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Unusual low-frequency volcanic seismic events with slowly decaying coda waves observed at Galeras and other volcanoes

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Abstract

Events with slowly decaying coda waves are observed in active andesitic volcanoes associated mainly with vulcanian-type eruptions or large gas emissions. However, these signals are also recorded in some quiescent volcanoes. These unusual signals are considered to be related to magmatic activity and generally occur beneath the active crater. The signals have been observed to be a short-term precursor (Galeras volcano, Colombia, 1992–1993; Asama-yama volcano, Japan, 1983), after eruption (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). Spectral analysis reveals common characteristics for this type of signal. The spectrum is characterized by one or several sharp frequency peaks. Fundamental frequencies are not affected by epicentral distance, azimuth or travel time, indicating a source effect. The damping coefficient for coda waves ranges from 0.002 to 0.02 and is related to large values of the Quality factor (Q_c) ranging from 250 to 25, respectively. These parameters may be the result of large amounts of gas bubbles in the magma body.

Keywords: Colombian volcanoes; Japanese volcanoes; andesitic volcanoes; seismic signals; tornillos; eruptions; quality factor

1. Introduction

Unusual low-frequency seismic signals have been observed at active volcanoes such as Galeras and Puracé in Colombia, and Meakan-dake, Tokachi-dake, Tarumai-san, Kusatsu-Shirane-san, Asama-yama, Sakurajima, Kirishima and Kushinocrabujima in Japan (Hamada et al., 1976; Gómez, 1994). For this report we have examined Galeras, Puracé, Tokachi-dake and Meakan-dake volcanoes, which are considered to be the most active and representative in terms of these unusual seismic signals.

Galeras is a 4270-m-high andesitic stratovolcano located in the southwest part of Colombia at 1°13.73′N, 77°21.55′W (Fig. 1; Hantke and Parodi, 1966; Simkin et al., 1981). It is considered to be one of the most active volcanoes in the country (Espinosa, 1988; Calvache, 1990). Since 1988 when the current cycle of re-activation began (SEAN, 1989; Williams et al., 1990), the volcano has had nine main eruptive episodes. Six of them occurred from July 16, 1992 to June 7, 1993. These episodes were preceded by low levels of seismicity such as long-period (LP) events, volcano-tectonic (VT) earthquakes and tremor episodes (Latter, 1979; Chouet, 1988, 1992, 1996), low SO_2 fluxes as measured by COSPEC, little surface deformation and low fumarolic activity. Pu-

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racé is a 4646-m-high andesitic stratovolcano located in the Cordillera Central of Colombia at 02°22′N, 76°23′W (Fig. 1; Hantke and Parodi, 1966; Simkin et al., 1981). The most recent geological record of this volcano shows remarkable explosive activity. Since 1816, certain eruptions have generated pyroclastic flows. During the last 150 years, Puracé has had five eruptive periods with quiescence intervals of between 10 and 20 years. The most recent eruption occurred in March 1977, and was characterized mainly by a small ash emission. At this moment, the volcano is active, showing gas emission with a significant magmatic component (M. Martini, written commun., 1992) and low-level seismicity (long-period events and volcano-tectonic earthquakes). Mount Tokachi is a 2077-m-high andesitic volcanic complex located in the central part of Hokkaido, Japan, at 43°25′N, 142°41′E (Fig. 1). The most recent major eruptions occurred in 1926 and 1962. After that, 23 small explosive eruptions occurred from December 16, 1988, to March 5, 1989 (Katsui et al., 1990; Nishimura et al., 1990; Nishimura and Okada, 1994). Meakan is another active andesitic volcano 1499 m high, located on the eastern part of Hokkaido at 43°23′N, 144°01′E (Fig. 1). The first recorded activity was rumblings reported in 1927. Explosive eruptions were then detected from 1955 to 1956. Other small eruptions were registered from

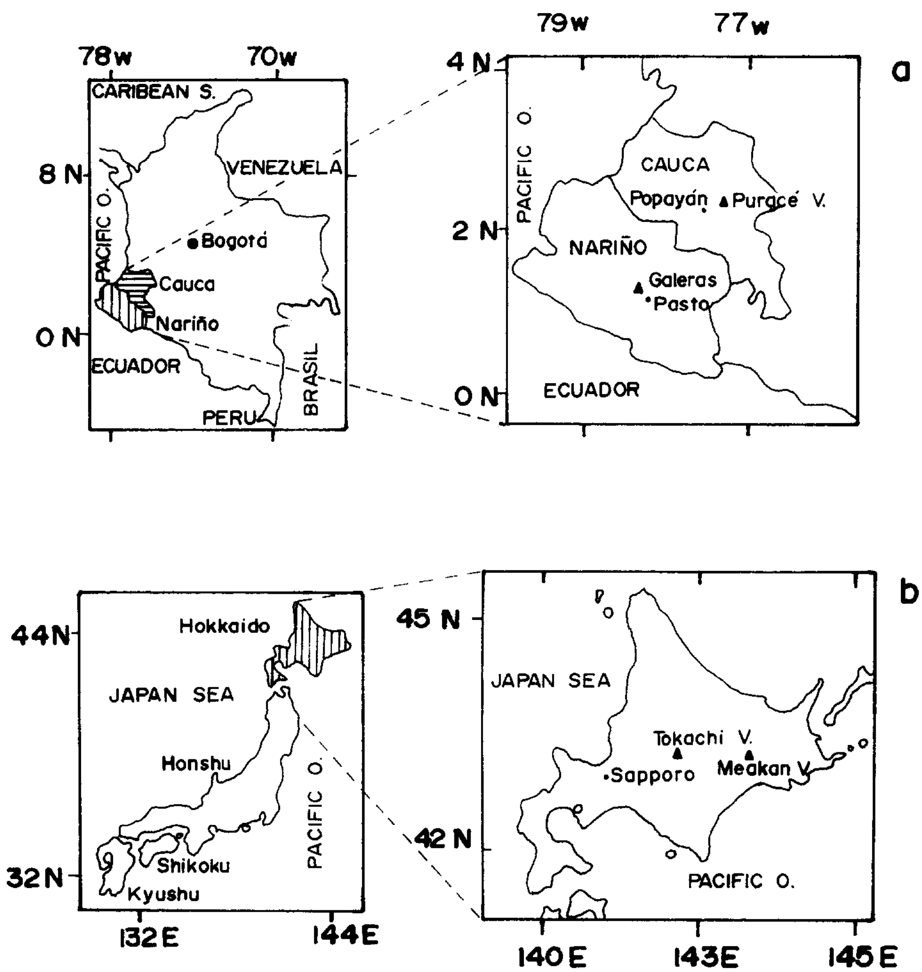

Fig. 1. Location maps of (a) Galeras volcano in Nariño Department and Puracé volcano in Cauca Department, in the southwest part of Colombia and (b) Hokkaido Island in Japan, where Meakan and Tokachi volcanoes are located.

1957 to 1966 (Nishimura and Yamashita, 1982). In 1987, a very small ash emission was observed around the active crater (Y. Nishimura, pers. commun., 1994).

In a common manner, the volcanoes mentioned above have recorded an unusual seismic signal during various timeframes and during different types of activity, such as before eruptions, during seismic

