ANNALI DI GEOFISICA, VOL. 42, N. 3, June 1999

Tornillo seismic events at Galeras volcano, Colombia: a summary and new information from broadband three-component measurements

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Abstract
Long-duration events have been recorded at several active, andesitic volcanoes. Their main characteristics are a single, sharp frequency peak, and an exceptionally long coda. Because their seismograms resemble a screw, these signals are called «tornillos» in Colombia. These events have been recorded during different stages of volcanic activity at various volcanoes worldwide. Tornillos have occurred for example, as a short-term precursor to eruptions at Galeras volcano, Colombia (1992-1993); and at Asama volcano, Japan, (1983). At Tokachi volcano, Japan, they were recorded after an eruption (1989). The Tornillo's dominant frequency appears to be related to the time of occurrence during an eruption cycle. It is independent of epicentral distance, azimuth, travel time, and lapse time, indicating that it is a source characteristic. Damping coefficients for the tornillo's coda range between 0.002 and 0.02. In contrast, damping coefficients for normal long-period events lies between 0.010 and 0.025 and for volcano-tectonic events between 0.010 and 0.040. In March 1996, the Galeras seismic network, which consists of short period, single-component seismometers, was augmented with a broadband, three-component station. This station, installed 1.5 km south of Galeras active cone, recorded a series of six tornillos. Narrowband and broadband tornillo records have similar characteristics in the time and frequency domains.

Key words *volcanoes – seismic events – broadband records – tornillos – Galeras volcano*

1. Introduction

Tornillo events are a type of low frequency volcanic events, commonly observed at active andesitic volcanoes such as Galeras, Puracé and Ruiz, in Colombia, and Meakan, Tarumai, Kusatsu-Shirane, Asama, Sakurajima, Kirishima, and Kushinocrabujima, in Japan. Their occurrence is mainly associated with vulcanian-type eruptions or large gas emission. This kind of seismic event was observed at Asama-yama volcano in 1961, 1964, 1970 and 1971 (Sekiya, 1967; Hamada *et al.*, 1976) and Sakura-jima volcano in 1970 (Hamada *et al.*, 1976), but were not included in Minakami's classification (Minakami, 1974). In Colombia we have named these events tornillo (Spanish for screw), since the signal's shape resembles the side view of a threaded metal screw. In Japan several names

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have been used for these particular signals, such as LC-events (Long Coda events), BS-events (Banded-Spectrum events), SF-events (Single-Frequency events) or *T*-type events (similarity with a *T*-square).

Tornillos have appeared during different stages of volcanic activity. They occur as a short-term precursor (Galeras volcano, Colombia, 1992-1993; Asama volcano, Japan, 1983), after eruptions (Tokachi volcano, Japan, 1989), during seismic swarms (Meakan volcano, Japan, 1982) and during quiescence (Puracé volcano, Colombia, 1994-1995; Tarumai volcano, Japan, 1970-1971, 1975). In addition, these events have occurred with either individually or as a part of a swarm (Gómez and Torres, 1997).

Galeras (1°13.73′N, 77°21.55′W) is an active andesitic stratovolcano which rises to 4270 m, 9 km west of San Juan de Pasto, a city of about 350 000 residents (fig. 1). Located in Southwestern Colombia, this volcano is considered to be one of the most active and representative

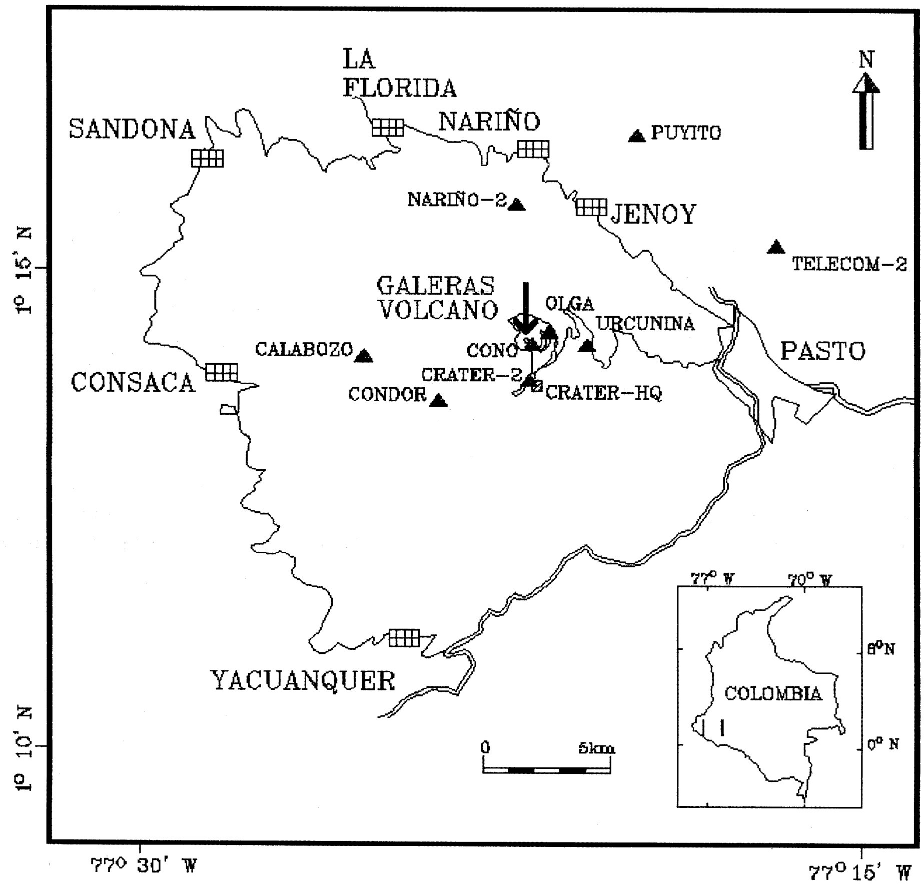

Fig. 1. Location of Galeras volcano and its telemetered seismic network. The narrowband stations are represented by triangles and the active crater by an arrow. The broadband station Crater-hq station is represented by a square. The Circum-Galeras road connecting villages around Galeras, and the road from Pasto to the summit of the volcano are also shown. Urcunina station is equipped with three components: URCR, URNS and UREW as vertical, north and east respectively.

producers of tornillos. More than 490 tornillo events have been recorded since July 11, 1992. Between April 4 and April 14, 1996, six tornillos were simultaneously recorded by the permanent Galeras seismic network and one broadband, high dynamic range station.

