Unusual seismic signals associated with the activity at Galeras volcano, Colombia, from July 1992 to September 1994

Roberto A. Torres C., Diego M. Gómez M. and Lourdes Narváez M.
INGEOMINAS, Observatorio Vulcanológico y Sismológico, Unidad Operativa Pasto, Colombia

Abstract
After the emplacement of a lava dome at Galeras volcano in 1991, seven eruptions occurred from July 16, 1992, to September 23, 1994, six of which were preceded by quasi-monochromatic, long-duration seismic events with slowly decaying coda named «tornillos» (screws). The dominant frequencies of these unusual seismic signals are related to source characteristics and show temporal changes, diminishing and then tending to stabilize before an eruption. At the same time, the accumulated number and the duration of these signals increase several days prior to the eruption. The increase in the duration of the tornillo events and the decline of the dominant frequencies both suggest an increasing impedance contrast between the surrounding solid material and the fluid. These characteristics may be associated with an increase in the free gas phase in the magma produced by saturation of volatiles due to cooling, crystallization and partial solidification of the column of magma plugging the conduits. The solidified magma can contribute to sealing the conduits and preventing free gas escape, with consequent generation of overpressure. An eruption is initiated when the overpressure exceeds the resistance strength of the solid material.

Key words *Galeras – tornillo events – seismic signals – eruptions*

1. Introduction

Galeras is a 4270 m andesitic stratovolcano located in the southwest of Colombia, near the Ecuadorian frontier, at 1°14′N, 77°22′W (Hantke and Parodi, 1966; Simkin *et al.*, 1981). Its active cone is located 9 km to the west of Pasto, a city with 350000 inhabitants (fig. 1).

In 1991, after a request from the Geological Survey of Colombia (INGEOMINAS) and the National Disaster Prevention Office (DNPAD), Galeras was named a «Decade Volcano» by the IAVCEI as part of the United Nations' International Decade for Natural Disaster Reduction (IDNDR) program.

Since 1988, when Galeras showed first signs of renewed activity (Global Volcanism Network Bulletin, 1989; Williams *et al.*, 1990), eight eruptive episodes have been observed. Six of these eruptions, from July 16, 1992 to September 23, 1994, were preceded by an unusual seismic signal (table I, fig. 2a-c). The seismic activity during 1989-1990 was A-type and B-type events accompanied by tremor episodes (Minakami, 1974). By 1991, seismicity showed increases in B-type events, and a few tremor episodes were observed. Since 1992, the seismicity gradually decreased. However, on July 11, 1992, the unusual seismic signal appeared for the first time. In this paper, we show some characteristics of these signals, such as their duration, dominant frequency and temporal behavior prior to eruptions. Additionally, we formulate an hypothesis in order to explain the possible source of these signals and their relationship to the Galeras eruptions since 1992.

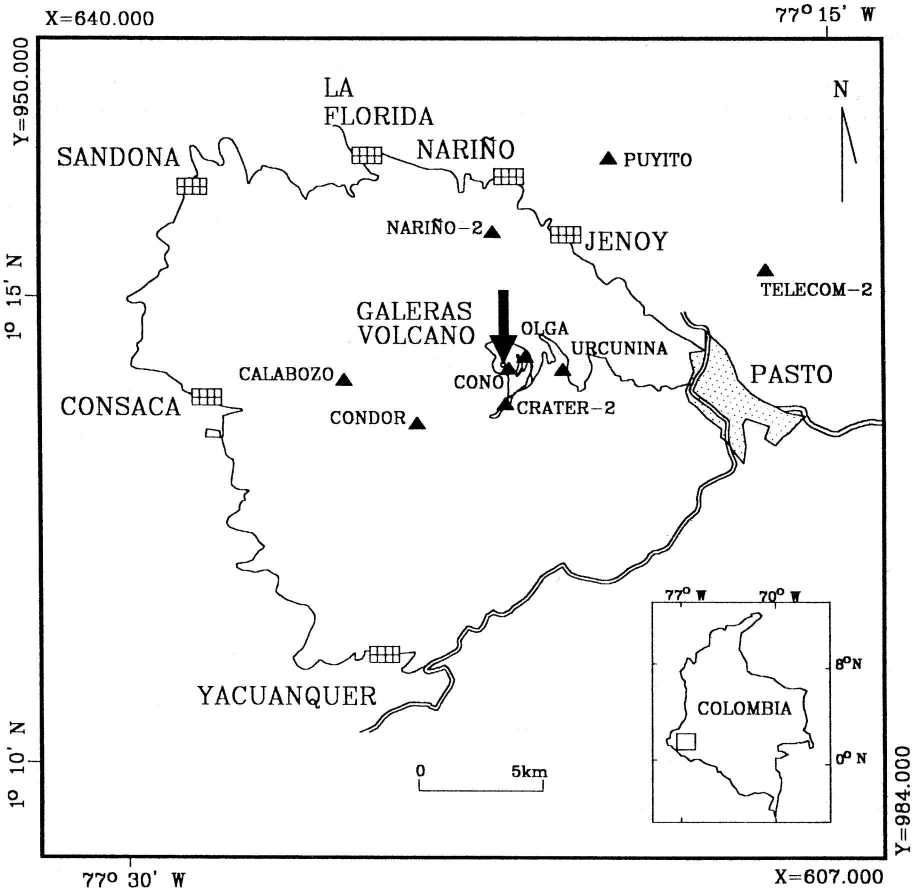

Fig. 1. Location of Galeras volcano and its telemetered seismic network. The stations are represented by triangles and the crater by an arrow. «Circunvalar» road connecting villages around Galeras, and the road from Pasto to the summit of the volcano are also represented.

