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RESEARCH ARTICLE

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Seismicity of an andesitic volcano during block-lava effusion: Volcán de Colima, México, November 1998–January 1999

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Abstract The block-lava effusion at Volcán de Colima, México began on November 20, 1998, after 12 months of seismic activity, and ended about 80 days later. Three types of seismic events were observed during the lava effusion. Volcano—tectonic earthquakes occurred mainly at the very beginning and after the termination of lava effusion. Explosion earthquakes occurred frequently during the period of the maximum rate in lava effusion. The remainder of the seismic signals were associated with pyroclastic flows and rockfalls from the lava dome. These latter signals increased sharply in number at the onset of lava effusion. The rate of occurrence remained high when the lava discharge rate decreased but gradually decreased after the termination of lava effusion. Maximum daily durations of seismic signals are proportional to the daily volumetric output of lava, indicating the dependence of the number of pyroclastic flows on the rate of lava output. A log-log plot of seismic signal duration vs. number of events with this duration displays a linear relationship. The short-period seismic signals can be divided into three categories based on duration: short events with durations less than 100 s; intermediate events with durations between 100 and 250 s; and long events with durations longer than 250 s. We infer that long events correspond to pyroclastic flows with mean deposit volume $\sim 2\times 10^5$ m^3, and intermediate events represent pyroclastic flows with mean deposit volume $\sim 1\times 10^3$ m^3.

Keywords Volcán de Colima · Andesitic volcano · Volcanic seismicity · Block-lava effusion · Pyroclastic flows

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Introduction

The andesitic, 3860-m-high, stratovolcano Volcán de Colima is one of the most active volcanoes in Mexico. It is located in the western part of the TransMexican Volcanic Belt, and together with the Pleistocene volcano, Nevado de Colima, forms the Colima Volcanic Complex (CVC) (Figs. 1 and 2). Colima displays a wide spectrum of eruption styles, including small phreatic explosions, major block-lava effusions, and large explosive events (Breton González et al. 2002).

Colima's most recent unrest began on November 28, 1997, with a sharp increase in seismic activity and a significant shortening of geodetic lines around the vol-

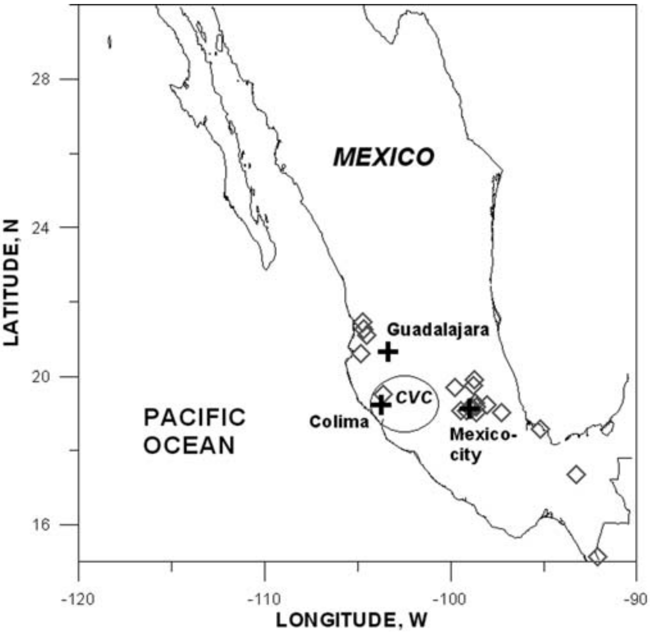

Fig. 1 Position of Colima Volcanic Complex (CVC) within the TransMexican Volcanic Belt. The active volcanoes are shown by *diamonds*. The *oval* shows the position of CVC. The cities are shown by *crosses*

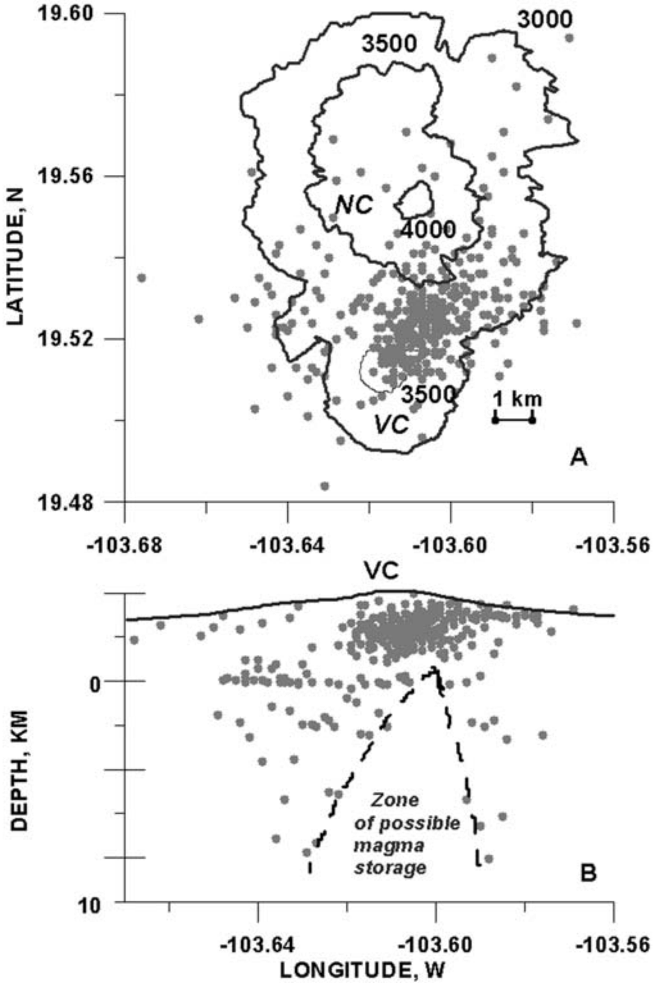

Fig. 2 Distribution of epicenters (**a**) and hypocenters of earthquakes (**b**) located within the Colima Volcanic Complex during the seismic crisis of 1997–1998 at Volcán de Colima. *Contour lines* at 3,000, 3,500 and 4,000 m show the relief of the Colima Volcanic Complex. *VC* Volcán de Colima; *NC* Nevado de Colima. The seismic stations are shown as *triangles*. An earthquake-free zone is outlined in the *cross section*