We summarize observations from the tornillos observed at Galeras volcano, as well as from other volcanoes, such as Puracé and Tokachi. In addition we compare results from the broadband records with those obtained from the narrowband seismic network at Galeras volcano.

2. Seismic network

The Galeras network consists of nine permanent, telemetered stations, located between 0.9 km and 10 km from the active crater (fig. 1). Seismometers are vertical component, Mark Products L-4C, short period (1 s) sensors, with output proportional to ground velocity. In addition at one of the nine stations the vertical sensor is augmented by two SS-1 Ranger Kinemetrics, short period (1 s), oriented horizontally toward the north and east. Digital data are recorded in real time at a rate of 100 samples per second. The instrument response with a total damping of 0.72 of the critical, shows a flat zone from near to 2 Hz with an output of 1.5 Vpp/cm/s. For the natural frequency of 1 Hz, the sensitivity is around 64% of the flat output, and for a frequency of 0.5 Hz, the output is around 30% of the flat output.

In early March 1996, as a part of a cooperative program between the Research Institute for Geosciences, Mining, and Chemistry (INGEOMINAS - Colombia) and the Federal Institute for Geosciences and Natural Resources (BGR - Germany), a high resolution, broadband seismic station, designated Crater-hq was installed 1.5 km south of Galeras active cone, near the network station Crater-2 (fig. 1). This station consists of a Teledyne Geotech PDAS-100 with a 16-bit, gain-ranged digitizer to record the velocity output from the three-component STS-2 seismometer. Digital data are recorded continuously at a sampling rate of 50 Hz. The seismometer components are oriented vertically and horizontally in the north and east directions.

3. Characterization of tornillo events

3.1. *Waveforms*

Tornillo events recorded at different volcanoes, exhibit quasi-sinusoidal waveforms characterized by a very long-duration due to a very slowly decaying coda. Thus, their amplitudes are usually small with respect to their durations. Some events show amplitude modulation effects (fig. 2a,b). In general, their onsets are emergent, but occasionally some events have moderately impulsive arrivals. For tornillo events recorded between April 4 and April 14, 1996, at Galeras, amplitudes on the horizontal components were higher than on the vertical component. Characteristic features of a Tornillo's waveform are independent of the instrumentation used for recording (fig. 3a-i).

3.2. *Damping coefficient for coda-waves*

Tornillo events have an unusually long coda which decays exponentially, $\exp(-\alpha t)$, where α is the amplitude decay coefficient that depends on the damping coefficient and the frequency of the signal

$$\alpha = 2\pi f h \tag{3.1}$$

The damping coefficient for coda waves is defined by Hamada *et al.* (1976) and is determined by the shape of the waveform, independent of the event size, according to

$$h = \frac{\ln A / A_0}{2\pi f(t - t_0)} \tag{3.2}$$

where A_0 is the initial amplitude in one part of the coda wave at time t_0, and A the final amplitude at time t.

On the other hand,

$$\alpha = \frac{\pi f}{Q} \tag{3.3}$$

$$Q = \frac{f}{\Delta f} \tag{3.4}$$

Q factor of the resonator obtained by the rela-

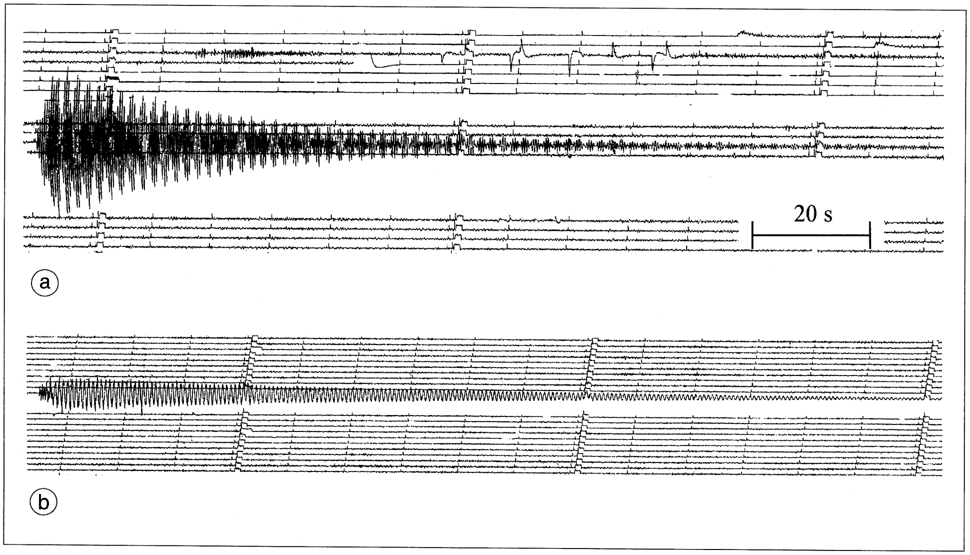

Fig. 2a,b. Examples of several typical Galeras tornillo events recorded on: a) March 12, 1993; b) June 4, 1993.

