Observations of two special kinds of tremor at Galeras volcano, Colombia (1989-1991)

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Abstract
Since the reactivation of Galeras volcano in 1988 its seismic activity has been dominated by a variety of LP waveforms and tremor events. Some of these signals occurred as a response to volcanic activity. Among them, two kinds of tremor deserve special attention, Flute tremor and Spasmodic tremor. Flute tremor has a spectrum of equally spaced peaks and is associated with a quasi-steady degassing process at the top of the lava dome. It is accompanied by a flute-like sound. Its spectral features and the correlation with field observations are consistent with a model generation indicating that a crack or set of cracks are excited to resonance by the release and flow of gas through the lava dome. Spasmodic tremor is composed of several distinct LP-like events joined together by a continuous signal with lower amplitudes. Two types of spasmodic tremor may be distinguished on the basis of their spectral characteristics and field observations. Spasmodic tremor type I is apparently dominated by a mix of *P*, *SH* and Rayleigh waves as determined from preliminary polarization analysis. The source appears to be located, in a region west of the active crater. As a first approximation, Spasmodic tremor type I could be associated with magmatic intrusion process occurred in 1989-1991.

Key words *Galeras volcano – harmonic tremor – spasmodic tremor – degassing activity – resonance – crack*

1. Introduction

The seismicity accompanying the reactivation process of Galeras volcano first observed in 1988 as well as that associated with the emplacement, extrusion and destruction of the lava dome in 1992, was dominated by a mixture of tremor and Long-Period events (LP) displaying a variety of waveforms. Distinct types of tremor observed on Galeras lasted from a few minutes up to several hours. They can be classified into two main types, namely sustained and spasmodic. The former represents a continuous signal with amplitudes and frequencies that remain stable through time. The latter consists of several distinct LP-like events joined together by a continuous signal with lower amplitudes (Gil-Cruz and Chouet, 1997). Sustained tremor can be also subdivided into different types depending on the spectral characteristics, signal duration and field observations of concurrent activity at the crater. One unusual tremor form, Flute tremor, was accompanied by degassing activity through the lava dome in November, 1991. Spasmodic tremor was associated with explosive and degassing activity. It may be separated into two types according to its spectral features and the field observations. This paper will describe these types of tremor and preliminary analysis of some samples of the Flute and Spasmodic tremors observed in the period 1989-1991.

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2. Data and processing

During the period 1989-1991 the Galeras seismic network was modified several times. The most stable configuration consisted of four or five stations equipped with Mark Products L-4C, 1 Hz, vertical seismometers and Sprengnether MEQ-800 recorders and one station equipped with a Benioff vertical seismometer with natural period of 1 s. The MDETECT and XDETECT programs, with a digitizing rate of 100 samples per second, were used for real-time data acquisition and recording (Tottingham and Lee, 1989; Rogers, 1993). From May 1989 until March 1990, a three-component station consisted of three individual seismometers was operating at the same site as the Benioff seismometer. This station had two horizontal Ranger SS-2 and one vertical L-4C seismometers with natural frequency of 1 Hz. In addition, for several months in 1990 three temporary digital three-component stations composed by Sprengnether L-4A seismometers with natural frequency of 2 Hz and DS-302 Terra recorders with digitizing rate of 100 samples, augmented the network. Figure 1 displays the configuration of this network. Spectra of tremor signals were obtained by using the amplitude spectrum algorithm from the program DADISP. The tremor amplitude was quantified using the reduced displacement calculated for Rayleigh waves using the expression (Fehler, 1983)

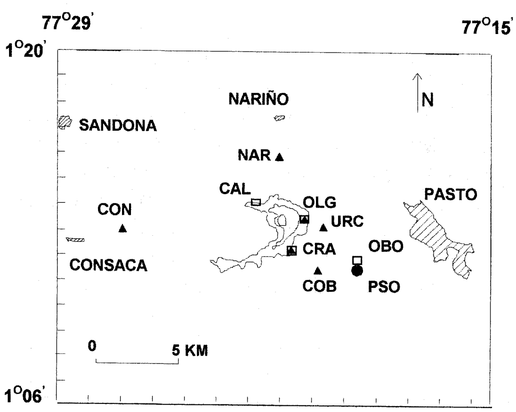


Fig. 1. Map of Galeras showing the seismic network operating on the volcano during 1989-1991. The solid triangles are telemetered vertical component stations operated by INGEOMINAS, filled circle is a station equipped with a Benniof seismometer, while squares denote the temporary three-component stations. The city of Pasto is located 8 km east of the active crater.

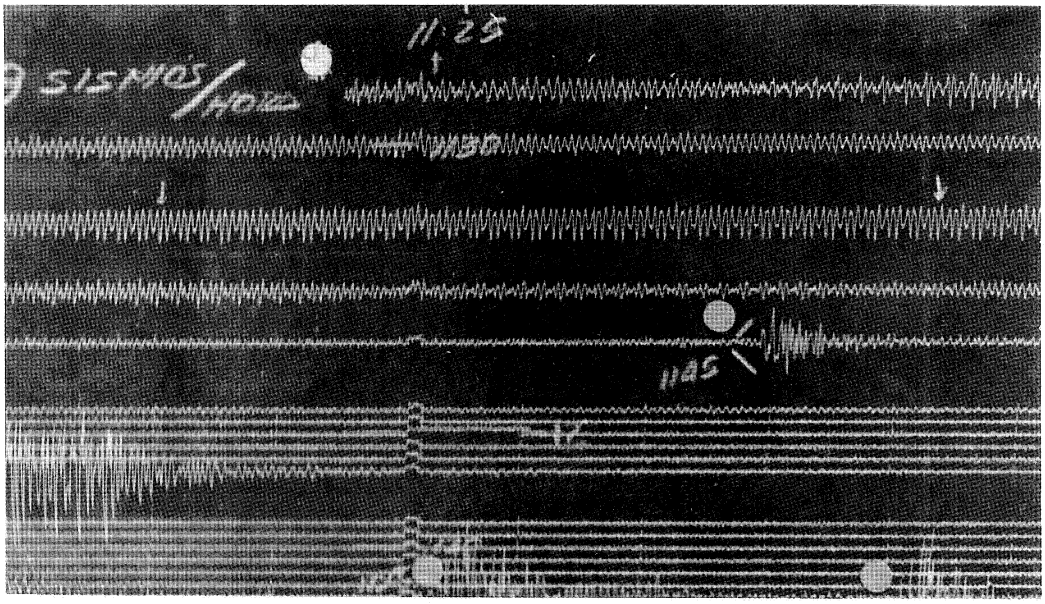
$$\mathrm{RMS}(u)\cdot\sqrt{\Lambda\, r} = \frac{A\sqrt{\Lambda\, r}}{2\sqrt{2G}} \tag{2.1}$$