2. Previous activity

At least six major eruptions of Galeras have been identified in the last 4500 years (4500, 4000, 2900, 2300, 1100 years before present and in 1886) (Calvache, 1990). These events are interpreted as Vulcanian-type eruptions, with small eruptive columns (less than 10 km in height) that produced small volume pyroclastic flow deposits, containing a high proportion of non-juvenile material, lava flow fragments and scoria clasts (Calvache and Williams, 1992). During the last 500 years the eruptions have been characterized by gas and ash emissions, small lava flows, and explosive eruptions producing pyroclastic flow deposits (Espinosa, 1988).

In 1988, after 52 years of rest, Galeras showed signs of activity (Espinosa, 1988) as shown by increased seismicity and by fumarole geochemistry (Williams *et al.*, 1990) with gas emissions in the inner crater which increased gradually over the following months until a moderate ash eruption occurred on May 5,

Table I. Relationship between «tornillo» events and eruptions at Galeras. The characteristics of the signals are calculated from the data of the Crater-2 station. Note the direct relationship between the accumulated number of events and the duration of the «tornillos» with the estimated volume of ejected material and eruptive column height. For the January 14, 1993 and September 23, 1994 eruptions it was not possible to estimate the volume of material emitted and the column height. The relative size of the eruptions has been estimated using the volume and eruptive column height. Refer to text for more information. (Table modified from Cortés and Calvache, 1993).

Date of eruption	Number of events	Days of record	Duration of events s		Ground velocity μm/s		Frequencies Hz	Volume emitted	Column height	Relative size of eruption
			Max	Aver	Max	Aver	Range	$\times 10^6$ m^3	km	
16/07/92	9	5	97	69	33	21	2.25-1.28	0.28	6	3th
14/01/93	20	16	200	75	55	23	1.22-0.90	–	–	?
23/03/93	74	37	185	80	40	19	2.63-2.20	0.835	8	2nd
13/04/93	6	3	67	44	8	5	1.43-1.20	0.22	6	4th
07/06/93	103	46	214	87	15	7	3.50-1.34	1.25	9	1st
23/09/94	31	25	180	67	22	6	3.23-2.40	–	–	?

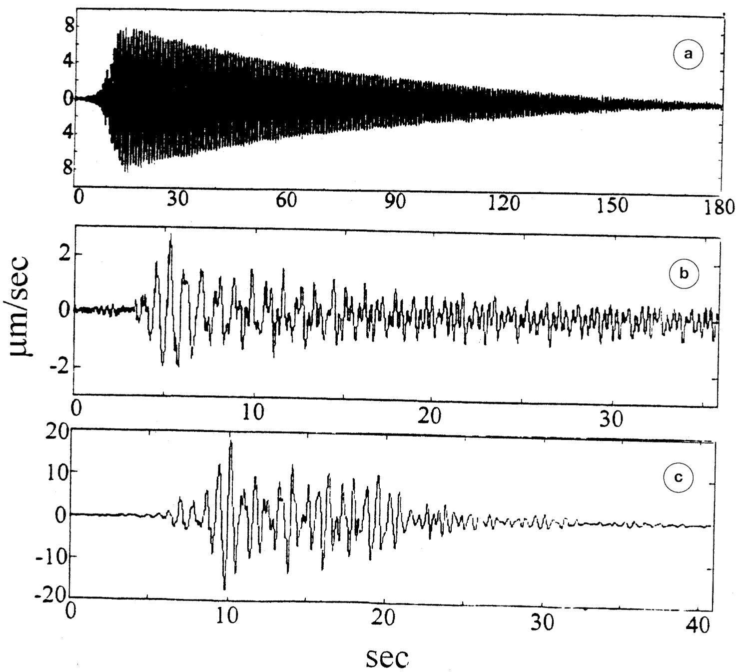

Fig. 2a-c. Examples of some seismic signals at Galeras recorded at Crater-2 station. a) «Tornillo» recorded on June 4, 1993. The duration of the signal is 206 s. Note the long duration compared to its amplitude (vertical ground velocity); b) «tornillo» observed on January 6, 1993. The duration of the signal is 53 s. This signal shows a domain of low frequencies on the onset; c) B-type event recorded after the March 23, 1993 eruption.

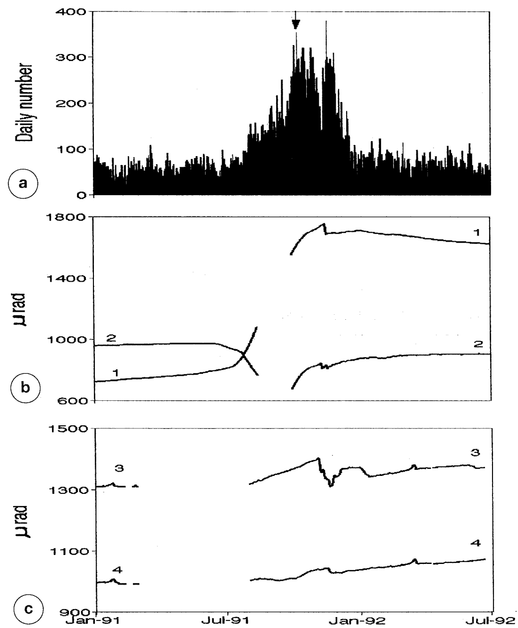

Fig. 3a-c. Some characteristics of Galeras activity from January 1991 to July 1992. a) Daily number of B-type events. The notable increase in the trend of seismicity beginning in June 1991 corresponds to the rise in magma associated with the emplacement of a lava dome, and the arrow indicates the date when the dome was observed for the first time. The following figures show the behavior of surface deformation according to two electronic tiltmeters located around the volcano; b) crater tiltmeter, with its two components tangential (1) and radial (2); c) Peladitos tiltmeter, with its components tangential (3) and radial (4). Note the positive correlation between seismicity and surface deformation and the subsequent emplacement of the lava dome.