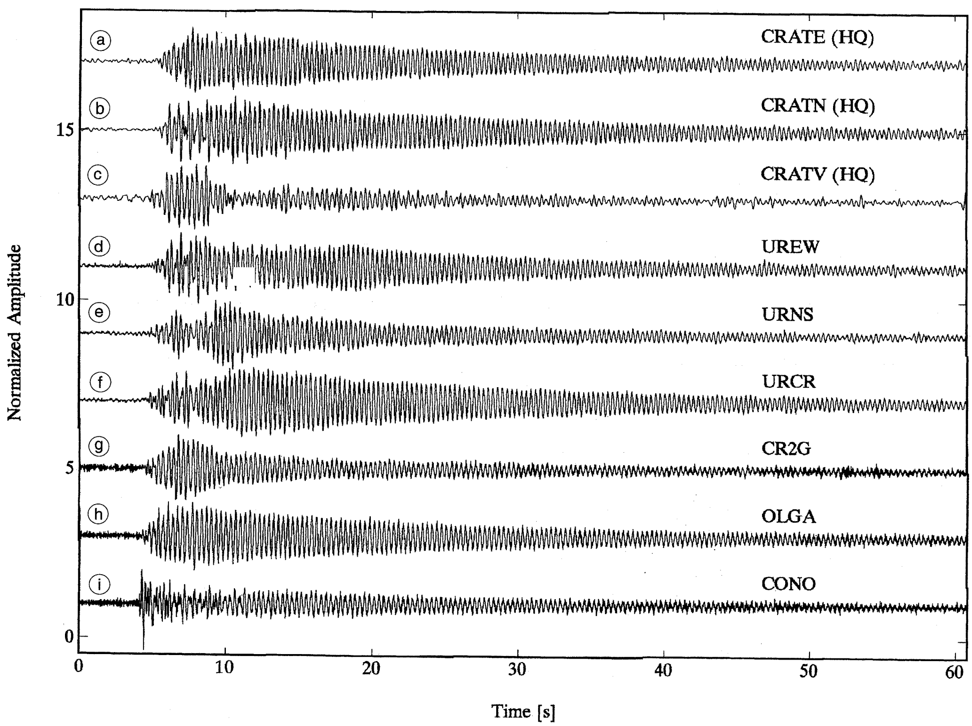

Fig. 3a-i. Seismograms of April 10, 1996 tornillo event recorded at (a), (b), and (c) broadband station, and (d)-(i) narrowband Galeras network.

Table I. Relevant characteristics of tornillo events recorded at some Colombian and Japanese volcanoes. Modified from Hamada *et al.* (1976).

Volcano	Number of events	Period of time tornillos observed	Dominant frequency (Hz)	Damping coefficient	References
Galeras	9	July 11-16, 1992	1.3-2.3	0.003-0.004	
	20	December 23, 1992-January 14, 1993	0.9-3.0	0.002-0.014	
	74	February 13-March 23, 1993	2.5-3.5	0.003-0.016	Gómez (1994);
	103	April 18-June 7, 1993	1.5-3.8	0.002-0.010	Torres *et al.* (1996)
	83	July 1-November 26, 1993	1.6-4.8	0.002-0.006	
	31	August 9-September 23, 1994	2.4-3.2	0.002-0.005	
	80	October 20, 1994 to January 5, 1995	2.2-8.0	0.002-0.006	
Puracé	27	July 6-November 11, 1994	4.6-8.0	0.002-0.005	This study
Tokachi-dake	35	April 3-April 19, 1989	3.3-5.0	0.004-0.011	After Usu Volcano Observatory (1989);
Meakan-dake	250	February 1990-July 1994	3.5-7.5	0.004-0.019	Nishimura and Okada (1994)
Taisetsu	7	August 1990-September 1991	0.9-3.0	0.003-0.004	
Asamayama	49	January-August 1961	1.0-5.0	0.002-0.03	
Tarumae-yama	34	February 1970-February 1971 and May-June 1975	0.7-3.3	0.005-0.03	After Hamada
Kusatsu	31	January-June 1975	1.1-3.3	0.003-0.005	*et al.* (1976)
Sakurajima	15	December 1967-February 1970	2.5-5.0	0.007-0.02	
Kushinoerabujima	1	June 1975	4.3	0.02	

tion between the dominant frequency peak and the width of the peak at its half energy level.

According to Bullen and Bolt (1985)

$$h = \frac{1}{2Q} \qquad (3.5)$$

In general, the damping coefficients for tornillos lie between 0.002 and 0.02. In contrast, for events named as current long-period (Chouet, 1988, 1992, 1996), damping coefficient values range from 0.010 to 0.025, while for volcano-tectonic earthquakes (Latter, 1979; Chouet, 1996), this coefficient varies between 0.010 and 0.040 (Gómez and Torres, 1997). Lower values imply more slowly decaying coda waves. Table I shows typical dominant frequencies and damping coefficients of coda waves for Galeras and Puracé volcanoes in Colombia as well as for several Japanese volcanoes. The lowest values have been observed at Puracé, Galeras and Asamayama volcanoes.

At Galeras, the damping coefficients are distributed between 0.002 and 0.016. Fifty percent of the events analyzed have especially low damping coefficients lying below 0.005 (table I). The longest tornillos (more than 100 s) correspond to the lowest values of the damping coefficient, namely between 0.002 and 0.004.

3.3. *Time of occurrence*

At Galeras, tornillos have preceded most of the eruptive episodes since the emplacement of a lava dome in the crater in October 1991 (table II).

Table II. Recording periods of tornillo events observed at Galeras volcano, Colombia.