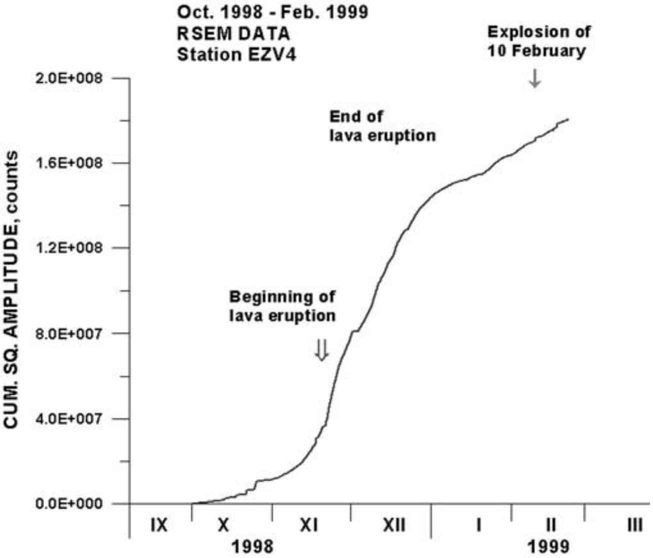

Fig. 3 Cumulative RSEM (real-time seismic energy measurement) curve of variations in seismic energy release at Volcán de Colima in October 1998–February 1999

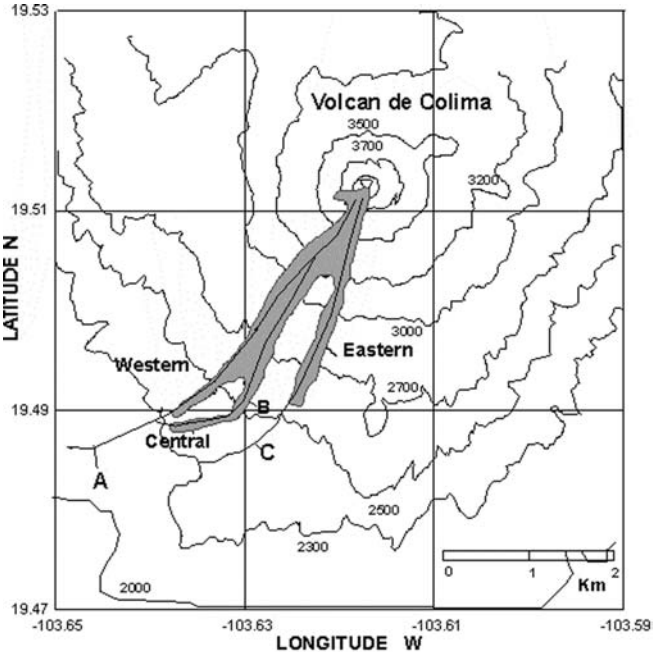

Fig. 4 Map showing the distribution of the 1998–1999 pyroclastic flow deposits and lavas. The final positions of the block lavas (western, central and eastern) are shown in *gray*. The maximum extents of pyroclastic flows are shown by *solid lines* **a**, **b**, and **c**. *Contour lines* show the relief of the Colima Volcanic Complex

cano. This early phase was marked by an absence of surface activity. Deformation of the volcanic edifice continued for 12 months and culminated in the production of a block-lava flow that began on November 20, 1998, and ended about 80 days later in early February, 1999. Activity then evolved to explosive eruptions that occurred during the next two years (Zobin et al. 2002b).

The seismic activity preceding the lava eruption (November 28, 1997 to November 19, 1998) has been studied in detail (Domínguez et al. 2001; Zobin et al. 2002a, 2002b). This seismic activity consisted of five swarms of volcano-tectonic microearthquakes that occurred in November–December 1997, March, May, June–July, and October–November, 1998. About 600 events with magnitude ranging from –0.5 to 2.7 were located within a 50 km^2 area including the active crater of Colima and the region between Volcàn de Colima and Nevado de Colima, 5.5 km to the north. Most hypocenters were shallower than 5 km depth below sea level (BSL) (Fig. 2). Temporal trends in event depths were identified in the November–December 1997 and June–July 1998 swarms (from 4 km BSL to 4 km above sea level (ASL) and in the October–November 1998 swarm (from 0 to 4 km ASL).

No decrease in the rate of seismic energy release was observed with the termination of the precursory volcano-