where G is the instrument magnification, A is the peak-to-peak amplitude of Rayleigh waves, Λ is the wavelength and r is the epicentral distance between the station and the source of the seismic signal. All times referred to in the text are Local Time (LT).

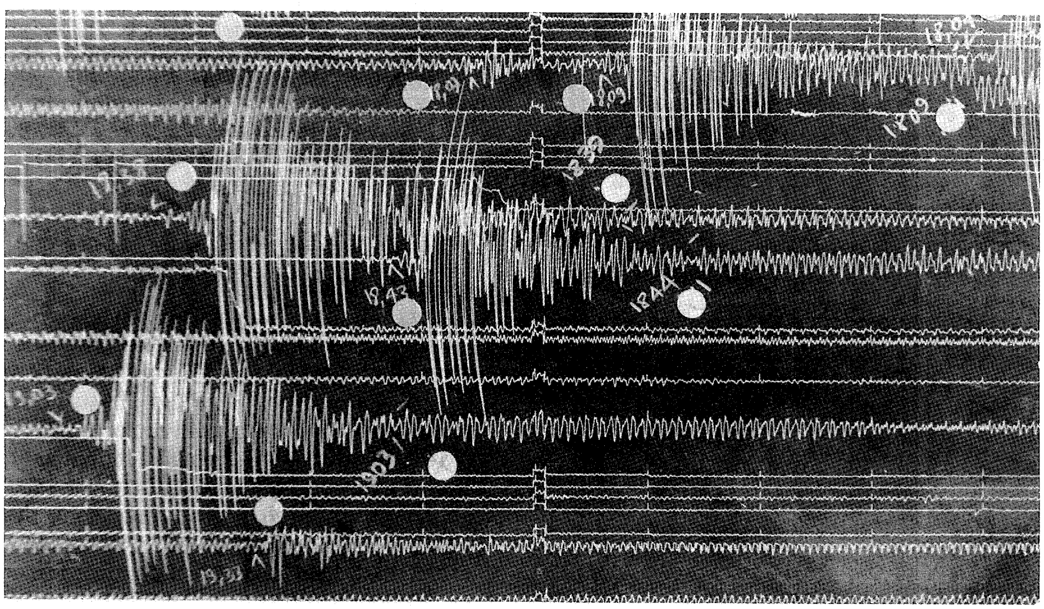
3. Flute tremor

3.1. *Field observations and general characteristics*

The most conspicuous occurrence of Flute tremor was associated with strong, explosive degassing activity just before and after the extrusion of the lava dome (August-November, 1991). On November 11 and November 20, 1991 intermittent emissions of gases were observed which were accompanied by a flute-like sound (hence its name). These emissions were occurred at times during which Flute tremor was recorded on the seismic network (fig. 2a,b). Gas emissions were observed to originate from two small joined vents located at the top of the lava dome (Gil Cruz and Chouet, 1997). The vents were 1-5 m long and a few centimeters wide. Released gases were essentially free of contamination with ashes and flowed fairly steadily. At the same time, strong, explosive, degassing activity from another crack on the surface of the lava dome was associated with the occurrence of LP events. This crack was about 120-150 m long and its estimated width was of the order of few centimeters (Gil Cruz and Chouet, 1997). Although correlation with field observations were possible only on November 11 and 20, similar waveforms and spectra of tremor signals recorded in other dates, imply that they share



(a)



(b)

Fig. 2a,b. a) Portion of a seismogram obtained at station CRA on November 7, 1991 which shows an individual short-duration episode of Flute tremor recorded between 11:25 and 11:44. The stability of the signal is noticeable. b) Seismogram obtained at station CRA which clearly displays three LP events each triggering a short episode of Flute tremor recorded at 18:38, 18:43 and 18:59 on October 29, 1991.

similar source. The reduced displacement calculated for Flute tremor recorded between August and November 1991 using eq. (2.1) ranged from 1-5 cm^2. It is therefore smaller than that of LP events during the same period, which reached values up to 110 cm^2 (Gil Cruz and Chouet, 1997). Tremor occurred as individual short episodes with durations ranging from 1-60 min. In some cases it was triggered by a LP event (fig. 2a,b).

3.2. *Spectral features*

The most remarkable characteristic of Flute tremor is its spectrum which has a clear pattern of regularly-spaced sharp peaks between 0.5-6 Hz (fig. 3). In some cases the peaks extended up to 10 Hz. Although their amplitudes differed from station to station, most of the peaks shared common frequencies. Thus they

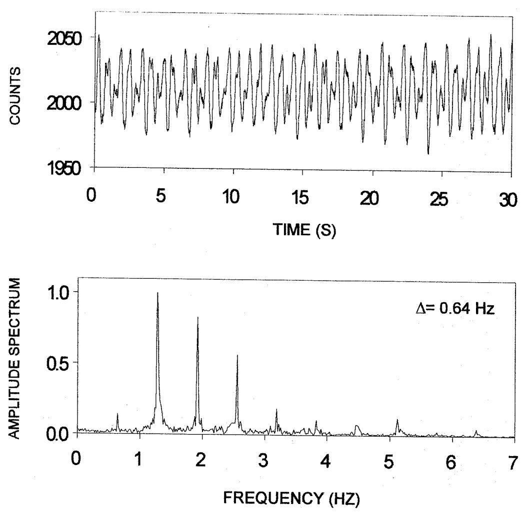


Fig. 3. A thirty-second sample of a digital seismogram from an event of Flute tremor recorded at station CRA on November 11 at 07:25 and its normalized amplitude spectrum. This tremor event was directly correlated with visual observations in the crater of degassing activity at the top of the lava dome. The spectrum shows ten regularly spaced peaks separated by 0.64 Hz.