Time and / or frequency	Swarm / individual	Specific volcanic activity	Earthquake at the beginning	Eruption precursor
9 events July 11-16, 1992	Individual	Short-term precursor to July 16 eruption	No	Yes
20 events December 23, 1992- January 14, 1993	Individual	Short-term precursor to January 14 eruption	No	Yes
74 events February 13-March 23, 1993	Individual	Short-term precursor to March 23 eruption	No	Yes
6 events April 10-12, 1993	Individual	Short-term precursor to April 13 eruption	No	Yes
103 events April 18-June 7, 1993	Individual	Short-term precursor to June 7 eruption	No	Yes
83 events July 1-November 26, 1993	Individual	During quiescence	No	No
31 events August 9-September 23, 1994	Individual	Short-term precursor to large gas emission on September 23	No	Yes
80 events October 20, 1994 to January 5, 1995	Individual	Short-term precursor to large gas emission on January 5	No	Yes

Immediately after each of these eruptions, the tornillo events disappeared for several days (Torres *et al.*, 1996).

The eruption on April 4, 1993 was an exception. While it was not preceded by tornillo events, it was of lower intensity than the other eruptions during this period. Furthermore, it may be interpreted either as the final stage of the March 23, 1993 activity or the initial stage of the June 7, 1993 activity. Another period of unusual tornillo activity occurred between July 1, 1993 and November 26, 1993. During this interval there were 83 tornillos before their occurrence ceased without being followed by an eruption (table II). For the 1992-1993 eruptions, there is a direct correlation between the total number of tornillos prior to an eruption and the volume of material ejected by the eruption (table III).

At Puracé, other active volcano in Southwest Colombia, between July 6, 1994 and November 11, 1994 a total of 27 tornillo events were recorded (table I). They were also observed in 1991 at low levels. These signals have not been related to any eruptive activity.

At Tokachi volcano, located in Hokkaido, Japan, between December 16, 1988, to March 5, 1989, twenty-three explosive eruptions were reported (Katsui *et al.*, 1990). One month later, from April 3-19, 1989, a swarm of thirty-five seismic signals characterized by slowly decaying coda waves, were recorded for the first time on this volcano (Nishimura and Okada, 1994; table I). These events were not accompanied by any eruptive activity.

At Meakan volcano, also located in Hokkaido, Japan, in March 1982, a swarm of volcano-tectonic earthquakes occurred, accompanied by fourteen events with long durations (Nishimura and Yamashita, 1982). In addition, in 1987, a very small ash emission was observed around the active crater which was preceded by several tornillo events (Y. Nishimura, personal commu-

Table III. Tornillo events and eruptions at Galeras volcano.

Date of eruption DD/MM/YY	Number of events	Tephra volume emitted [c] x $10^6 m^3$	Ash column height [c] km
16/07/92	9	0.28	6
14/01/93	20	... [b]	... [b]
23/03/93	74	0.835	8
13/04/93	6	0.22	6
07/06/93	103	1.25	9
23/09/94 [a]	31	... [b]	... [b]
5/01/95 [a]	80	... [b]	... [b]

[a] Correspond to large gas emissions; [b] estimates not possible; [c] data from Cortés and Calvache (1993).

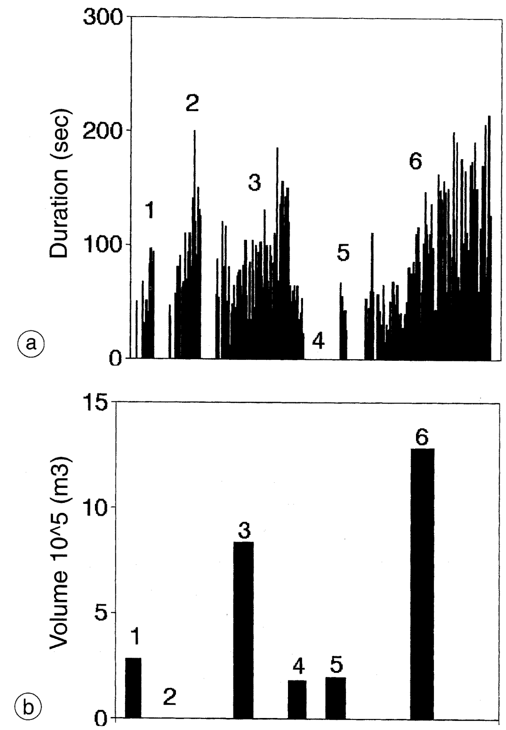

Fig. 4a,b. a) Durations of individual tornillo events recorded prior to different Galeras eruptive episodes marked as: 1 = July 16, 1992; 2 = January 14, 1993; 3 = March 23, 1993; 4 = April 4, 1993; 5 = April 13, 1993; 6 = June 7, 1993. b) Volume of solid material ejected (ash and rocks) in cubic meters for different eruptions of 1992-1993. The volume of the January 14, 1993 eruption was not estimated.

nication, 1994). Tornillo events were observed at this volcano from 1990 to 1994 (table I), but generally, this type of seismic signal has been recorded without eruptions or any special observable activity.

3.4. *Durations*

Tornillo events at Galeras have had durations between 25 s and 330 s. Before an eruption, the durations of tornillos tend to increase progressively until they reach a maximum value. The eruption occurs following a small decrease in tornillo duration. In addition, there appears to be a direct correlation between the tornillos' duration and the volume of material ejected. If the individual tornillos before the eruption had very long durations, a larger volume of material was emitted (fig. 4a,b).

