



Seismic Activity Associated with Volcán de Colima

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Abstract

Many different types of seismic events are registered simultaneously at Volcán de Colima, reflecting the variety of physical processes that occur at the same time. Formal recording of seismic activity began in 1989, when seismic short-period sensors were installed. This has been expanded to a network of broadband sensors currently working on the volcano. Seismicity associated with the most recent volcanic activity has consisted of Volcano-Tectonic events (VTs) and/or High Frequency events (HFs), Long-Period events (LPs), tremor, explosions with associated Very Long-Period events (VLPs), rockfalls, pyroclastic flows and lahars. The time evolution of these signals varies along with the depth and its characteristics. The seismicity and related energy release have been a good indicator of the magnitude of volcanic activity. Combined

with other observations, seismic monitoring has been a very efficient tool for forecasting volcanic activity and helping to reduce volcanic risk at Volcán de Colima.

Keywords

Volcán de Colima · Volcano seismicity
Seismic monitoring · Seismic events
Forecast

1 Introduction

The objective of this chapter is to give an overview of the seismicity at Volcán de Colima and its relationship with volcanic activity. The history of the seismic network is reviewed, along with the different types of seismic signal and how their presence is being interpreted in the context of eruptive activity.

1.1 Seismic Monitoring Network

The Colima seismic network (*Red Sísmica Telemétrica del Estado de Colima* or RESCO) was established at the Universidad de Colima and has been monitoring seismic activity of Volcán de Colima since 1989, when five telemetered seismic stations on and around the volcano were installed. Each station was equipped with a short-period ($T_s = 1$ s) vertical seismometer,

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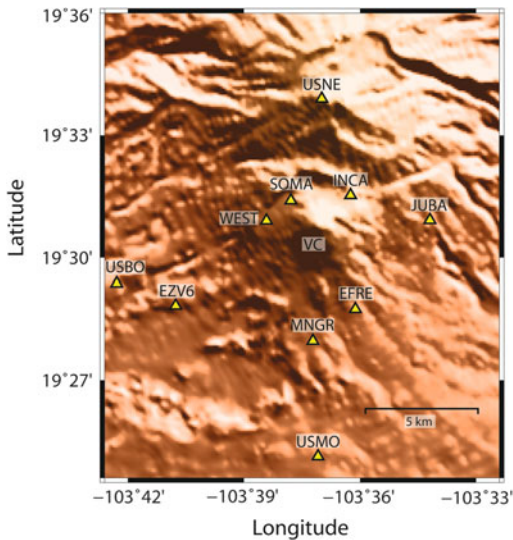


Fig. 1 Current seismic monitoring network at Volcán de Colima operated by RESCO. The EZV6 is a short-period station. INCA, JUBA, MNGR and WEST are broadband stations. At USNE, SOMA and EFRE there are both short-period (EZV3, EZV4, EZV5) and broadband sensors. All the signals are sent by radio to RESCO-Universidad de Colima. Additionally, RESCO have others seismic stations for monitoring tectonic seismicity. ‘VC = Volcán de Colima’

with analogue recording. The first episode of lava dome growth recorded by RESCO was in 1991.

During the 1998–1999 effusive episode, RESCO was able to record seismicity digitally, with continuous recording achieved since March 1999. The data generated has proved to be a powerful tool for monitoring and studying the volcanic activity. In recent years RESCO has been upgraded with more stations and broadband sensors. Figure 1, shows the current seismic network: four short-period SS-1 Ranger vertical seismometers, and five broadband seismometers Guralp CMG-6TD and one broadband Guralp CMG-40TD. Due to their location, stations MNGR, WEST and EZV6 also record the occurrence of lahars.

2 Seismicity Associated with Volcanic Activity

2.1 Volcano-Tectonics Events (VTs)

Volcano-Tectonic events (VTs) generally take place during the first stage of eruptive activity at volcanoes (White and McCausland 2015). At Volcán de Colima they appear in swarms, usually after extended periods of quiescence. Since the start of seismic recording of volcanic activity, the following episodes have produced this type of event: 1991 (Núñez-Cornú et al. 1994), 1994 (Jiménez et al. 1995), and 1997–1998 (Dominguez et al. 2001; Zobin et al. 2002a, b, c; Zamora-Camacho et al. 2007). Some of these events have been linked with the Tamazula fault (Dominguez et al. 2001; Zobin et al. 2002b). The tensional tectonic regimen associated with the Colima Graben can also produce VTs without a clear relationship with the ascent of magma. As is typical for this type of event, they have well-defined P and S phases (Fig. 2a), meaning their origin can be located. Their frequency content is mainly between 1 and 15 Hz (Fig. 2b, c), and their origin is typically at depths of up to 12 km below the crater (Zobin et al. 2002a, b, c). During the recent eruptive period from 2013 to present, a small number of isolated VTs have also been observed, probably associated with an open system, whereby the magma ascends without significant resistance. Also, with the more recently added broadband seismometers, high frequency events (HFs) without a clear S phase have been registered by the closest stations to the crater. These events are likely to be associated with lava dome growth as a brittle rupture process at shallow depth.

During the 1991 episode, VTs were located to the north of the summit, some of them relatively deep (7–11 km below the summit), underneath the saddle between Volcán de Colima and Nevado de Colima (Núñez-Cornú et al. 1994).

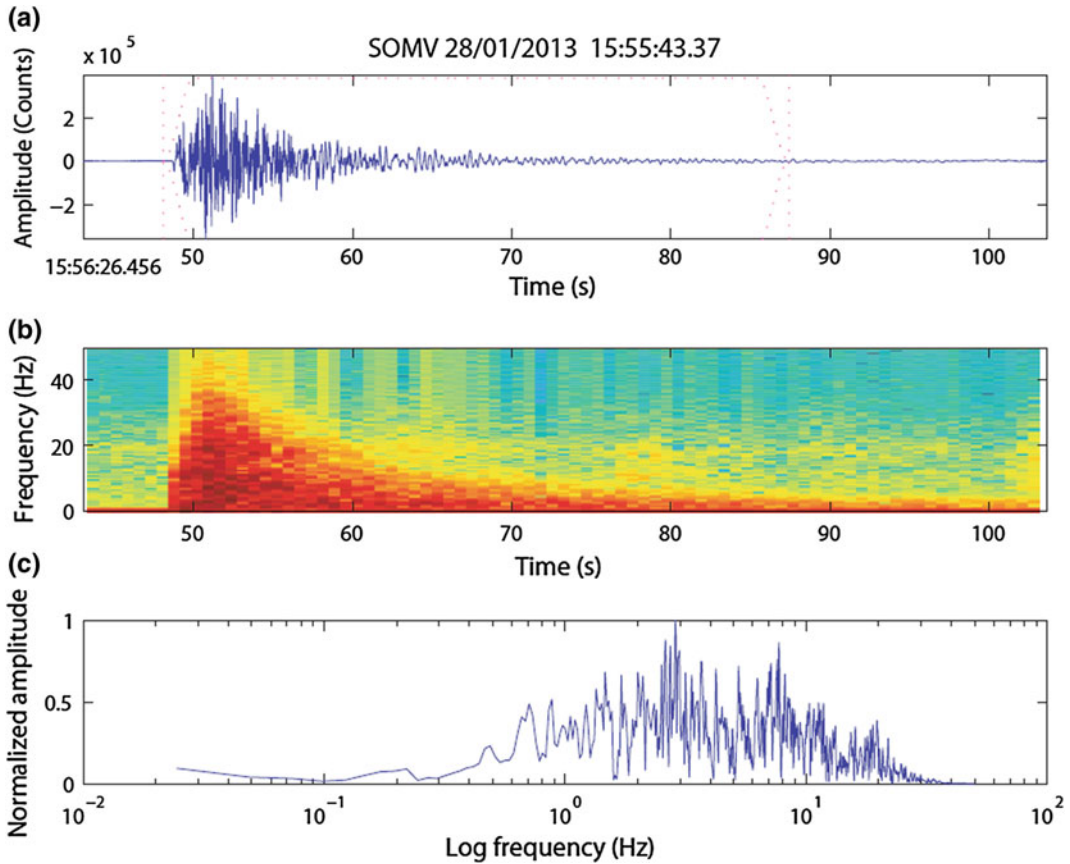


Fig. 2 Volcano-Tectonic event (VT) at SOMA (vertical component), on 28 January 2013. **a** Velocity signal, **b** spectrogram, where the exponential decay of the