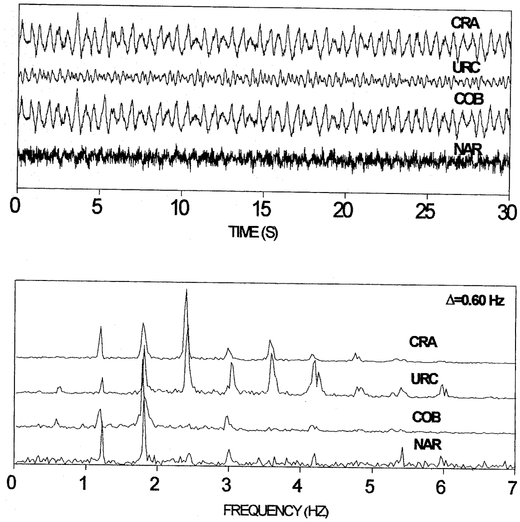


Fig. 4. The upper part displays thirty seconds of seismogram from stations CRA, URC, COB and NAR recording Flute tremor which occurred on November 7 at 11:38 local time. The amplitude has not been corrected for instrumental response. The lower part of the figure shows the normalized amplitude spectrum for each trace. Note that the dominant frequency is not the same at each of the four stations; CRA and URC have a coincident dominant peak of 2.39 Hz, while the COB and NAR peaks are at 1.80 Hz.

reflect a source effect rather than path or site effects (fig. 4). It was possible to observe up to 14 peaks coinciding within ± 0.05 Hz in at least three stations (table I). The typical peak spacing, Δ, varied from 0.55-0.94 Hz (table II). In some cases, the interval between peaks increased slowly (or gradually) during an individual Flute tremor episode. Apparently, there is a relationship between the changes in Δ and some threshold in signal amplitude, while there is not clear effect on it, from changes in dominant frequency. Although sometimes the dominant spectral peak was the same at all stations, the most common case was that it changed from one station to another (fig. 4). In addition, dominant spectral peak at a single station, also changed with time, apparently without any clear correlation with other parameters (table II). While the spec-

Table I. Frequencies of spectral peaks common (within ± 0.05 Hz) to at least three stations for typical tremor events recorded on October 29 and November 11, 1991. Bold numbers identified the dominant peak in each spectrum. Also is shown the regular spacing between peaks denoted by Δ.

Pear number	October 29 at 18:41				November 11 at 7:25			
	CRA	Δ	COB	URC	CRA	Δ	COB	URC
1	0.64		0.67	0.67	0.63		0.63	0.63
		0.67				0.64		
2	**1.31**		1.31	1.31	**1.27**		1.27	1.27
		0.67				0.65		
3	1.98		**1.98**	1.98	1.92		**1.92**	**1.92**
		0.67				0.64		
4	2.65		2.62	2.62	2.56		2.56	2.56
		0.64				0.63		
5	3.29		3.29	**3.29**	3.19		–	3.19
		0.67				0.63		
6	3.96		3.96	3.96	3.82		3.82	3.82
		0.64				0.66		
7	4.60		4.60	4.63	4.48		4.48	4.48
		0.67				0.63		
8	5.27		5.27	5.27	5.11		5.11	5.09
		0.67				0.64		
9	5.94		5.94	5.94	5.75		5.75	5.75
		0.64				0.63		
10	6.58		6.58	6.56	6.38		6.38	–
		0.67						
11	7.25		7.25	7.25				
		0.65						
12	7.90		7.90	7.90				
		0.67						
13	8.57		8.57	8.57				
		0.67						
14	9.24		9.24	9.24				

tra of Flute tremor initiated by a LP event does not differ from those of «independent» episodes, their spectra are clearly different from those of the initiating LP events (fig. 5).

4. Spasmodic tremor

Spasmodic tremor consists of several distinct LP-like events joined together by a continuous signal with lower amplitudes. It occurred during the reactivation of Galeras volcano starting in 1989 and during the emplacement and extrusion of a lava dome in 1991. Spasmodic tremor is divided into two types, based on its spectral characteristics and field observations.

4.1. *Type I*

Type I has a broadband multipeaked spectrum between 0.7 and 7 Hz with dominant peaks at frequencies between 3-5 Hz (fig. 6). Episodes last from 1 to 4 min, and reduced displacement

Table II. Some spectral characteristics for 25 samples of Flute tremor recorded between August and November, 1991 at station CRA. *F* denotes the dominant frequency, Δ the regular spacing between peaks, *df* is the bandwidth measured at a half of the amplitude of the maximum spectral peak and *Q* is the quality factor of the resonator. Dominant frequencies ranged between 0.83 and 2.52 Hz.

Tremor event		*F* (HZ)	Δ (Hz)	*df* (Hz)	*Q*
August 24	22:26	1.56	0.77	0.06	22
October 29	18:22	1.56	0.77	0.02	52
October 29	18:41	1.31	0.66	0.04	33
October 29	20:28	1.45	0.74	0.09	16
October 29	23:53	1.46	0.69	0.02	73
October 30	07:09	1.65	0.83	0.06	28
October 30	07:14	2.47	0.82	0.04	62
October 30	07:16	0.83	0.82	0.02	42
October 30	08:10	1.97	0.66	0.03	66
October 30	14:59	0.94	0.94	0.02	47
October 30	18:05	1.31	0.65	0.04	33
November 07	11:25	1.11	0.55	0.05	22
November 07	11:26	1.65	0.55	0.05	33
November 07	11:27	1.68	0.57	0.03	56
November 07	11:31	2.29	0.57	0.03	76
November 07	11:32	1.74	0.58	0.04	44
November 07	11:36	1.81	0.60	0.05	36
November 07	11:38	2.39	0.60	0.06	40
November 07	11:42	1.90	0.63	0.04	48
November 07	11:44	1.34	0.68	0.03	45
November 11	07:24	1.27	0.63	0.02	64
November 11	07:25	1.27	0.64	0.04	32
November 11	07:29	2.52	0.63	0.03	84
November 11	07:31	1.27	0.65	0.04	32
November 11	07:34	1.31	0.65	0.03	44

calculated using eq. (2.1) reached values up to 30 cm^2. Type I Spasmodic tremor was recorded during intervals when observations at the crater show that noise intensity and mass flux of gases emitted by the main crater increased. Typically, the emissions occurred 10-13 min, after the onset of Spasmodic tremor, and showed a weak character estimated from the gas and ashes released. Sometimes, there was no clear correlation with surficial activity (Gil Cruz and Chouet, 1997).