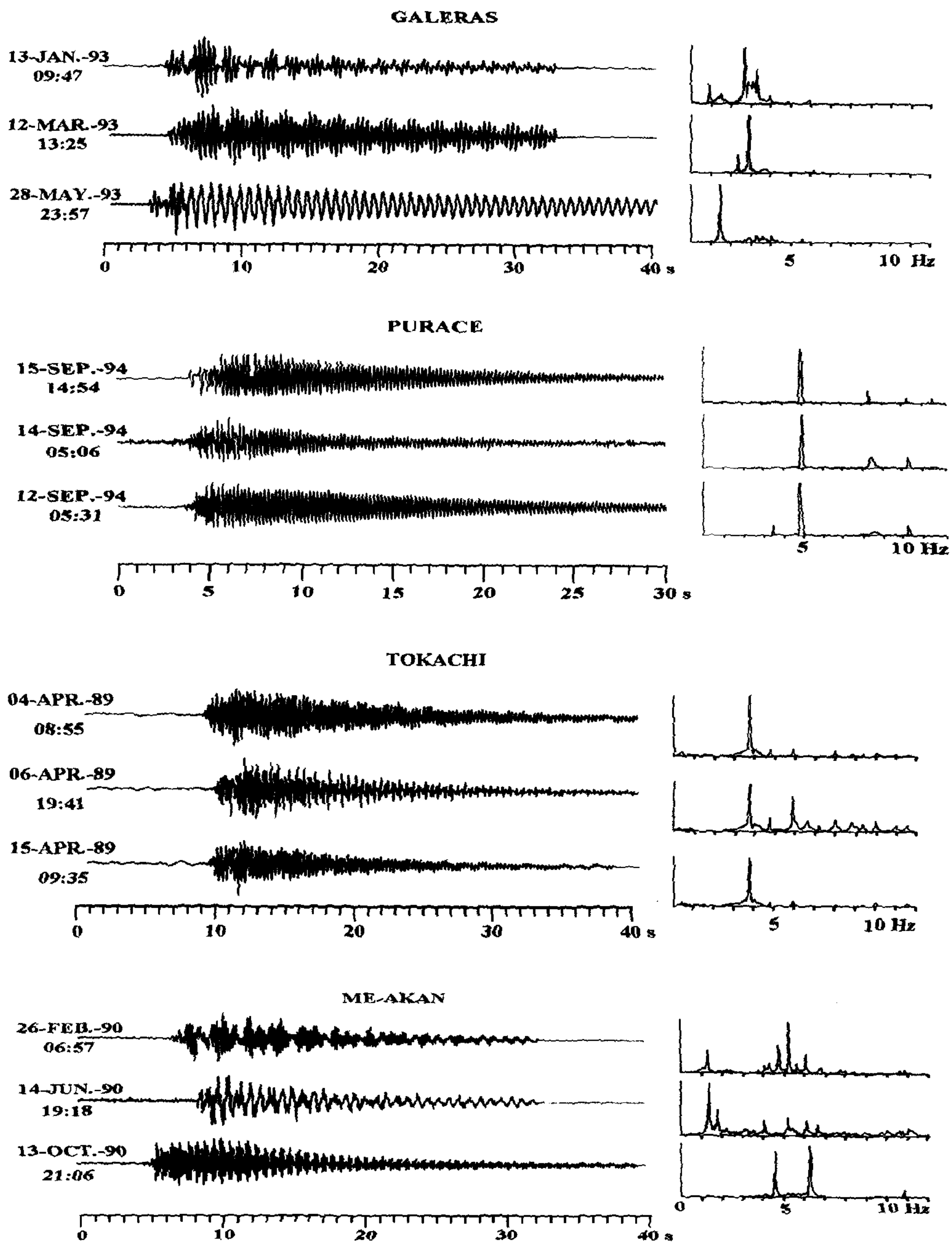

Fig. 2. Examples of some typical tornillo events and their respective spectra registered at seismic stations nearest to the active craters of Galeras (a–c), Puracé (d–f), Tokachi (g–i) and Meakan (j–l).

Table 1
Brief review of seismic signals with slowly decaying coda waves observed at Colombian and Japanese volcanoes. Modified from Herman (1990)

Volcano	Time and/or frequency	Swarm/individual	Coda character	Specific volcanic activity	Name of events	Earthquake at the beginning	Eruption precursor	Spectral analysis	Reference/remarks
Galeras	9 events, July 11–16, 1992	individual	slowly decaying coda	short-term precursor to July 16 eruption	tornillo events	no	yes	yes	Gómez, 1994; Torres et al., 1996
	20 events, December 23, 1992–January 14, 1993	individual	slowly decaying coda	short-term precursor to January 14 eruption	tornillo events	no	yes	yes	Gómez, 1994; Torres et al., 1996
	74 events, February 13–March 23, 1993	individual	slowly decaying coda	short-term precursor to March 23 eruption	tornillo events	no	yes	yes	Gómez, 1994; Torres et al., 1996
	6 events, April 10–12, 1993	individual	slowly decaying coda	short-term precursor to April 13 eruption	tornillo events	no	yes	yes	Gómez, 1994; Torres et al., 1996
	103 events, April 18–June 7, 1993	individual	slowly decaying coda	short-term precursor to June 7 eruption	tornillo events	no	yes	yes	Gómez, 1994; Torres et al., 1996
	83 events, July 1–November 26, 1993	individual	slowly decaying coda	during quiescence	tornillo events	no	no	yes	Gómez, 1994; Torres et al., 1996
	31 events, August 9–September 23, 1994	individual	slowly decaying coda	large gas emission	tornillo events	no	yes	yes	this study
	80 events, October 20, 1994 to January 5, 1995	individual	slowly decaying coda	large gas emission	tornillo events	no	yes	yes	this study
Puracé	20 events, 1994	individual	slowly decaying coda	during quiescence	tornillo events	no	no	yes	this study
Kusatsu-Shirane-san	31 events, 6 months, 1975		overtone spectrum slowly decaying coda	high seismic activity	T-type earthquakes	yes	no	yes	Hamada et al., 1976
	10 events, 15 days, 1984		overtone spectrum slowly decay coda	during quiescence	type 1–type 6	unclear	no	yes	Ueki et al., 1985
Tarumai-san	34 events, 19 months, from 1970–71, 1975	individual	slowly decaying coda	no activity	T-type earthquakes	yes	no	no	Hamada et al., 1976

Asama-yama	1 event January 15, 1961		special oscillation		special type		no	no	Sekiya, 1967
	49 events, 20 months, from 1961–1964, 1970–1971		overton spectrum slowly decaying coda	seismicity decrease	T-type earthquakes	not always	no	no	Hamada et al., 1976
	hundreds in several days, April 1983	swarm	monochromatic slow-decay	after high-frequency swarm	N-type earthquake	(?)	yes	no	Kagiyama et al., 1985
Miyake-jima	many events, 16 days, October–November 1983	swarm	equally spaced spectrum peaks	after 1983 eruption	L-period earthquake type 2	no	no	yes	Shimizu et al., 1984
Krishhima-yama	13 events, 5 months, 1968		slowly decaying coda	beginning of seismic swarm	T-type earthquakes	(?)	no	no	Hamada et al., 1976
Sakura-jima	15 events, 1967–1970	individual	slowly decaying coda	explosive activity since 1955, no eruption	T-type earthquakes	(?)	no	no	Hamada et al., 1976
Kushino-crabujima	some events in 20 days, June 1975	individual	slowly decaying coda		T-type earthquakes	(?)	no	no	Hamada et al., 1976
Tokachi-dake	7 events, December 1985–March 1987	individual	overtone spectrum slowly decaying coda	long-term precursor to 1988–1989 eruptions	Banded spectrum earthquakes	unclear	yes	yes	Matsushima et al., 1987
	4 events, December 4–5, 1988	swarm		before 1988–1989 eruption	Banded spectrum earthquakes		yes	no	Usu Volcano Observatory, 1989
	35 events, April 3, 1989	swarm	overton spectrum slowly decay coda	after 1988–1989 eruption	Banded spectrum earthquakes	unclear	no	yes	Usu Volcano Observatory, 1989
Meakan-dake	14 events, March 28–April 5, 1982	swarm	Abnormally long coda	during 1982 seismic swarm	L-type earthquakes	yes	no	no	Nishimura and Yamashita, 1982
		individual	monochromatic, long coda		type III,	no	no	no	Sapporo Meteorological Observatory, 1988
					type IV	yes	no	no	
	many events December 10–12, 1987	swarm	monochromatic, long coda	precursor swarm to 1988 eruption	single frequency earthquake	often	yes	yes	Usu Volcano Observatory, 1988

swarms of volcano-tectonic earthquakes, after eruptions, or during quiescent periods (Table 1; Fig. 2). We call these signals 'tornillos' (Spanish for 'screw'), whose shape resembles the side view of threaded metal screw (Torres et al., 1996), while in Japan several names have been used to refer to these particular signals, such as LC events (long-coda events), BS events (banded-spectrum earthquakes), SF events (single-frequency earthquakes) or T-type events (similarity with a T-square; Table 1).

