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Spectral characteristics of volcano-tectonic earthquake swarms in Nevado del Ruiz Volcano, Colombia

John M. Londono[a,b,*], Yasuaki Sudo[a]

[a]Aso, Volcanological Laboratory, Kyoto University, Aso gun, Choyo mura, Kumamoto ken 869-1404, Japan

[b]INGEOMINAS, Volcanological and Seismological Observatory, Avenida, 12 de Octubre 15-47, Manizales, Colombia

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Abstract

Spectral analyses for volcano-tectonic earthquakes were carried out at Nevado del Ruiz Volcano (NRV) for the period 1985–1996 for several earthquake swarms around the volcano, named North, East, West, South and Crater swarm zones. Important spectral peaks for each earthquake swarm zone were found by counting the number of spectra that had the same spectral peaks. Each swarm zone showed some characteristic peaks, which could help to differentiate between them; however, the most important peaks were similar for all the zones. These results suggest that the earthquake swarms at NRV were influenced directly by the source (activity of the volcano) and could also be influenced by the site effect. Some temporal changes were observed in spectral parameters such as a change in the frequency contents in almost all the swarm zones, and the frequency of the P-waves in the West earthquake swarm zone. Before the eruptions on November 13, 1985 and September 1, 1989, P-waves showed low frequencies (1–2 Hz) at the West earthquake swarm. After the eruptions, the frequencies of P increased (2–4 Hz). This fact showed that changes (decreasing of frequencies) in the spectra of P-waves at the West earthquake swarm could help in the monitoring of volcanic activity at NRV. This swarm zone seems to be related directly with the most important volcanic crises that have occurred. This suggests that the West swarm zone should be monitored in more detail in the future.

Keywords: volcano-tectonic; Nevado del Ruiz Volcano; swarm zone; seismicity; earthquake families

1. Introduction

The study of volcanic seismicity is a useful tool for monitoring a volcano as well as for the understanding of its behavior. There are many kinds of volcanic seismic signals. In this study, we are dealing with those named volcano-tectonic (VT) earthquakes. The VT earthquake is defined as an earthquake associated with volcanic activity, and produced probably by the same process as the normal tectonic earthquakes, i.e. it can be produced by faults or small fractures but interacting with the volcanic activity. Both P- and S-waves are distinguished clearly (Lahr et al., 1994). In some occasions, such earthquakes are associated with magmatic intrusions (e.g. Karpin and Thurber, 1987). The spectral characteristics and waveforms of VT swarms can help to distinguish one swarm zone from the others. Okada et al. (1981) could differentiate 'families' of earthquake swarms by studying local earthquakes associated with volcanic activity at Usu volcano, Japan. They

* Corresponding author. Address: Aso, Volcanological Laboratory, Kyoto University, Aso gun, Choyo mura, Kumamoto ken 869-1404, Japan.

E-mail address: john@aso.vgs.kyoto-u.ac.jp (J.M. Londono).

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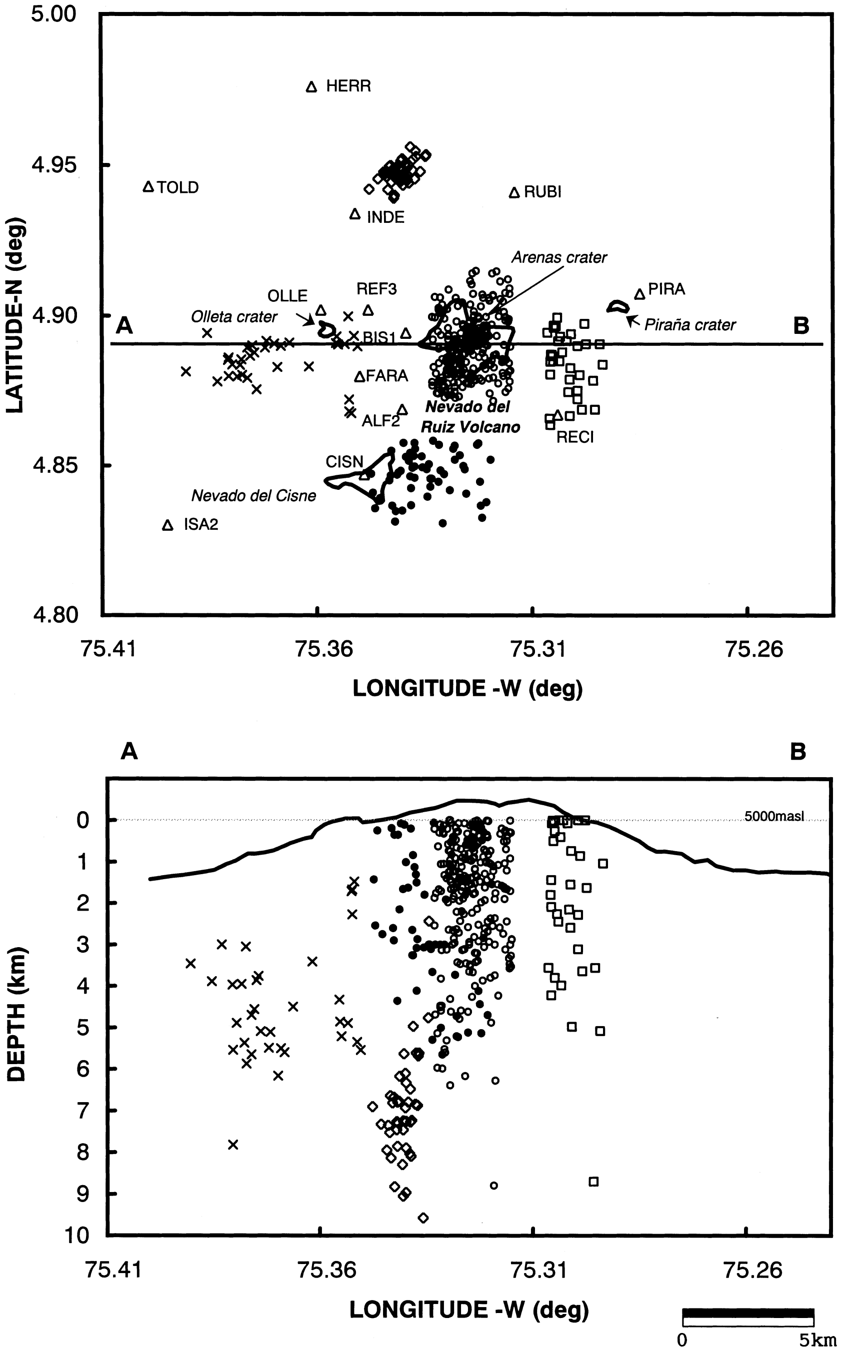


Fig. 1. Location of NRV and hypocentral location of the earthquakes (circles) used in this work (upper: plan view. lower: cross-section A–B). Triangles represent seismic stations. The topographic curve of 5200 m is showed for NRV volcano, and 4200 m for Nevado del Cisne. Different symbols were used for each swarm zone (rhomboids: north zone, open squares: east zone, cross: west zone, closed circles: south zone, open circles: crater zone). The zero (0) level of depth is located at 5000 m asl.