4.2. *Type II*

Type II Spasmodic tremor has a narrower spectrum than type I. Its dominant peaks are at frequencies between 1-2 Hz, and the main portion of the energy is concentrated in a band between 0.8 and 4.5 Hz (fig. 7). Like type I, episodes ranged in duration from 1 to 4 min. On the other hand, reduced displacement calculated using eq. (2.1) were higher than for type I, with

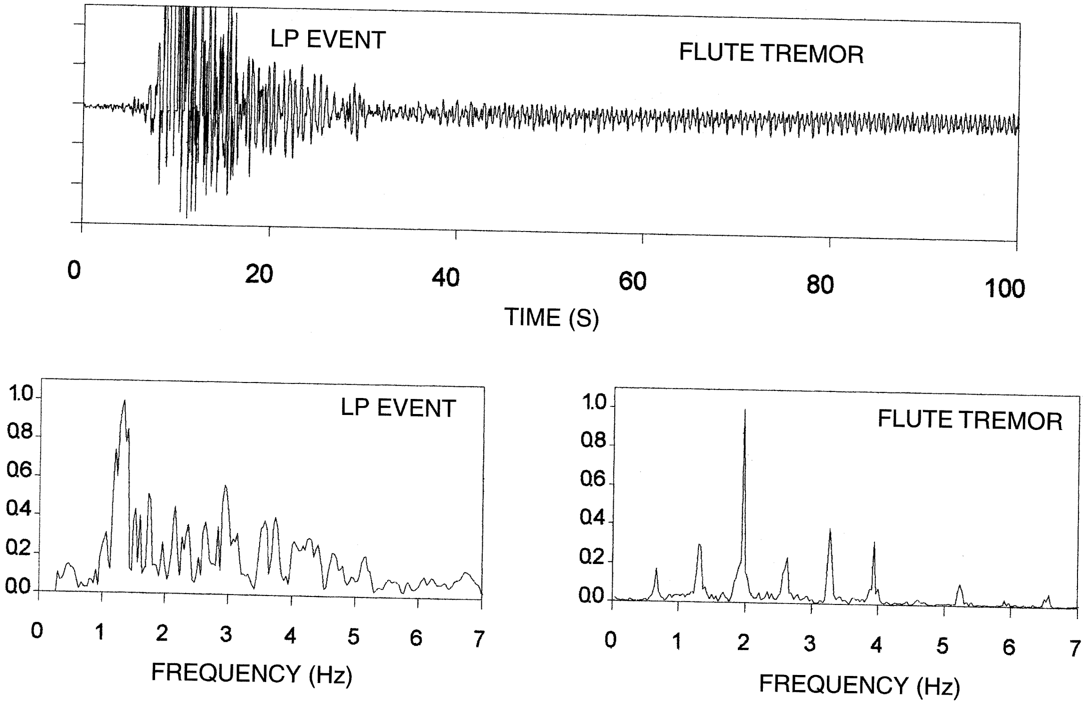
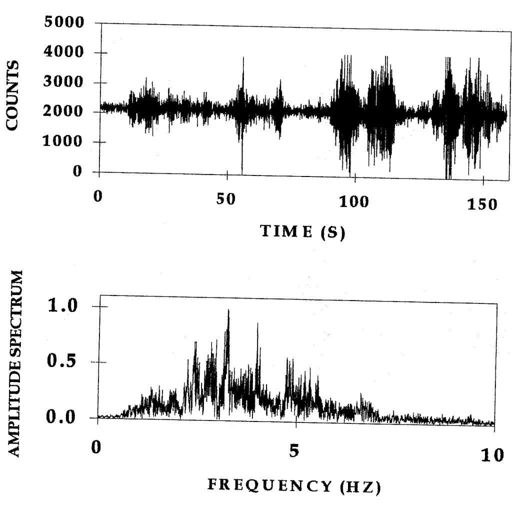


Fig. 5. Comparison between the spectrum of a LP event that triggered an episode of Flute tremor, and the Flute tremor's spectrum. Above is 100 s of the signal recorded at station CRA on October 29 at 18:59, which shows the LP event and the subsequent tremor. The LP signal is artificially saturated in order to observe the tremor more clearly. Lower part of the figure displays the corresponding normalized amplitude spectra which clearly show the difference between the randomly peaked LP event with dominance of 1.33 Hz, and the Flute tremor with the dominant frequency of 2 Hz and a very harmonic character.



values reaching 45 cm². This tremor is clearly correlated with observations of explosion and ash emissions, usually following the onset of the seismic signal by a few seconds. The ash columns of these emissions produced rose 1-1.5 km above the crater, and were clearly visible from Pasto (fig. 8). From the early 1991 until the lava dome extrusion occurred in October 1991, this tremor evolved toward episodes of more continuous tremor with a quasi-monochromatic dominant frequency of 1-2 Hz.

Fig. 6. Seismogram (top) from a typical Spasmodic tremor type I recorded at station CRA on July 15, 1989 at 01:54 and its normalized amplitude spectrum (bottom).