amplitude can be observed and **c** normalized amplitude spectrum of the signal

In 1994 the earthquakes had hypocentres towards the SSW of the summit and under the crater, with depths of up to 6 km (Jiménez et al. 1995). The location of the earthquakes during the years 1997–1998 lie within a 50 km² area including the active crater of Volcán de Colima and the region that extends towards Nevado de Colima, 5.5 km to the north (Fig. 3). During 1997–1998 the majority of hypocentres within this area did not exceed a depth of 5 km below sea level, and were mainly distributed within the volcanic edifices of Volcán de Colima and Nevado de Colima (Domínguez et al. 2001; Zobin et al. 2002a, b, c).

2.2 Long-Period Events (LPs)

Long-period events (LPs), are the events that most frequently occur at Volcán de Colima. They are seismic events of short duration (<1 min in most cases), with an emergent first arrival P phase, but no observable second S phase (Fig. 4a). Their frequency is mainly below 5 Hz (Fig. 4b, c), and they are commonly located at depths of less than 3 km (Jiménez et al. 1995; Arámbula-Mendoza 2011a; Petrosino et al. 2011).

LP events have been observed mainly prior to effusive activity and preceding explosions.

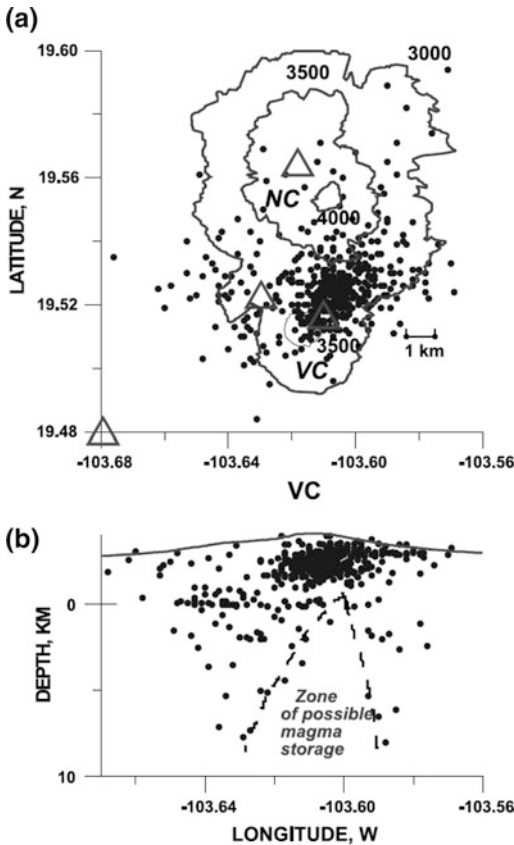


Fig. 3 **a** Location of epicentres for VTs located during the seismic crisis of 1997–1998. **b** Distribution of hypocentres for the same interval projected onto an E-W cross section through the summit of Volcán de Colima. An earthquake-free zone is outlined as a possible zone of magma storage. The error is about 0.6 km in depth (after Zobin et al. 2002a, b, c)

A number were detected during the third seismic crisis of the 1991 volcanic activity, coincident with an increase in fumarolic activity (Núñez-Cornú et al. 1994). Similarly they were detected during the seismic swarm that preceded the explosion of 1994 (Jiménez et al. 1995), and within the swarm of earthquakes that preceded the effusion of 1998. LPs preceded the 1999 Vulcanian explosions and were observed during the 2001–2003 effusive activity. During September 2004, an LP swarm announced the beginning of an effusive stage (Arámbula-Mendoza et al. 2011b). Between February and

September of 2005, low amplitude LPs known in Colima as ‘*pulgas*’ occurred preceding episodes of small lava dome growth and moderate Vulcanian explosions (Fig. 5, Varley et al. 2010a, b; Arámbula-Mendoza et al. 2011b). They appeared frequently during the 2007–2011 volcanic episode, as well as in January 2013 with the reactivation and fresh lava dome growth (see Varley, this volume).

Recent observations of abundant brittle–ductile fault textures within silicic lavas, such as andesite, has led to the hypothesis that seismic events, including LPs, may be triggered by fracturing and faulting within the erupting magma itself (Tuffen et al. 2008). A trigger mechanism of the earthquake within the conduit, which could be the breaking of magma along the conduit walls or within the dome itself, as has been proposed by various authors as an explanation for the generation of LP events (Goto 1999; Tuffen et al. 2003; Neuberg et al. 2006). The LPs observed at Volcán de Colima are probably generated by the fracturing of magma during magma ascent. Observations during the 2005 eruptive period indicated that repetitive sources are active for long durations in swarms lasting hours to days (Varley et al. 2010a, b; Arámbula-Mendoza et al. 2011b), generating LP families, as is the case with other volcanoes producing silicic lavas (e.g. Green and Neuberg et al. 2006; Neuberg et al. 2006). Twelve families were identified during the 2004–2005 episode (Arámbula-Mendoza et al. 2011b).

During the 2004–2005 effusive and explosive stages, another type of LP event was observed: monochromatic LP events or ‘*tornillos*’ (Arámbula-Mendoza et al. 2011b). These events were characterised by having only one fundamental frequency and a slowly diminishing coda, and likely to be due to very strong pressure differences within the conduit. A popular model that explains the existence of this type of event is the resonance of fractures associated with the pressurization processes that precede Vulcanian explosions in some cases, for example at Galeras volcano (Stix et al. 1997; Kumagai and Chouet 1999).