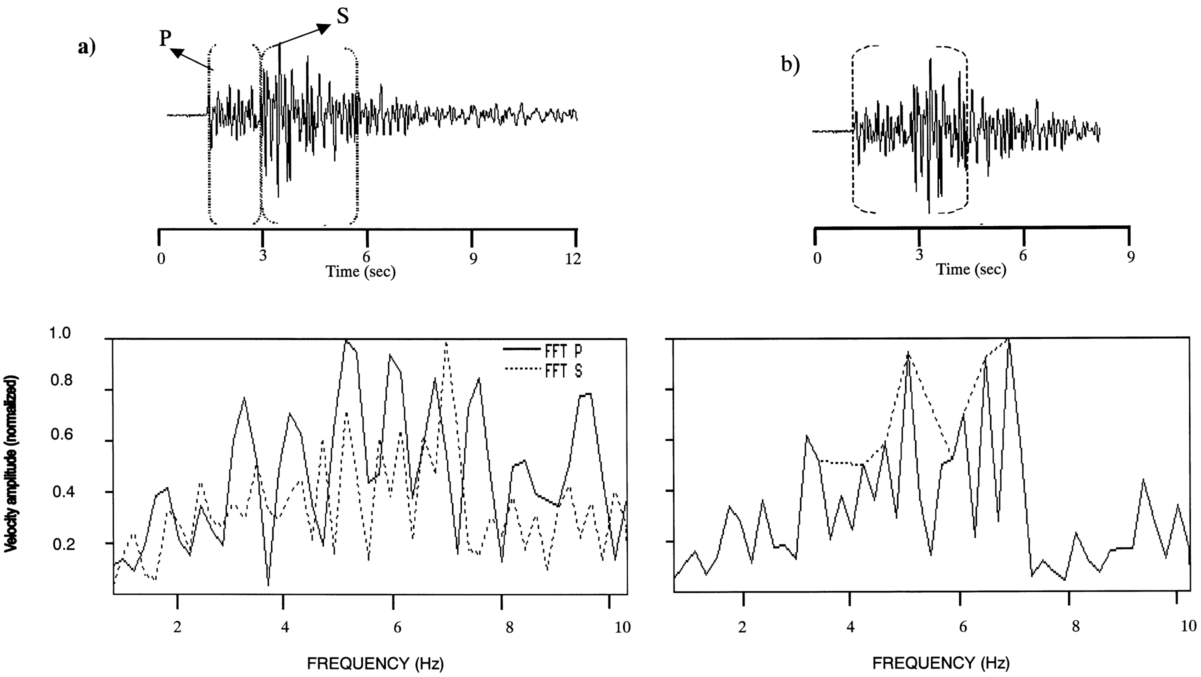


Fig. 2. Examples of the processing for the spectral analysis: (a) time window used for calculation of the spectrum of the P- and S-waves (top) and the spectrum normalized by the maximum peak (bottom) and (b) time window for the calculation of the spectrum used to obtain the important peak spectrum (top). The spectral peaks above 50%, taking as 100% the maximum peak, connected by broken lines, represent the important peak spectrum (bottom).

explained such earthquake families in terms of barriers of different sizes and strengths. Moreover, Okada (1983) summarized the concept of 'earthquake families'. He found that in several volcanoes around the world, earthquakes families are a distinctive characteristic, and that major earthquake families are associated with large amount of deformation in volcanic areas.

Some researchers have used the temporal changes in spectra of long-period (LP) events and tremor as a tool for surveillance of volcanic activity (Chouet et al., 1994; Stephens et al., 1994; Bryan and Sherburn, 1999). On the other hand, temporal variations of spectral contents of VT earthquakes also may be used as a tool for surveillance of volcanic activity. Zobin (1979) found an increase in the predominant P-wave periods before the 1975 Tolbachik, Kamchatka eruption. He associated this increase as the consequence of a stress drop decrease. Lesage and Surono (1995) found interesting characteristics of VT earthquake swarms as a seismic precursor of the eruption of Kelut volcano, Java. In the same way, Hurst and McGinty (1999) found that VT earthquake swarms preceded the eruption of Mt Ruapehu in 1995.

Although another techniques have been used for monitoring the volcanic activity of Nevado del Ruiz Volcano (NRV), the spectral analysis as a tool for surveillance has not been used completely. Few studies have been made of the spectral characteristics of the VT earthquakes at NRV. Londoño and Kobayashi (1994) made a spectral analysis for VT earthquake swarms that occurred during August and October 1990, finding three areas characterized by similar waveforms and similar spectral shapes.

In this study, the Fast Fourier Transform (FFT) spectral technique will be used to analyze the seismic signals of VT earthquake swarms in NRV, and to determine distinctive characteristics of each of the earthquake swarms. The main purpose of this study is to find patterns in the spectra that characterize the VT earthquake swarms at NRV and their relation with the volcanic activity.

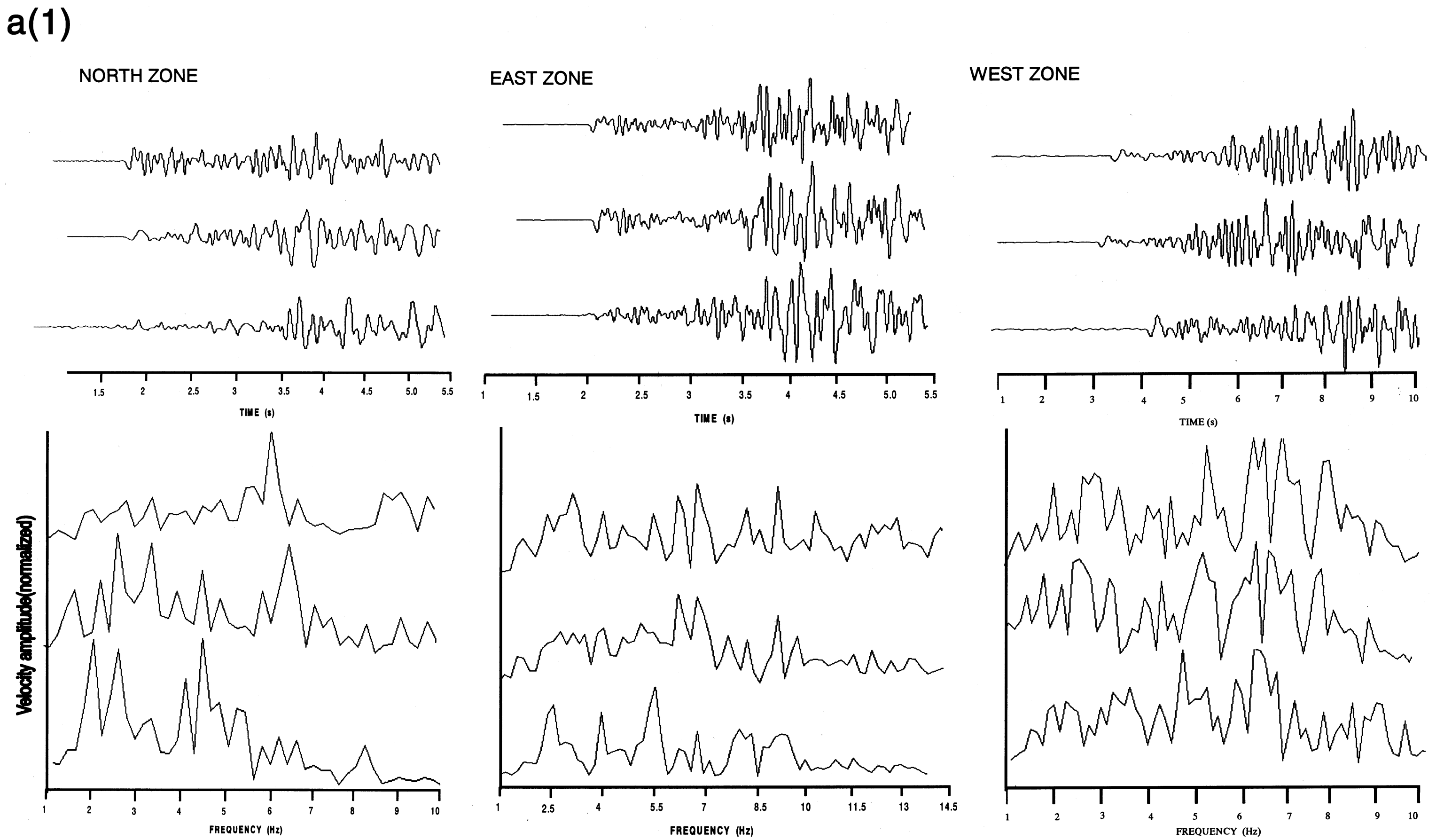


Fig. 3. (a) Example of waveforms and spectra for each swarm zone. Three or four examples (of waveforms) for each swarm zone are shown for REF3 station. In the upper part of each frame, the waveforms are displayed, and in the lower part, their corresponding spectra. (b) Important peak spectra for OLLE station in all swarm zones. Only the spectral peaks above 50% of the maximum level are plotted for all the spectra (left side frames). The distribution of the frequencies for all important peak spectra used for each swarm zone in all stations is presented in the right side frames. Each horizontal pattern (closed rectangles) represents the most important frequency peaks in one spectrum. In the vertical axis, all the spectra used including all the stations are plotted. The numbers represent the ordinal number of the spectrum.