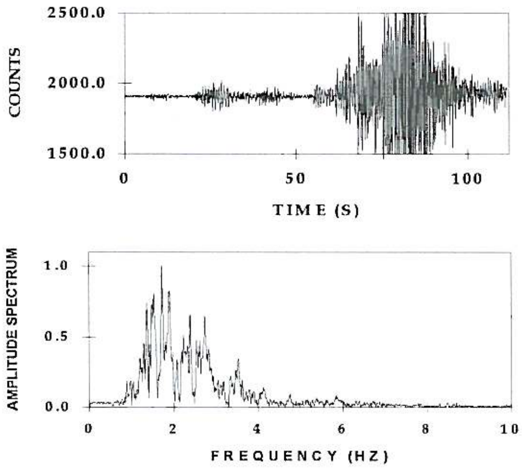


Fig. 7. Seismogram (top) from a typical Spasmodic tremor type II recorded at station CRA on December 4, 1990 at 07:19 and its normalized amplitude spectrum (bottom). The signal is artificially saturated in order to emphasize the complete envelope of the tremor.

4.3. *Polarization analysis*

Polarization analysis was performed on an interval of type I Spasmodic tremor. The signal recorded at 1:59 on July 15, 1989 at OBO station located 5.3 km SE of the crater (fig. 1). It has a duration of 160 s with higher amplitudes on the vertical component than on the horizontals. Spectra of the three components show many sharp peaks. The dominant frequencies for V, N and E components are 3.25 Hz, 3.21 Hz and 3.26 Hz, respectively (fig. 9). With an uncertainty of + 0.03 Hz the dominant frequency is the same for the three components. Thus, the polarization of the peak at 3.26 Hz was analyzed. The complete signal was filtered using a Butterworth bandpass filter in a narrow band of $B = 0.16$ Hz around this spectral peak. Particle motion was analyzed at intervals of time t_a equal to coherence time $t_c = \frac{1}{\pi B} = 2\,\mathrm{s}$ defined in

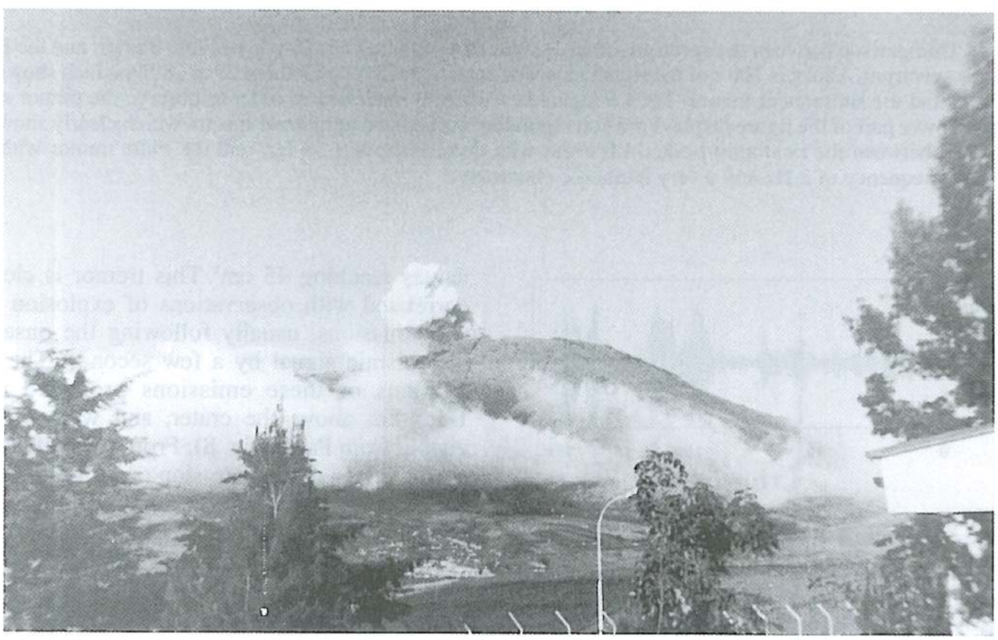


Fig. 8. Ash emission which occurred at 07:19 on December 4, 1990, observed from the city of Pasto. It was associated with the signal of Spasmodic tremor type II shown in fig. 7. The explosive column reached 1.5 km height. (Photo by Observatorio Vulcanológico y Sismológico de Pasto).

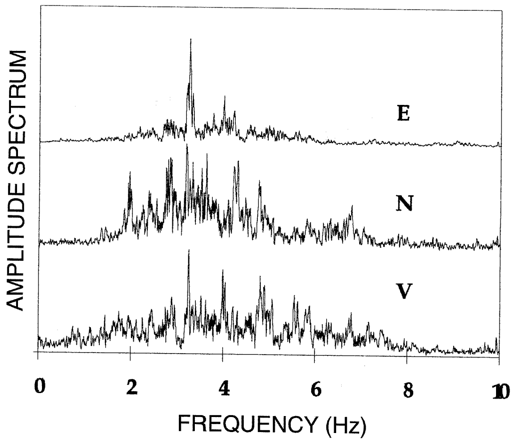


Fig. 9. Three component amplitude spectra for a Spasmodic tremor recorded at 01 :59 on July 15, 1989 at OBO station. Each spectrum was normalized to its maximum amplitude, averaged and smoothed. Although the spectra showed a multipeaked character, the maximum peak is coincident in the three components.

Seidl and Hellweg (1991) in order to determine statistically independent polarization ellipsoids. Polarization ellipses were determined for the planes of the wave- coordinate system: L-T (Longitudinal, Transverse), L-Q (Q perpendicular to L and T) and Q-T (Hellweg, 1997). The seismograms were rotated from the seismometer-coordinate system. At the same time, because the three seismometers of the station OBO are independent of each other, the results were checked by varying the phase between them by a value of ± 0.1 s. This produced no relevant differences in the various particle motion diagrams. For a more detailed polarization analysis, four seismograms portions representing quasi-individual events were chosen using the envelope of the signal. There is no clearly dominant type of wave. Apparently, the spectrum is produced by a mixture of *P*, Rayleigh and *SH* waves (fig. 10a-e). The variations in the orientation and ellipticity of the horizontal and vertical particle motion imply that the apparent azimuth and incidence angle change as a function of time. Although azimuths were sometimes directed toward almost north and west, most particle motion corresponds to 290-315° (fig. 10a-e). In order to check this possible source position, a portion of another type I Spasmodic tremor event, recorded at station CAL at 19:40 on November 1, 1990, was analyzed. The results suggest a source in the direction 150-180° from N. This direction pointed toward a common zone delimited by azimuth determined at OBO (fig. 11).