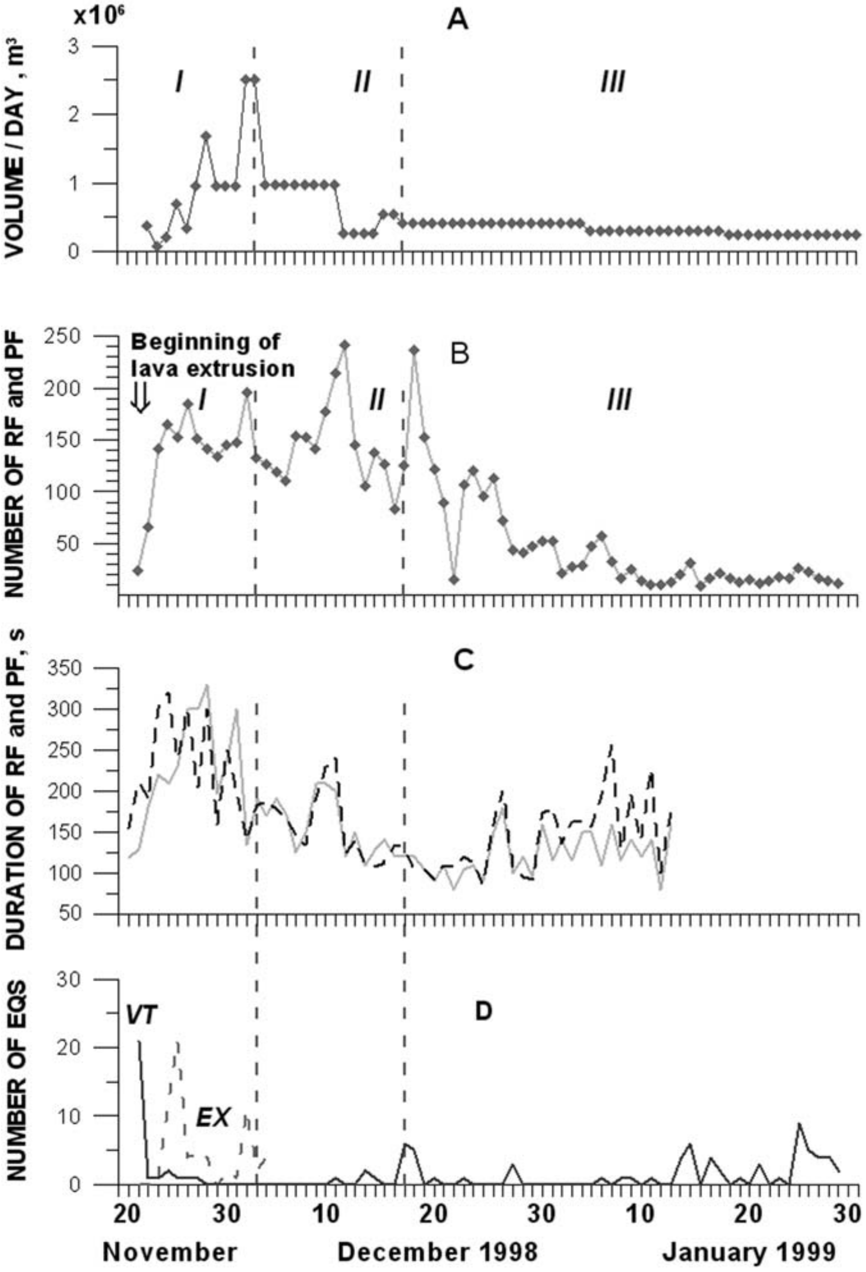

Fig. 5 Daily variations in the volume of lava erupted (**a**), number of "avalanche" (*RF*, rockfalls and *PF*, pyroclastic flows) earthquakes (**b**), maximum duration of seismic signals of "avalanche" earthquakes (**c**), and volcano-tectonic (*VT*) and explosion (*EX*) earthquakes (**d**), during the 1998–1999 lava eruption at Volcán de Colima. I, II, and III indicate three stages of lava eruption. In C, the data from station EZV5 are shown by the *solid line*; data from station EZV6 are shown by the *dashed line*

tectonic earthquake swarm and the beginning of lava eruption (Fig. 3). The volcano-tectonic earthquakes changed to the seismic signals associated with the lava eruption that were characterized by the same or higher magnitude of energy release. This paper investigates the seismic activity observed during the block-lava eruption of November 1998–January 1999 at Volcàn de Colima.

Short description of the block-lava eruption of Volcán de Colima

A new block lava dome began to grow on November 20, 1998, in the crater formed by explosive destruction of the dome emplaced in 1991. The new dome grew rapidly (~4.4 m^3/s) in the SW part of the crater reaching a volume of about 3.8×10^5 m^3 in 24 h. By the morning of November 21, the block lava was spilling over the SW rim of the crater, resulting in the production of block-and-ash flows (pyroclastic flows) ahead of an advancing lobe of andesitic block lava. Pyroclastic flows initially occurred at intervals of 3–5 min, reached speeds of 80–90 km/h, and extended out to 4.5 km from the crater.

The block lava flow extended ~150 m by the afternoon of November 21. The lava flow eventually split into three arms extending down the three branches of Barranca Cordobán on the SW flank of Volcán de Colima and covering older pyroclastic-flow deposits (Fig. 4). The three branches of the lava flow reached 2.8–3.9 km from the crater, had flow fronts ~30 m high, and contained an