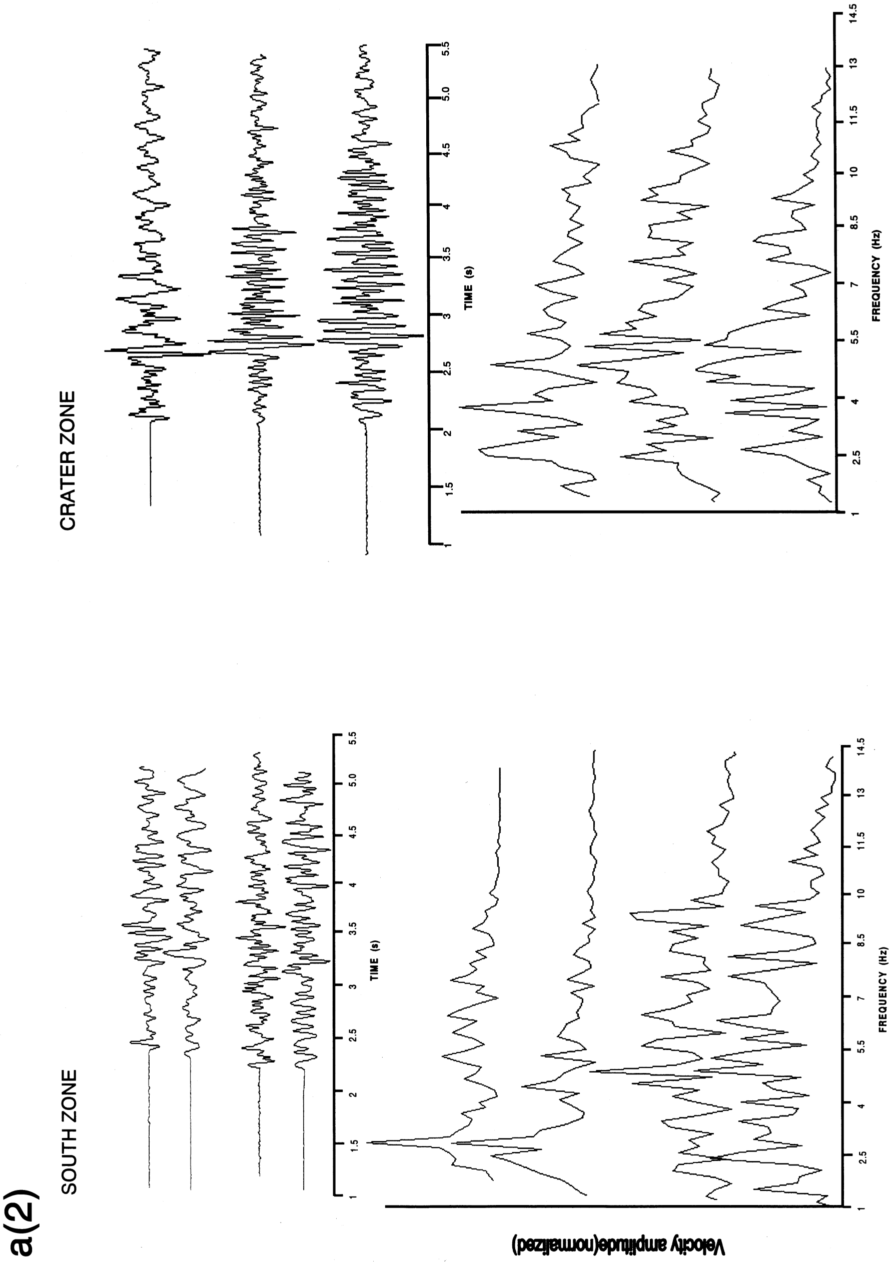


Fig. 3. (*continued*)

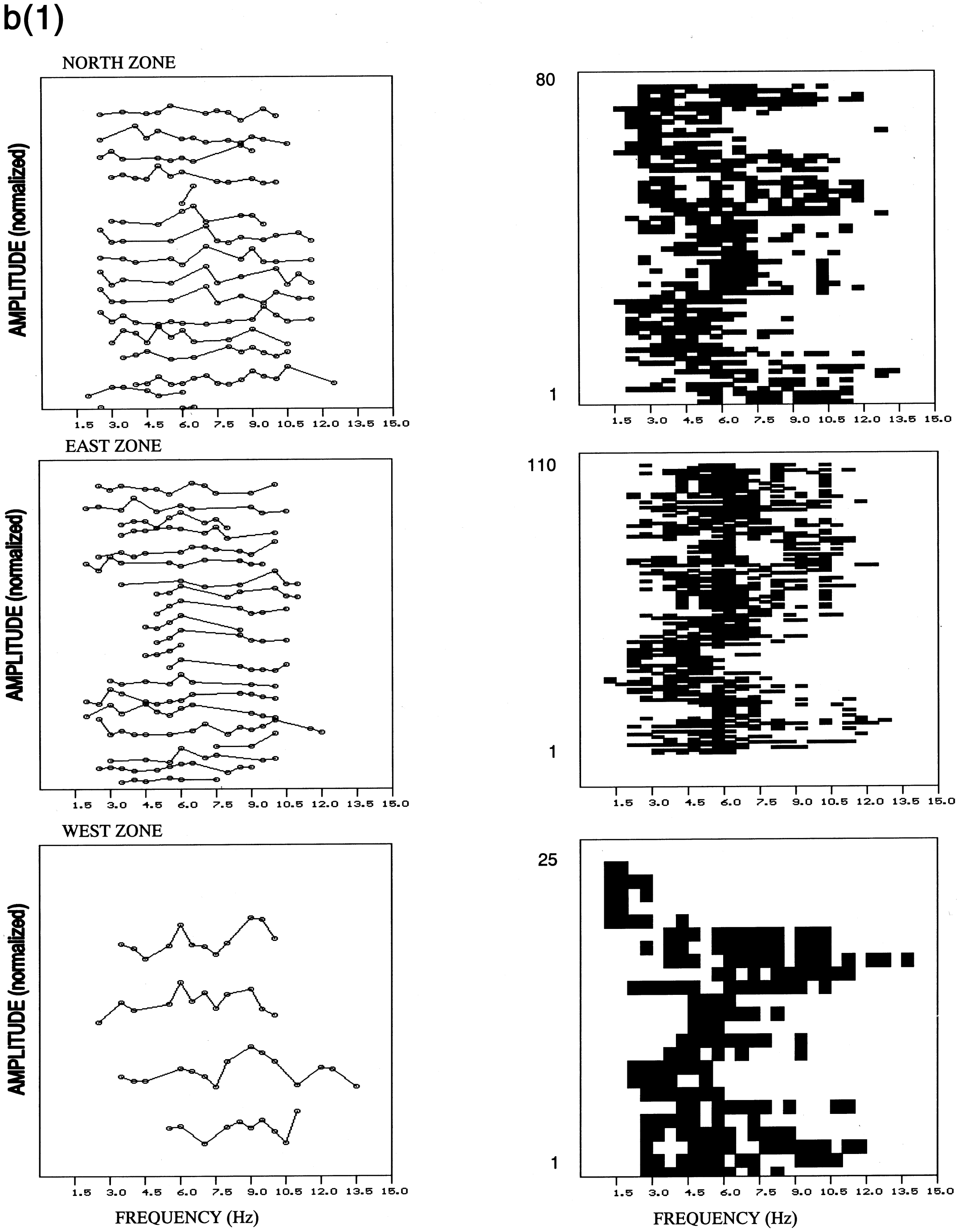


Fig. 3. (*continued*)