3.5. *Frequency contents*

The spectrum of a tornillo has one, or at most a few, narrow peaks, which are the same frequencies at all recording stations (fig. 5a-i). The frequency of the peak with the highest amplitude, which we call the dominant frequency, varies from one tornillo to another. At the volcanoes studied, dominant frequencies have been observed between 0.7 Hz and 8.0 Hz (table I). Most tornillo waveforms are quasi-monochro-

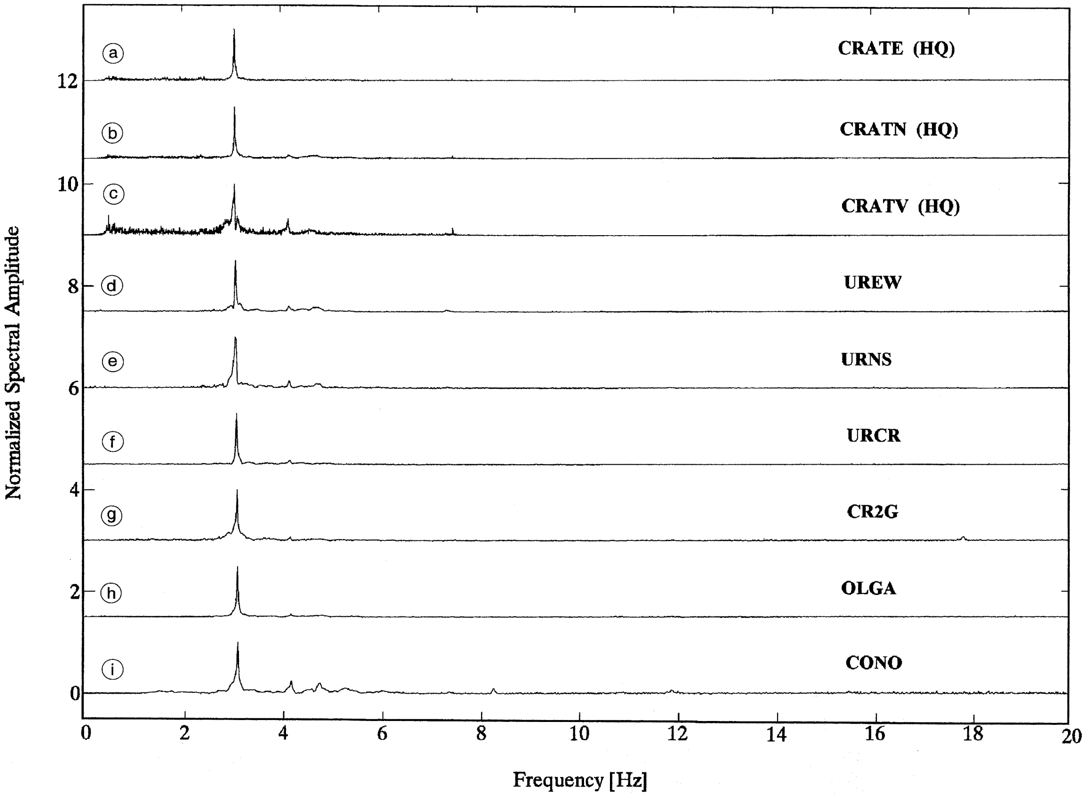

Fig. 5a-i. Spectra of April 10, 1996 tornillo event recorded at (a), (b), and (c) broadband station, and (d)-(i) narrowband Galeras network.

matic; sometimes the onset has low amplitude higher frequency signals superimposed. The spectrograms show the stability of the dominant frequency during the entire signal (fig. 6a-i).

The dominant frequencies of tornillo events recorded at Galeras volcano, are the same at all stations for an individual event. This suggests that the dominant frequency reflects a source effect. In contrast, the dominant frequencies vary during and among eruptive episodes suggesting that source conditions change (Torres *et al.*, 1996; Gómez and Torres, 1997). At Galeras, the dominant frequencies lie between 0.9 Hz and 8.0 Hz (table I).

One of the most interesting characteristics is the decrease in the dominant frequency as an eruption becomes immanent. Just before the eruption, however, the dominant frequency seems to remain stable for several days (fig. 7). This pattern may indicate that conditions in the volcano have evolved to a stable, critical state prior to an eruption. The decrease and subsequent stabilization of the dominant frequency have important implications for eruption forecasting at Galeras volcano (Torres *et al.*, 1996; Gómez and Torres, 1997).

The tornillos recorded from April 4 to April 14, 1996, have the same dominant frequencies on both the broadband and narrowband systems indicating that this parameter is also independent of the instrument type. For these tornillos, the dominant frequencies lie between 3.0 and 3.2 Hz. A second, smaller peak around 4.1 Hz was also noted in some of the events.