1989 (Cepeda *et al.*, 1989). In 1990 the activity was characterized by fumarolic activity, incandescence, seismic events (A-type, B-type and tremor) and moderate ash emissions (Muñoz *et al.*, 1993). In this period, a relatively small explosive eruption occurred on August 2, 1990 (Zapata, 1993). As indicates fig. 3a-c, from June 1991 there was a significant increase in the B-type events accompanied by deformation at the volcanic surface (according to two electronic tiltmeters located at 0.9 and 1.6 km from the active crater). These observations were also accompanied by small amounts of ash and gas emissions. These processes were associated with the emplacement of a lava dome which was first seen in the crater in October 1991 (Gómez and Torres, 1993). Beginning in November 1991, a pronounced decrease in both the B-type events and ash emissions, together with no significant deformation of the volcanic edifice, was observed (fig. 3a-c). This situation ended with the violent eruption of July 16, 1992 which destroyed 90% of the lava dome (Gómez and Torres, 1993). The subsequent five eruptions on January 14, March 23, April 4, April 13, and June 7, 1993 were also sudden Vulcanian explosions laden with pyroclastic materials (ash and rocks) and accompanied by increased levels of gas emission (Cortés and Calvache, 1993; Stix *et al.*, 1993; Komorowski *et al.*, 1993). The January 14, 1993, eruption occurred during a field-trip related of the Galeras International Workshop and killed six scientists and three tourists and injured several others (Muñoz *et al*, 1993). The March 23, 1993, eruption altered the topography of the active cone with new craters and fumaroles, collapses, fissures, being formed (Ordoñez and Cepeda, 1993). Table I shows aspects like date, high of plume, or emitted volume for the eruptions registered from July 16, 1992 to September 23, 1994. Except for July 16, 1992, these eruptions were preceded by low levels of seismicity (less than 10 B-type events per day) and low amounts of gas emission (fig. 4a,b). Tremor episodes were recorded with small size amplitudes (vertical ground velocity), low dominant frequencies and durations from 3 to 30 min, immediately after all eruptions except that of April 4, 1993 (table II). After the tremor, a noticeable increase in the B-type events, accompanied by degassing processes, was observed for all eruptions except those of July 16, 1992, and April 4, 1993 (fig. 4a,b, table II). No immediate precursors prior to the eruptions were recorded, except the unusual seismic signals which are the subject of this report.

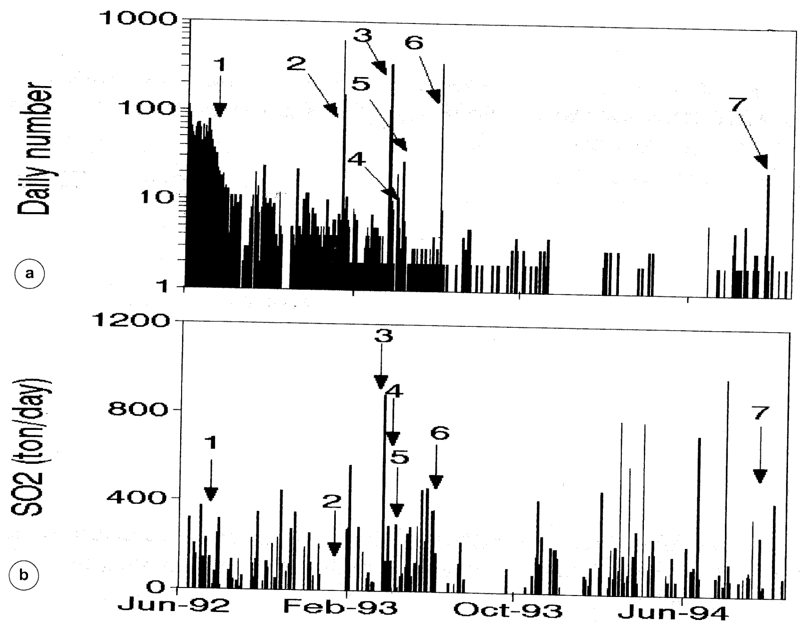

Fig. 4a,b. a) Daily number of B-type seismic events recorded at Galeras volcano from June 1992 to October 1994. Arrows indicate date of eruptions in the following order: (1) July 16, 1992; (2) January 14, 1993; (3) March 23, 1993; (4) April 4, 1993; (5) April 13, 1993; (6) June 7, 1993; and (7) September 23, 1994. In general, the eruptions were preceded by low levels of seismicity. Large peaks in seismicity occurred immediately after eruptions. b) SO_2 flux in metric tons per day, also showing with arrows and numbers the occurrence of eruptions in the order mentioned above. The SO_2 flux is measured using a correlation spectrometer (COSPEC). Except for the period prior to the September 23, 1994 eruption, the eruptions were preceded by low amounts of SO_2. After the eruptive events, SO_2 was generally observed to increase.

Table II. Some parameters related to the seismicity recorded after the Galeras eruptions, calculated at Crater-2 station. Tremor episodes did not occur subsequent to the April 4, 1993 eruption. On June 7, 1993 there were two eruptive episodes, the first beginning in early morning (03:42 local time) and the second occurring at night (21:37 local time). The time interval corresponds to the time the B-type events were recorded.