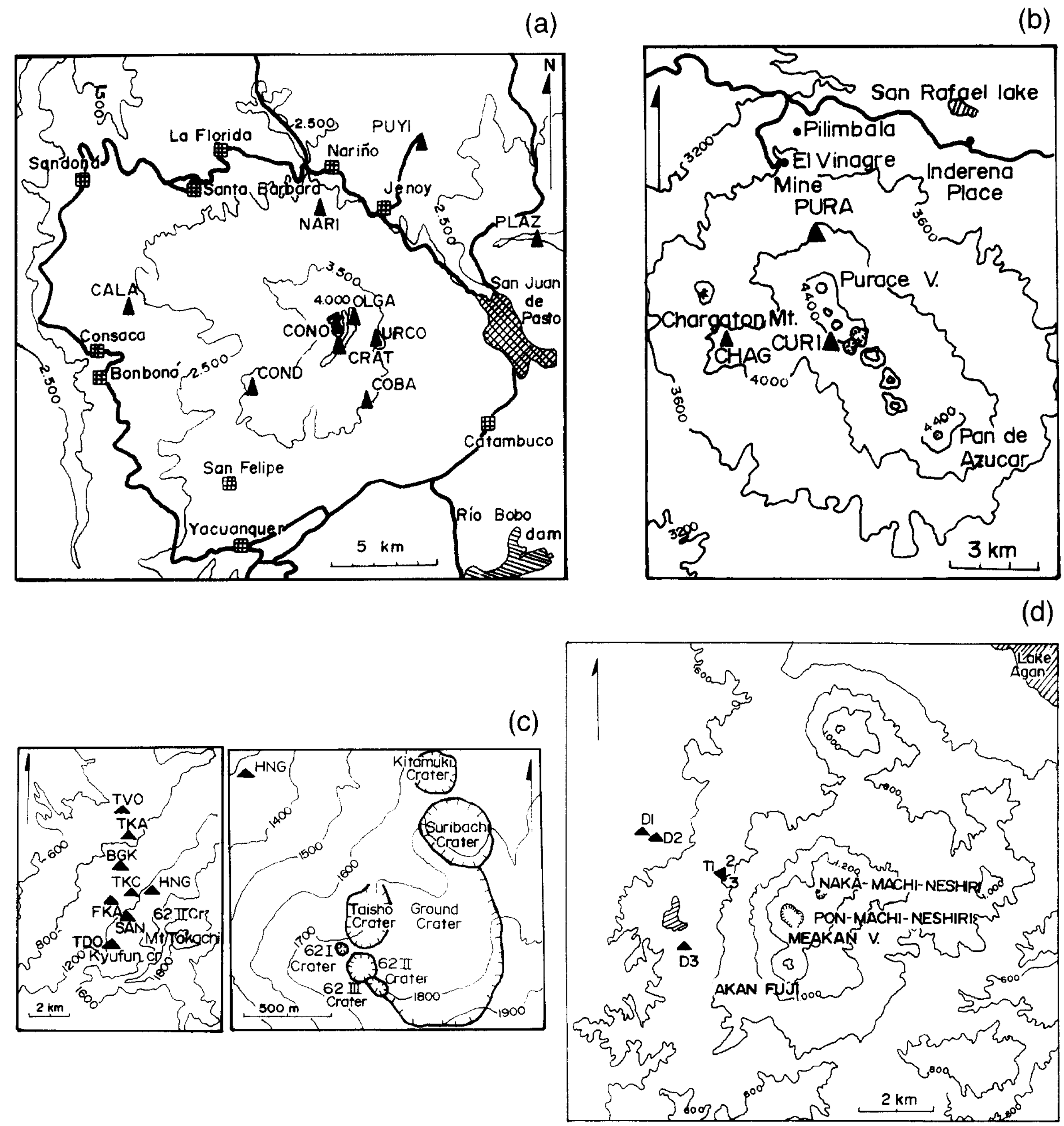

Fig. 3. Maps showing the various volcanic seismic networks: (a) Galeras; (b) Puracé; (c) Tokachi (after Okada et al., 1990); and (d) Meakan (after Nishimura and Yamashita, 1982).

In this paper, 55 of these signals from Galeras, 20 from Puracé, 26 from Tokachi-dake and 40 from Meakan-dake volcanoes were described and analyzed for parameters such as occurrence, frequency content, damping coefficient, and Quality factor (Q_c). These parameters are compared among the different volcanoes to arrive at a common interpretation of these signals.

2. Seismic networks

Seismic data were acquired by permanent seismic networks operated by the Instituto de Investigaciones en Geociencias, Minería y Química (INGEOMINAS) in Colombia and Usu Volcano Observatory of Hokkaido University in Japan. The Galeras network consists of eight telemetered stations located from 0.9 to 10 km from the active crater. At Puracé volcano, the seismic activity is monitored by three telemetered stations at distances of 1.5 and 4 km from the crater. The signals of Tokachi volcano were recorded by three stations at about 2.0, 2.8 and 3.5 km from the active crater. At Meakan volcano, the seismic signals were registered by one permanent station and three stations that were placed close to each other at about 2.0 km northwest of the active crater, forming a small triangle of about 600 m on a side. The stations were equipped with vertical-component Mark Products L-4C seismometers of 1 Hz natural frequency which are damped at 0.72 of critical damping. Fig. 3 depicts the seismic networks for the different volcanoes. The signals are telemetered to the observatories where the events are recorded simultaneously in analog and digital formats. A digitizing rate of 100 samples per second was used for real-time data acquisition and recording.

3. Characterization of tornillo events

3.1. Waveforms

The volcanoes considered in this report exhibit several quasi-sinusoidal waveforms that are long-duration events with slowly decaying coda waves and small amplitudes compared to their durations. Some tornillos show amplitude modulation effects. During the entire signal, a low-frequency and quasi-monochromatic waveform predominates, sometimes showing a weak high-frequency onset which is superimposed on the low frequency (Fig. 2; Torres et al., 1996). In general, the signals show emergent onsets (Fig. 4a), but occasionally some events have slight impulsive onsets. First arrivals show mainly positive polarities (Fig. 4c) or a weak impulsive onset with negative polarity, followed by a larger positive polarity (Fig. 4b). For Galeras tornillos, we define the 'Slenderness' parameter as the ratio between the duration of the signal and its respective maximum ground velocity, since they have a slowly decaying coda wave. Slenderness values ranging from 5 to 145 s/(μm/s) were obtained for the Galeras tornillo events. By contrast, normal long-period events at Galeras have slenderness values less than 10 s/(μm/s). For the other volcanoes, it was not possible to calculate this parameter due to the lack of available instrument responses.

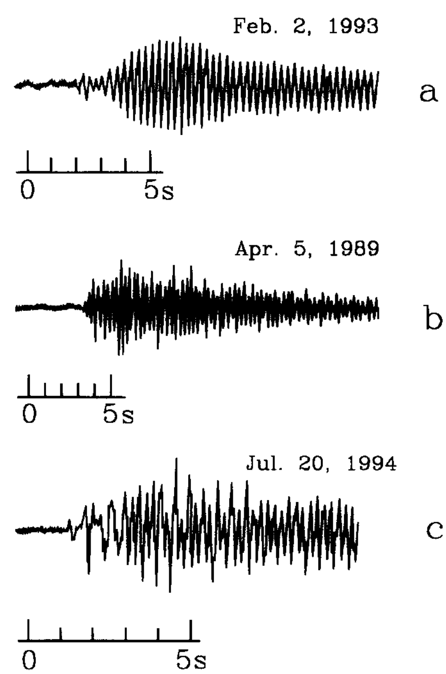

Fig. 4. Onsets of tornillo events at three volcanoes. (a) Galeras, showing emergent onsets. (b) Tokachi, exhibiting a weak impulsive onset with negative polarity, followed by a larger amplitude with a positive polarity. (c) Puracé, showing an impulsive arrival onset.

It is important to mention that Cumbal and Nevado del Ruíz volcanoes in Colombia have shown some quasi-sinusoidal and quasi-monochromatic waveform events. However, these events are not tornillos, since they do not have long durations compared to their amplitudes and do not exhibit a clear slowly decaying coda wave.

3.2. Spectrum

The spectrum was calculated over the entire signal using the FFT algorithm. The vertical axis displays the normalized amplitude. The spectrograms have been calculated with moving windows of 2 seconds having an overlapping interval of 1 second running through the entire signal.

The spectral content of the tornillos analyzed shows one or several narrow peaks, with the same values at all stations where the signals were recorded (Fig. 5). The events are quasi-monochromatic signals, with dominant frequencies between 0.9 and 3.5 Hz for Galeras, from 3.4 to 8.0 Hz for Puracé, around 3.7 Hz for Tokachi and from 1.2 to 7.0 Hz for Meakan. The weak high frequency noted in the onset, which is superimposed on the low frequency, produced small spectral peaks ranging from 6 to 12 Hz.