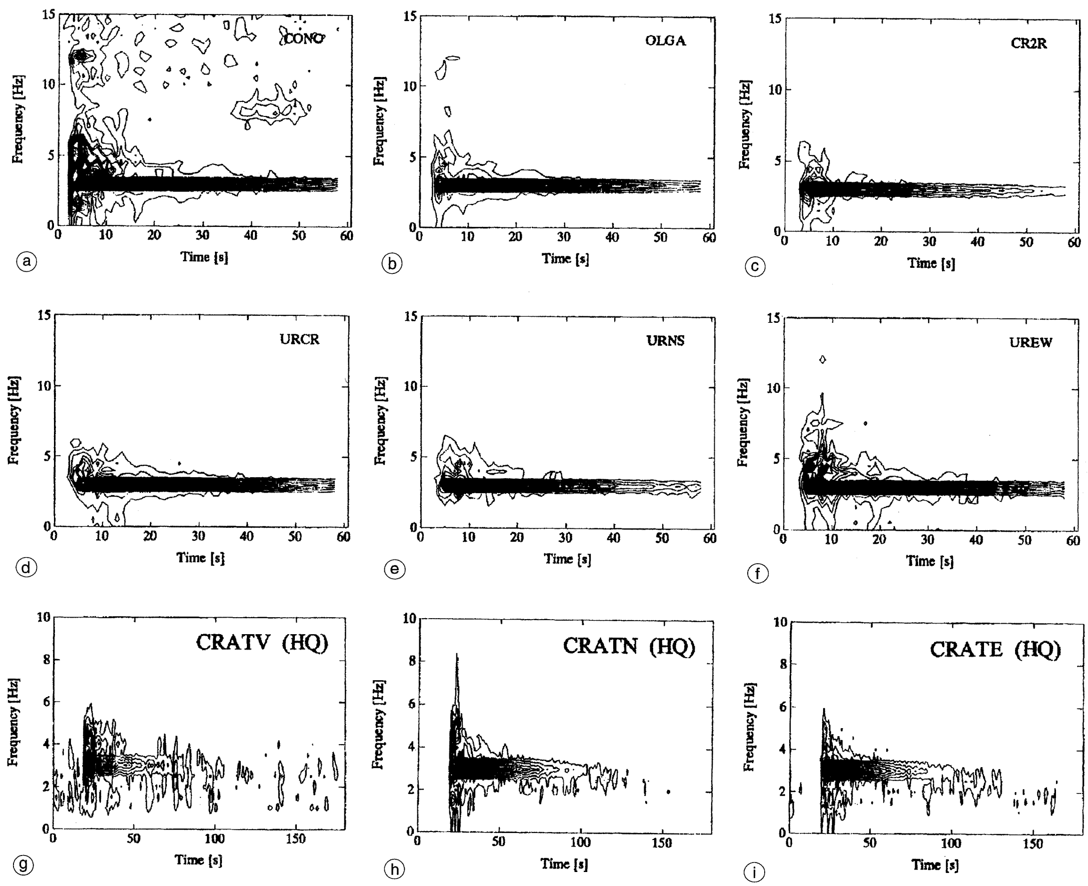

Fig. 6a-i. Spectrograms of April 10, 1996 tornillo event recorded at (a)-(f) narrowband Galeras network, and (g)-(i) broadband station. The spectrograms for the entire signal have been calculated with moving windows of 2 s and 50% overlapping. The narrowband data are recorded by triggering algorithm limiting the length of the data, while the broadband data are continuously recorded.

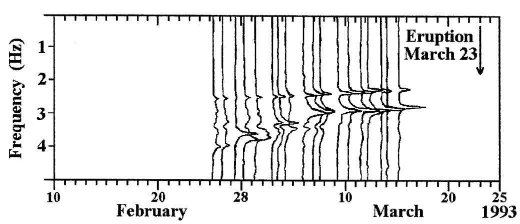

Fig. 7. Behaviour of dominant frequencies of tornillo events recorded prior to the March 23, 1993 Galeras eruption. The dominant frequencies tend to decrease with time. The eruption date is represented by an arrow.

Table IV summarizes the behaviour of dominant frequencies of several tornillos recorded at both Crater-hq and the narrowband stations. The data from Crater-hq was band-pass filtered between 1.0 and 8.0 Hz before the analysis.

3.6. *Particle motion*

Particle motion analysis is presented for the tornillos recorded at both Crater-hq and Urcunina stations. After the onset of the event the

Table IV. Dominant frequencies of Galeras tornillo events recorded at Crater-hq and Crater-2 stations.

Date	Local time (GMT-5 h)	Dominant frequency (Hz)			
		Crater-2 [a]	Crater-hq [b]		
DD/MM/YY	hh:mm	Vertical	Vertical	North	East
04/04/96	12:10	3.1	3.1	3.1	3.1
05/04/96	01:09	3.2	3.2	3.2	3.2
09/04/96	20:21	3.0	3.0	3.0	3.0
10/04/96	01:34	3.1	3.1	3.1	3.1
14/04/96	14:56	3.0	3.0	3.0	3.0

[a] Narrowband station; [b] broadband, high dynamic range station (data using a band-pass filter between 1.0 and 8.0 Hz).