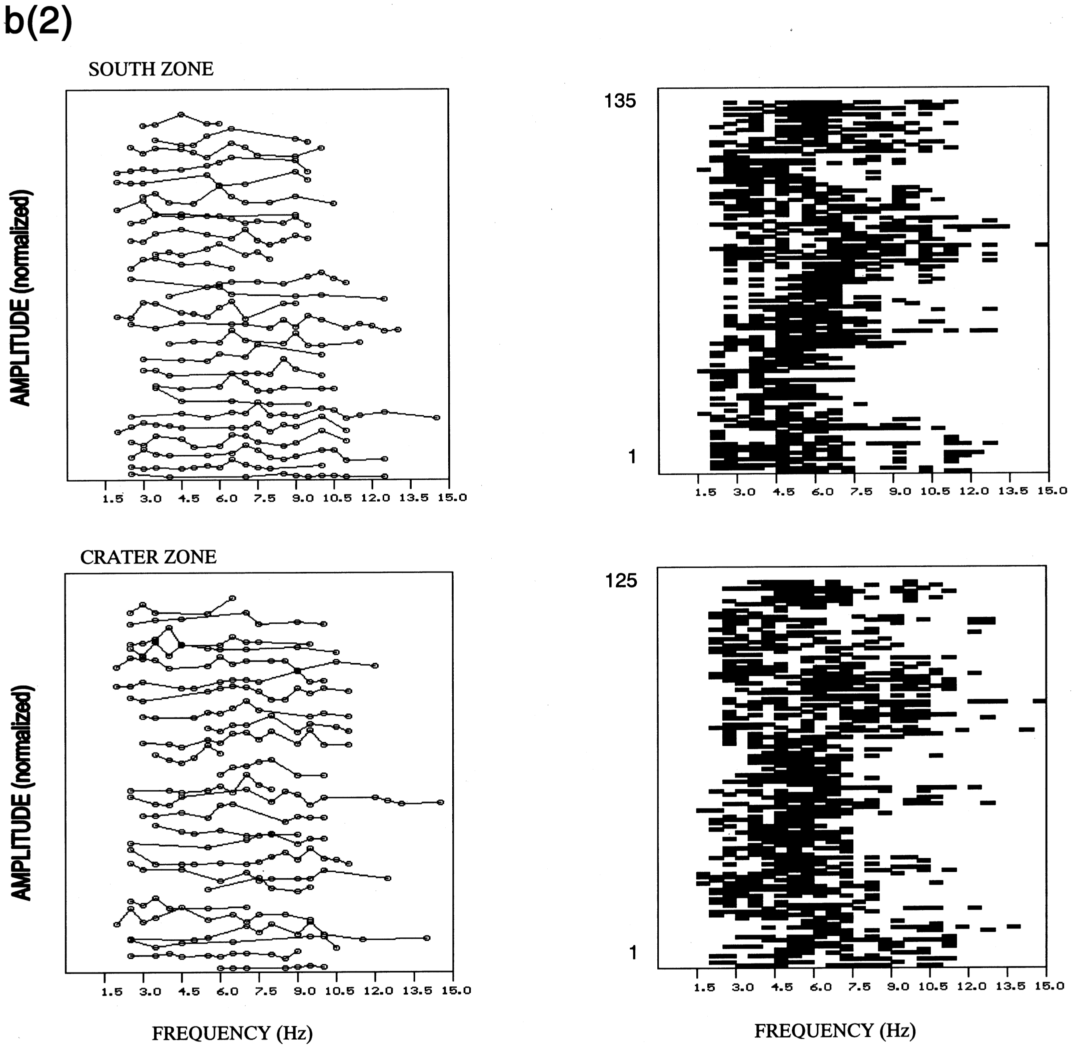


Fig. 3. (*continued*)

2. Data

For this study, digital signals of VT earthquakes obtained by the 13-station seismic network of the NRV volcanic activity (Fig. 1) during the period 1985–1996 were used. The seismometers are vertical-component, 1 Hz natural frequency, velocity transducers. The seismic signals were telemetered to the volcanological observatory and then digitized with a sampling rate of 200 sps. We selected those VT earthquakes occurring as swarm-like, which were recorded at least at five stations, with high signal-to-noise ratio (e.g. Figs. 2 and 3a).

For the hypoc enter determination, we use the HYPO71 computer program (Lee and Lahr, 1985), and a 1-D velocity model for P-waves proposed by Zollweg (1990) for the NRV area. We selected the most well-located earthquakes based on HYPO71 program output (vertical and horizontal errors less than 0.2 km, and RMS residual times less than 0.09 s). Fig. 1 shows the locations of the earthquakes used in this work, as well as the seismic stations used for hypocenter determination and spectral analysis.

Table 1
Important frequencies for each earthquake swarm zone at NRV (the percentage and the number of spectra with the same spectral peak are shown)

North zone			East zone			West zone			South zone			Crater zone		
Frequency (Hz)	No. of spectra	%	Frequency (Hz)	No. of spectra	%	Frequency (Hz)	No. of spectra	%	Frequency (Hz)	No. of spectra	%	Frequency (Hz)	No. of spectra	%
1.0			1.0			1.0	5	20.0	1.0			1.0		
1.5	4	5.0	1.5			1.5	5	20.0	1.5	4	3.0	1.5	4	3.2
2.0	20	25.0	2.0	22	20.0	2.0	5	20.0	2.0	44	32.6	2.0	26	20.8
2.5	41	51.3	2.5	36	32.7	2.5	13	52.0	2.5	71	52.6	2.5	60	48.0
3.0	42	52.5	3.0	28	25.5	3.0	8	32.0	3.0	52	38.5	3.0	45	36.0
3.5	47	58.8	3.5	56	50.9	3.5	10	40.0	3.5	94	69.6	3.5	67	53.6
4.0	40	50.0	4.0	62	56.4	4.0	14	56.0	4.0	56	41.5	4.0	63	50.4
4.5	48	60.0	4.5	70	63.6	4.5	16	64.0	4.5	103	76.3	4.5	86	68.8
5.0	51	63.8	5.0	71	64.5	5.0	11	44.0	5.0	86	63.7	5.0	77	61.6
5.5	62	77.5	5.5	93	84.5	5.5	15	60.0	5.5	99	73.3	5.5	92	73.6
6.0	47	58.8	6.0	86	78.2	6.0	12	48.0	6.0	80	59.3	6.0	77	61.6
6.5	47	58.8	6.5	62	56.4	6.5	9	36.0	6.5	86	63.7	6.5	70	56.0
7.0	40	50.0	7.0	54	49.1	7.0	12	48.0	7.0	55	40.7	7.0	65	52.0
7.5	22	27.5	7.5	24	21.8	7.5	8	32.0	7.5	46	34.1	7.5	29	23.2
8.0	27	33.8	8.0	36	32.7	8.0	9	36.0	8.0	45	33.3	8.0	45	36.0
8.5	27	33.8	8.5	25	22.7	8.5	5	20.0	8.5	32	23.7	8.5	23	18.4
9.0	24	30.0	9.0	31	28.2	9.0	9	36.0	9.0	41	30.4	9.0	35	28.0
9.5	19	23.8	9.5	14	12.7	9.5	6	24.0	9.5	23	17.0	9.5	30	24.0
10.0	30	37.5	10.0	38	34.5	10.0	7	28.0	10.0	33	24.4	10.0	32	25.6
10.5	14	17.5	10.5	12	10.9	10.5	3	12.0	10.5	16	11.9	10.5	20	16.0
11.0	13	16.3	11.0	10	9.1	11.0	4	16.0	11.0	22	16.3	11.0	15	12.0
11.5	11	13.8	11.5	6	5.5	11.5			11.5	10	7.4	11.5	3	2.4
12.0			12.0			12.0			12.0	3	2.2	12.0	8	6.4
12.5	4	5.0	12.5			12.5			12.5	9	6.7	12.5	7	5.6
Total number of spectra used	80			110			25			135			125	