Eruption date	Post-eruptive B-type events		Post-eruptive tremor episodes		
	Number	Time interval h	Duration min	Range of dominant frequencies Hz	Range of ground velocity μm/s
16/07/92	3	0.5	7	1.3-3.3	8.0-53.0
14/01/93	761	24	4	1.6-3.6	4.0-21.8
23/03/93	440	25	11	1.2-5.0	1.5-46.7
04/04/93	19	8	–	–	–
13/04/93	7	3	27	1.2-3.3	0.6-33.1
07/06/93	354	17	17	1.3-6.7	19.0-46.8
	23	5	95	1.2-3.1	0.6-22.0
23/09/94	21	13	97	5.7-10.0	0.6-4.7

3. Data and processing

Since February 1989, the seismicity at Galeras has been monitored by eight telemetered stations with vertical component seismometers. The seismometers are Sprengnether 1-component, short period, model L-4C with a natural period of 1.0 s. Figure 1 shows the location of the permanent monitoring network in operation at Galeras, located at a distance from 0.9 km to 10 km from the crater. Figure 5 depicts the total instrumental responses for the stations discussed in this paper (sensitivity in counts/cm/s). The curves were constructed by connecting points obtained experimentally. The total damping is 0.72 of the critical one. The XDETECT program with a digitizing rate of 100 samples per second was used for real-time data acquisition and recording (Tottingham and Lee, 1989; Rogers, 1993). The spectrum was calculated over the entire seismogram using the FFT algorithm and used an instrumental response correction. Each spectrum represents a vertical component of ground velocity. The spectrograms have been calculated with moving windows of 2 s having an overlapping interval of 1 s running through the entire signal.

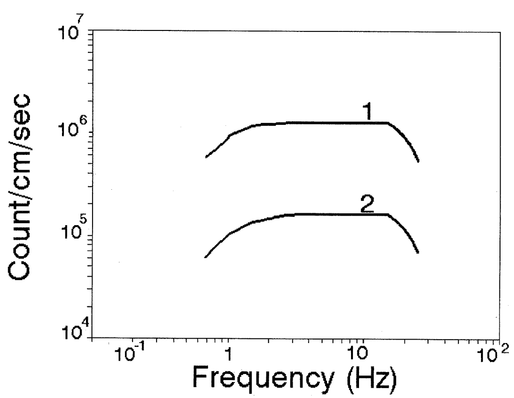

Fig. 5. Total instrumental response (sensitivity in counts/cm/s) for the digital stations used in calculations: (1) Crater-2 and (2) Olga. Experimental points are connected by straight lines.

4. «Tornillo» events

Unusual seismic events preceding the eruptions have been clearly observed mainly at seismic stations within 2 km from the active crater (fig. 1). After an eruption, these signals disappeared for several days to months (fig. 6a). These signals show a pattern like a «screw». These kinds of volcanic seismic events were thus named «tornillos» at the observatory, which is Spanish for screw.

The main features of tornillo signatures (fig. 2a,b) are:

– a long duration compared to its amplitude;

– a long, quasi-linear slowly decaying coda;

– a low frequency and monochromatic or quasi-monochromatic wave-form sometimes showing a weak high frequency onset of the signal superimposed on the low frequency.

Tornillo events at Galeras have showed durations from 25 to 214 s(*) with amplitudes from 0.6 to 55 μm/s evaluated at the Crater-2 station located 1.6 km from the active cone. For the tornillos analyzed, the dominant frequencies are between 0.9 and 3.5 Hz (table I, fig. 7a-f).

Figure 8a shows an example of a tornillo recorded on August 9, 1994, at Olga station located 0.9 km from the active cone; note the typical onset (fig. 8b), the stability of the dominant frequency during the entire signal (fig. 8c), and the monochromatic value of this event (fig. 8d).

The frequency analysis shows one or a few narrow peaks, with the same value at all stations where the signal was recorded (fig. 9a-l). At the stations near the crater, a peak of greater spectral amplitude, corresponding to higher frequencies, sometimes occurs. At stations more distant from the crater, these peaks diminish rapidly, and thus the peaks of the lowest frequencies stand out.

The main characteristics of tornillos have been the following: an increase in the daily number of the events and in the coda durations

(*) After writing this manuscript, we observed at December 7, 1994 a tornillo of 330 s duration.

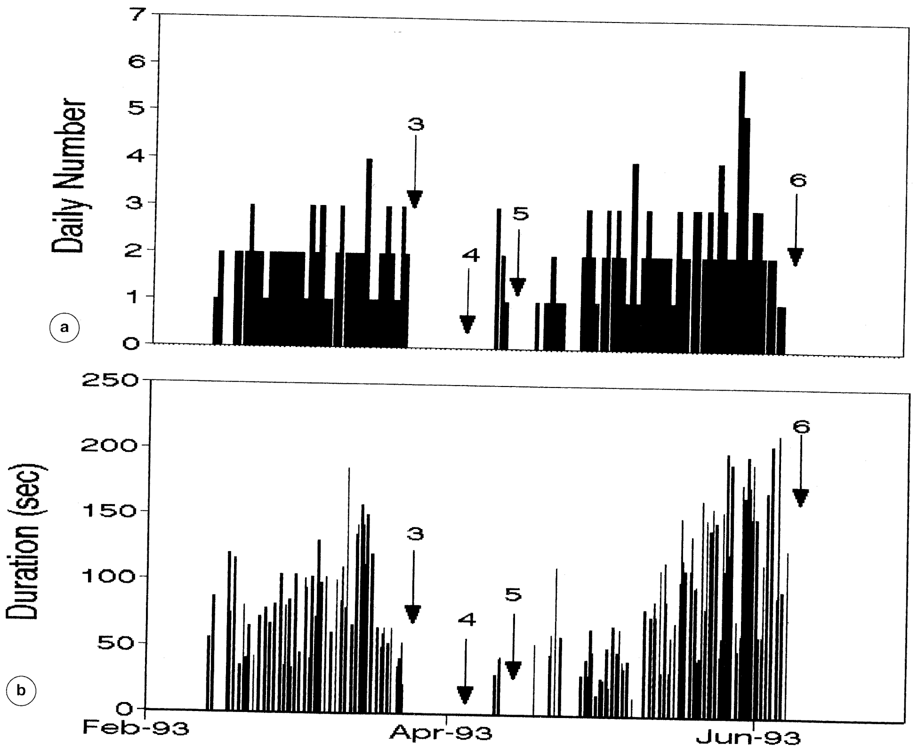

Fig. 6a,b. a) Daily number of tornillo events corresponding to the eruptions of March 23, 1993, April 13, 1993, and June 7, 1993 (arrows 3, 5, and 6 respectively). The eruption of April 4, 1993 (number 4) was not preceded by tornillos. Immediately after each eruption tornillo events disappeared. b) Individual durations of tornillos for the eruptions mentioned above. For each period, the durations tend to increase with time and decrease slightly a few days just before of the eruptions.