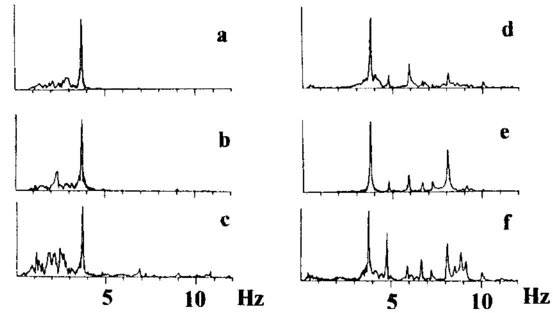

Fig. 5. Spectra of tornillo events at different volcanoes and stations. (a), (b) and (c) correspond to a tornillo event registered at Galeras on April 22, 1993 at Crater-2, Urcunina and Cobanegra-2 stations, respectively. The spectra for a tornillo event registered on April 13, 1989, at Tokachi are shown in (d), (e) and (f) for TKC, TDO and BGK stations, respectively. For each individual network, the dominant frequencies are the same among the different stations.

3.3. Damping coefficient for coda waves

The tornillo signals appear to show a long, quasi-linear, slowly decaying coda. However, their amplitudes can be characterized by an exponential function defined by $\exp(-\alpha t)$, where α is the amplitude decay coefficient that depends on the damping coefficient (h) and the frequency (f) of the signal:

$$\alpha = 2\pi f h \tag{1}$$

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

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

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. Low values of the damping coefficient imply gradually decaying coda waves, while higher values correspond to a more rapidly decaying waveform. The damping coefficient values for tornillo events are between 0.002 and 0.02, corresponding to lower values. By contrast, for normal long-period events, damping coefficient values range from 0.010 to 0.025, while for volcano-tectonic earthquakes this coefficient varies between 0.010 and 0.040.

4. Data analysis

4.1. Time of occurrence

4.1.1. Galeras volcano

The importance of tornillos at Galeras is that they have preceded all but one of the six 1992–1993 eruptions that occurred after the emplacement of the lava dome, which was first seen in the crater in October 1991 (Table 1; Gómez and Torres, 1993; Stix et al., 1993). Immediately after each of these eruptions, the tornillo events disappeared for several days (Fig. 6). An exception was the eruption on April 4, 1993, when Galeras had a small eruption that was not preceded by tornillo events, but it was of lesser intensity in comparison with the others (Cortés and Calvache, 1993). Furthermore, this eruption may be interpreted as the final stage of the

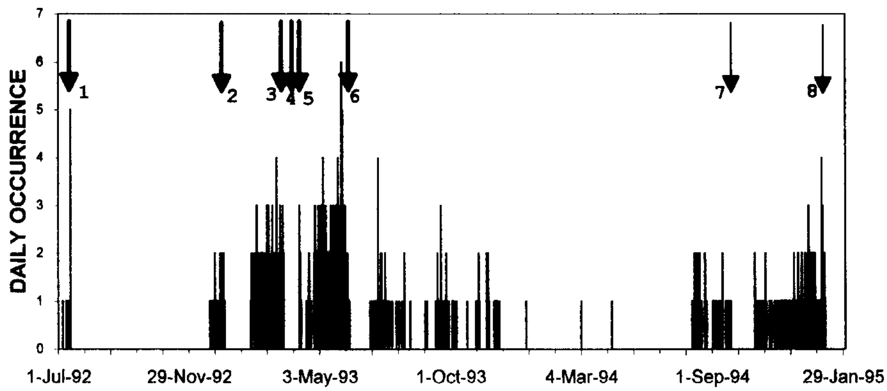

Fig. 6. Daily number of tornillo events recorded at Galeras volcano from July 1, 1992 to January 5, 1995. The thick arrows indicate the occurrence of eruptions: (*1*) July 16, 1992; (*2*) January 14, 1993; (*3*) March 23, 1993; (*4*) April 4, 1993; (*5*) April 13, 1993; and (*6*) June 7, 1993. The narrow arrows indicate large gas emissions on (*7*) September 23, 1994 and (*8*) January 11, 1995. After the eruptions, the tornillo events disappeared for several days.

March 23, 1993, activity or the initial stage of the June 7, 1993, activity. Another period of interest was noted from July 1 to November 26, 1993, since there was occurrence of 83 tornillos, but without an eruption (Table 1). For the 1992–1993 eruptions, a direct relationship exists between the total number of tornillos prior to an eruption and the volume of material ejected by the eruption (Table 2).

4.1.2. Puracé volcano

Between July 6 and November 11, 1994, 27 tornillo events were recorded. They were registered also in 1991 at low levels. In both cases, this kind of seismicity was not related to any eruptive activity. Presently, the activity at Puracé volcano is characterized by gas emission with a significant magmatic component (Martini, written commun., 1992) but low levels of seismicity.

4.1.3. Tokachi volcano

From December 16, 1988 to March 5, 1989, 23 explosive eruptions occurred (Katsui et al., 1990). One month later, from April 3 to 19, 1989, a swarm of 35 seismic signals characterized by slowly decaying coda waves were recorded for the first time on this volcano (Nishimura and Okada, 1994). These events were not accompanied by any eruptive activity.

Table 2
Parameters of 'tornillo' events and eruptions at Galeras

Date of eruption (dd/mm/yy)	Events (#)	Days of record	Duration of events [b] (s) Max	Duration of events [b] (s) Aver	Tephra volume emitted ($\times 10^6$ m^3)	Ash column height (km)	Relative size of eruption [d]
16/07/92	9	5	97	69	0.28	6	3rd
14/01/93	20	16	200	75	— [c]	— [c]	?
23/03/93	74	37	185	80	0.835	8	2nd
13/04/93	6	3	67	44	0.22	6	4th
07/06/93	103	46	214	87	1.25	9	1st
23/09/94 [a]	31	25	180	67	— [c]	— [c]	?
05/01/95 [a]	80	56	330	105	— [c]	— [c]	?

[a] Correspond to large gas emissions.
[b] Values from Crater-2 seismic station.
[c] Estimates not possible.
[d] Estimated from volume and eruption column height (Cortés and Calvache, 1993).

4.1.4. Meakan volcano

In March 1982, a swarm of volcano-tectonic earthquakes occurred, accompanied by fourteen events with long durations (Nishimura and Yamashita, 1982). In 1987, a very small ash emission was observed around the active crater which was preceded by some long coda events (Y. Nishimura, pers. commun., 1994). Generally, this type of seismicity has been registered without eruptions at Meakan volcano.

4.2. Durations

4.2.1. Galeras volcano

Tornillo events at Galeras have shown durations from 25 to 330 seconds. In general, there is a progressive increase in the duration of tornillos to a maximum value, followed by a slight decrease, prior to eruptions. Additionally, there is a relationship between the duration and the volume of material ejected. Longer durations of individual tornillos are followed by larger volumes of material emitted (Table 2).

4.2.2. Other volcanoes

Tornillo events on Puracé volcano have shown durations from 20 to 65 seconds. The Japanese volcanoes considered in this report have recorded durations less than 120 seconds. Similar to Puracé, Tokachi and Meakan volcanoes do not show a clear pattern with respect to signal durations.

4.3. Amplitude decay

4.3.1. Galeras volcano

The damping coefficient values for the Galeras tornillo events are distributed from 0.002 to 0.016. Twenty-nine of the 55 events analyzed (about 52%) indicate low values for the damping coefficient between 0.002 and 0.005.

The relationship between the damping coefficient and the duration of the signal was also examined and is shown in Fig. 7. No clear trend is observed, which may be due to the fact that the duration of signals is affected by many factors, such as the signal amplitude, frequency content, travel distance, and path effects. However, from Fig. 7 we note that the

Table 3
Damping coefficients of coda waves and dominant frequencies of tornillo events registered in some Colombian and Japanese volcanoes. Modified from Hamada et al. (1976)

Volcano	Events (#)	Period of time tornillos observed	Dominant frequency (Hz)	Damping coefficient	References
Galeras	20	December 23, 1992–January 14, 1993	0.90–3.0	0.002–0.014	Gómez, 1994; Torres et al., 1996
	74	February 13–March 23, 1993	2.5–3.5	0.003–0.016	Gómez, 1994; Torres et al., 1996
	103	April 18–June 7, 1993	1.5–3.8	0.002–0.010	Gómez, 1994; Torres et al., 1996
Puracé	27	July 6–November 11, 1994	4.6–8.0	0.002–0.005	this study
Tokachi-dake	25	April 3–April 19, 1989	3.3–5.0	0.004–0.011	after Usu Volcano Observatory, 1989; Nishimura and Okada, 1994
Meakan-dake	250	February 1990–July 1994	3.5–7.5	0.004–0.019	after Usu Volcano Observatory, 1989; Nishimura and Okada, 1994
Taisetsu	7	August 1990–September 1991	0.9–3.0	0.003–0.004	after Usu Volcano Observatory, 1989; Nishimura and Okada, 1994
Asamayama	49	January–August 1961	1.0–5.0	0.002–0.03	after Hamada et al., 1976
Tarumae-yama	34	February 1970–February 1971 and May–June 1975	0.7–3.3	0.005–0.03	after Hamada et al., 1976
Kusatsu	31	January–June 1975	1.1–3.3	0.003–0.005	after Hamada et al., 1976
Sakurajima	15	December 1967–February 1970	2.5–5.0	0.007–0.02	after Hamada et al., 1976
Kushinocrabujima	1	June 1975	4.3	0.02	after Hamada et al., 1976