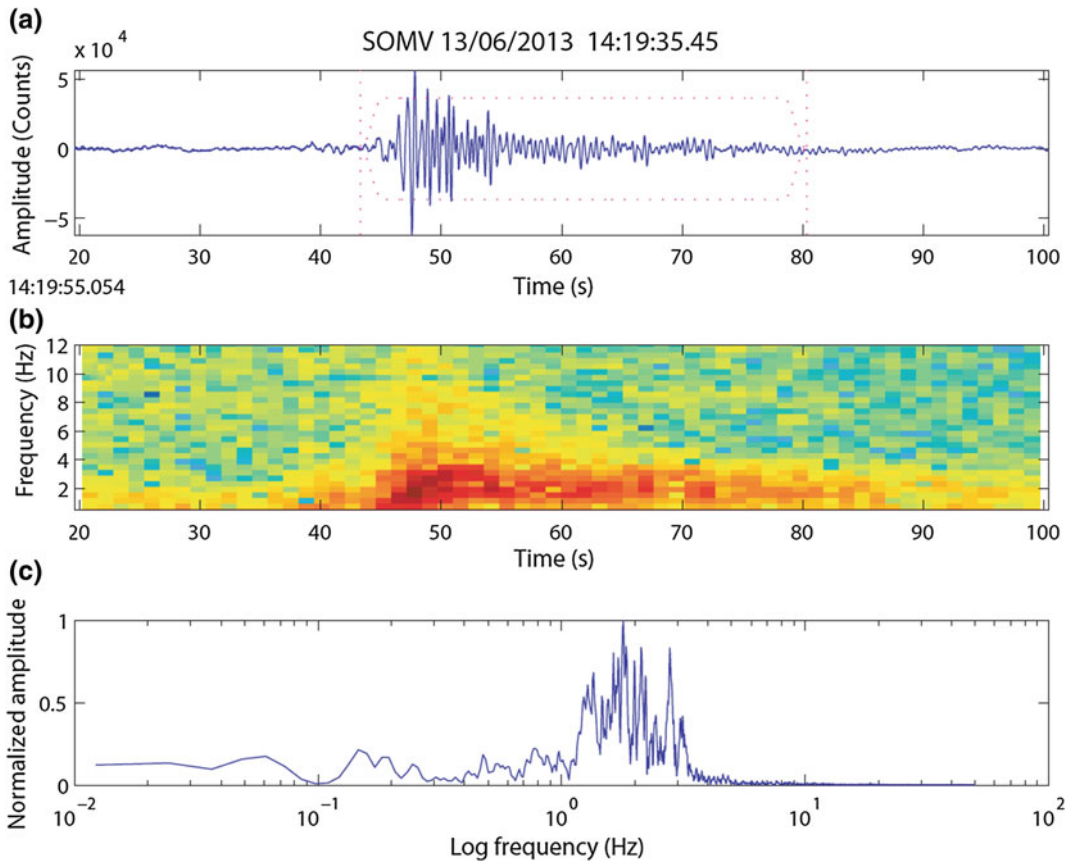


Fig. 4 Long-Period event (LP) at SOMA (vertical component) on 13 June 2013. **a** Velocity signal, **b** spectrogram and **c** normalized amplitude spectrum. These kinds of events have energy mainly between 1 and 5 Hz

2.3 Volcanic Tremor

Another type of event frequently observed at Volcán de Colima is volcanic tremor. It is a continuous signal that can last seconds to hours and sometimes days (Fig. 6a). The frequency content is mainly between 1 and 5 Hz, although this can be higher, up to 8 Hz, or as low as 0.5 Hz (Fig. 6b, c). At Volcán de Colima, three types of tremor have been observed: harmonic (with a clear fundamental frequency and harmonics; Fig. 6), spasmodic (with large variation in both the amplitude and frequency; Fig. 7), and pulsating (formed of a series of discrete events closely spaced in time; Fig. 8). For further information on the classification of tremor see Konstantinou and Schlindwein (2003).

Volcanic tremor at Volcán de Colima can be associated with every observed episode of volcanic activity, but variations in its characteristics have been registered. Typically, tremor is observed as a precursor, e.g. during the explosive episode of 1999, harmonic tremor appeared a few hours before the occurrence of large explosions. During many episodes, the tremor has continued up to the onset of the explosion. At times occurrences do not coincide with clear variations in eruptive activity, e.g. during the 2002 effusive period, an isolated period of medium to small amplitude monochromatic tremor was observed, which was likely a consequence of the degassing process or an interaction between the magma and groundwater. Some episodes were continuous with durations in excess of 24 h. During this

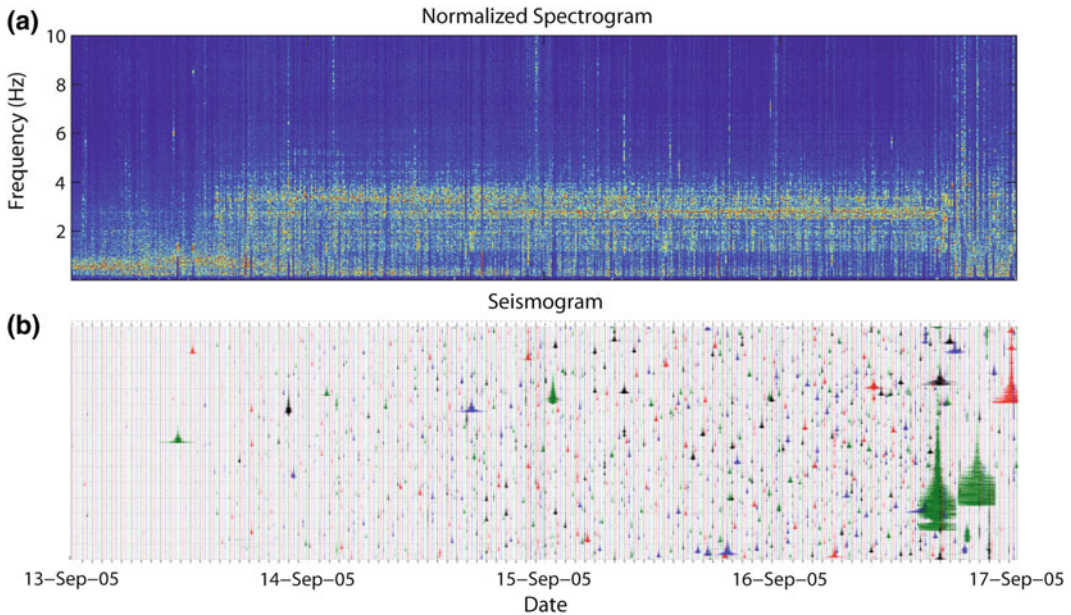


Fig. 5 **a** Normalized spectrogram and **b** seismogram from 13 to 16 September 2005, from short-period station (EZV4). Here the occurrence of low amplitude LPs (*'pulgas'*) before an explosion can be observed

period, gliding frequencies were observed similar to those seen at Soufrière Hills volcano, Monserrat (Powell and Neuberg 2003). This variation in frequency is probably generated by changes in the pressure within the conduit and/or an opening and sealing processes. The source location of the tremor is identical to that of the LPs and explosions, mainly between 0 and 3 km below the crater (Arámbula-Mendoza 2011a), although some episodes of harmonic tremor in 2015 have been located at a greater depth.

There are various models that aim to explain the existence of tremor at volcanoes: (a) fluid-flow-induced oscillations of conduits transporting magmatic fluids; (b) excitation and resonance of fluid-filled cracks; (c) bubble growth or collapse due to hydrothermal boiling of groundwater; (d) a variety of models involving the oscillations of magma bodies with different geometries (summarized in Konstantinou and Schlindwein (2003)). Also, the similar frequency content of LPs and tremor suggest they are physically related, indeed tremor can be considered a continuous manifestation of LP events as suggested for other volcanoes (e.g. Neuberg et al. 2000). At Volcán of Colima, it is models (a),

(b) and (c) that are the most likely processes to occur, but further research is necessary to understand the generation of tremor.

2.4 Explosion Events

Since the major eruption of 1913, volcanic activity has largely consisted of periods of effusive activity followed by explosive stages. The characteristics of the seismic signals associated with the explosive events vary depending on the style and size of the eruption. Commonly for Volcán de Colima, the seismic signals begin with an emergent low frequency phase (LF, Fig. 9a), followed by an impulsive high amplitude phase (Zobin et al. 2002a, b, c); this last phase can be attributed to magma fragmentation. The energy is concentrated at low frequencies (mainly 1–5 Hz) although we have observed high frequency content related to the occurrence of rockfalls and/or pyroclastic density currents related to the explosions (Fig. 9b, c). Sometimes the shockwave or airwave generates a high-frequency pulse in the seismogram (Fig. 9a).