until they reach a maximum value prior to the eruption. In most cases the daily number and duration decrease slightly a few days just before the eruption (fig. 6a,b). Another remarkable characteristic observed has been the decrease of the dominant frequency before an eruption. In some cases, the dominant frequency tends to stabilize some days prior to an eruption (fig. 7a-f).

It should be noted that the eruption of April 4, 1993, was not preceded by this type of seismic event. Between July and November 1993, numerous tornillos were recorded, but no eruption followed. For these tornillos, no progressive increase in the duration of the signal was observed. This is in contrast to the tornillos preceding the eruptions from July 1992 to June 1993. Beginning August 9, 1994, a series of tornillos were recorded, ending by an eruption on September 23, 1994. This event was characterized mainly by a significant increase in the gas emission from the active crater.

Some direct relationships between the occurrence of tornillos and the volume of the subsequent eruptions have been established. The total number of tornillo events prior to an eruption correlates positively with the volume of material ejected during the eruption (table I, fig. 10a-c). In general, the larger volumes of ejected material were associated with longer average durations of tornillo events prior to the eruptions (table I, fig. 10a-c).

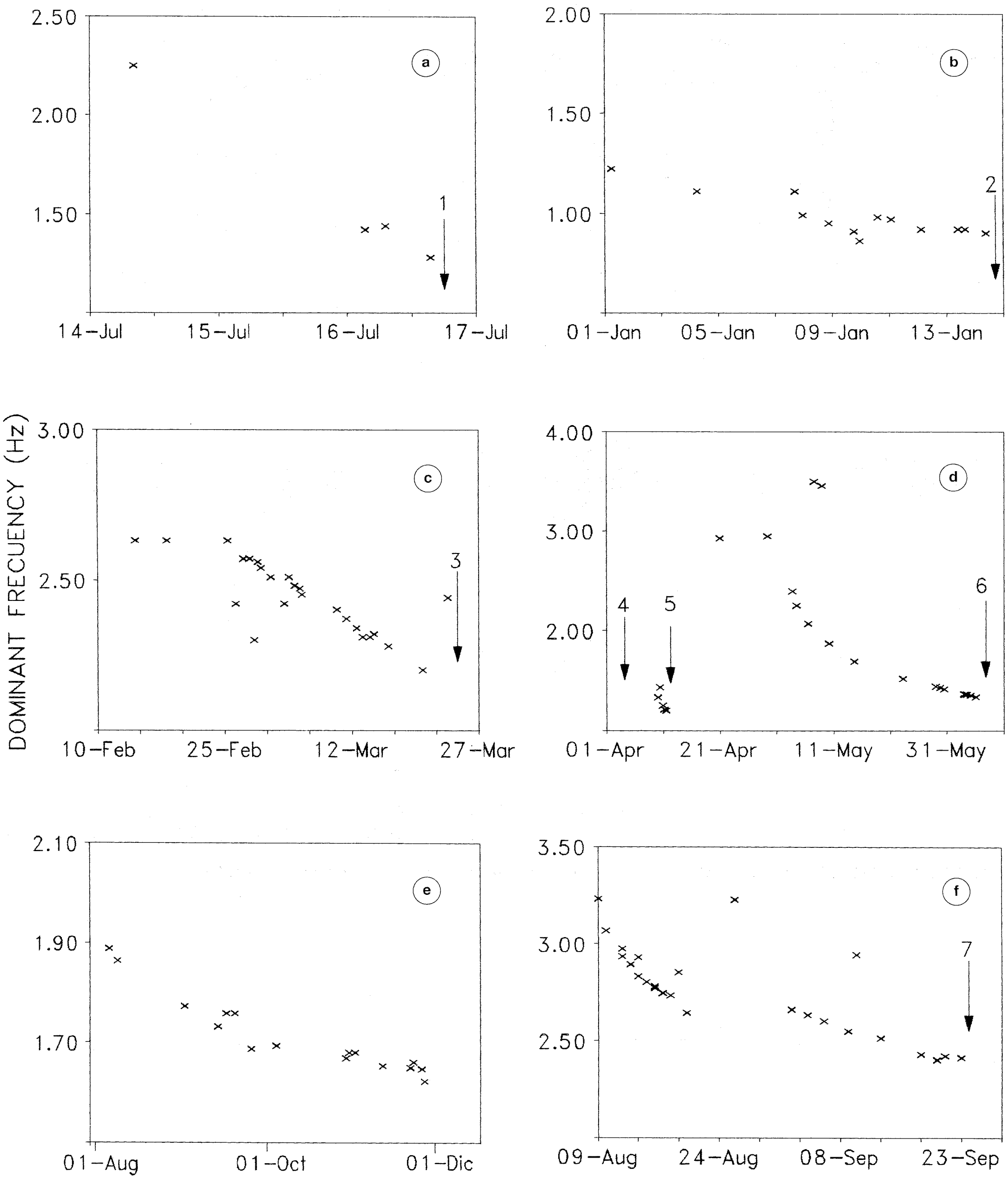

Fig. 7a-f. Dominant frequencies of tornillo events ranging from 0.9 to 3.5 Hz, for different time periods: a), b), c), d) and f) ended with eruptions while e) did not end with an eruption. Arrows indicate dates of eruptions in the following order: (1) July 16, 1992; (2) January 14, 1993; (3) March 23, 1993; (4) April 4, 1993; (5) April 13; 1993, (6) June 7, 1993; and (7) September 23, 1994. For each period analyzed, the dominant frequencies tend to decrease with time and, in some cases, to stabilize a few days prior to the eruptions.