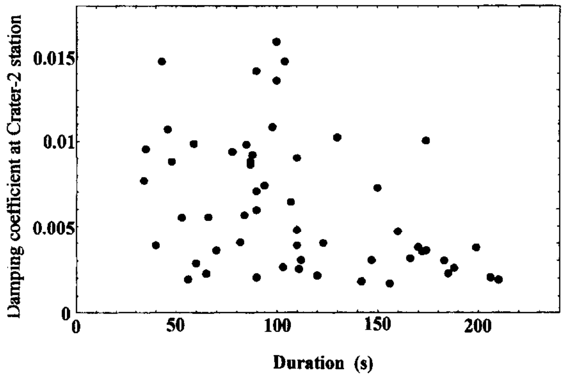

Fig. 7. Relationship between damping coefficients and durations of tornillo events for Crater-2 station at Galeras. Durations were measured by using the analog seismograms.

longest tornillos (more than 100 s) correspond to the lowest values of the damping coefficient, namely between 0.002 and 0.004.

4.3.2. Puracé volcano

For the events on this volcano, the damping coefficient shows values from 0.002 to 0.005, which is reflected in the slowly decaying amplitude of coda waves. This range is the same as that for about half of the Galeras tornillos.

4.3.3. Tokachi and Meakan volcanoes

The signals on Tokachi indicate damping coefficient values between 0.004 and 0.011, while those of Meakan volcano range from 0.004 to 0.019. The dominant frequencies and damping coefficients of coda waves for the different volcanoes in Japan and for Galeras and Puracé volcanoes are shown in Table 3, as modified from Hamada et al. (1976). The damping coefficient for all the volcanoes ranges from 0.002 to 0.03, with the lowest values for Puracé, Galeras and Asamayama.

4.4. Frequency contents

4.4.1. Galeras volcano

Prior to the January 14, 1993, eruption, the spectra showed two main peaks of about 0.9 and 3.0 Hz and other small peaks of around 1.5, 3.4 and 4.0 Hz (Fig. 8d). Prior to the March 23, 1993 eruption, the spectra indicated three dominant peaks of approximately 2.5, 3.0 and 3.5 Hz and smaller peaks between 1.0–2.0 and 5.0–7.5 Hz during the first days of recording. Thereafter, the spectra displayed only two dominant frequencies of about 2.5 and 3.0 Hz and weaker peaks similar to those observed at the beginning (Fig. 8i). The single tornillo event recorded

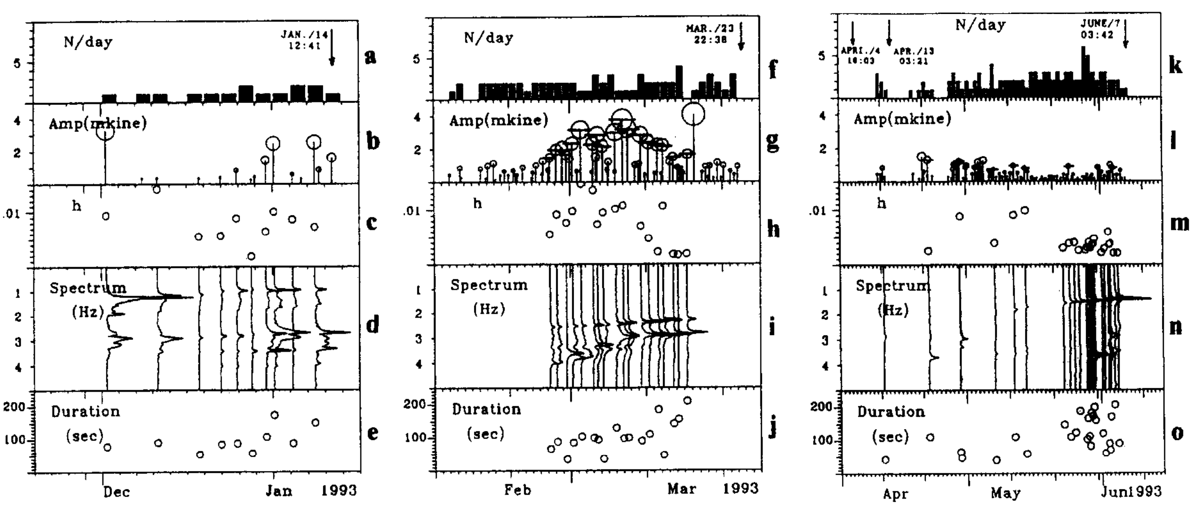

Fig. 8. Some examples of the spectra for tornillo events of Galeras volcano at different stations, during various eruptive episodes: (a) prior to January 14, 1993; (b) before March 23, 1993; and (c) prior to June 7, 1993. For a particular episode, dominant frequencies are the same at the different stations. However, the dominant frequencies change from one episode to the next.

before the April 13, 1993 eruption indicated two main peaks of around 1.2 and 2.8 Hz and other small intermediate values. Tornillos prior to the last eruptive episode on June 7, 1993 were initially characterized by one main peak at around 3.8 Hz and another at about 2.8 Hz. After a few days, the frequency changed to one dominant peak near 1.5 Hz and another peak of about 3.6 Hz. Minor peaks between these frequencies and between 5.0 and 7.5 Hz also were noted (Fig. 8n). It was observed that during the January 14, March 23 and June 7 episodes (particularly that of the March 23 event), the signal spectrum showed peaks with small variations, as reflected in the waveform by amplitude modulation. These variations ranged from 0.3 to 0.7 Hz. Fig. 2b is a good example of this amplitude modulation effect.

Fig. 9 shows examples of spectra of tornillo events from three different stations and from three pre-eruptive episodes for Galeras. It is observed that dominant frequencies are the same at all stations for an individual tornillo event. This characteristic suggests that these frequencies reflect a source effect. By contrast, the peak frequencies are different for all four eruptive episodes, suggesting that source conditions changed.

Variations in the spectra also were noted among the different stations (Crater-2, Urcunina and Cobanegra-2), which could be associated with path effects or seismometer locations. In particular, the Urcunina station shows prominent modes of power for relatively high frequency contents. On the other hand, the most distant station (Cobanegra-2) showed attenuation for the high frequency contents in many cases. This indicates that the high frequencies are more easily attenuated with distance than the low frequencies.

A most interesting characteristic observed for the Galeras tornillos has been the decrease of dominant frequencies prior to eruptions. After the decrease, the frequencies tend to stabilize for several days before the eruptions (Fig. 8d,i,n). This pattern could indicate that conditions evolve to a stable, critical state prior to eruptions. The decline and subsequent stabilization of the dominant frequencies have important implications for eruption forecasting.

4.4.2. Puracé volcano

The spectra for Puracé volcano generally are characterized by one narrow peak, but in some cases they show several sharp frequency peaks. The dominant frequencies are in the range of 4.6–8.0 Hz, while the small peaks are obtained in the range of about 2.0–3.0 Hz with other peaks of about 8.0–11.0 Hz (Fig. 2d–f). The peak frequencies are the same among stations. At the beginning of one period of tornillos on July 7, 1994, the dominant frequencies