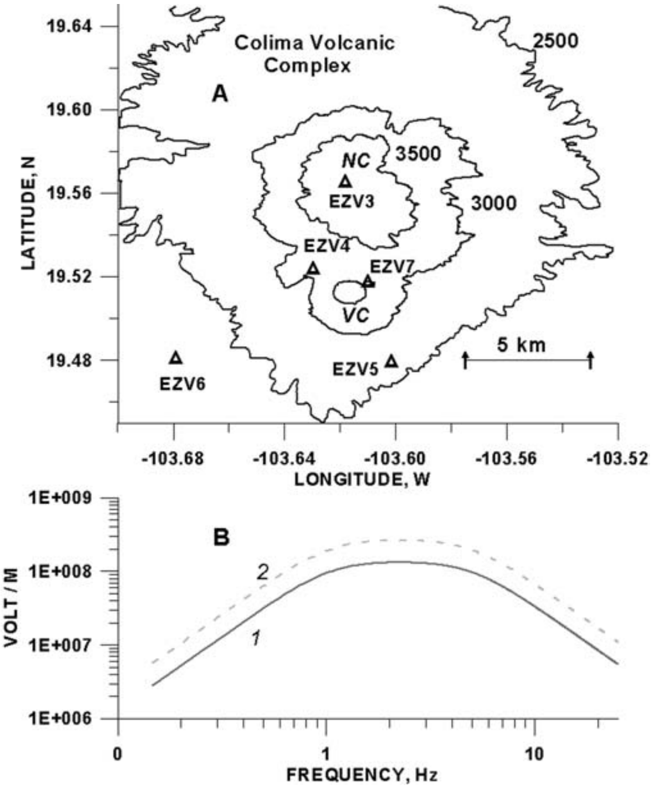

Fig. 6 Network of seismic stations around Volcán de Colima (**a**) and their amplitude responses (**b**). The stations EZV3-EZV7 are shown as *open triangles*. *Contour lines* at 3,000, 3,500 and 4,000 m show the relief of Colima Volcanic Complex. 1, 2 in B are two types of response for seismic stations

estimated total volume of 39×10^6 m^3 (Navarro-Ochoa et al. 2002). The total volume of the pyroclastic flow deposits was estimated to be 2.4×10^6 m^3 (Saucedo et al. 2002).

The temporal evolution of lava effusion is shown in Fig. 5a. Three stages of evolution may be distinguished: (1) an initial stage of strong and increasing lava flow, from November 20 through December 1; (2) rapidly decreasing lava flow, from December 2 through December 17; and (3) very low and decreasing lava flow, from December 21 through January 30. By early February 1999, the lava flow was no longer being fed from the summit crater and activity evolved to an explosive stage.

Seismic network around the Volcán de Colima and types of seismic signals recorded during the block-lava effusion

The Colima seismic network (Red Sísmica de Colima, RESCO) has been monitoring seismic activity in the area surrounding the volcano since 1989. The network consists of 5 telemetered seismic stations (EZV3–EZV7) located on and around the volcano (Fig. 6). Each station is equipped with a short-period (natural period of 1 s) vertical seismometer. Instrumental responses are shown in Fig. 6b. Analog data from these stations are digitized at 100 samples/s. The methodology of signal processing for locating earthquakes and estimating their magnitudes and spectral characteristics was presented in Zobin et al. (2002a).

Three types of seismic signals were observed during the block-lava effusion in November 1998–January 1999 (Fig. 7). The first type consists of volcano-tectonic earthquakes with clear P and S arrivals (Fig. 7, VT). They are similar to events recorded prior to the lava eruption. The second type was associated with explosions and non-explosive degassing (exhalations) in the crater. Figure 7 shows the record of seismic signal produced by an exhalation (EX). All records from explosions were saturated. The third type was associated with pyroclastic flows and rockfalls from the block-lava flows along the slope of the volcanic edifice; we call them "avalanche" earthquakes (Fig. 7, AV). These signals have a spindle-shaped amplitude envelope and their durations vary from 30 to 350 s.

The three types of seismic events were distributed unevenly during the lava effusion (Fig. 5b and d). The number of volcano-tectonic earthquakes sharply decreased with the onset of lava effusion and increased again only in the second part of January, during very low and decreasing lava flow. Explosion earthquakes were numerous on November 23–25 during the period of maximum lava emission rate, following which they appeared rarely and without regularity.

The majority of seismic signals observed were earthquakes produced by pyroclastic flows and rockfalls of incandescent fragments of lava dome. These earthquakes sharply increased in number after the onset of lava effusion. Their number was still high when the lava emission rate decreased but gradually decreased at the stage of very low and decreasing lava flow. Below we discuss the characteristics of "avalanche" and volcano-tectonic earthquakes.

"Avalanche" earthquakes

Roughly 6,000 "avalanche" earthquakes were recorded during the period of lava effusion. For their analysis, we used records obtained at seismic stations EVZ5 and EVZ6 located at distances of 4 and 7 km from the crater, respectively (Fig. 6). We studied their relationship with eruptive process and the possibility of quantification of pyroclastic flow deposit volume using seismic records.

The earthquake signals may be quantified by the area contained within their amplitude envelope, their peak amplitude, and their duration. The analog records of seismic signals at Colima seismic network were saturated for larger events and did not allow measurement of their amplitudes. Therefore, we selected the duration of seismic signals as the parameter to compare the deposit volume of pyroclastic flows. We measured the durations of the signals for events with maximum amplitude greater than 2 mm on the record.