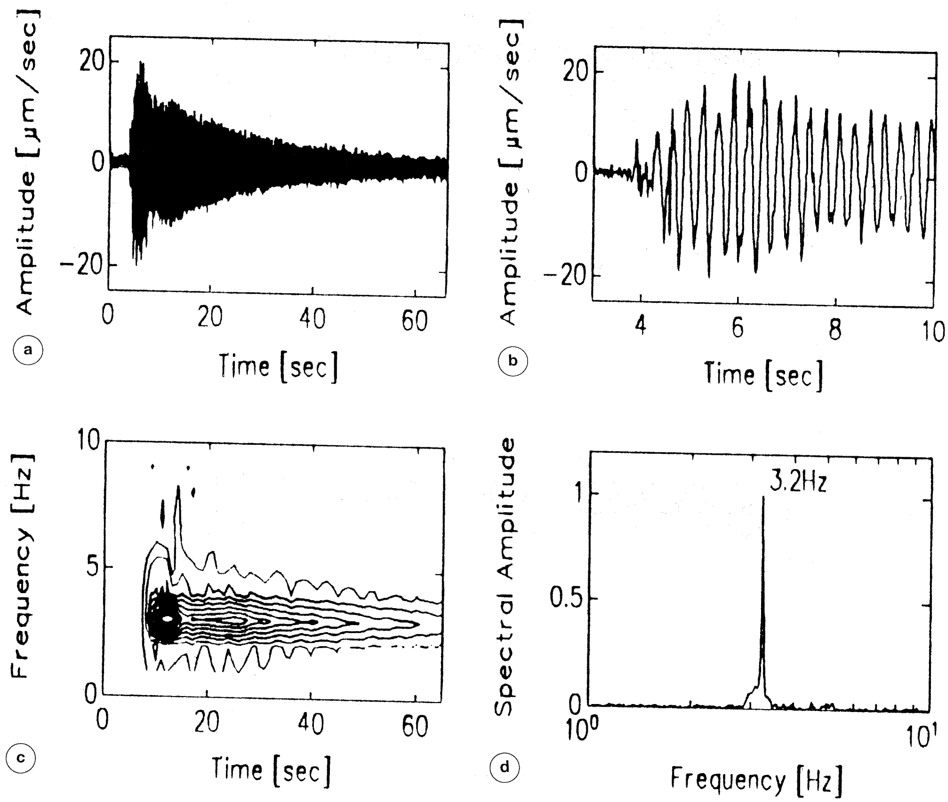

Fig. 8a-d. Example of a «tornillo» recorded on August 9, 1994 at Olga station. a) Temporal signature, the duration of the signal is 62 s; b) onset of the signal with a weak high frequency superimposed on low frequency; c) map of the spectral amplitudes of ground velocity (heights above a plane) versus frequency and time, the spectrogram, indicating the stability of the dominant frequency. Note the weak high frequency in the onset of the signal and d) spectrum showing the value of the sharp dominant frequency peak.

5. Concluding remarks

The eruptions from July 16, 1992, to June 7, 1993, can be explained from a point of view of pressurization and degassing processes. These eruptions were preceded by tornillo events, low gas emissions and low SO_2 fluxes. Immediately after the eruptions, tremor episodes with swarms of B-type events were recorded, accompanied by increased gas emissions from the active crater, as recorded by visual observations and increased SO_2 fluxes. The tornillo events always disappeared after each eruption. The material ejected during the eruptions showed the presence of juvenile material (Cortés and Calvache, 1993).

The source of tornillo events can be modeled as resonance modes in a fluid-filled crack, induced by a pressure transient applied over an area of the crack wall (Chouet 1985; Chouet, 1992). The origin of this pressure transient may be bubble bursts in a vesiculating fluid (Kieffer, 1984) or unsteady fluid flow (Chouet, 1992). The fact that the dominant frequency is maintained at all stations where the events were recorded, independent of their epicentral distance and azimuth, strongly suggests that this feature is due to a source effect. The energy loss by radiation is stronger for high frequencies, producing a seismic signature that is marked by a high-frequency content near the onset of the signal but dominated by a longer-period component of much longer duration in the rest of the signal coda (Fehler and Chouet, 1982; Bame and Fehler, 1986; Chouet, 1988). The elastic wavefield by the fluid-driven crack is a function of the crack geometry, the physical properties of the fluid and solid, and the spatio-temporal characteristics of the trigger that excites the crack (Chouet, 1992).

The appearance of tornillo events may therefore be an indication of physical interaction and conditions between the fluid flow and the neighboring solid material in the conduit. The increase in the duration of the tornillo events and the lowering of the dominant frequencies before the eruptions both suggest an increasing impedance contrast (Aki *et al.*, 1977) between the surrounding solid material and the fluid (Chouet, 1992). These characteristics can be explained by an increase in the free gas phase in the magma with consequent decrease of the sound speed-value of the mixture (Kieffer, 1977).