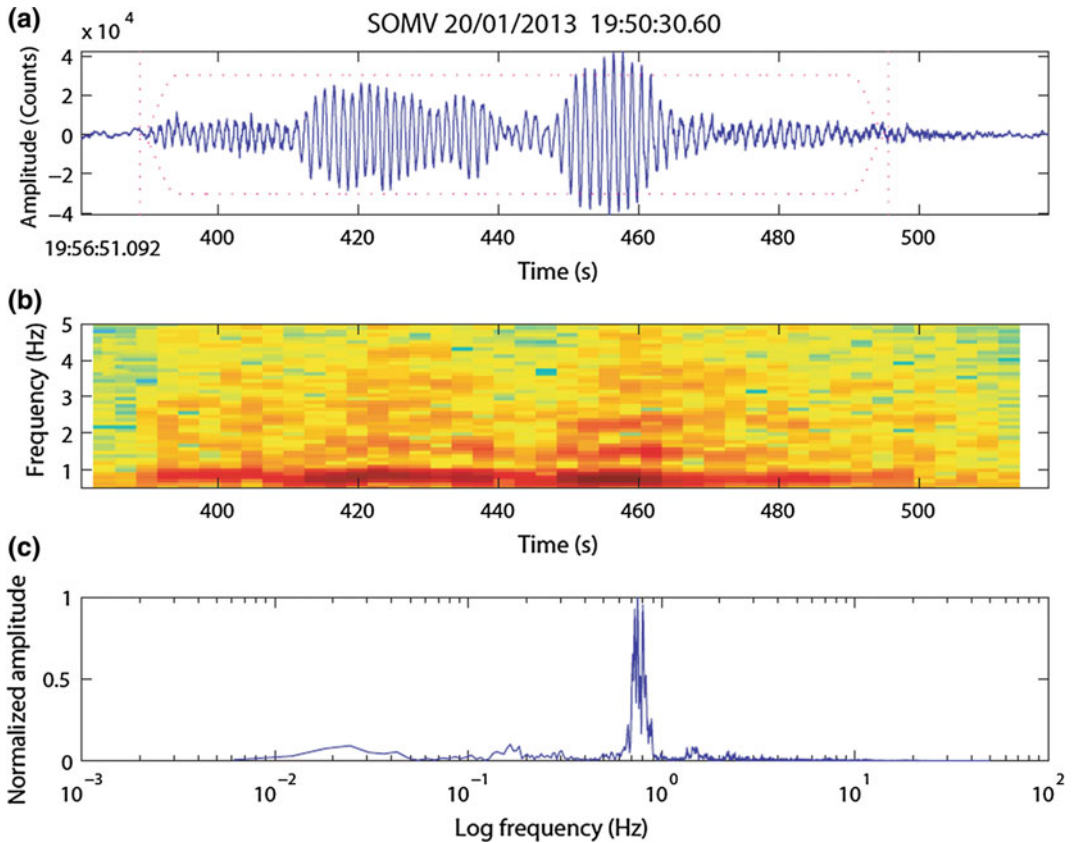


Fig. 6 Harmonic tremor at SOMA (vertical component) on 20 January 2013. **a** Velocity signal, **b** spectrogram and **c** normalized amplitude spectrum. In this case, this tremor is practically monochromatic

Explosive events at Volcán de Colima occur frequently when a fresh dome is emplaced in the crater. During cooling of either the lava dome or the magma column within the conduit there is an acceleration of crystallization, resulting in the formation of an impermeable cap within the vent at a relatively shallow level. Gas pressure then increases in the pore spaces beneath the cap until the lithostatic pressure above is exceeded, the cap fails, and a Vulcanian eruption occurs (Varley et al. 2010a). The first arrival of the seismic signal could reflect the breaking of the seal, but the explanation of the LF phase is still open to debate. Zobin et al. (2009) consider that it is due to fragmented magma movement within the conduit, whilst Varley et al. (2010b) suggest that after the initial rupture of the plug there is a rapid pressure drop and degassing of the magma, which generates the LF phase.

The majority of the larger explosive events tend to be associated with lava dome destruction. The largest explosions in the most recent periods of activity occurred in 1994, 1999, 2003, 2005, 2011, 2013, 2014 and 2015. In Table 1, the main Vulcanian explosions can be observed with the corresponding seismic energy calculated with the methodology proposed by Boatwright (1980), and subsequently used by Johnson and Aster (2005). The energy was calculated using only the vertical component of the EFRE station.

The largest explosions registered to date in 2005, with more than 30 significant events, the majority with pyroclastic flows generated by column collapse (Zobin et al. 2006b; Varley et al. 2010a, b; Varley, this volume). In a dense seismic array installed at Volcán de Colima, an apparent slowness variation of the first onset of the LF phase associated with the explosions was

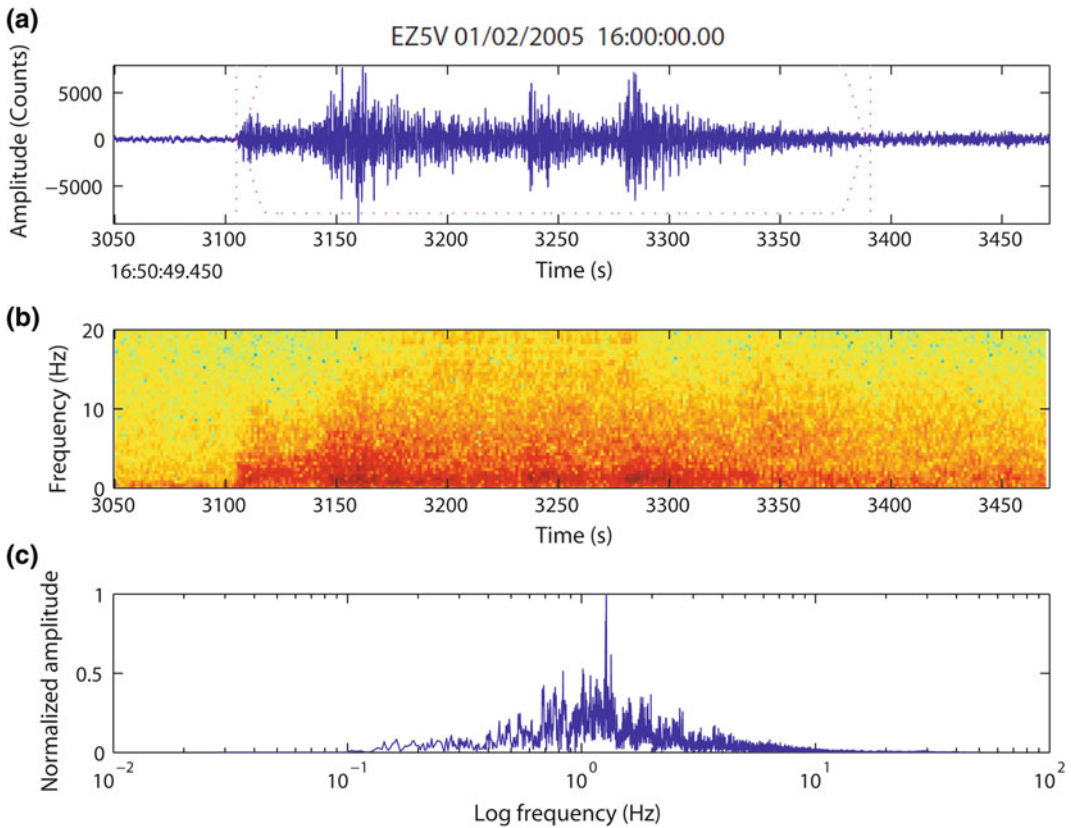


Fig. 7 Spasmodic tremor at EFRE (vertical component), on 01 February 2005, associated with an ash and gas emission. **a** Velocity signal, **b** spectrogram and **c** normalized amplitude spectrum

observed, with a possible upward migration of the source, the depth of which has been identified within a range of between 2.6 and 3.3 km below the crater (Palo et al. 2009). The location of these events in the last years, has been determined using a method based on seismic amplitudes (Battaglia and Aki 2003), whereby the attenuation of the seismic energy with distance is considered, the source being defined when the error between the theoretical model of attenuation and the observed data is a minimum for all the seismic stations. During recent activity, the start of the larger explosions (first 6 s of signal) have been localized between 3 and 0 km beneath the crater (Fig. 10).