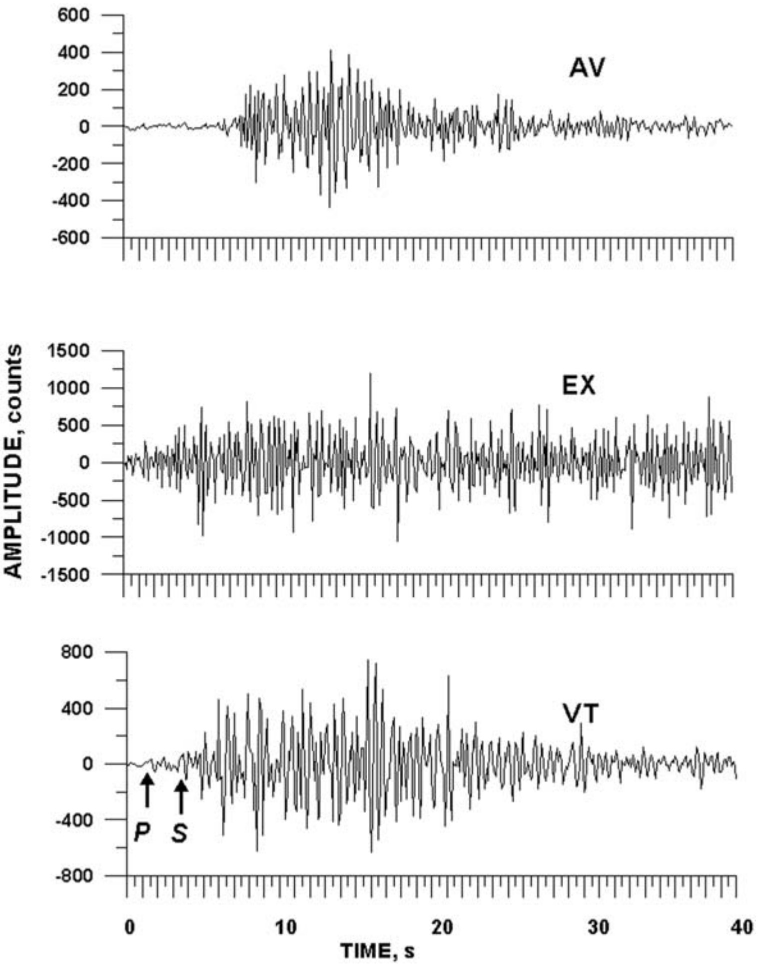

Fig. 7 Seismic signals recorded during the 1998–1999 lava eruption at Volcán de Colima. The records shown are from station EZV5, at a distance of 4 km from the crater. *VT* volcano-tectonic earthquake; *EX* explosion earthquake, and *AV* "avalanche" earthquake

Relationship between the duration of "avalanche" earthquakes, pyroclastic flow deposit volume and the rate of lava emission

Visual observations showed that the larger durations of seismic signals corresponded to the larger pyroclastic flows. At least, two large pyroclastic flows that occurred on November 22, 1998, at 08:30 (Zobin et al. 2002b) and on December 10, 1998, at 16:31 (Saucedo et al. 2002) were photographed and identified in time with the long seismic records of 300 s and 240 s, respectively. The numerous small rockfalls were identified with the short seismic records of about 50–100 s.

Figure 5c shows the maximum daily signal duration of "avalanche" earthquakes measured at two seismic stations. The duration measurements made at two stations EZV5 and EZV6 show similar results. The comparison of temporal variations in these seismic characteristics and in lava emission rate (Fig. 5a) suggests that the variations in maximum daily durations of "avalanche" earthquakes (and in the size of pyroclastic flows and rockfalls) generally follow the variations in lava emission rate, with some irregular temporal drift. The formal coefficient of correlation between these two parameters is equal to 0.37 that is significant at 99% level. A further inference is that the larger pyroclastic flows occur when the rate of lava output increases.

Duration-frequency relations of "avalanche" earthquakes at different stages of lava effusion

Gutenberg and Richter (1956) suggested that the relation between the magnitude of seismic events and their frequency of occurrence might characterize the physical conditions of material fracturing. Assuming that the "avalanche" earthquakes result from the destruction of lava bodies, we constructed category-frequency plots for the three stages of lava eruption (Fig. 8). We plotted the number of events for each 50-s interval of duration beginning from the duration of 100 s.

The events recorded during stage 1 of the intensive lava effusion are the most representative, having a sample of event durations from 100 to 330 s. The log-log plot of event duration vs. number of events with this duration shows a linear relationship, pointing to a power-law distribution of seismic signals associated with "avalanche" earthquakes. Such a linear relationship is typical of fractal sets (Scholz 1990) and suggests self-similarity in the di-

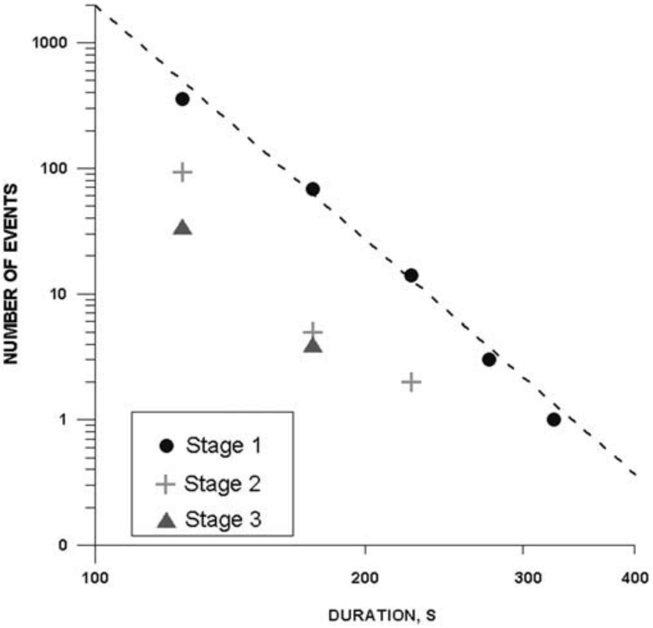

Fig. 8 Log-log plot of the number of "avalanche" earthquakes vs. duration of seismic signals of these earthquakes. The events observed at different stages of the eruption are shown by different symbols. The number of events are given for the 50-s intervals (100–150 s; 151–200 s; 201–250 s; 251–300 s, and 301–350 s) and attributed to the central points of the intervals: 125, 175, 225, 275, and 325 s. The least-square regression line for stage 1 is shown. This line is given by $\log N$=15.7–6.2 log D (s), where N is the number of events and D is the event duration in s

mensions of lava chunks that broke off during gravitational collapse of the lava body.

During the second and third stages of lava effusion, the durations of seismic signals of "avalanche" earthquakes were more limited. During stage 2, the maximum duration did not exceed 250 s, and during the third stage, it was shorter than 200 s. The shorter durations may reflect a decrease in the maximum volume of lava chunks that broke off during these stages.