The presence of free gas in magma can be caused by saturation of volatile components (*e.g.*, H_2O) due to cooling of the magma, crystallization and partial solidification of the column of magma plugging the conduits (Stix *et al.*, 1993; Fisher *et al.*, 1994). At the same time, the presence of solid material in magma can contribute to sealing the conduits and preventing free gas escaping, with consequent generation of overpressure in parts of the conduits (Stix *et al.*, 1993). Once the overpressure exceeds the strength of the solidified rock, an eruption is initiated. The characteristics of the tornillos and the observed eruptive activity may support the essential role of the gas in preparing and initiating the eruptions.

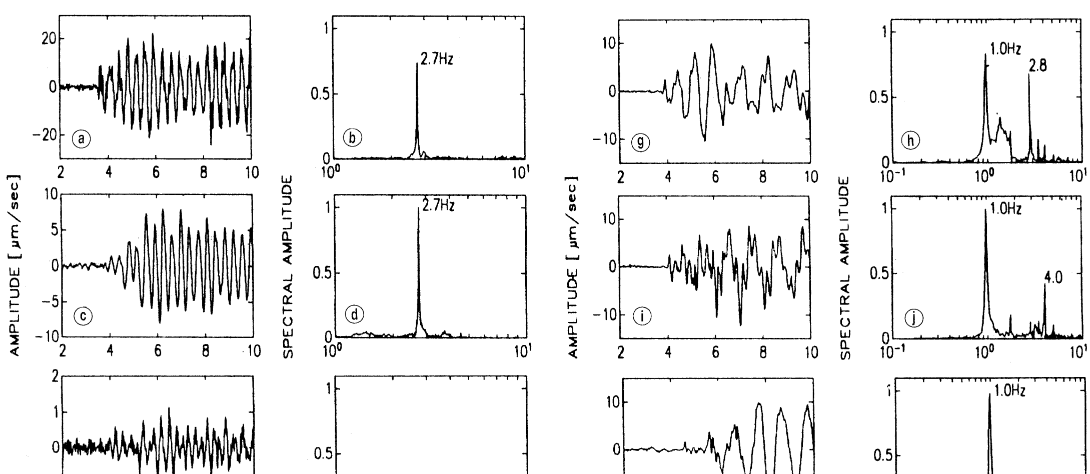

Fig. 9a-l. Examples of «tornillos» recorded on August 17, 1994 a), c), e) and January 8, 1993 g), i), k) showing the initial part of the signals and the associated spectra (b, d, f and h, j, l respectively) at different stations: a) Olga, located 0.9 km east of the active crater; c), g) Crater-2, located 1.6 km south of the active crater; e), i) Urcunina, located 2.1 km east of the active crater; k) Cobanegra-2, located 4.0 km south of the active crater. Note that the dominant frequency for each signal is the same at all stations. The spectral amplitude (ground velocity) is normalized with regard to the maximum value present considering all the stations.

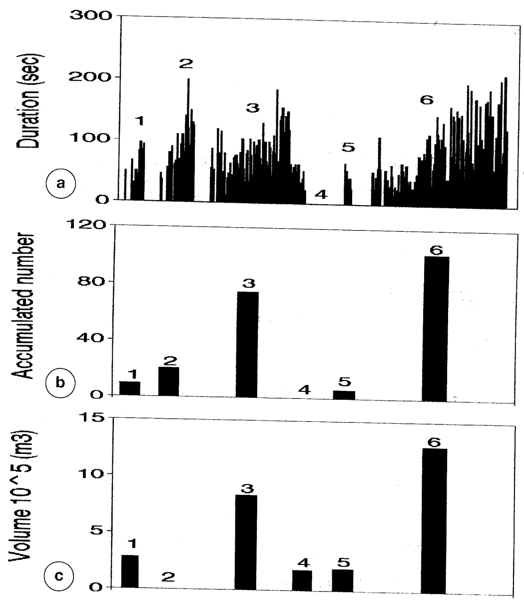

Fig. 10a-c. a) Durations of individual tornillo events recorded prior to different eruptive episodes marked as: (1) July 16, 1992; (2) January 14, 1993; (3) March 23, 1993; (5) April 13, 1993; and (6) June 7, 1993. No tornillo events were observed for the April 4, 1993 eruption (number 4). b) Accumulated number of tornillos for the periods of time mentioned above. c) Volume of solid material ejected (ash and rocks) in cubic meters for the different eruptions of 1992-1993. The volume of the January 14, 1993, eruption was not estimated. Using the positive relationships among «tornillo» durations, accumulated number of «tornillo» events and eruptive volume, we have estimated the relative size of eruptions from largest to smallest: June 7, 1993; March 23, 1993; January 14, 1993 (?); July 16, 1992; and April 13, 1993.

Based on our analysis of the tornillos at Galeras, it is possible to identify the following parameters to help forecast an eruption at Galeras. The lowering and subsequent stability of the dominant frequencies and the increase in the duration of the signals can indicate proximity to an eruption, while the total number of these events prior to the eruption can indicate the relative size of the eruptive event.

Further modeling and analysis of mechanisms which generate tornillo events will constitute an invaluable tool in the understanding of physical processes triggering eruptions and helping forecast eruptions at Galeras and other similar volcanoes.

Acknowledgements

The authors are grateful to the European Seismological Commission for supporting the participation of Roberto Torres at the Workshop. We also wish to thank the Japan International Cooperation Agency (JICA) for financing the participation of Diego Gómez in a training course on Volcanology in Japan from March to September 1994, where part of this work was accomplished. We appreciate helpful discussions with Bruno Martinelli. Martin Heiligmann and John Stix helped us in preparing the English manuscript. Our sincere thanks to Mario Castellano and an anonymous reviewer who help us to improve this paper.

REFERENCES

AKI, K., M. FEHLER and S. DAS (1977): Source mechanism of volcanic tremor: fluid-driven crack models and their application to the 1963 Kilauea eruption, *J. Volcanol. Geotherm. Res.*, **2**, 259-287.