5. Discussion

5.1. *Flute tremor*

Harmonic tremor, characterized by a spectrum with equally-spaced peaks, has been observed at several volcanoes such as Lascar (Hellweg, 1997), Arenal (Benoit *et al.*, 1995), Langila and Tokachi (Herman, 1990), and Sakurajima volcanoes (Kamo *et al.*, 1977). This tremor appear to be related to the resonance of a 1D conduit within the volcano such as a cylindrical or spherical body excited by fluid flow instabilities. At Galeras volcano, the possibility of making direct visual and acoustic observations at the crater provided a useful tool for interpreting the source of this kind of tremor. These observations show that fluid involved in generation of Flute tremor is a single-phase fluid composed of superheated gas with very little contamination. On the other hand, the length and width of the vents from which the release of gases was observed, namely $W \approx$ 1-5 m and $d \approx$ few cm, suggest the resonance of a crack with a very small width to length ratio. In this case a lateral mode of resonance is not relevant in the spectrum, mimicing the behaviour of 1D resonator. The lack of symmetry of spectral characteristics observed must reflect asymmetric conditions at the source. In general, there are three main characteristics to consider with respect to asymmetric conditions: 1) the differences of the dominant spectral frequency at different stations for a single episode; 2) the change in dominant frequency with time at a single station, and 3) changes in the spacing frequency Δ of the spectral peaks for different episodes. While a source with symmetrical geometry such as a cylinder or sphere must radiate the same domi-

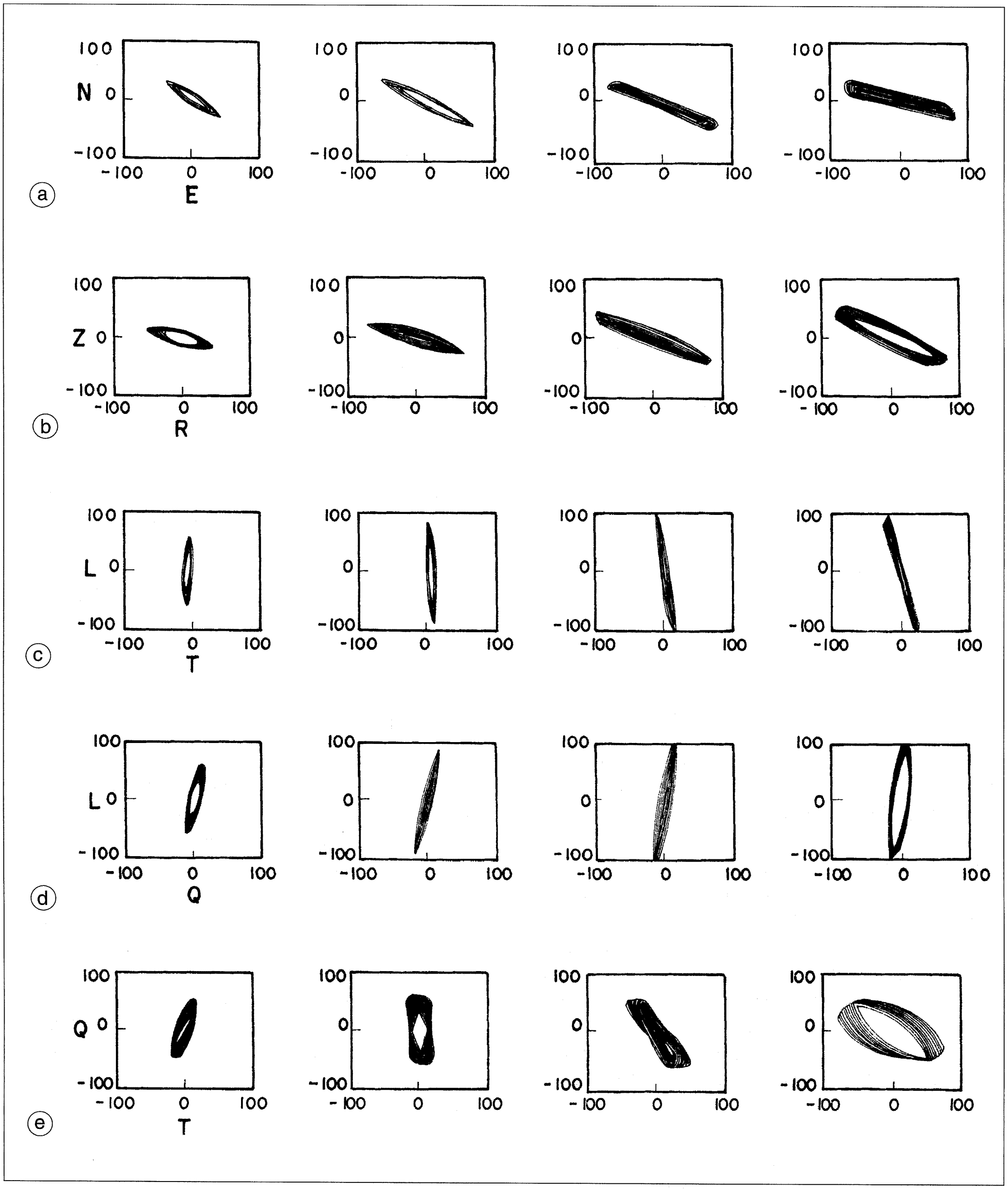


Fig. 10a-e. Examples of the results obtained from polarization analysis of the third portion of Spasmodic tremor signal recorded at 01:59 on July 15, 1989 at OBO station. Each diagram is separated by two seconds. a) Apparent azimuth varies between 290° and 315°; b) variations in apparent incidence angle show a general stability around 125°; c), d) and e) display the particle motion in planes LT, LQ and QT respectively, showing that motion is predominantly longitudinal but is accompanied by transverse and normal components.