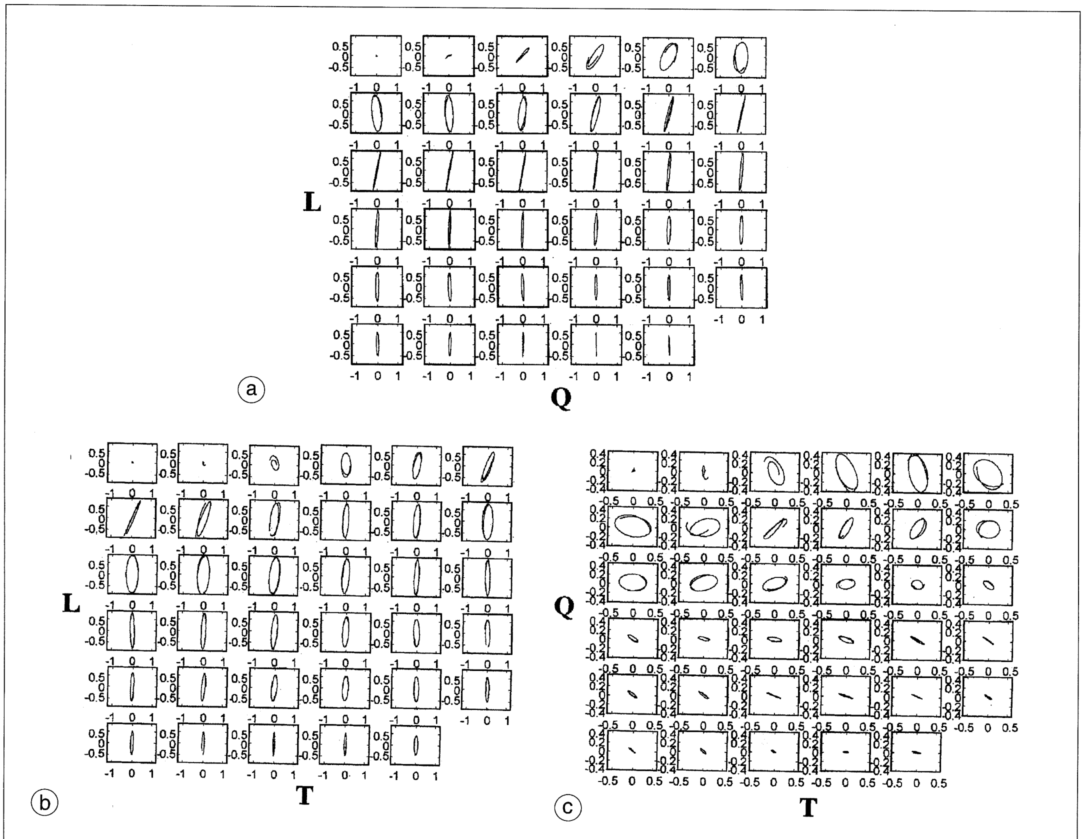

Fig. 8a-c. Particle motion plots for time windows duration of 0.5 s over a segment of 17.5 s for the tornillo event recorded on April 10, 1996. The data have been bandpass filtered between 2.6 and 3.6 Hz. The axes L, Q and T correspond to the wave coordinate system, where L axes is parallel to the direction of the wave propagation. a-c) Plots for the broadband Crater-hq station polarization for the dominant frequency peaks is highly stable at both stations (figs. 8a-c and 9a-c). The energy is concentrated in the horizontal plane. However, the particle motion for some tornillos is more complex (fig. 10). Table V lists some results of the particle motion analysis.

3.7. *Source location*

Preliminary location of several tornillo events, using both first arrivals and cross-correlation methods, place the source just beneath the active crater at depths less than 1.5 km. The fact that the tornillo events are only recorded clearly at the stations nearest to the active crater, also suggests shallow sources. On the other hand, attenuation of maximum vertical ground velocities among different stations for tornillo events recorded during different timeframes prior to the Galeras eruptive episodes show: 1) similar patterns among tornillos recorded during the same timeframe, and 2) slight increases in depth levels from one timeframe to the next.

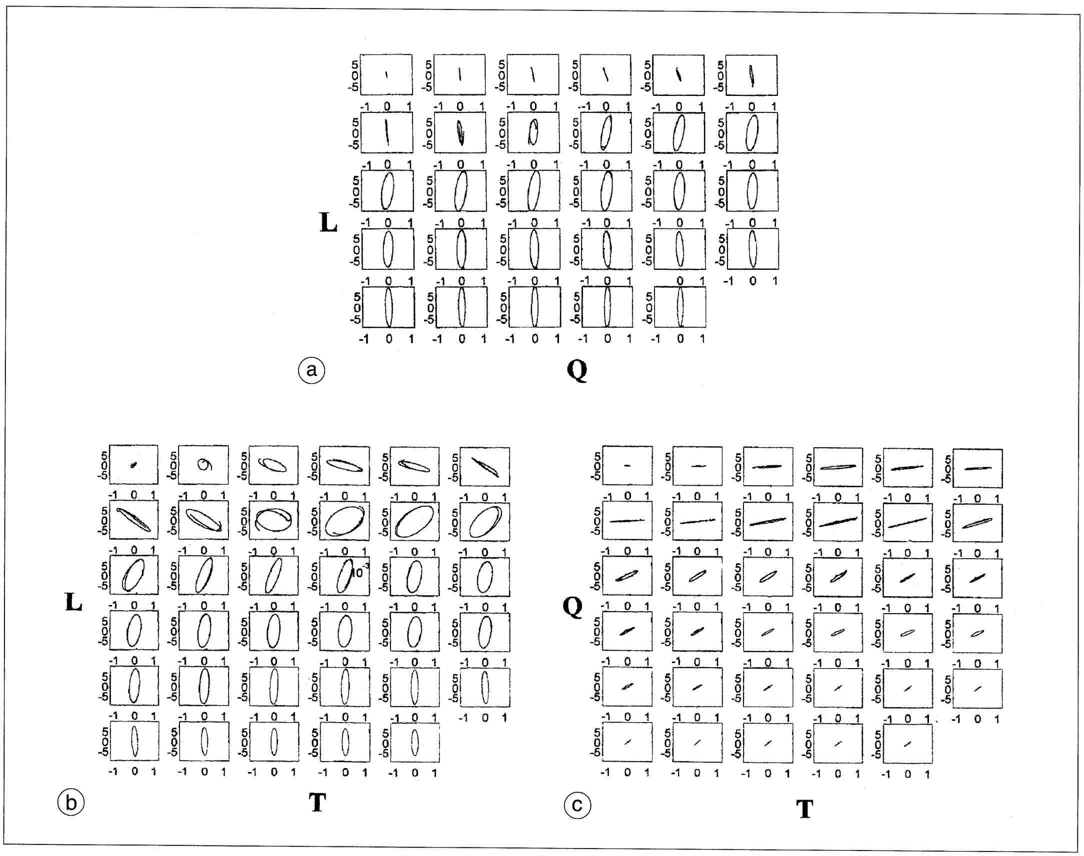

Fig. 9a-c. Particle motion plots for time windows duration of 0.5 s over a segment of 17.5 s for the tornillo event recorded on April 10, 1996. The data have been bandpass filtered between 2.6 and 3.6 Hz. The axes L, Q and T correspond to the wave coordinate system, where L axis is parallel to the direction of the wave propagation. a-c) Plots for the narrowband Urcunina station.

Table V. Some results of the polarization analysis for tornillo events recorded at Galeras volcano.

Date	Local Time	Bandpass filter (1-8 Hz)				Bandpass filter (2.6-3.6 Hz)[a]					
	(GMT-5h)	Urcunina	Crater-Hq			Urcunina			Crater-Hq		
DD/MM/YY	hh:mm	Azimuth	Azimuth	Incident	Type wave	Azimuth	Incident	Type wave	Azimuth	Incident	Type wave
09/04/96	20:21	135°	45°	74°	*P*	141°	88°	*P*	41°	75°	*P*
10/04/96	01:34	110°	35°	85°	*P*	135°	87°	*P*	45°	81°	*P*

[a] Around the dominant frequency.