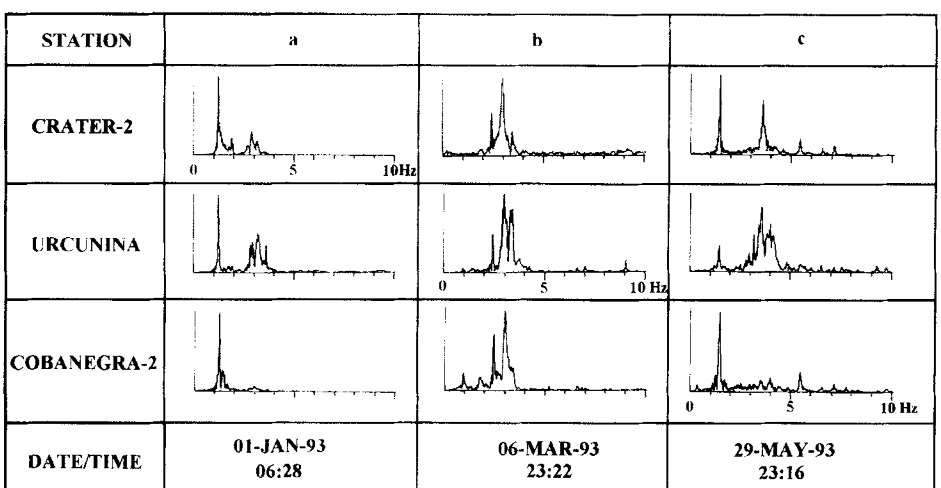

Fig. 9. Comparison of characteristics of tornillo events at Galeras just before the January 14, 1993, eruption (a–e), prior to March 23, 1993, eruption (f–j) and before the June 7, 1993, eruption (k–o). Daily number of events are shown in (a), (f) and (k), peak-to-peak amplitudes in (b), (g) and (l), damping coefficients in (c), (h) and (m), spectra in (d), (i) and (n), and durations of events in (e), (j) and (o). The arrows indicate the dates and times of eruptions.

showed a value of 4.6 Hz. After that, they changed to 5.0 Hz in September 1994. From September 9 to 15, 1994, the peak frequencies ranged from 4.9 to 5.3 Hz. Afterwards, the dominant frequencies increased to 8.0 Hz on November 11, 1994.

4.4.3. Tokachi volcano

The spectra for this volcano also are characterized by several sharp frequency peaks. These frequencies are in the range of 3.7 to 10 Hz. The peak frequencies are the same among the events and also among different stations. The frequency contents do not show variations relative to time or with the location of the seismic stations. For all events at the three stations, the common dominant frequency is 3.75 Hz as shown in Fig. 2h–j. For the stations nearest to the active crater (TKC and TDO), two other important peaks of about 5.75 and 7.80 Hz were noted. Other small peaks also were observed at about 4.75, 6.50, 7.10, 7.80 and 9.00 Hz. The interval between the peaks was nearly the same, with values from 0.6 to 1.0 Hz, and amplitude modulation was noted in several seismograms (Fig. 2g–i).

4.4.4. Meakan volcano

With regard to the frequency contents of tornillo events, this is the most complex system compared with Galeras, Puracé and Tokachi volcanoes. Numerous sharp spectral peaks were observed in the seismograms. Fig. 2j–l indicates that the predominant frequencies were unstable with time. The range of frequencies for these events is between 1.0 and 12.0 Hz. In most cases, the dominant frequency peaks are from 3.5 to 7.5 Hz. For several cases, another range of predominant frequencies between 1.0 and 2.0 Hz was noted. However, the dominant frequency contents are the same for the three stations, but different from one event to the next. For several sesimograms, amplitude modulation was again noted, as shown by the signals in Fig. 2j–l.

5. Evolution of tornillo events at Galeras volcano

The temporal development of daily occurrences, amplitudes, damping coefficients of coda waves, dominant peak frequencies and durations of tornillo events was evaluated for three eruptive episodes of January 14, March 23 and June 7, 1993 at Galeras volcano.

Prior to the January 14, 1993 eruption, a total of twenty tornillo events were registered sporadically from December 23, 1992 to January 14, 1993, as shown in Fig. 8a. Fig. 8b shows the amplitude of signals, expressed in mkine (Japanese conventional velocity units), where 1 kine is equivalent to 1 cm/s. The values were computed from the analog data. The episode started with a relatively large signal, then changed to small-sized signals which gradually became larger with time for the days before eruption. The damping coefficient of coda waves does not show a clear pattern (Fig. 8c).

The dominant frequencies show small temporal variations. The tendency is from higher to slightly lower values. These frequencies showed stability several days before the eruption (Fig. 8d). The duration times shown in Fig. 8e were evaluated from the analog records and suggest that a greater number of events of longer duration were recorded several days prior to eruption.

Before the March 23, 1993 eruption, a total of 74 tornillo events were observed over 37 days. The events were registered sporadically, with an average of about 2 events per day (Fig. 8f). Amplitudes showed early stability and small-size signals, then began increasing on February 25 (Fig. 8g). After this, the amplitudes decreased, with a combination of larger and smaller signals. Additionally, a few days before the eruption, a large amplitude signal occurred, indicating an abnormality in the trend. The damping coefficients of coda waves do not show a clear trend in the earlier days. Nearer to the eruption, however, these coefficients exhibit a decline and subsequent stability (Fig. 8h).

It was observed that the frequencies gradually declined to lower values, then stabilized a few days before the eruption (Fig. 8i). By contrast, the duration of signals tended to increase several days prior to eruption (Fig. 8j). The episode prior to the March 23, 1993, eruption was the most stable in terms of waveform pattern. For this episode, no clear events with high frequencies at the onsets were observed.

After the March 23, 1993 event, two small eruptions occurred on April 4 and 13. These eruptions may be considered to be a final stage of the March activity or an initial stage of the eruptive episode of

June 7, 1993. With the data used in this study, it is not possible to clarify these hypotheses.

For the last eruptive episode of June 7, 1993, tornillo events also were registered sporadically, totaling 103 events in 46 days, with an average of about two events per day (Fig. 8k). In comparison to the previous episodes, a maximum daily number of six tornillos was observed on May 28, 1993. The amplitudes for this episode were characterized by the occurrence of small-size events (Fig. 8l). However, a combination of larger and smaller size events also was noted. The damping coefficients of coda waves show no clear trend in the earlier days, but the coefficients were low for several days prior to the eruption (Fig. 8m). The frequency trend is similar to the previous eruptive episodes (Fig. 8n). At the beginning of this episode, the frequencies showed instability for dominant peaks, then gradually declined to relatively lower values. For several days before the eruption, the frequencies were stable. The duration of signals showed a tendency to increase with time, although there is some variation immediately before the eruption (Fig. 8o). Comparing Fig. 8l, m and n, it is clear that small-amplitude signals show a positive correlation among low amplitudes, low damping coefficients, and stable low-frequency peaks (less than 2 Hz), particularly for the last few days before the eruption.

From July 1 to November 26, 1993, there were 83 tornillo events during 75 days. No eruption occurred following these events. The dominant frequencies of these events showed a range from 1.6 to 3.8 Hz and a maximum duration of 127 seconds. For this period, no clear pattern was observed for the parameters discussed above, in contrast with the previous periods that concluded with eruptions.

Another period of tornillos at Galeras occurred from August 9 until September 23, 1994, ending with a large gas emission from different points of the active cone. In this period, 31 events were recorded, with a maximum duration of 180 seconds. The spectra were characterized by one narrow peak ranging from 3.23 to 2.63 Hz. For this episode, a gradual decrease in the frequency values again was observed, as was reported for the eruptions of 1992–1993.

The final period of tornillos recorded at Galeras occurred from October 20, 1994 to January 5, 1995, which ended on January 11, 1995 with another gas emission from the active cone, similar to that reported for the previous period. A total of 80 tornillo events were recorded, showing a maximum duration of 330 seconds, which corresponds to the longest tornillo duration observed at Galeras volcano until now (August 1996).

6. Quantitative analysis

The sinusoidal waveforms and spectra of tornillos are characteristic of hydraulically generated seismicity by the water hammer effect (Lawrence and Qamar, 1979) and hydrofracture experiments (Bame and Fehler, 1986; Ferrazzini et al., 1990). The fact that the spectra of these signals usually contain one or a series of narrow frequency peaks, sometimes regularly spaced, suggests several possible source models which consider oscillation modes of a resonant system (Chouet, 1981) associated with opening cavities, pipes or cracks, which are induced by a pressure transient applied over an area of the wall (Aki et al., 1977; Chouet, 1981, 1985, 1988; Ferrick et al., 1982). The origin of this pressure transient may be bubble bursts in a vesiculating fluid (Kieffer, 1984) or unsteady fluid flow (Chouet, 1992). Some of these events are remarkably monochromatic, and their spectra contain only one peak without harmonics. These observations indicate that only one vibration mode of the resonator is excited, and that a relative simple source model could account for their features (Lesage and Surono, 1995). 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 frequency stability indicates that the source parameters remain constant, while changes in frequency could reflect variations of the source dimensions, the physical properties of the fluid, and/or the surrounding solid material.