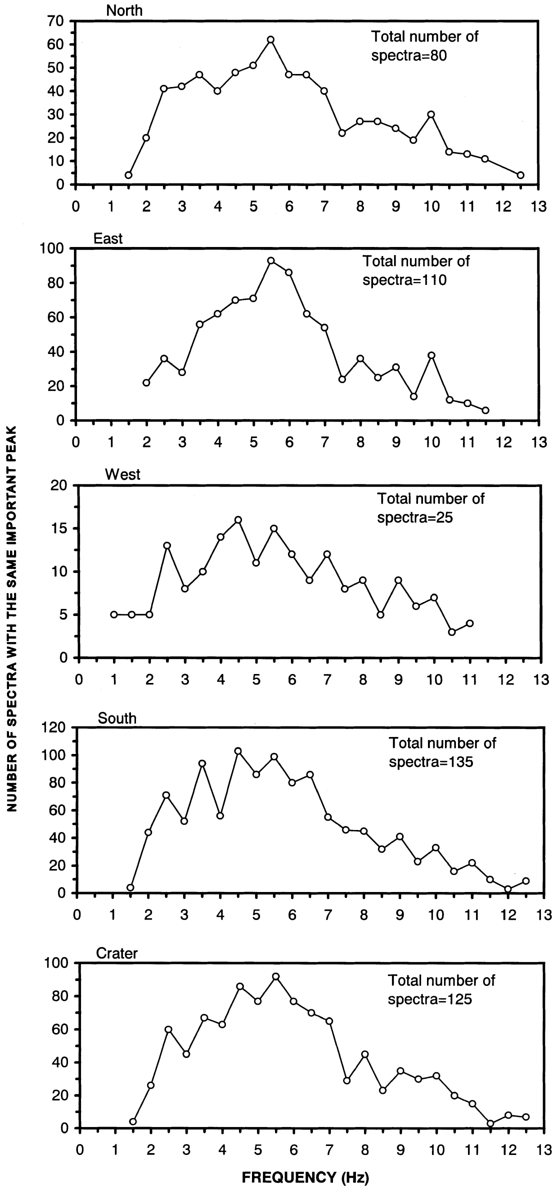


Fig. 4. Important spectral peaks for each earthquake swarm zone by integrating the smoothed spectra in all the stations. In the vertical axis, the number of spectra which contain the same spectral peaks in all the stations, is plotted.

3. Method

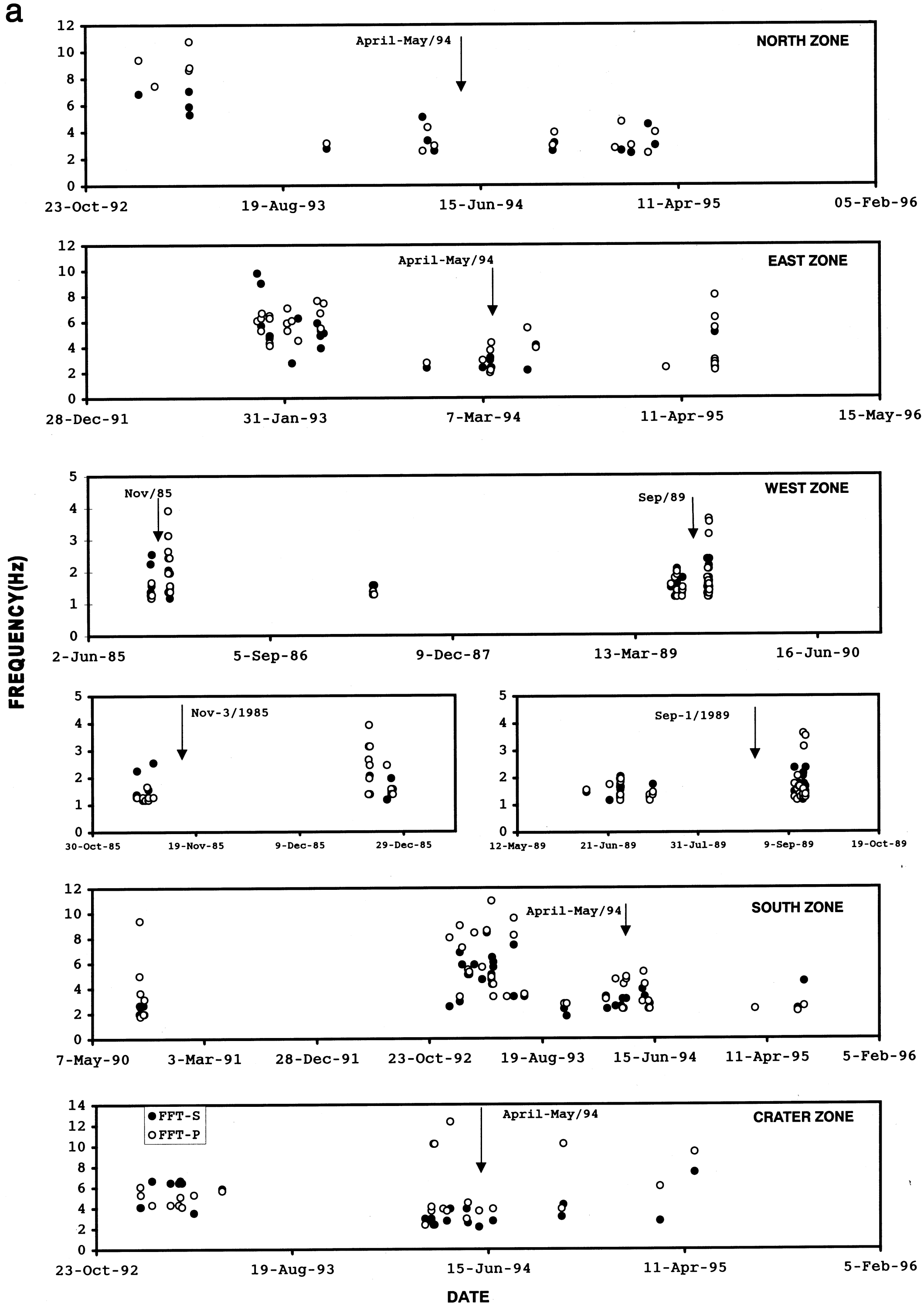
For the calculation of the velocity spectrum of the earthquakes, the algorithm of the FFT was used. The selected earthquakes for the spectral analyses were based on the highest signal-to-noise ratio, no clipping, and the best hypocenter determination in order to delimit clearly the spatial VT swarms. Non-instrumental corrections were applied since we are not interested in absolute values of amplitude.

3.1. Spectra for the P- and S-waves

The spectrum of the P-wave was calculated for a time window starting just before the onset of the P-wave until the beginning of the S-wave. The spectrum of the S-wave was calculated in a window of 2.5 s starting from the beginning of S-wave. Before spectral calculation, we applied a tapered Hanning cosine window. For both P- and S-wave, we took the predominant frequency as the frequency associated with the maximum peak of amplitude in the spectrum (Fig. 2a).