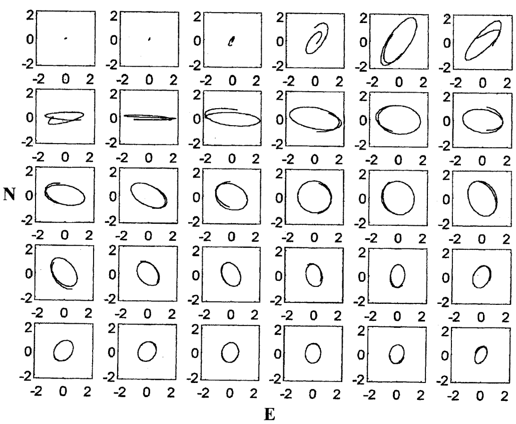

Fig. 10. Particle motion plots for time windows duration of 0.5 s over a segment of 15.0 s of the tornillo event recorded on April 14, 1996. The data have been bandpass filtered between 2.6 and 3.6. Plots correspond to seismometer system for the broadband station Crater-hq. The azimuth is not easy to identify.

4. Conclusions about tornillos at Galeras volcano

Tornillo events at Galeras volcano were first seen prior to the eruptive episodes which occurred just after the emplacement of a lava dome at the bottom of the main crater in early October 1991 (Gómez and Torres, 1993). Samples of the eruption products of the 1992-1993 eruptive episodes show the presence of juvenile material (Cortés and Calvache, 1993). Thus, Galeras tornillo events are considered to be related to magmatic activity and to occur just beneath the active crater, less than 1.5 km beneath the surface.

The six tornillo events recorded simultaneously on the Galeras narrowband seismic network and at the broadband station in April 1996, exhibit common characteristics on both systems. Thus, dominant frequencies, signal duration, quasi-sinusoidal waveforms, and shape of the events determined by the damping coefficient must be related to source effects rather than effects due to the azimuth, travel time or path, or the recording instruments. If the source is a resonator, only one vibration mode is excited, and a relatively simple source model could account for these features (Lesage and Surono, 1995).

The duration of resonance can be measured by the Quality factor (Q) describing the damping or decay of oscillations. This factor can be calculated from the damping coefficient (h) by means of eq. (3.5) (Bullen and Bolt, 1985).

Quality factors for Galeras tornillos range between 31 and 250, corresponding to damping coefficient values of 0.016 to 0.002. Chouet (1992) attributes high values of Q to the presence of gas bubbles in the magmatic fluid. However, it is difficult to explain values of Q greater than 40 solely by the addition of more bubbles to the fluid.

The resonance, and consequently the Q factor, also depend on the impedance contrast Z between the fluid flow and the solid material (Aki *et al.*, 1977). Large values of Q imply a high impedance contrast. The Q values at Galeras give impedances between 20 and 159 (Gómez and Torres, 1997). An increase in the gas fraction in the magma could explain the increase in the impedance contrast and Q factor prior to the eruptions. Other parameters such as source dimensions may also affect these parameters.

Thus, Galeras tornillo events may provide an indication of physical conditions and interactions between the magma in the chamber and the surrounding solid material. The increase in the duration of tornillo events, which implies a decrease in the damping coefficient, along with the decrease in the dominant frequencies, suggests an increase in the 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 (Chouet, 1992), and/or by the increase in the rigidity of the surrounding solid material as a consequence of saturation of volatiles due to cooling, crystallization and partial solidification of the magma column plugging the conduits (Stix *et al.*, 1993; Fisher *et al.*, 1994; Torres *et al.*, 1996).

5. Discussion

We have studied a particular type of low frequency volcanic seismic events called tornillos. These events have been recorded at andesitic volcanoes during Vulcanian-type eruptions, large gas emissions, or unassociated with any observable volcanic activity. In addition, tornillos have been observed during different stages of volcanic activity cycles. They have occurred as short-term precursors to eruptions (Galeras volcano, Colombia, 1992-1993; Asama-yama volcano, Japan, 1983), after eruptions (Tokachi-dake volcano, Japan, 1989), during seismic swarms (Meakan-dake volcano, Japan, 1982) and during quiescence (Puracé volcano, Colombia, 1994-1995; Tarumai volcano, Japan, 1970-1971, 1975)

The main common features of tornillos can be summarized as follows:

1) Long durations compared to their amplitudes and slowly decaying coda, reflected by low damping coefficients distributed between 0.002 and 0.02.

2) Spectra are characterized by one, or at most a few, sharp frequency peaks. Dominant frequencies are not affected by epicentral distance, azimuth or travel time, indicating a source effect. The dominant frequencies differ at different volcanoes.

3) Spectrograms demonstrate that energy-content is concentrated in a narrow frequency band almost throughout the entire signal.

4) Narrow and broadband tornillo records show similar results in the time and frequency domains at Galeras volcano.

For Galeras volcano, tornillos were observed as a short-term precursor for all but one of the eruptions between July 16, 1992 and January 5, 1995. These events are considered to be related to magmatic activity and to occur just beneath the active crater. Prior to the Galeras eruptions, tornillo durations increase while the dominant frequencies decreases, while at the other volcanoes analyzed, these parameters did not show a clear trend.

The analysis of tornillos at Galeras disclosed the following parameters which may help forecast an eruption at Galeras (Torres *et al.*, 1996):

1) Eruption imminence is implied by the decrease and subsequent stability of the dominant frequencies and the increase in the duration of the signals.

2) Relative size of the eruptive event is related to the total number of these events prior to the eruption.

Acknowledgements

The authors are grateful to Dr. Bruno Martinelli for his helpful discussions and for financial support for the participation of D. Gómez and R. Torres in 1996, in the workshop on *Physics of Volcanic Phenomena, Understanding Eruptions and Searching for Precursors*, in Italy, where part of this work was presented. Thanks also to Dr. Ugo Coppa, who, on behalf of the Osservatorio Vesuviano, also supported D. Gómez and R. Torres during the mentioned workshop. Our thanks to INGEOMINAS (Colombia) and BGR (Germany) institutions for including us in the cooperative research project at Galeras volcano, and providing us the support necessary for carrying out this work.

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