Very-Long-Period events (VLPs) have also been recorded, associated with moderate-large Vulcanian explosions in 2003, 2005, 2011, 2013, 2014 and 2015. These events have been observed

once the signal is filtered, leaving just low frequencies. The VLPs at Volcán de Colima have periods of between 10 and 30 s, whereas in other volcanoes these events have been seen to be characterized by larger periods, e.g. at Popocatepetl volcano, VLPs associated with Vulcanian explosions were observed with periods between 25 and 100 s (Arciniega-Ceballos et al. 1999). Other examples of VLPs associated with Vulcanian explosions have been observed at Stromboli, Italy (D’Auria et al. 2006), Tungurahua, Ecuador (Kumagai et al. 2010, 2011), Augustine, USA (Dawson et al. 2011) and Redoubt, USA (Haney et al. 2012).

In Fig. 11, seventeen of these events can be observed; regrettably they were only observed with a single broadband sensor installed in 2005 (EFRE). The similar waveforms represent the process of pressurization and depressurization

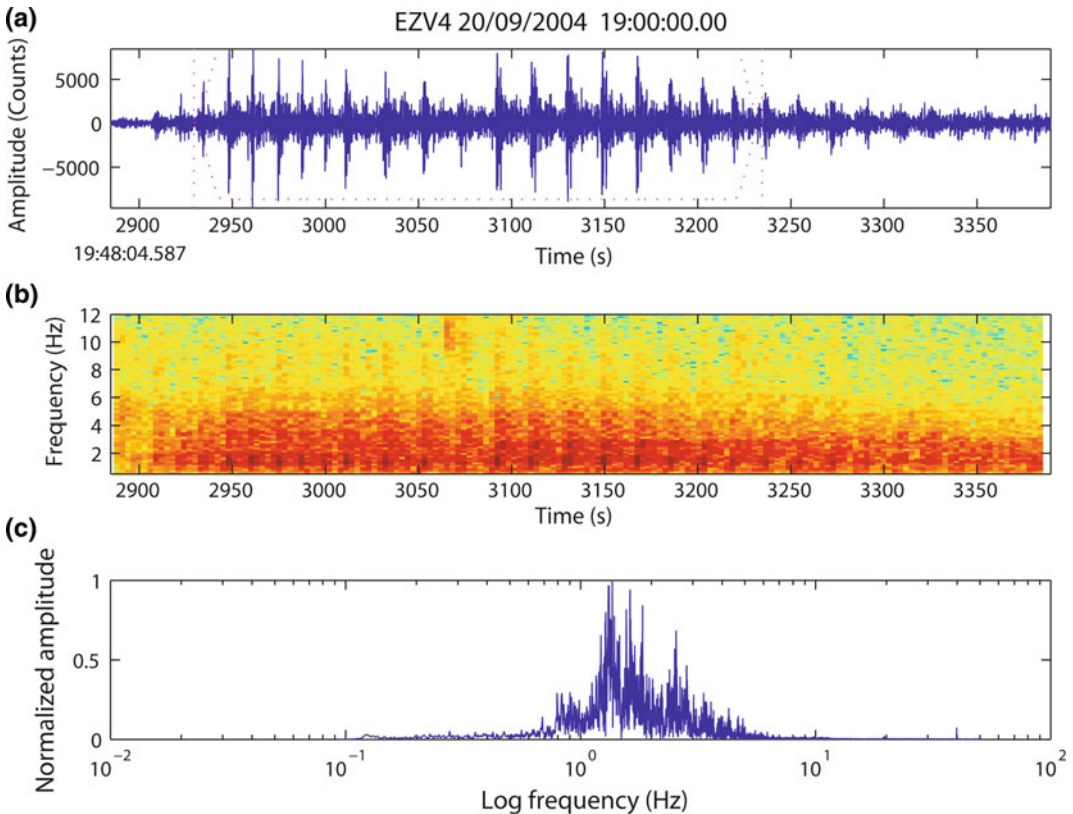


Fig. 8 Pulsating tremor at short-period seismometer EZV4 on 20 September 2004. **a** Velocity signal, **b** spectrogram and **c** normalized amplitude spectrum

during the explosions. In 2013, 2014 and 2015, VLPs were recognized at all the broadband stations.

The source mechanism of VLPs observed at many volcanoes is generally well reproduced by inversion, assuming six moment tensor components and three single force components in a volumetric source (Chouet 2003), although De Barros et al. (2013) mentioned that errors in both source location and velocity modelling can lead to strong spurious single forces. The moment tensor represents expansion or contraction of rock around a source, and a vertical single force can be generated as a consequence of the release of gravitational energy within the source volume (Takei and Kumazawa 1994). In the case of Vulcanian explosions, the recoil force generated by a volcanic jet during an eruption can generate one single force (Uhira and Takeo 1994; Chouet

2003), although this and other models are still being debated. A more detailed study is necessary to determine the origin of these events at Volcán de Colima.

2.5 Rockfalls and Pyroclastic Density Currents

In effusive episodes such as those observed at Volcán de Colima, the lava dome expands within the crater until it reaches the edges when it begins to flow down the flanks of the volcano. Due to the relatively high viscosity of andesite, lava flows are blocky, which generate rockfalls and possibly pyroclastic flows, particularly when the slope is steep. This kind of activity has been recorded in every episode of effusive activity at Volcán de Colima since 1991 (Fig. 12).