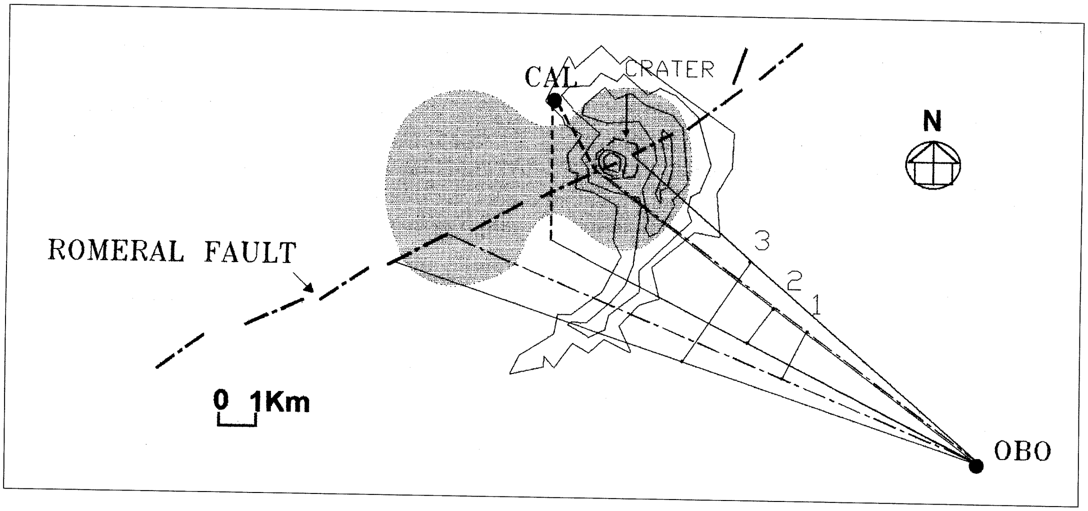


Fig. 11. Possible source of Spasmodic tremor type I determined from the direction of the apparent azimuths obtained from polarization analysis of signals recorded at OBO station at 01:54 on July 15, 1989, as well as from the signal recorded at CAL station at 19:40 on November 1, 1990. The ranges of azimuths displayed for station OBO have been calculated for three segments of the entire seismogram and are represented by numbers 1, 2 and 3. These directions show that the source of waves is a region west of the active crater. This zone is coincident with directions of azimuths obtained at CAL station for the other tremor sample mentioned above (dotted lines). The inferred trace of the Romeral fault is also shown, along with the main sources of VT earthquakes during the period 1989-1991 (shaded area).

nant frequency in all directions, radiation properties of a resonant crack could explain the differences in the dominant frequency at different stations. The change in the dominant frequency at a single station can be caused by changes in the source dimensions and physical properties of the fluid involved in tremor generating system, changes in position and area of the applied pressure pulse which produces the resonance of the crack, as well as the time history of the applied pressure (Chouet, 1986, 1988, 1992). Finally, changes in spacing frequency Δ must reflect changes in the source dimensions as well as changes in physical properties of the fluid and solid. The occasional connection between Flute tremor and LP events (which were associated with explosive activity through a crack) suggests that the region of gas release which generates these two signals may be the same. Thus the length of the vents where tremor is generated must have the same order of magnitude as the crack associated with LP events, which Gil Cruz and Chouet (1997) calculated to be 270-390 m. Thus, at this time a crack or a set of cracks excited into resonance by gas release seem to be the system responsible for generating the Flute tremor.

Values of $Q = \frac{f}{df}$ (Aki and Richards, 1980), where f is the dominant frequency and df is the bandwidth at half of the maximum spectral amplitude ranged from 16-84, with a mean value of 45 (table II) as is expected for a source involving high impedance contrast (Chouet, 1992) as is the observed case.

5.2. *Spasmodic tremor*

Gil-Cruz and Chouet (1997) demonstrate a correlation between the occurrence of Spasmodic tremor type I and Volcano-Tectonic (VT) earthquake activity and SO_2 emission measured by

Cospec, as well as that obtained from direct gas sampling of fumaroles. This, along the time shift observed between the onset of this type of tremor and the visually observed beginning of shallow activity, implies that this tremor may be related to a deeper intrusion process. On the other hand, the immediate relationship of the onset of tremor type II with explosive activity implies it has a shallower origin. The daily occurrence of Spasmodic tremor events was marked by a predominance of type I over type II during the period of March 1989 to February 1990. By late 1989 type II events begin to occur more frequently and gradually grew in number until they exceeded the number of type I Spasmodic tremor episodes as can be seen in fig. 12. Just before lava dome extrusion began, type I Spasmodic tremor episodes diminished considerably. Thus, as the magma body was rising, the character of the Spasmodic tremor changed from type I to type II. The apparent source, deduced from the polarization of Spasmodic tremor type I, is located in a region to the west of the crater (fig. 11), coincident with the primary location of VT earthquakes which occurred in 1989-1991 (Gómez and Torres, 1993). This source is assumed to be related to a magmatic reservoir (Gil Cruz and Chouet, 1997; Calvache, 1990). Thus, this appears to confirm the relationship between Spasmodic tremor type I and the deeper magmatic system. It is also interesting to note that the possible source area is located near the inferred crossing of the Romeral fault trace with the edifice of Galeras. Variations with time in the apparent azimuth calculated for Spasmodic tremor type I may indicate that this tremor is generated by a moving, or extended source or by several point sources within an area bounded by the extreme values of azimuth. Figure 11 shows the range of azimuths calculated for three segments of signal. The azimuths which are far from the crater region may be associated with scattering and reflection phenomena. Gil Cruz and Chouet (1997) associated Spasmodic tremor type I with gas transport within the volcano, characterized by a high impedance flow in order to explain the time delay between the signal and the degassing activity. Calvache (1995) pointed out that a magma mixing process took place during the early lava dome emplacement. This