3.2. Important peaks spectra

To carry out a detailed analysis of the spectra, the most important peaks in each spectrum were used. We named those frequencies, which were presented in many spectra at the same station for each swarm zone, 'important peaks'. We made several tests in order to find the best time window for the calculation of the important peak spectra. We found that a window of 3.5 s starting at the onset of P-wave of the signal seemed to be the most suitable. We selected this portion of the signal because our goal was to find the most important frequencies in the main part of the signal independently if it was P- or S-wave. We infer that the S-wave has more influence on these spectra since the P-wave is too short (about 1.5 s). Also S-amplitude is greater than P-amplitude. The amplitudes were normalized taking the maximum amplitude as the unit (1). Then, taking the maximum peak as 100%, the spectral peaks above 50% were selected. Those spectral peaks that were above 50% were considered important in the spectrum. We made a test choosing those spectral peaks above the 30% and we did not find any difference in the final results, comparing those peaks above 30% with those above 50%. For this reason, we used those spectral peaks above 50% with respect to the maximum peak. With these data, some plots were elaborated that represented a kind of 'smoothed' spectrum of all earthquakes in an earthquake swarm (Fig. 3). The


a
NORTH ZONE
April-May/94
23-Oct-92
19-Aug-93
15-Jun-94
11-Apr-95
05-Feb-96
EAST ZONE
April-May/94
28-Dec-91
31-Jan-93
7-Mar-94
11-Apr-95
15-May-96
WEST ZONE
Nov/85
Sep/89
2-Jun-85
5-Sep-86
9-Dec-87
13-Mar-89
16-Jun-90
Nov-3/1985
30-Oct-85
19-Nov-85
9-Dec-85
29-Dec-85
Sep-1/1989
12-May-89
21-Jun-89
31-Jul-89
9-Sep-89
19-Oct-89
SOUTH ZONE
April-May/94
7-May-90
3-Mar-91
28-Dec-91
23-Oct-92
19-Aug-93
15-Jun-94
11-Apr-95
5-Feb-96
CRATER ZONE
FFT-S
FFT-P
April-May/94
23-Oct-92
19-Aug-93
15-Jun-94
11-Apr-95
5-Feb-96
FREQUENCY(Hz)
DATE

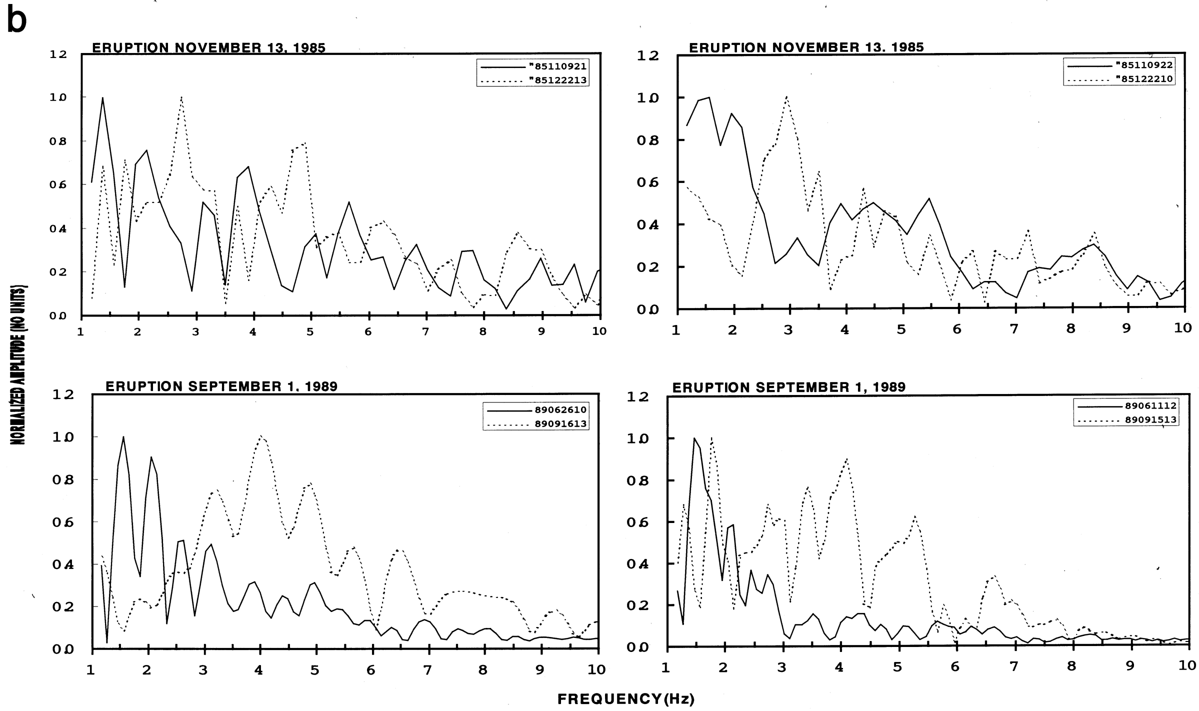


Fig. 5. (*continued*)

stations used for this analysis were REF3, OLLE, RECI, ALF2, and BIS1 (Fig. 1). We aligned all the spectra for each station at each swarm zone. We used the same number of spectra for each station in order to avoid that some stations had more influence in the final spectra. In other words, we assigned the same weight to each station to obtain the important peak spectra by using the same earthquakes and the same number of spectra per station for each swarm zone. Then, we counted the number of spectra that had the same peaks of frequency in a band of 0.5 Hz, i.e. we gathered those peaks in 0.5 Hz frequency steps. Then, histograms were constructed. Fig. 3b shows an example of the alignment of the important peaks in each spectrum used for each swarm zone in the OLLE station and the total distribution of the frequencies for all the stations for each swarm zone.

4. Results

Once all the data of spectral parameters were obtained, we proceeded to analyze each earthquake swarm zone in order to find differences among them. Next, each of the earthquake swarm zones are described and analyzed from the point of view of spectra.

North swarm zone: this swarm zone showed 21 spectral peaks above the 50% level of all the data used. The peak located at 5.5 Hz was displayed in 62 spectra, that is around 77% of the earthquakes (Table 1). The most important spectral peaks for this swarm zone ranged from 2.5 to 7.0 Hz, with the second most important frequency located at 5.0 Hz, displayed in 51 different spectra, and the third located at 4.5 Hz, displayed in 48 different spectra (Fig. 4).

Fig. 5. (a) Change of the predominant frequencies of the P-waves (open circles) and S-waves (solid circles), with the time, in the REF3 station. Note the change of the predominant frequency of P-wave for the West swarm zone after the eruptions on 13 November 1985 and 1 September 1989 (arrows). (b) Examples of the change in the spectral content of P-wave before (solid lines) and after (dotted line) the eruptions at REF3 station.

The spectra of the P- and S-waves showed a temporal change. It seems that before 1992, the frequency of P- and S-waves ranged from 5 to 10 Hz. After 1992, the P- and S-waves showed a tendency for the frequency to decrease ranging from 5 to 2 Hz (Fig. 5).

East swarm zone: in the same way as the North swarm zone, the East swarm zone showed a similar range of spectral peaks in its spectral content. This swarm zone showed 20 important frequency peaks above the 50% level of all the data used. The most predominant peaks are located at 5.5, 6.0 and 5.0 Hz, and are displayed in 93, 86 and 71 different spectra, respectively (Fig. 4). The spectra of the P- and S-waves, showed a tendency to be more concentrated during the volcanic crisis on April–May 1994. During the other dates the spectra of P- and S-waves were more scattered (Fig. 5).