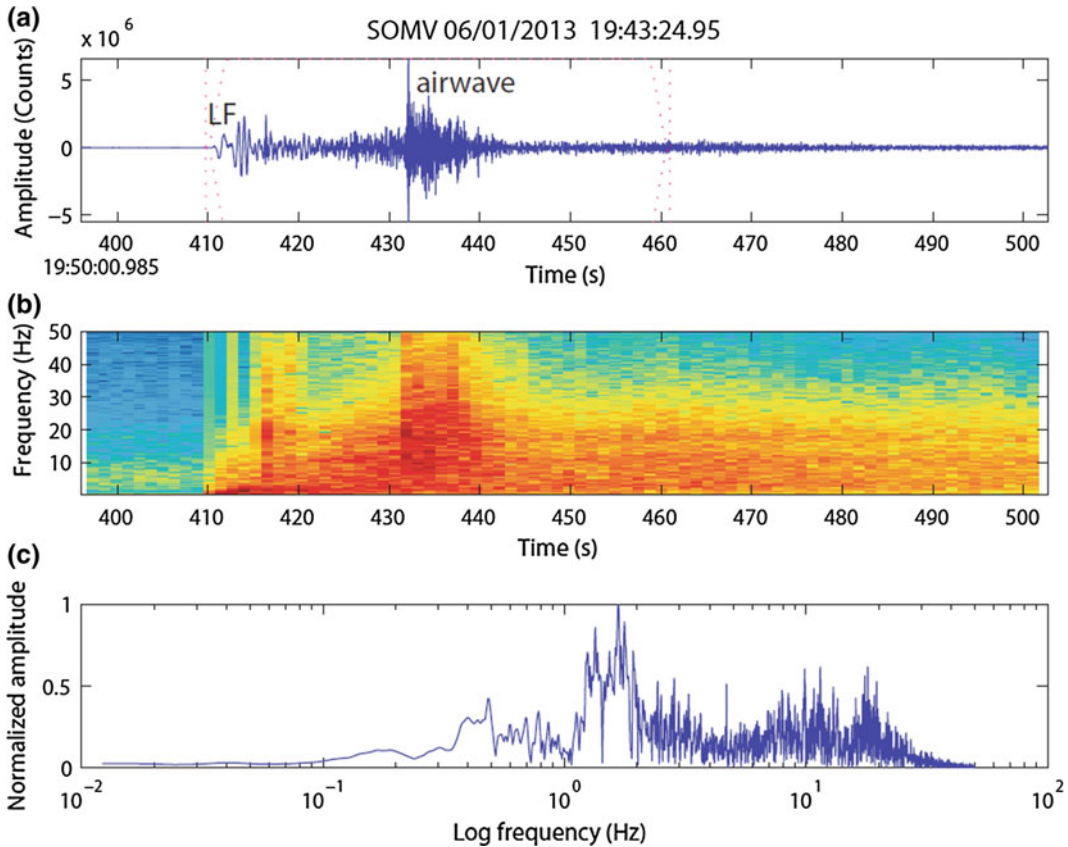


Fig. 9 Explosion event on SOMA (vertical component), on 06 January 2013. **a** Velocity signal; LF phase at the beginning and a shockwave that generates a high frequency pulse. **b** Spectrogram and **c** normalized amplitude spectrum for entire window

The seismic response to these events is an emergent high frequency signal with a duration of seconds to minutes. The generally symmetrical seismic waveform starts as an emergent signal, reaching its maximum amplitude near the centre, then finally decaying (Fig. 14a). The waveforms are of high frequency (mainly 1–15 Hz), but what is recorded is influenced by the distance between the seismic station and the source. Due to the generation of mainly surface waves and being of high frequency, they attenuate rapidly with distance (Fig. 13b, c). Zobin et al. (2009b) observed that seismic records of pyroclastic density currents generated by either the collapse of a lava dome or of an eruptive column, have a similar spectral content. The number and duration of rockfalls per day are

directly related to the emission rate of the magma: when the rate increases, the number and duration of rockfalls also increase (Mueller et al. 2013).

2.6 Lahars

The eruption rate of Volcán de Colima is one of North America's highest. During the last twenty years, there have been more than ten episodes of volcanic activity (see Varley, this volume). Frequently, there are significant amounts of non-consolidated material waiting to be remobilised during the rainy seasons. Each year there are around ten to fifteen lahars during the rainy season but after a year of volcanic activity this

Table 1 Details of the seismicity associated with the main Vulcanian explosions at Volcán de Colima during recent activity (derived from the vertical amplitude of EFRE)

Date (GMT)	Comment	Energy $\times 10^9$ (J)
10-02-1999	Explosion with incandescent blocks that showered the flanks out to 5 km, forming impact craters and triggering numerous forest fires (Zobin et al. 2002a, b, c)	Short-period seismometers saturated
10-05-1999	Explosion was felt and heard in Colima city; it was accompanied by two small pyroclastic flows that mainly descended the SW flank, where they entered into the ravines La Lumbre and Cordobán 04/1999 (BGVN 24:04)	Short-period seismometers saturated
17-07-1999	Large explosion, column reached ~ 11 km altitude. Pyroclastic flows had 4–4.5 km runout distances 08/1999 (BGVN 24:08)	Short-period seismometers saturated
22-02-2001	Column reached ~ 7 km altitude and produced ashfall at a distance of ~ 25 km from the volcano in Tuxpan, Jalisco. Small pyroclastic flows formed in the SW sector and descended to 3000 m. 04/2001 (BGVN 26:04)	Short-period seismometers saturated
17-07-2003	Explosion sent incandescent volcanic material to 500 m above the volcano, and produced a SW-drifting ash cloud to a height of ~ 7 km asl. At least five pyroclastic flows travelled down the volcano's flanks to a maximum distance of ~ 2 km. 08/2003 (BGVN 28:08)	0.27
02-08-2003	Large explosion was recorded on 2 August at 15:41. The Washington VAAC reported a plume at ~ 7.6 km altitude. 08/2003 (BGVN 28:08)	2.00
29-08-2003	The explosion produced an ash column at 7 km altitude with ashfall up to 60 km W-NW of the volcano and was accompanied by pyroclastic flows out to 2.5 km. 08/2003 (BGVN 28:08)	0.98
10-03-2005	Major explosion whose eruptive column reached up to 9.1 km asl and its pyroclastic flows travelled about 3 km into the Montegrande ravine ^a	0.48
13-03-2005	Column reached 8.9 km asl, with pyroclastic flows following principally the Muerto, Montegrande, Cordobán and San Antonio ravines. Ashfall in Los Mazos, Jalisco, located 12.5 km from the volcano ^a	1.50
26-03-2005	Moderate explosion ^a	0.38
12-04-2005	Moderate explosion ^a	0.09
20-04-2005	Moderate explosion, aviation authorities report an ash cloud reaching a maximum height of 6.1 km asl ^a	0.73
10-05-2005	Major explosion occurs with an ash column of 7.6 km asl ^a	0.99
16-05-2005	Major explosion with pyroclastic flows covering all the volcano's slopes ^a	2.14
24-05-2005	Major explosion occurred, whose ballistics reached up to 2.5 km and whose pyroclastic flows mainly travelled down the San Antonio and Montegrande ravines, causing some forest fires ^a	5.38
30-05-2005	A major explosion occurred. The column reached 8.5 km asl with pyroclastic flows mainly to the west ^a	7.13
02-06-2005	One major explosion occurred, causing ashfall in Colima city ^a	3.98
05-06-2005	Major explosion with a column of 8.9 km asl. Reports of broken glass were received from Juan Barragan 9 km away and in San Marcos, Jalisco, at 14 km. The Buenavista National Airport located to SSE of the volcano, remained closed for more than 12 h due to ashfall ^a	14.43
07-06-2005	Column reached a height of 8.5 km asl, the wind carried some of the ash to Colima city ^a	1.47
10-06-2005	Major explosive event occurred at night; this explosion was audible within a radius of 50 km, with probable pyroclastic flows up to 5 km ^a	0.94

(continued)

Table 1 (continued)