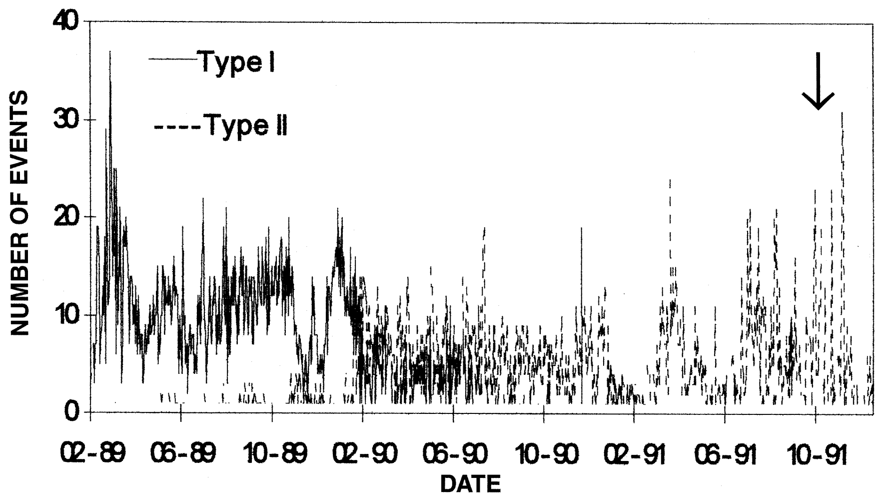


Fig. 12. Plot illustrating the daily occurrence of the two types of Spasmodic tremor during the period of March 1989 through December 1991. Type I dominated in the beginning of the reactivation, while type II dominated in the later phase. Occurrence of type II reached its maximum while the lava dome was being extruded. Date of the lava dome extrusion is indicated by an arrow.

fact, together with the weak nature of the shallow activity (represented by a small volume of visible gas) related with type I Spasmodic tremor, as well as its high values of reduced displacement indicating high pressures involved in the source, may also support the hypothesis that the source of type I Spasmodic tremor may be the movement of new batches of hotter magma within the conduit filled with older magma.

6. Concluding remarks

The source of Flute tremor recorded at Galeras volcano in August-November, 1991 may be the resonance of a crack or of a set of cracks with very small width and thick but that their length is of the same order of magnitude as that calculated for LP events generation system. To confirm this, we must calculate signals for a model using the appropriate dimensions and physical parameters. Release and flow of gas through the lava dome body toward the surface provide the excitation of such a crack. The lack of symmetry radiation for the dominant spectral peaks must reflect a lack of symmetry in the characteristics of the source.

A possible source location for Spasmodic tremor type I is a region west of the active crater. Its origin may be associated with the magmatic intrusion process which occurred in 1989-1991.

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REFERENCES

AKI, K. and P.G. RICHARDS (1980): *Quantitative Seismology: Theory and Methods* (W.H. Freeman and Co., New York), vol. 1, pp. 560.

BENOIT, J.P., S.R. MCNUTT, W. MELSON, V. BARBOZA and J. BARQUERO (1995): Spectral and polarization analysis of broadband recordings of volcanic tremor at Arenal volcanoi, Costa Rica, *Eos, Trans. Am. Geophys. Un.*, **76** (46), 349-350.

CALVACHE, M.L. (1990): Geology and volcanology of the recent evolution of the Galeras volcano, Colombia, *M.S. Thesis*, Louisiana State University, Baton Rouge, LA, pp. 171.

CALVACHE, M.L. (1995): The geological evolution of Galeras volcanic complex, *Ph.D. Thesis,* Arizona State University, pp. 180.

CHOUET, B. (1986): Dynamics of a fluid-driven crack in three dimensions by the finite difference method, *J. Geophys. Res.*, **91,** 13967-13992.

CHOUET, B. (1988): Resonance of a fluid-driven crack: radiation properties and implications for the source of long-period events and harmonic tremor, *J. Geophys. Res.*, **93,** 4373-4400.

CHOUET, B. (1992): A seismic model for the source of long-period events and harmonic tremor, in *Volcanic Seismology*, edited by P. GASPARINI, R. SCARPA and K. AKI, *IAVCEI Proc. Volcanol.*, **3**, 133-156.

FEHLER, M. (1983): Observations of volcanic tremor at Mount St. Helens volcano, *J. Geophys. Res.*, **88**, 3476-3484.

GIL CRUZ, F. and B. CHOUET (1997): Long-period events, the most characteristic seismicity accompanying the emplacement and extrusion of a lava dome in Galeras volcano, Colombia, in 1991, *J. Volcanol. Geotherm. Res.*, **77**, 121-158.

GÓMEZ , D. and R. TORRES (1993): Aspectos relevantes de la actividad del volcán Galeras desde 1991, y estudio de algunos parámetros cinemáticos de las fuentes sismogénicas de alta frecuencia (in Spanish), in *International Workshop on Galeras Volcanic Complex, Pasto Colombia, January 11-16, 1993*, pp. 20.

HELLWEG, M. (1999): Listening carefully: unique observations of harmonic tremor at Lascar volcano, Chile, *Ann. Geofis,* **42** (3), 451-464 (this volume).

HERMAN, P. (1990): Comparative study on volcanic harmonic tremor, *Report of the Individual Studies* (Volcanology Course), JICA.

KAMO, K., T. FURUZAWA and J. AKAMATSU (1977): Some natures of volcanic micro-tremors at the Sakurajima volcano, *Bull. Volcanol. Soc. Jpn.*, **22**, 41-58.

ROGERS, J.A. (1993): XDETECT version 3.17 Users Reference, *U.S. Geological Survey, Open-File Report* #OF93-XXX-A, Menlo Park, California, p. 12.

SEIDL, D. and M. HELLWEG (1991): Volcanic tremor recordings: polarization analysis, in *Volcanic Tremor and Magma Flow*, edited by R. SHICK and R. MUGIONO, KFA, 31-46.

TOTTINGHAM, D.M. and W.H.K. LEE (1989): User manual for XDETECT, in *Toolbox for Seismic Data Acquisition, Processing and Analysis*, edited by W.H.K. LEE, Int. Assoc. Seismol. Phys. Earth Inter., 85-113.