West swarm zone: this swarm zone showed 21 important spectral peaks above the 50% level of all the data used. It is one of the deepest swarm zones (Fig. 1). The most important spectral peak was located at 4.5 Hz, displayed in 16 different spectra. There are also peaks at 5.0 and 4.0 Hz, registered in 15 and 14 different spectra, respectively. The West swarm zone did not show important activity after 1990. However, an interesting temporal variation exists in this swarm zone with respect to the spectral contents of P-waves. Before the eruptions of November 13, 1985 and September 1, 1989, the P-waves showed spectral contents in a narrow band (around 1–3 Hz). After the eruptions, the spectral content of P-waves tended to be very narrowly distributed with a tendency to increase (Fig. 5a and b). This change in the spectra of P-waves suggests changes of inner conditions of the volcano after the eruptions, mainly in the western part of the volcano (about 3 km from the active crater). This swarm zone was active for a few days before, during or after the two recent eruptions at NRV (November 1985 and September 1989).

South swarm zone: this swarm zone showed 23 important spectral peaks above the 50% level of all the data used. The three most important peaks of frequency are located at 4.5, 5.0 and 3.5 Hz, displayed in 103, 99, and 94 different spectra, respectively. This swarm zone and the West swarm zone showed the lowest frequencies (Fig. 4). There was a temporal change for the spectra of the P- and S-waves. Until 1992–1993, the P and S showed frequencies that ranged from 2 to 10 Hz. After 1993, the frequencies showed a decrease and are more concentrated, ranged from 2 to 5 Hz (Fig. 5a).

Crater swarm zone: the Crater swarm zone presents 24 important frequency peaks above the 50% level of all the data used. The most important frequency peaks are located at 5.5, 4.5, and 6.0 Hz and displayed in 92, 86, and 77 different spectra, respectively (Fig. 4). A temporal change in the spectral parameters can be observed in this swarm zone for the volcanic crises in April–May 1994. The frequency contents for both P- and S-waves were more concentrated (2–4 Hz) during the volcanic crisis than those before or after the crisis (2–10 Hz) (Fig. 5a).

5. Discussion and conclusions

With the spectral analysis done in this study, we know now that the most important frequencies registered at NRV for VT earthquake swarms are mainly between 2 and 7 Hz. All earthquake swarm zones presented similar frequency contents. We found that all the swarm zones have a similar spectral shape with small variations between them. This suggests that the VT earthquake swarm zones have some similar characteristics, due probably to the sources. Although intrinsic spectral characteristics are possible to see for each swarm zone (Fig. 3, see later), the similarity in the spectral shape suggests that all the VT earthquake swarm zones occurred at NRV have similar source characteristics (Fig. 4).

The site effects in the NRV will affect to some extent the seismic signals and therefore the spectra. Fig. 6 shows average spectra stressing the site effect for each station. It was obtained by stacking all spectra of all earthquakes from all the swarm zones for each station. We can notice that each station has a very different site effect spectrum. For instance, the OLLE station is very rich in high frequencies (above 7 Hz) while RECI or ALF2 stations are poor, and only a few important peaks are present in the spectra. Moreover, we calculated for each swarm zone the ratios of the average spectra stressing the path effect (obtained averaging all the spectra for each pair of swarm zone and station) to the average spectra stressing source spectra (obtained averaging

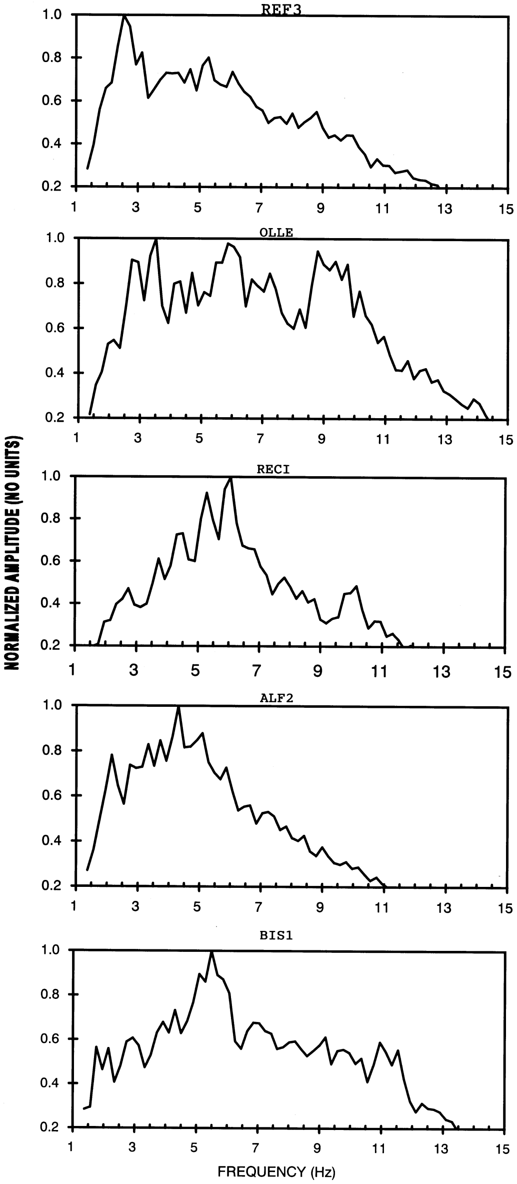


Fig. 6. Average site effect spectrum for each station at NRV. It was obtained by stacking all spectra of all earthquakes from all the swarm zones for each station. Note that each station has a very different average site effect spectrum.

all the spectra for all station for each swarm zone) and corrected by site effect average spectra. Fig. 7 shows those ratios. From this figure, it is possible to see that the ratios are very flat and similar for all the swarm zones in the range of frequencies from around 3 to 9 Hz. Therefore, we suggest that the path effect is strong for frequencies higher than 9 Hz but rather weak for lower frequencies.

The range of frequencies of P- and S-waves for all the swarm zones was almost the same, ranging from 3 to 12 Hz. This suggests that a similar process is occurring at NRV, i.e. the interaction of volcanic activity with tectonic activity is taking place throughout the volcano, although some differences in the mechanisms for the different seismic spatial swarms can be seen.

It is possible that the pre-existing structures present in such areas (such as faults) have some influence on the spectra of P- and S-waves. The West and North swarm zones showed the deeper hypocenters (Fig. 1). This suggests, at least, different properties of the materials. Rautian et al. (1978) found in the Tadjikistan region some differences between the spectra of P-and S-waves for local earthquakes. They attributed this change to the type of rock and to the depths of the hypocenters. We think that in NRV, the western part has a different structure. Also, we suggest that the North and East, and South and Crater swarm zones have similar mechanisms of generation of earthquakes, while the West swarm zone has a mechanism different from the others. Moreover, it seems that the focal and physical mechanisms of generation of VT earthquakes are different too.