Relation between the category of "avalanche" earthquakes and the volume of deposits from pyroclastic flows

The results of two previous sections suggest that the duration of the short-period records of "avalanche" earthquakes may provide a means of quantifying the volume of deposits from pyroclastic flows. Duration varied from 30 to 350 s allowing us to discriminate at least three categories of signals. The following categories are based on the durations of "avalanche" earthquakes measured at station EVZ5 at a distance of 7 km from the crater: short events have durations less than 100 s; intermediate events have durations between 100 and 250 s; and long events have durations greater than 250 s (Fig. 9). Short events are attributed mainly to small rockfalls whereas intermediate and long events are attributed to pyroclastic flows and large rockfalls.

Self-similarity in the dimensions of lava chunks broken off during the gravitational failure of the lava body allows an estimation of the mean volume of the materials that were carried away by pyroclastic flows of different sizes.

The volume of deposits from pyroclastic flows (7.2×10^5 m^3) that occurred between November 25 and 26, 1998, and of the total volume of deposits from pyroclastic flows (1.6×10^6 m^3) that occurred during the eruption from November 1998 through January 1999 were estimated by Navarro-Ochoa et al. (2002) and Saucedo et al. (2002), respectively. These results were used to obtain estimates of the mean volume of flows associated with seismic records with different durations. Between November 25 and 26, three long events, 123 intermediate events, and 219 short events were recorded. Over the entire eruption, four long events, 577 intermediate events, and 4,939 short events were recorded. Field observations suggest that short events correspond to rockfalls with a mean volume of ~50 m^3. Based on these data, two linear equations were devised as follows:

$$577V_2(\mathrm{m}^3) + 4V_3(\mathrm{m}^3) = 1.6\times10^6(\mathrm{m}^3) - 50(\mathrm{m}^3)\times 4,939 \tag{1}$$

$$123V_2(\mathrm{m}^3) + 3V_3(\mathrm{m}^3) = 7.2\times10^5(\mathrm{m}^3) - 50(\mathrm{m}^3)\times 219 \tag{2}$$

where V_2 and V_3 are the mean volumes of material carried by pyroclastic flows that produced the seismic records of intermediate and long events, respectively. From these equations, we obtain a mean volume of 2×10^5 m^3 as a value for pyroclastic flows producing the long seismic events and a mean volume of 1×10^3 m^3 as a value for pyroclastic flows producing the intermediate seismic events.

These values are very approximate but may be useful for monitoring an eruption. We had no estimate of the volume of deposits from any single pyroclastic flow at Volcàn de Colima to check the proposed values but they are in agreement with the volume estimates of deposits from single pyroclastic flows at Unzen volcano, Japan (0.6×10^4 to 5.7×10^4 m^3; Uhira et al. 1994; Yamasato 1997) and Soufriére Hills volcano, Montserrat (small pyroclastic flow deposits, 10^3–10^4 m^3; medium-sized pyroclastic flow deposits, 10^4–10^6 m^3; Calder et al. 2002).

Volcano-tectonic seismicity

Volcano-tectonic seismicity was recorded mainly at the beginning and end of the eruption. The majority of events occurred on November 19–20, 1998, and January 21–31, 1999. All events were of small magnitude, ranging from –0.3 to 1.3 in November, 1998, from 0.2 to 1.0 in December, 1998, and from –0.2 to 0.9 in January, 1999. Figure 10 shows the position of located earthquakes. Most