Considering the Spherical Source Model proposed by Crosson and Bame (1985), the displacements at a distance R from the source center (Fig. 10) are given by:

$$U(R;P) = 2P_0 \frac{\rho f}{\alpha f} a^3 b^3 p^3 T_s(pR) \frac{1}{R^2} \frac{1}{\Delta} e^{(-p/\alpha_s)R} \tag{3}$$

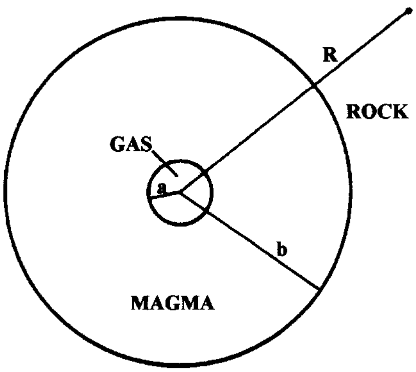

Fig. 10. Figure showing Crosson and Bame (1985) two-boundary model. The inner cavity contains gas or bubble froth within the magma body. The outer cavity is a fluid–solid interface. Field observation points are in country rock outside the outer boundary.

where

$$\begin{aligned}\Delta = {} & Q_f(pa)e^{(\rho_f/\alpha_f)(b-a)}e^{(-\rho_s/\alpha_s)b}\\ & \times[Q_f(-pb)T_s(pb) - Q_s(pb)T_f(-pb)]\\ & +\left[Q_f(-pa)e^{(-\rho_f/\alpha_f)(b-a)}e^{(-\rho_s/\alpha_s)b}\right]\\ & \times[Q_s(pb)T_f(pb) - Q_f(pb)T_s(pb)]\end{aligned} \tag{4}$$

with

$$Q_i(x) = \rho_f x^2 + 4\frac{\mu_i}{\alpha_i}x + 4\mu_i \tag{5}$$

and

$$T_i(x) = \left[1 + \frac{x}{\alpha_i}\right] \tag{6}$$

where $i = \mathrm{s}$ for wallrock and $i = \mathrm{f}$ for magma, and where $x = pa$ or $x = -pa$ for the bubble, and $x = pb$ or $x = -pb$ for the magma body. In these expressions, p is the Laplace transform parameter, and we obtain the frequency domain solutions by making the transformation $p \to iw$, where w is the angular frequency ($2\pi f$). The properties of the solid rock and the fluid magma are given, respectively, by densities (ρ_s, ρ_f), the compressional wave velocities (α_s, α_f), the shear wave velocitites (β_s, β_f), the rigidity of the solid (μ_s) and the shear modulus of the magma (μ_f).

For the solidified andesitic magma which constitutes the wall of the cavity, we assume $\rho_s = 2600$ kg/m^3, $\mu_s = 3.12 \times 10^{10}$ N/m^2, where $\mu_s = \alpha_s^2 \rho_s/3$, $\alpha_s = 6000$ m/s and $\alpha_s/\beta_s = \sqrt{3}$. Although the physical parameters for the fluid-filled magma cavity are more difficult to ascertain, we consider $\rho_s = 2400$ kg/m^3 (Murase and McBirney, 1973).

In the model proposed by Crosson and Bame (1985), the signal is generated by the sudden expansion of a gas bubble in the center of the volume of magma. Table 4 shows a summary of the values for the model parameters selected in our calculations. Estimates based upon the volume of erupted products during the 1992–1993 Galeras eruptions indicate that about 2.6×10^6 m^3 of solid material were ejected (Cortés and Calvache, 1993). Asuming that this value corresponds to 10% of the magma chamber (Smith, 1979), we estimate a magma chamber radius of 185 m. Raigosa (1995) has summarized the variation in the spectra, changing some parameters (size of the bubble, source size, velocity of the shear wave and distance to the source) and leaving the remainder as constant parameters, applying the model

Table 4
Parameters for the spherical source model

Property	Notation	Value	Unit
Bubble radius in inner cavity	a	6	m
Magma chamber radius	b	185	m
Distance to the source	R	1600	m
Magma density	ρ_f	2400	kg/m^3
Rock density	ρ_s	2600	kg/m^3
Magma compressional wave velocity	α_f	2500	m/s
Rock compressional wave velocity	α_s	6000	m/s
Magma shear wave velocity	β_f	50	m/s
Rock shear wave velocity	β_s	3460	m/s
Magma shear modulus	μ_f	6×10^6	N/m^2
Rock rigidity modulus	μ_s	3.11×10^{10}	N/m^2

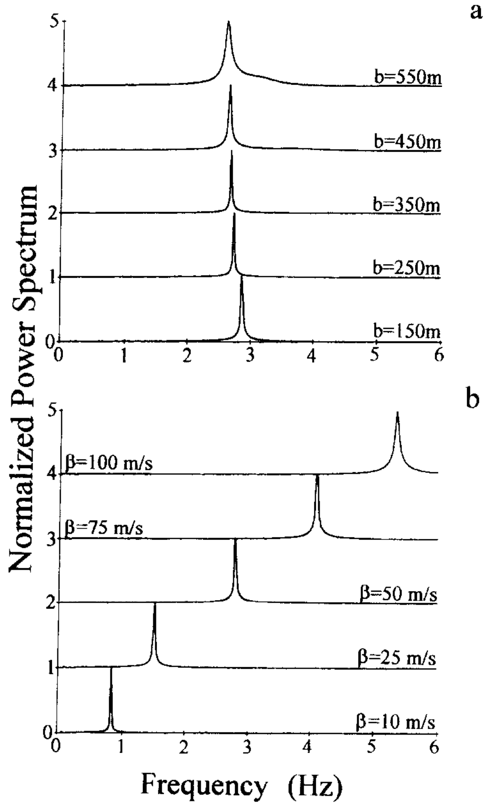

Fig. 11. Synthetic power spectra with (a) all parameters constant except the source radius and (b) all parameters constant except the share wave velocity (modified from Raigosa, 1995).

proposed by Crosson and Bame (1985) for some tornillo events recorded at Galeras volcano.

Fig. 11a shows the variation of the dominant frequency upon varying the magma chamber radius from 150 to 550 m and leaving the other parameters as constants (Table 4). This increase in source radius results in only a very small decrease in the frequency. Fig. 11b depicts the frequency changes upon varying the magma shear velocity from 10 to 100 m/s and also leaving the other parameters constant (Table 4). By contrast with variations in the source radius, a decrease in shear velocity results in a large decline in frequency. It is therefore much easier to cause notable variations in frequency content by changing the shear velocity of the magma than by changing the size of the magma body. Thus, with regard to the decrease of dominant frequencies for tornillos at Galeras, a change in the source volume is unlikely because it requires a large variation in the source size. However, we did not observe any significant change in deformation of the volcano's surface during the 1992–1993 activity.

The tornillo waveforms are mainly dependent on the physical properties of the fluid and surrounding solid material in the conduit as a consequence of increase of the free gas phase in the magma produced by saturation of volatiles due to cooling, crystallization and partial solidification of the magma column plugging the conduits (Stix et al., 1993; Fischer et al., 1994; Torres et al., 1996). The increase in the duration of the tornillo events and the decline of the dominant frequencies before the Galeras eruptions together 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 of the free gas phase in the magma, with consequent decrease of the sound-speed value of the mixture (Kieffer, 1977).

The duration of resonance can be measured by the Quality factor (Q) describing the damping of oscillations. This factor can be obtained using the relation (Bullen and Bolt, 1985):

$$Q = \frac{1}{2h} \tag{7}$$

where h is the damping coefficient. This coefficient reflects the amplitude decay of a wave. It can be determined for coda waves by examining the shape of the waveform, which is independent of the size of the event (Hamada et al., 1976). The relation for calculating the damping coefficient is shown in Eq. (2) above.