Muñoz et al. (1990) found a different focal mechanism for the western sector of NRV, compared with the south and eastern sectors. They found for the western sector a normal fault with strike to the NW, while the focal mechanism for the E and SE sectors were reverse fault (NW) and normal fault (NE), respectively. Osorio and Saenz (1997) found for the North swarm zone a normal fault (NE) mechanism. On the other hand, Thouret et al. (1990) suggested that there is a caldera rim around the active crater. This rim seems to be located between the western swarm zone and the others (crater, north, south and east). In addition, Sturchio et al. (1988) suggested that there are two different circulating hydrothermal systems at NRV: one located in the north and east of the volcano, and other located in the west. They associated these two circulating systems with two different sources. Based on these results, we think that the west zone could have a behavior different from the other zones, at least from 'temporary' spectral point of view

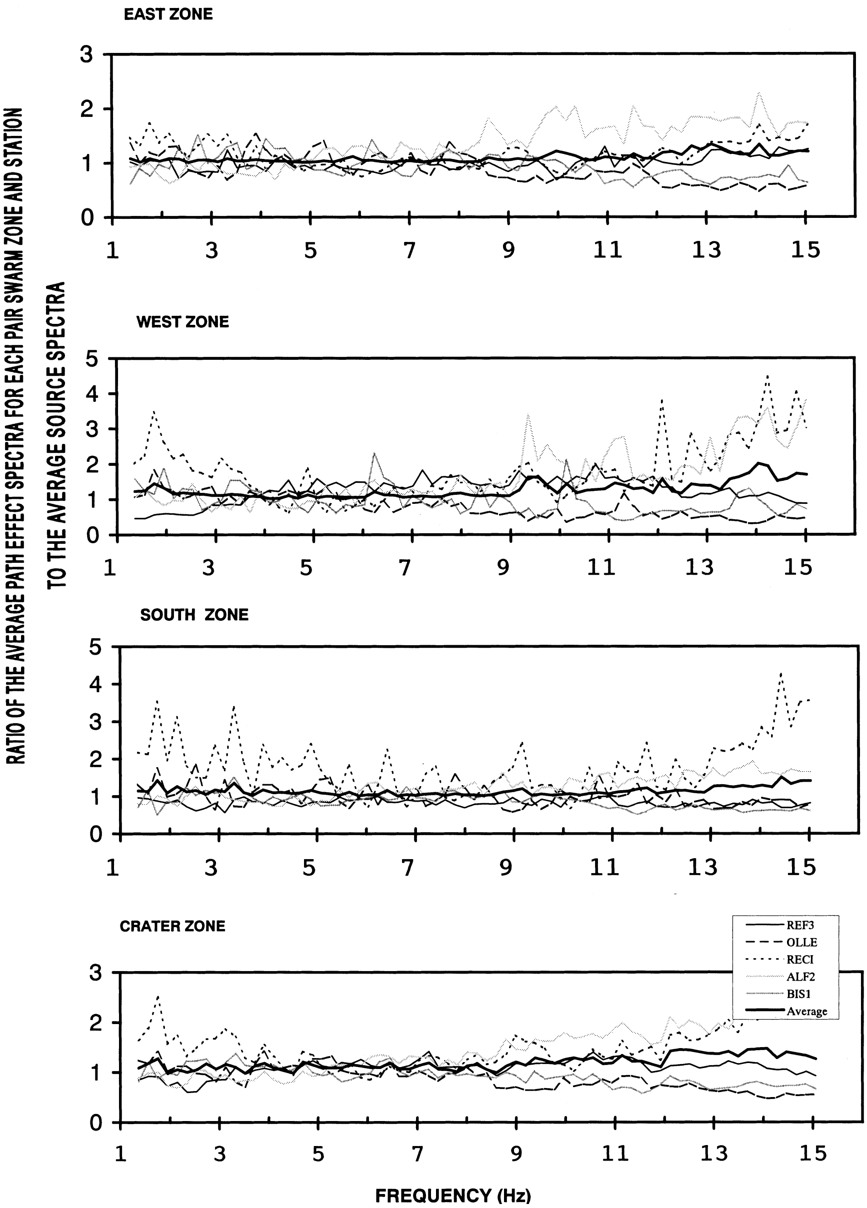


Fig. 7. Ratio of the average path effect spectrum to the average source effect spectrum for each pair of swarm zone and station. The average spectra stressing the path effect were obtained averaging all the spectra for each pair of swarm zone and station and corrected by site effect average spectra for each station. The average spectra stressing source spectra was obtained averaging all the spectra for all stations for each swarm zone. Note the flat part from 3 to 9 Hz in almost all the stations for all the swarm zones.

(temporal changes in frequency content), although from 'stationary' spectral point of view, all the earthquake swarm zones seem to have similar frequency contents. Even though, the West swarm zone as well as the South swarm zone seem to be slightly richer in low frequencies than the others. It is to be noted that the REF3 is that station which shows the lowest frequencies, judging from the average site effect spectra (Fig. 6). This station is located near the West swarm zone. OLLE station also has a low frequency

Table 2
Statistical significance test, F-test for temporal changes in frequency of P-wave

	Average frequency (Hz)	Standard error	F-Test (significance)
Before Nov-85	1.3	0.05	0.001
After Nov-85	2.8	0.24	
Before Sep-89	1.5	0.07	0.046
After Sep-89	1.9	0.22	

portion in the site effect spectrum and it is located near the West swarm zone too, as well as ALF2 that is located in the SW. Moreover, the West swarm zone seems to be active before or during the main volcanic crises. It is possible that this earthquake swarm zone has influence in the increasing of the volcanic activity, or that the volcanic activity has some effect in this swarm zone. We think they are interacting. The changes in the spectra of P-waves in the west swarm zone before and after the two eruptions can be used as a monitoring tool for the surveillance of NRV.

With respect to the Crater swarm zone, we infer that this zone is very complex because it is located just in the middle of the active crater, and it is difficult to conclude anything since many factors can affect the spectra.

All the swarm zones showed temporal changes in the spectra of P- and/or S-wave. It seems that the frequency contents became concentrated in a lower-frequency band during the period including eruptive activities (Fig. 5). The clearest change was observed at P-wave before and after the phreato-magmatic eruptions on November 1985 and September 1989 in the west swarm. A statistical significance test was made in order to determine the reliability of those temporal changes. The available predominant frequencies of P-wave for the West swarm zone were grouped before and after each eruption mentioned before. The statistical significance test by using the F-test method (Press et al., 1992) was performed for those frequencies before the eruption versus those after the eruption. Table 2 shows the results of the significance test. From this table, it is possible to conclude that the temporal changes observed at West swarm zone before and after the two mentioned eruptions seems to be real. The significance for those frequencies before versus those after the November 1985 eruption is 0.001, and for the eruption of September 1989 is 0.046. Those small significance values are indicative of a temporal change in the frequencies.

On the other hand, temporal changes in the depth could be one of the causes of the temporal change in spectrum. We made a test in order to check if temporal changes in depth could cause changes in spectrum. The test showed that there exists no important correlation between temporal changes in depth and temporal changes in spectrum for all the swarm zones. The depth of the earthquakes did not show any observable change through time for all the swarm zones. Rather, the depths were distributed indistinctly in the volume of the swarm sources through the time. The temporal changes in the frequency content for the West swarm zone related with volcanic activity could be attributed hypothetically to phase changes, such as water to gas, fluid to gas or vapor, interaction of water and gas or vapor within small cracks or fractures that produce changes in stress, and could trigger the earthquake swarm and produce some temporal changes in spectra. It is noteworthy that long period earthquakes located near the active crater were detected during or before the eruptions (Gil, 1987). Those earthquakes seemed to occur contemporaneously with the West earthquake swarms. We think that this fact could help one to explain the temporal changes in frequency contents for the West swarm zone as a phase change. Moreover, Alguacil et al. (1999) suggested that the differences in frequency content for some volcanic earthquakes (hybrid earthquakes) at Deception Island (Antarctica) could be related with phase changes. A detailed analysis of the relationship between western swarm zone and long periods at NRV is in preparation.

In summary, we can conclude that the range of frequencies of P- and S-waves for all the swarm zones was almost the same, ranging from 3 to 12 Hz. It is possible that the temporal changes in spectral contents of the VT swarms are related with the volcanic activity.

As we mentioned before, the West swarm zone seems to be in close relationship with the volcanic activity, and a clear change in frequency contents of P-waves were observed before the both phreato-magmatic eruptions at NRV. In the other swarms zones, it seems that the frequency contents became concentrated in a lower-frequency band during the period including eruptive activities. Therefore, we suggest that the monitoring of temporal changes in spectral contents of VT swarms can be useful as another tool for surveillance of the activity of NRV.

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