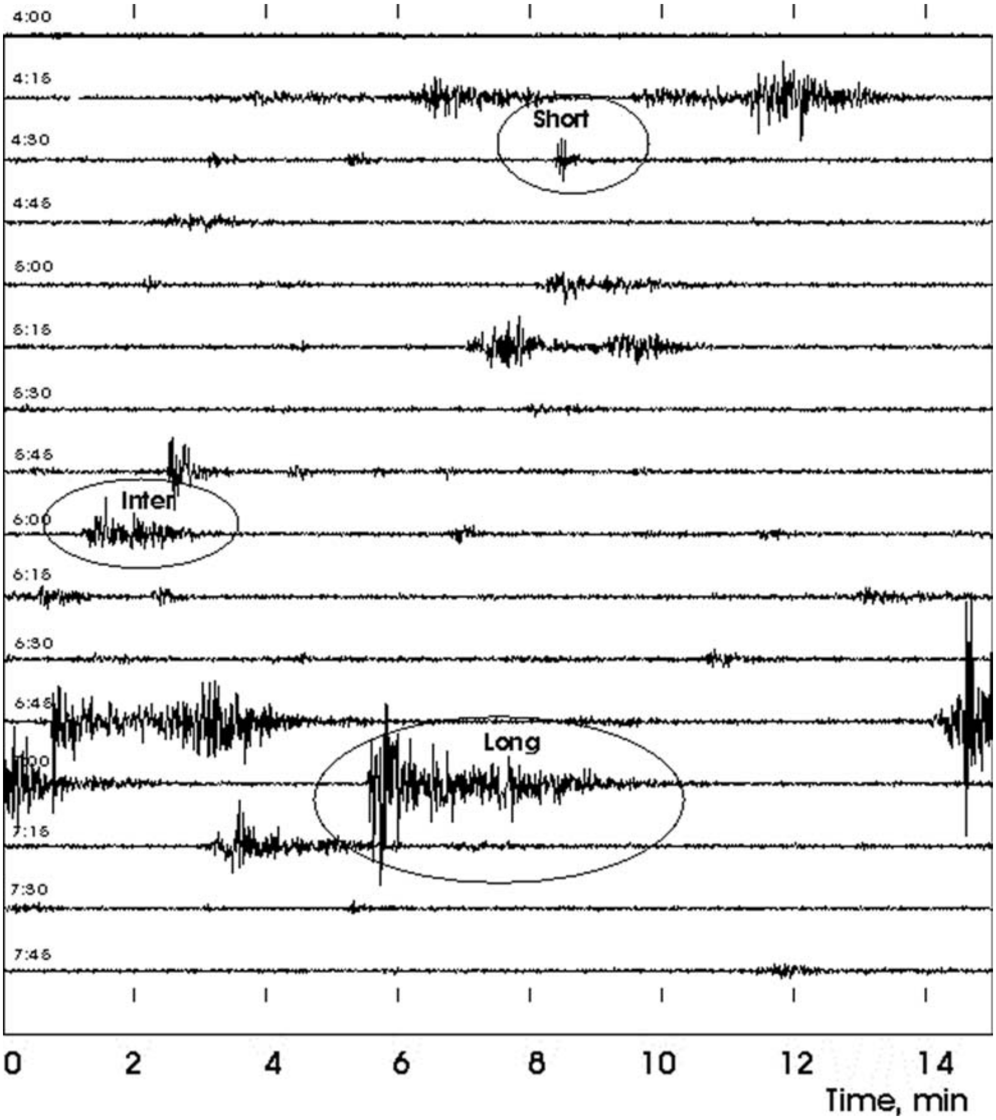

Fig. 9 Records of "avalanche" earthquakes of different durations at a distance of 4 km from the crater (station EZV5, November 25, 1998). Short, intermediate (inter) and long duration records of "avalanche" earthquakes are illustrated

earthquakes occurred above a zone of possible magma storage marked by an absence of events during precursory swarms in 1997–1998 (Zobin et al. 2002a) (Fig. 2). Events in November were densely clustered within an area of 2×1 km located within the volcanic edifice between sea level and the crater floor. The five events in December occurred within the same zone. Events in January clustered within an elongate area of 5×1 km along the Colima graben between the crater of Volcán de Colima and the crater of Nevado de Colima.

Comparison with seismicity that was observed at other volcanoes

The change of volcano-tectonic seismicity to "avalanche" seismicity with the onset of lava eruption has been observed at many volcanoes. Malone (1983) noted that the typical dome-building eruption episodes at Mt. St. Helens, Washington, began with a few volcano-tectonic earthquakes several weeks before the actual eruption. When the eruption of lava started, volcano-tectonic events were replaced by "avalanche" signals and explosion events. Both of the latter types of events occurred for several days, slowly decreasing in number. Umakoshi et al. (2001) also noted that volcano-tectonic seismicity at Unzen Volcano, Japan, was at a high level before the appearance of the lava dome on May 20, 1991, and that with the onset of lava effusion, volcano-tectonic earthquakes virtually ceased to occur within a radius of 5 km from the crater.

An interrelation between volcano-tectonic seismicity and pyroclastic flow activity was also observed at Soufriére Hills Volcano, West Indies (Aspinall et al. 1998; Miller et al. 1998). The beginning of pyroclastic flow activity in April, 1996, more-or-less coincided with the termination of volcano-tectonic seismicity (Fig. 11). This coincidence closely resembles our observations at Volcán de Colima (Fig. 5d).

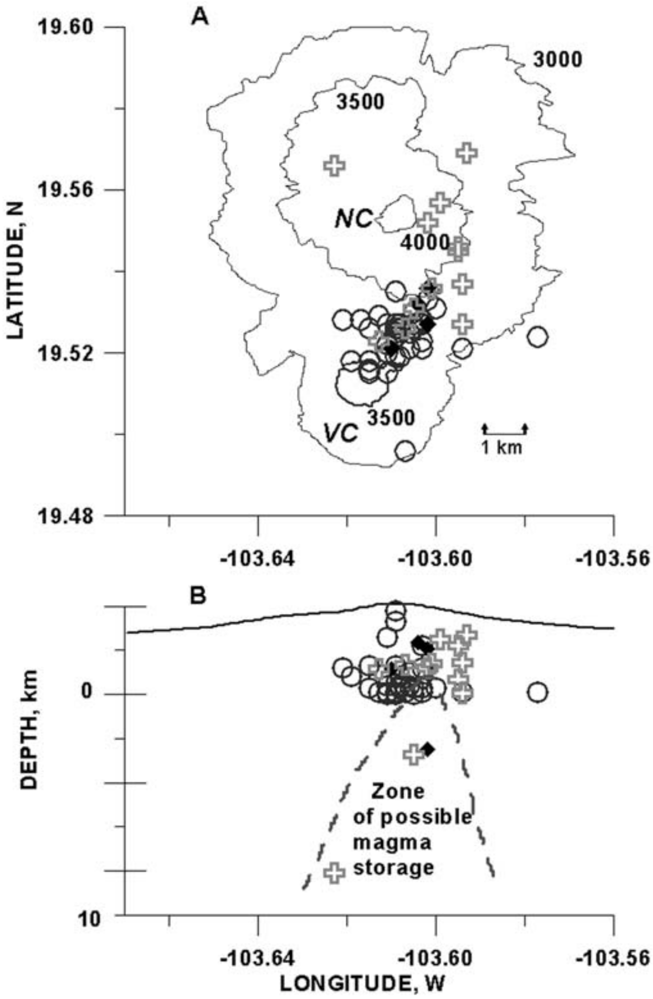

Fig. 10 Distribution of epicenters (**a**) and hypocenters (**b**) of volcano-tectonic earthquakes located during the 1998–1999 lava eruption at Volcán de Colima. The *circles* show the events recorded from 19 to 30 November, 1998, the *diamonds* depict events in December, 1998, and *crosses* represent events in January, 1999. *Contour lines* at 3,000, 3,500 and 4,000 m show the relief of Colima Volcanic Complex. *VC* is Volcán de Colima; *NC* is Nevado de Colima. The seismic stations are shown as *open triangles*. An earthquake-free zone (Zobin et al. 2002a) is outlined in the *cross section*

The relationship between "avalanche" seismic signals and eruption dynamics has also been demonstrated at other andesitic volcanoes. Ratdomopurbo and Poupinet (2000) noted that these signals ("guguran" in Indonesian) at Merapi Volcano, Java, usually last several minutes and that their frequencies are higher than that of tremor. Purbawinata et al. (1997) suggested that the "gugurans" are indicative of the level of stability of the lava dome. When the dome is unstable, "guguran" occur at a rate of more than 500/day, whereas, when the dome is stable, only three "guguran" events occur daily. A rate of more than 50 events/day usually indicates that the dome is in an unstable state.