Date (GMT)	Comment	Energy $\times 10^9$ (J)
05-07-2005	Major explosion with pyroclastic flows to 4.8 km to SE; there were reports of ashfall in the Becerrera and Yerbabuena villages ^a	0.89
27-07-2005	Major explosion, eruptive column reaching 9.1 km asl ^a	0.22
16-09-2005	Major explosion with an eruptive column of 9.8 km asl, with ashfall in some villages to the NW. Pyroclastic flows in all directions ^a	1.17
27-09-2005	Explosion with an eruptive column that reached 7.6 km asl, depositing ash in Comala, Villa de Alvarez and Colima city ^a	0.71
21-06-2011	Explosion with pyroclastic flows mainly to the west, this event destroyed a small part of the lava dome formed during 2007–2011	0.11
06-01-2013	Explosion with pyroclastic flows mainly to west, the ash plume rose 2 km above the crater. Ash fell on Ciudad Guzman	0.08
11-01-2013	Explosion with pyroclastic flows mainly to west; this event destroyed another part of lava dome formed during 2007–2011	0.06
13-01-2013	Moderate explosion	0.02
29-01-2013	Explosion with ballistics covering the entire edifice, residents up to 20 km away reported a loud noise, shaking ground, and rattling windows. The ash plume rose to 6.5 km asl. 04/2013 (BGVN 38:04)	0.15
21-11-2014	Explosion with pyroclastic flows to the south and southwest	0.06
30-11-2014	Largest explosion during the period 2013–2015	0.23
03-01-2015	Explosion with pyroclastic flows to the north	0.04

^aTaken from Arámbula-Mendoza et al. (2011b)

can increase to as many as sixteen (see Capra et al., and Varley, this volume). Lahars can last from minutes to hours (Fig. 14a), and have signals with a broadband frequency range, from low frequencies to 50 Hz or higher (Fig. 14b, c). Similar to rockfalls, frequencies observed depend on the distance to the source. Sometimes lahars have many pulses or surges, associated with variations in the intensity of rain. Recent studies have observed that the amplitude and duration of the seismic signal is proportional to the volume of solid material and water (Vázquez et al. 2014).

3 Forecasting of Volcanic Eruption Using Seismicity

Real-time Seismic Energy Measurements (RSEM; De la Cruz-Reyna and Reyes-Dávila 2001) is the variable that represents the volcano seismic activity in a simple and effective way, although sometimes the RSEM can be affected by wind,

noise, tides, etc. RSEM represents the RMS or Root Mean Square of the seismic signal in a defined period of time. It is proportional to the seismic energy, and is only slightly different from the RSAM (Real-time Seismic-Amplitude Measurement) that is traditionally used at many volcanoes around the world, and is the mean of the seismic signal amplitude. The RSEM is defined as:

$$RSEM = \sqrt{\frac{1}{N} \sum_{i=1}^N A_i^2} \quad (1)$$

where A is the amplitude of the velocity of the ground (m/s), and N is the number of samples of the seismic signal. In Fig. 15, the accumulative monthly RSEM can be observed, highlighting the main periods of activity, 1998–1999, 2001–2003, 2004–2005, 2007–2011 and 2013–present (December 2016). In many cases, first lava dome growth was observed (effusive stage), then moderate-large explosions destroyed the lava

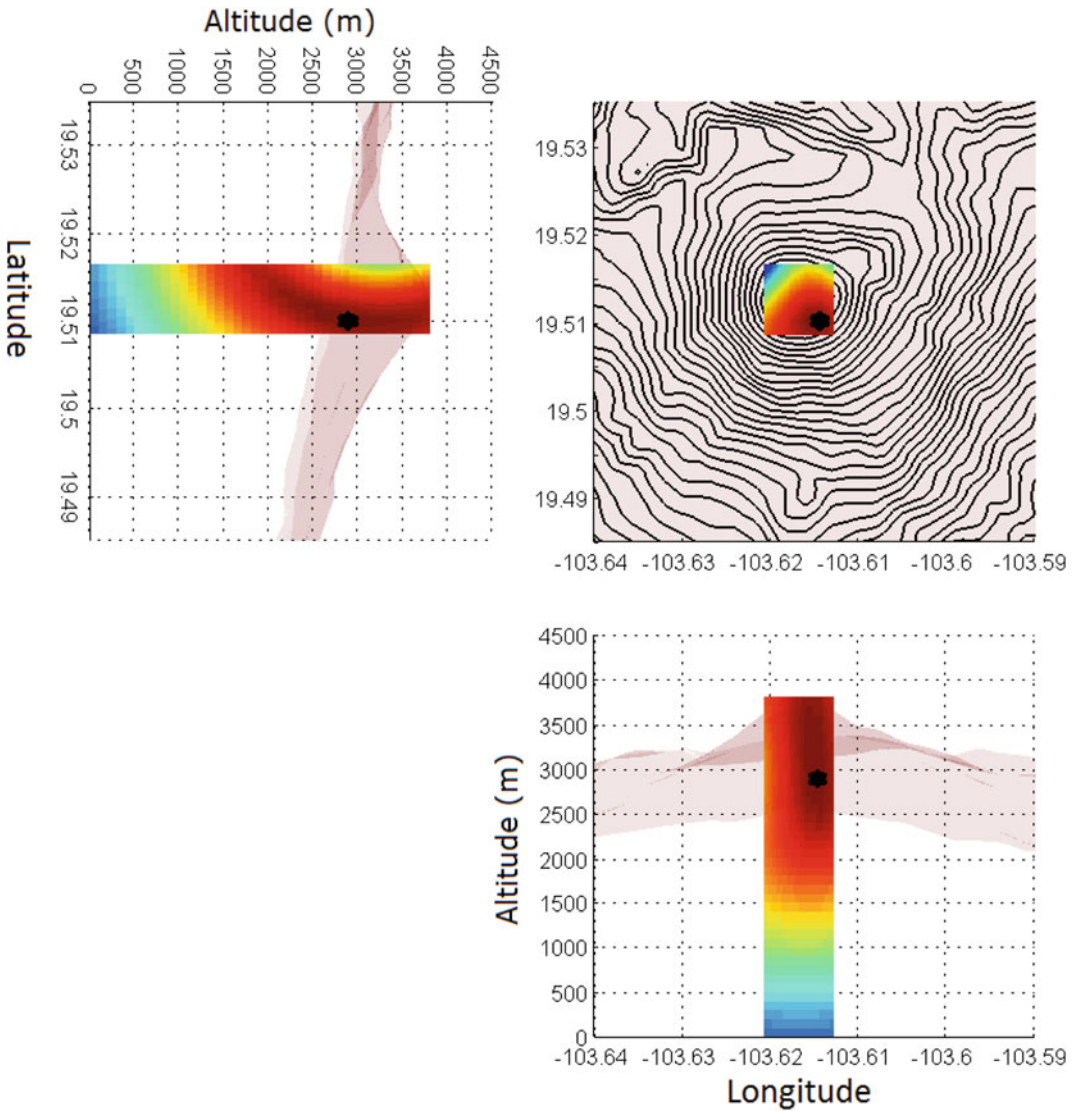


Fig. 10 Location of the start (first 6 s) of the explosion on 29 January 2013, using the seismic amplitudes method; the star is the location with a minimum misfit (difference between theoretical model and the data

observed). The dark red colours indicate a better fit or less error. Further details of the method are available in Battaglia and Aki (2003)

dome (explosive stage). Only in 2001 and 2013, has the period of activity started with one or more explosions, followed by effusion with lava dome growth then flows.

During July 2015, a major episode of lava dome growth and two partial dome collapses generated large deposits from pyroclastic density currents within the Montegrande ravine up to distances of 10 km (Reyes-Dávila et al. 2016;

Varley, this volume). This episode of activity was preceded by an increase in rockfalls and LP activity about two days before; only few VTs were observed, indicating that the system was “open” and the magma was easily able to reach the surface.

