocity does not depend on the vertical dimensions of the gas pockets, but only on the diameter of the conduit (D). The relationship is only valid if Froude's number (Fr) and Eotov's number (Eo) are greater than 300 and 100, respectively

$$\mathrm{Fr} = [D^3 g\,(\rho_l - \rho_g)\rho_l]^{1/2} / \mu$$

$$\mathrm{Eo} = D^2 g\,(\rho_l - \rho_g) / \sigma$$

where σ is the surface tension coefficient, μ represents the viscosity, ρ_l and ρ_g are the densities of liquid and gas, and g is the gravitational acceleration.

For values of $\rho_g = 0.2\ \mathrm{kg/m^3}$, $\rho_l = 1530\ \mathrm{kg/m^3}$, $\mu = 300$ Pa.s, $\sigma = 0.4$ N/m corresponding to the strombolian basalt (Chouet et al. 1974; Vergniolle et al. 1996), the above relationship may be applied with the condition $D \geq 7$ m.

For a diameter c. 10 m, upward velocity for gas pockets is c. 3 m/s. Taking the values observed for Δt_l and Δt_2, we may then calculate the depth of formation of the gas pockets, which gives us values from 6 to 60 m. A diameter of c. 10 m is realistic for the common magma conduit which feeds the three vents at Stromboli or Yasur.

This makes it difficult to accept the theory that would see the formation of such pockets within a "near-surface magmatic chamber" located several hundred metres from the surface (Giberti et al. 1992). Furthermore, the time variations Δt cannot be said to correspond to any possible variations in upward velocity of the gas pockets as a function of their volume, as no relationship has ever been established between variations in Δt, amplitude of forerunner signals, and intensity of explosion.

The model of gas pocket vibration in which the vibration mode is closely connected to the bubble size cannot explain the spectral similarity observed between volcanic noise (bubbly flow) and b and c phase of seismic signals (slug flow). One must therefore consider discontinuous triggering

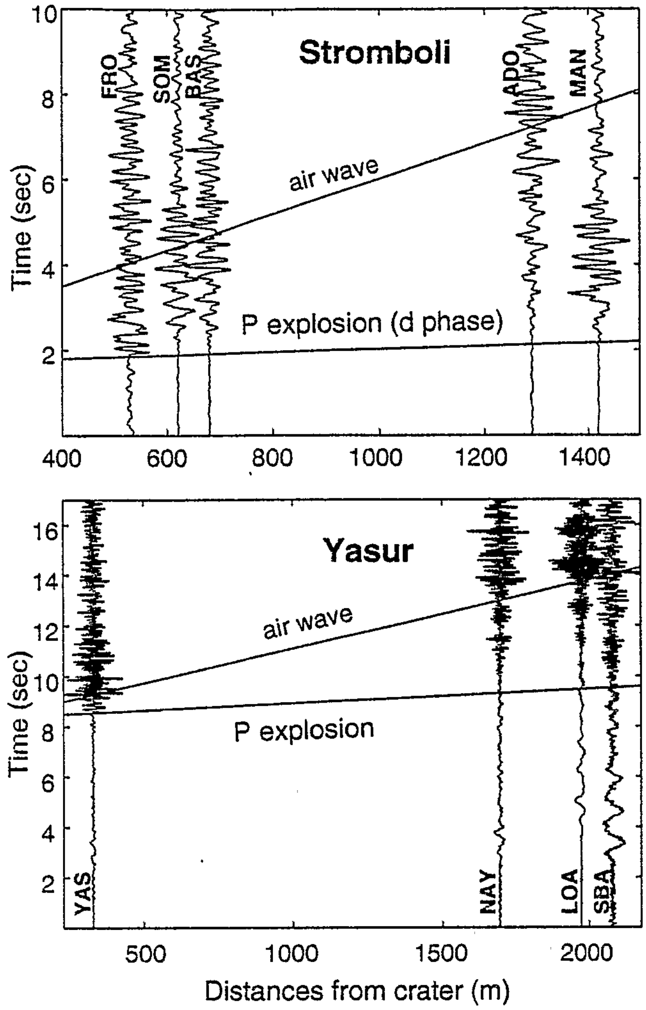

Fig. 11 Explosion recordings from the C3 crater of Stromboli (*top*) and A crater of Yasur (*bottom*). The P explosion ground wave (d phase) is followed by the air wave much clearer on Yasur. The origin of time scale is arbitrary.