A dacitic lava dome at Unzen Volcano, Japan, emerged in May, 1991, and its collapse generated multiple pyroclastic flows. Yamasato (1997) studied the seismic signals produced by the collapse of lava blocks from the dome, dropping of blocks onto the slope below the dome, and the movement of pyroclastic flows down the mountain slope. Comparison of seismic signals with video records allowed identification of seismic signals produced at different stages in the formation of pyroclastic flows. Small-amplitude seismic waves with predominant frequencies in the band 2–3 Hz were excited simultaneously with the collapse of a section of the lava dome. Within a few seconds, as lava blocks fell onto the slope below, the amplitude of the seismic signal became large and dominated by low-frequency components near 0.5 Hz. Then, the movement of the pyroclastic flow down the mountain generated high-frequency (>2 Hz) seismic waves.

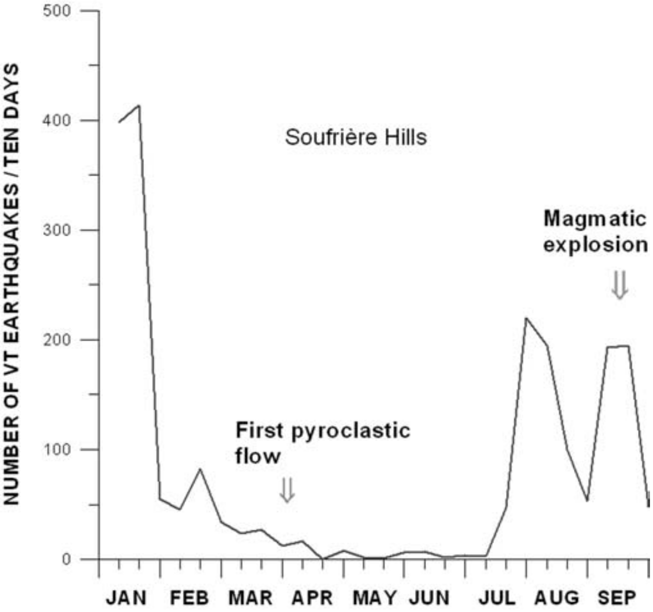

Fig. 11 Variations in the number of volcano-tectonic earthquakes during the quiet lava dome building (January–February, 1996), its collapse (end of March, 1996), the pyroclastic flow activity (April–September, 1996), and the first magmatic explosion (September 17, 1996), at Soufriére Hills volcano, West Indies. Data were taken from the local catalog of Montserrat Volcano Observatory

Post-eruption volcano-tectonic earthquakes occurring within zones that were active during an eruption have been observed at many volcanoes also. Following the eruption of Mount St. Helens, Washington, in 1980, the active fault was marked by clusters of earthquakes to the north and south of the volcano. Earthquakes occurred in the depth range 0–10 km before the eruption and in the depth range 16–22 km during the eruption. The gap between the two groups was filled by post-eruption earthquakes during one year of activity (Weaver et al. 1981). In the case of Pinatubo Volcano (Philippines 1991), post-eruption earthquakes occurred within a volume significantly larger than the volume occupied by precursory events, and showed an increase in the epicentral area and depths of earthquakes (Mori et al. 1996).

These data show that the seismic activity observed during the block-lava effusion at Volcán de Colima was typical for this type of volcanic eruption.

Conclusions

The andesitic block-lava effusion at Volcán de Colima, México in November 1998–January 1999 proceeded in three stages: a first stage of rapid effusion of lava, a second stage of slow effusion of lava, and a third stage of very slow effusion of lava.

Three types of seismic events, unevenly distributed in time, were observed during the lava effusion. Volcano-tectonic earthquakes occurred mainly at the very beginning and after the termination of lava effusion. Numerous explosion earthquakes were observed during the period of maximum rate in lava effusion. The remaining and most frequently occurring seismic signals were "avalanche"-type earthquakes associated with pyroclastic flows and rockfalls of incandescent fragments from the lava flow front. These seismic signals sharply increased in number following the onset of lava effusion. Their number was still high when the lava effusion rate decreased, but gradually decreased in the final stage of lava effusion. Volcano-tectonic seismicity that had prevailed during precursory swarms changed to "avalanche" seismicity after the onset of lava eruption.

The characteristics of "avalanche" earthquakes reflected the eruption dynamics:

1. Maximum daily durations of "avalanche" earthquakes generally followed the variations in daily volumetric output of lava, indicating that the larger pyroclastic flows accompanied higher rates of lava effusion.
2. A log-log plot of seismic signal duration vs. number of events with this duration displays a linear relationship suggestive of a power-law distribution of seismic signals associated with "avalanche" earthquakes and self-similarity in the dimensions of lava chunks that broke off during gravitational collapse of the lava body and formed the pyroclastic flows.
3. The durations of short-period signals of "avalanche" earthquakes measured at station EVZ5 were categorized into: short events with durations less than 100 s; intermediate events with durations between 100 and 250 s; and long events with durations longer than 250 s. The longer seismic events were produced by pyroclasic flows involving a larger volume of material.

A comparison of the locations of volcano-tectonic earthquakes during the initial stage of lava effusion (19–21 November) and during the final stage, when the effusion was practically over, reveals the wide extent of the epicentral zone during the termination of lava effusion.

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