BAME, D.A. and M. FEHLER (1986): Observations of long-period earthquakes accompanying hydraulic fracturing, *Geophys. Res. Lett.*, **13**, 149-152.

CALVACHE, V., M.L. (1990): *Geology and Volcanology of the Recent Evolution of Galeras volcano, Colombia*, M.S. Thesis, Louisiana State University, Baton Rouge, pp. 171.

CALVACHE, V., M.L. and S.N. WILLIAMS (1992): Lithic-dominated pyroclastic flows at Galeras Volcano, Colombia. An unrecognized volcanic hazard, *Geology*, **20**, 539-542.

CEPEDA H., M.L. CALVACHE V., F. MUÑOZ, I. MEJÍA, B. PULGARÍN, M. MERCADO, E. PARRA and R. MENDEZ (1989): Emisión de cenizas del Volcán Galeras (Mayo 4-9, 1989) (in Spanish), INGEOMINAS, *Internal Report*, pp. 6.

CHOUET, B. (1985): Excitation of a buried magmatic pipe: a seismic source model for volcanic tremor, *J. Geophys. Res.*, **90**, 1881-1893.

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**, 4375-4400.

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 (Springer-Verlag), 133-156.

CORTÉS J., G.P. and M.L. CALVACHE V. (1993): Erupciones explosivas del volcán Galeras-Colombia en el período Julio 16 de 1992 - Junio 7 de 1993 (in Spanish), INGEOMINAS-O.V.S.P, *Internal Report*, Pasto, pp. 55.

ESPINOSA, A. (1988): Actividad del volcán Galeras en épocas históricas (in Spanish), INGEOMINAS-Popayán, *Internal Report*, pp. 85.

FEHLER, M. and B. CHOUET (1982): Operation of a digital seismic network on Mount St. Helens volcano and observations of long-period seismic events that originate under the volcano, *Geophys. Res. Lett.*, **9**, 1017-1020.

FISCHER, T.P., M. MORRISSEY, M.L. CALVACHE V., D.M. GÓMEZ M., R.A. TORRES C., J. STIX and S.N. WILLIAMS (1994): Correlations between SO_2 flux and long-period seismicity at Galeras Volcano, *Nature*, **368**, 135-137.

GLOBAL VOLCANISM NETWORK BULLETIN (1989): Smithsonian Institution, March, vol. 14 (3).

GÓMEZ M., D.M. and R.A. TORRES C. (1993): Aspectos relievantes 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.

HANTKE, G. and I. PARODI (1966): *Catalogue of Active Volcanoes of the World: Part XIX, Colombia, Ecuador, and Perú: Rome*, International Association of Volcanology, pp. 73.

KIEFFER, S.W. (1977): Sound speed in liquid-gas mixtures: water-air and water-steam, *J. Geophys. Res.*, **82**, 2895-2904.

KIEFFER, S.W. (1984): Seismicity of Old Faithful Geyser: an isolated source of geothermal noise and possible analogue of volcanic seismicity, *J. Volcanol. Geotherm. Res.*, **22**, 59-95.

KOMOROWSKI, J.C., C. SIEBE, H. CEPEDA, M.L. MONSALVE and M.L. CALVACHE V. (1993): *Informations Additionnelles sur l'Èruption Tragique du 14 Janvier 1993 au Volcan Galeras (Colombie)*, (in French with summary in English), Association Volcanologique Européenne, No. 42, pp. 16.

MINAKAMI, T. (1974): Seismology of volcanoes in Japan, in *Physical Volcanology*, edited by L. CIVETTA, P. GASPARINI, G. LUONGO and A. RAPOLLA (Elsevier Scientific Publishing Company, Amsterdam, The Netherlands), 1-27.

MUÑOZ C., F.A., M.L. CALVACHE V., G.P. CORTÉS J., D.M. GÓMEZ M., L. NARVÁEZ M., M. ORDOÑEZ V., A. ORTEGA E., R.A. TORRES C., B. SILVA P., S.N. WILLIAMS, C.O. SANDERS and J. STIX (1993): Galeras volcano: international workshop and eruption, *EOS, Trans. Amer. Geophys. Un.*, **74** (26), 281; 286-287.

ORDOÑEZ V., M. and H. CEPEDA (1993): Proceso morfológico en el cono activo del Volcán Galeras (in Spanish), INGEOMINAS, *Internal Report*, pp. 32.

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

SIMKIN, T., L. SIEBERT, L. MCCLELLAND, D. BRIDGE, C. NEWHALL and J.H. LATTER (1981): *Volcanoes of the World: Stroudsburg, Pennsylvania*, Smithsonian Institution and Hutchinson Ross, pp. 232.

STIX, J., J.A. ZAPATA G., M.L. CALVACHE V., G.P. CORTÉS J., T.P. FISHER, D.M. GÓMEZ M., L. NARVÁEZ M., M. ORDOÑEZ V., A. ORTEGA E., R.A. TORRES C. and S.N. WILLIAMS (1993): A model of degassing at Galeras Volcano. Colombia 1988-1993, *Geology*, **21**, 963-967.

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, published by IASPEI, 85-113.

WILLIAMS, S.N., M.L. CALVACHE V., N.C. STURCHIO, J.A. ZAPATA G., R.A. MENDEZ F., B. CALVACHE O., A. LONDOÑO C., F. GIL C. and Y. SANO (1990): Premonitory geochemical evidence of magmatic reactivation of Galeras volcano, Colombia, *EOS, Trans. Amer. Geophys. Un.*, **71**, 647.

ZAPATA G., J.A. (1993): Actividad Geoquímica del Volcán Galeras (in Spanish), in *International Workshop on Galeras Volcanic Complex*, Pasto, Colombia, January 11-16, 1993, pp. 13.