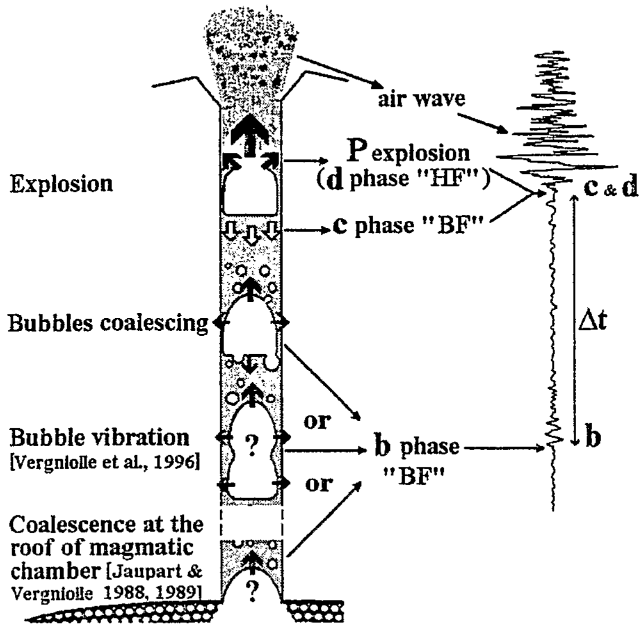

Fig. 12 Sketch showing some likely mechanisms to generate the seismic signal before (b phase) and during the explosion (c and d phases).

mechanisms (formation of gas pocket) at different levels within the magmatic column as the source of the forerunner seismic signals. The lower limits for Δt observed on both volcanoes may correspond to the production of forerunner signals at the upper face of the magmatic column, from which originate various branchings leading to the different vents.

At Stromboli, the evidence would indicate that the predominance of the 1–3 Hz frequency band which characterises both the volcanic noise and phases b and c of type I_S signals is linked to a single common oscillator, namely the magmatic column. Its excitation at depth (volcanic noise and type I_S phase b) and near the surface (explosions, type I_S and II_S phase c) results in the same oscillations. In both cases, frequencies of 1–2 and 2–3 Hz were present, but the predominance of one or the other in each of the three components is probably related to the depth at which the signal triggering the oscillation takes place (excitation of the fundamental mode or of the harmonics). This similarity between the low-frequency seismic signal and the seimic signal generated by the explosions was also reported by McNutt (1986) at Pavlof.

CONCLUSION

We noted similarities between the signals observed at Stromboli and Yasur. This analogy suggests similarity in the parameters which govern the production of the signals. These latter are characterised by a phase which anticipates the surface explosion by anywhere from a few seconds to several tens of seconds. The Δt_1 and Δt_2 time lag are of similar magnitude for both volcanoes. This time interval is probably linked to the depth where the formation of gas pocket takes place. This discontinuous triggering mechanism is the source of the forerunner seismic signals observed at both volcanoes. The comparison of the frequency analyses of volcanic noise and low-frequency events shows dominant and subdominant peaks which are shared by both types of signal. This suggests that the volcanic noise is generated by the same sources which produce the low-frequency signals.

Nevertheless, two important differences must be pointed out: (1) the amplitude of Yasur's forerunner signals is highly variable and often greater than that observed at Stromboli; and (2) there is absence of a phase c in even violent Yasur's explosions (no effect on the magmatic column). This may be the result of an unusual geometry of the magmatic pipes. Another characteristic is that type II_Y (2–3 Hz) always appear before type I_Y signals (1–2 Hz). Type III_Y signals occur simultaneously with type I_Y, or later. Their source would seem to be closer to the surface, and be independent of that of the other two types.

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