Quality factors for Galeras tornillos are in the range of 31 to 250, corresponding to damping coefficient values of 0.016 to 0.002. According to Chouet (1992), the high values of Q can be achieved through the presence of gas bubbles in the magmatic fluid. However, it is difficult to explain values of Q greater than 40 solely by adding 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):

$$Z = \frac{\rho_s \alpha_s}{\rho_f a} \tag{8}$$

where ρ_s and ρ_f are the densities of the solid and fluid, α_s is the velocity of the compressional wave in the solid and a is the acoustic wave speed of the liquid:

$$a=\sqrt{\frac{\lambda+2\mu}{\rho_s}} \tag{9}$$

$$a=\sqrt{\frac{b}{\rho_f}} \tag{10}$$

where λ and μ_s are the Lamé elastic constants and b is the bulk modulus of the fluid. Assuming $\lambda=\mu_s$ in the solid, the impedance contrast is then (Chouet, 1992):

$$Z=\sqrt{\frac{3\rho_s\mu}{\rho_f b}} \tag{11}$$

There are several resonator models that have been suggested to explain the source of long-period events: a fluid-filled sphere (Crosson and Bame, 1985), fluid-filled cylinder (Riuscetti et al., 1977), fluid-filled pipe (Chouet, 1985) and fluid-filled crack (Chouet, 1986, 1988, 1992). We consider a fluid-filled spherical resonator model, due to the similar characteristics that Galeras tornillo events share at all stations, such as durations, damping coefficients, and the spectra characterized by dominant sharp peaks and the presence of some peaks with a regular distribution, which are compatible with the overtones of this resonator. For a fluid-filled spherical resonator obtained by damping of the fundamental mode, the Q factor is defined by (Aki et al., 1977):

$$Q=\frac{\pi}{\ln[(Z+1)/(Z-1)]} \tag{12}$$

Large values of Q imply a high impedance contrast, and we obtain values for Z between 20 and 159 for a Q factor from 31 to 250, respectively. For a fluid-driven crack model, several factors can influence the Q factor values, such as the crack stiffness and impedance contrast (Chouet, 1992). In fact, the spherical resonator model shows a higher energy decay compared to the real resonator, whose geometry is different. Consequently, the Q factor values are lowest for the spherical model.

The previous parameters given in Table 4 allow us to calculate a bulk modulus b ranging from 4.00×10^6 to 2.60×10^8 N/m^2 for Z values from 20 to 159, respectively. The bulk modulus then permits us to estimate the amount of gas bubbles in the magmatic fluid, using the expression for the liquid–gas mixture (Aki et al., 1978):

$$b=\frac{1}{[(1-\epsilon)/b_l]+(\epsilon/b_g)} \tag{13}$$

where ϵ is the volume fraction of gas, and b_l and b_g are the bulk moduli of the liquid and of the gas, respectively. For a molecular gas under pressure P, the bulk modulus of gas is given by $b_g=1.4\ P$ (Aki et al., 1978). We assume that the magma pressure can be represented by the lithostatic pressure or magmastatic (hydrostatic) pressure. Considering experimental data for liquid andesite magma, b_l is approximately 1.48×10^{10} N/m^2 (Murase and McBirney, 1973). The presence of free gas in the 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 magma plugging the conduits (Stix et al., 1993; Fischer et al., 1994).

The generally emergent arrival of tornillos, the difficulty of recognizing the S phase in the record, and the small number of seismic stations constitute a problem in the location of the source of the tornillos. However, the attenuation pattern suggests a shallow source for these events. Assuming 100 m depth for the source, we obtain a volume fraction for gas from 0.01 for bulk modulus of 2.60×10^8 N/m^2 to 0.86 for bulk modulus of 4.00×10^6 N/m^2. This implies that tornillo events at Galeras volcano may be generated in a conduit filled with a variably vesiculated magma. For volcanic events of low frequency like tornillos, several types of source models have been proposed (Kubotera, 1974; Riuscetti et al., 1977; Aki et al., 1977; Ferrick et al., 1982; Chouet, 1985; Crosson and Bame, 1985); most of them are based on the observation of dominant frequencies and the damping of wave amplitude with time. In order to check the validity of the models, studies of the vibration mode of the source and excitation of seismic waves are crucial. Such studies, however, are very small in number, probably because of the complicated features of observed seismograms and/or lack of three-component seismographs of high quality (Ukawa and Ohtake, 1987).

An increase of the gas fraction in the magmatic fluid could explain the strong increase in the impedance contrast and the Q factor. However, several factors could modify the above results. First, there is a degree of uncertainly regarding the location of the tornillo source. Although the source appears to be shallow, it is not necessarily at 100 m depth. Second, we have not considered other damping mechanisms for small energy losses. The apparent Q factor of the tornillo source represents the sum of the energy loss per cycle due to seismic radiation and energy loss per cycle due to viscous damping in the resonating fluid, expressed by (Aki, 1984):

$$\frac{1}{Q}=\frac{1}{Q_r}+\frac{1}{Q_v} \tag{14}$$

where Q_r and Q_v are the Q factors due to seismic radiation and fluid viscosity. These individual factors can modify the overall Q factor values calculated for the spherical source model.

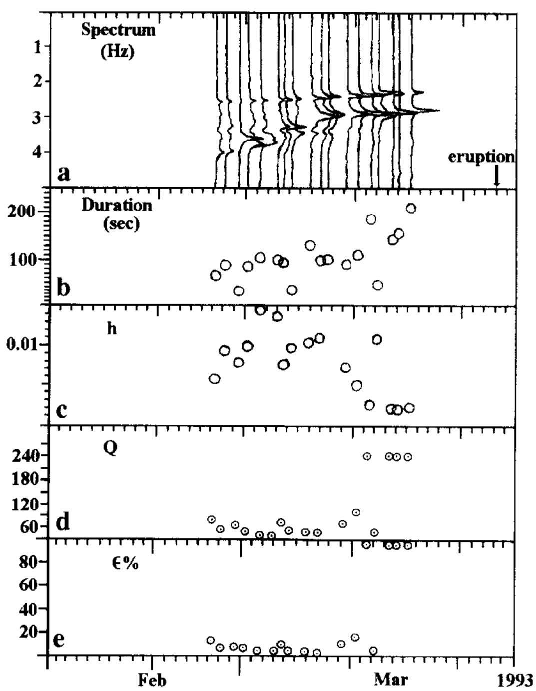

Fig. 12. Summary of characteristics of tornillos before the March 23, 1993, eruption at Galeras: (a) spectra showing dominant frequencies; (b) durations of individual events; (c) damping coefficients for coda waves; (d) quality factor of coda waves; and (e) volume fraction of gas in the fluid. The trend in the decrease of dominant frequency, the increase in the signal durations and the decline in the damping coefficient values, can be explained by an increase of the free gas phase in the fluid during the days just before the eruption. The eruption is shown by the vertical arrow.

The above discussion is shown in Fig. 12 which summarizes the frequency spectrum, duration, damping coefficient, Quality factor and volume fraction of gas prior to the March 23, 1993, Galeras eruption. Notably, the calculated volume fraction of gas in the magma increases significantly from less than 20 to more than 80% eleven days before the eruption.

7. Concluding remarks

In a common manner, the volcanoes considered in this report are andesitic in composition. They are characterized by vulcanian-type eruptions, large gas emissions, or neither. Another common aspect is that these volcanoes have recorded tornillos in different timeframes, such as short-term precursors (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). These events are considered to be related to magmatic activity and occur beneath the active crater.

The following points summarize the characteristics for Galeras, Puracé, Tokachi and Meakan tornillo events:

(1) The events show larger durations compared to their amplitudes and slow decay coda, reflected in low values of the damping coefficient distributed between 0.002 and 0.02. These values are related to large Quality factors (Q_c) of 250–25.

(2) Spectral analysis reveals that the spectrum is characterized by one or several sharp frequency peaks. Fundamental frequencies are not affected by epicentral distance, azimuth or travel time, indicating a source effect. The peak frequencies are, in most cases, very different among volcanoes.

For Galeras volcano, tornillos were a short-term precursor for all but one of the eruptions from July 16, 1992 to June 7, 1993. Prior to these eruptions, an increase in the duration of tornillos and a decline of the dominant frequencies was observed, while at the other volcanoes analyzed, these parameters do not show a clear tendency. Immediately after the Galeras eruptions, tremor episodes with swarms of long-period events were registered, accompanied by increased gas emissions from the active crater as recorded by visual observations and increased SO_2 fluxes. The tornillo events always disappeared immediately after each eruption. The material ejected during the eruptions showed the presence of juvenile material (Cortés and Calvache, 1993).

The appearance of Galeras tornillo events may therefore be an indication of physical interaction and conditions between the fluid and the surrounding solid material in the cavity. The increase in the duration of the tornillo events and the lowering of the dominant frequencies both suggest an increasing impedance contrast (Aki et al., 1977) between the surrounding solid material and the fluid (Chouet, 1992). In the same manner, the decline of the damping coefficient immediately before an eruption suggests an increase of Q factor values, which also implies an increase in the impedance contrast. These characteristics can be explained by an increase of the free gas phase in the magma (Chouet, 1992) with consequent decrease of the sound-speed value of the mixture (Kieffer, 1977).

Based on our analysis of 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 (Torres et al., 1996).

Further efforts are needed in order to formulate less speculative hypotheses to explain the source mechanism of tornillo events. More comprehensive comparisons of similar events at different volcanoes will also be useful for understanding this unusual type of seismic event, particularly for prediction of future eruptions and consequent mitigation of hazard.

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