The seismicity has been used for forecasting eruptions, De la Cruz-Reyna and Reyes-Dávila (2001), and Reyes-Dávila and De la Cruz-Reyna

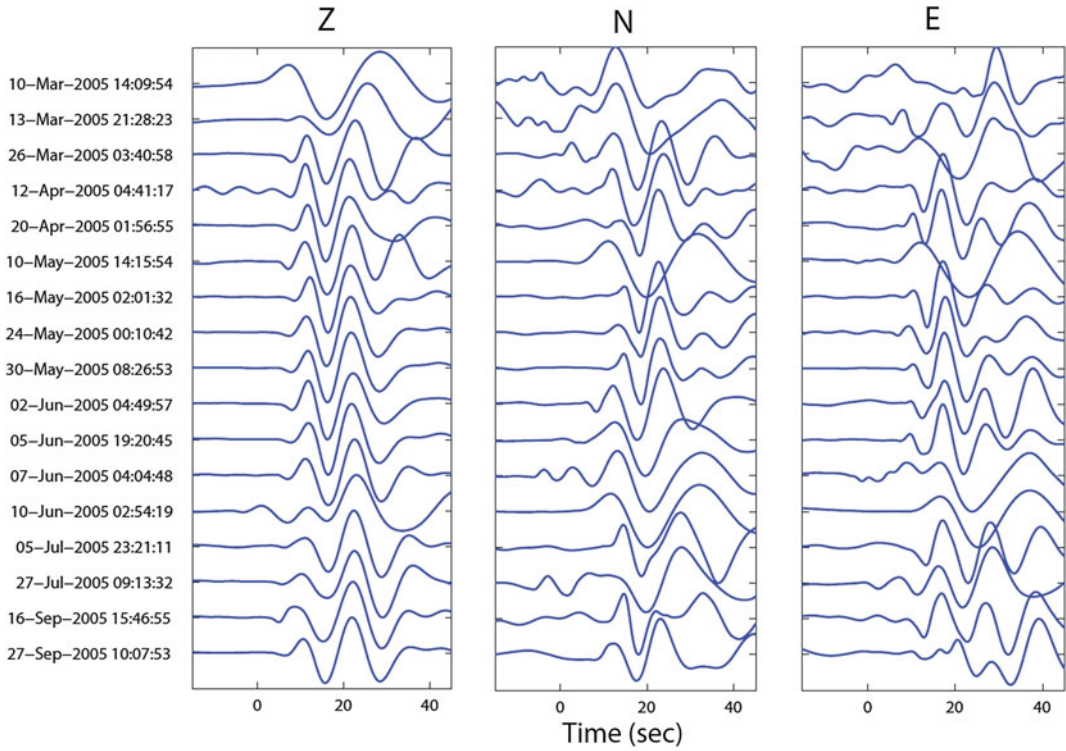


Fig. 11 17 Seismograms filtered to show VLPs observed in each of the three components of the broadband station of Fresnal (EFRE) during the 2005 moderate-large Vulcanian explosions. The signals are filtered between 30 and 10 s. The instrument response has been removed

Fig. 12 Example of small pyroclastic density current down southern flank of Volcán de Colima on 11 July 2015



(2002) used a continuum-mechanical model that reproduces the observed increase of strain rate preceding eruptions. The model is based on the strain response of a generalized Kelvin-Voigt viscoelastic body with an exponential retardation spectrum to forecast the time of eruptions at

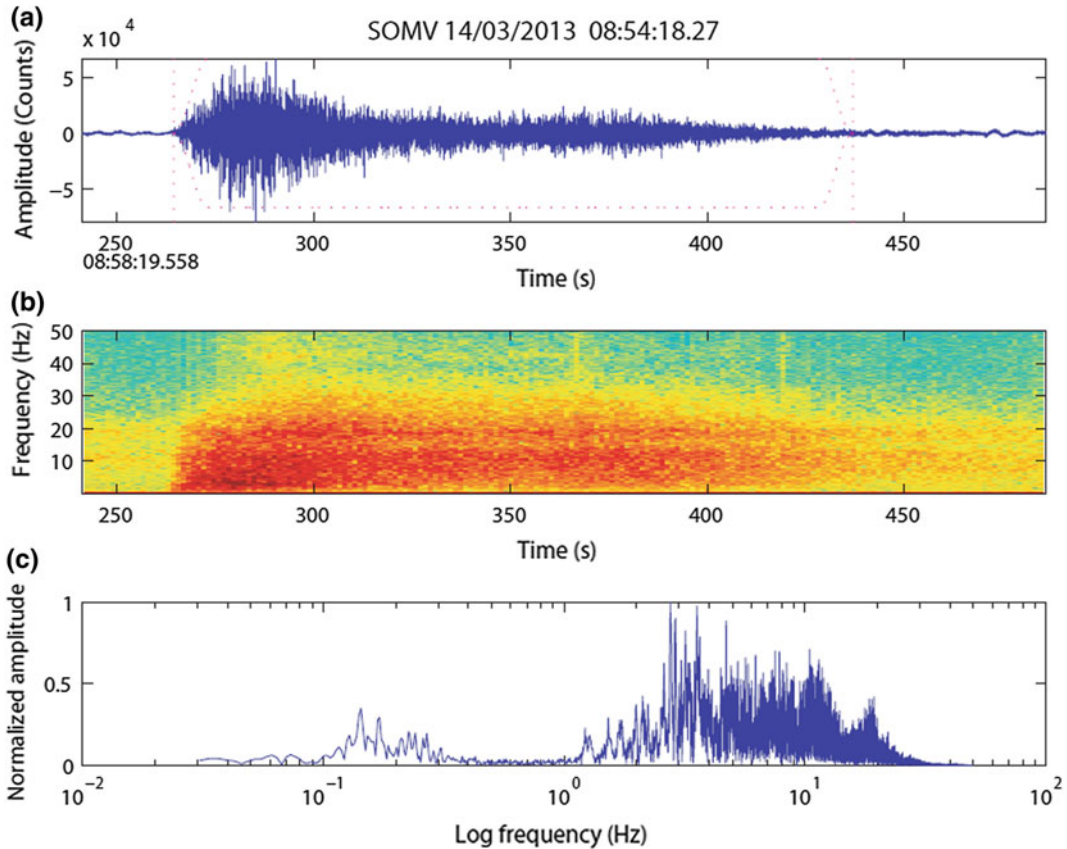


Fig. 13 Rockfall event at SOMV on 14 March 2013. **a** Velocity signal, **b** spectrogram. High frequencies can be observed here, **c** normalized amplitude spectrum

Volcán de Colima. This is a representation of how a material can undergo failure in a rigid state when it is subjected to pressure. When the volcano generates an explosion or a new emission of lava, this model can be applied. To model the process they used RSEM, which is a quantity directly proportional to the rate of strain release (De la Cruz-Reyna and Reyes-Dávila 2001). The pattern of RSEM evolution preceding eruptions at Volcán de Colima may be classified into three groups: type A, no precursory patterns can be recognized, type B precursory patterns are difficult to recognize or appear over time scales too short to allow warning or response, and type C precursory activity with patterns that can be recognized several days before an eruption (Fig. 16, Reyes-Dávila and De la Cruz-Reyna 2002). Seismicity during the precursory eruptive

periods analysed (1994–2001) was composed mainly of HFs and LPs. Some of these eruptions were predicted before of the event, e.g. the extrusion in November 1998; others were analysed a posteriori as is the case for the explosion in July 1994 (De la Cruz-Reyna and Reyes-Dávila 2001). In these two cases the forecast was successful.

In a posteriori study Arámbula-Mendoza et al. (2011b) also observed an increase in the rate of liberation of seismic energy, mainly comprising of LPs, before each major explosion that occurred in 2005. The time of the explosion was estimated by applying the material failure forecasting method (FFM, Voight 1988, 1989). The FFM helps to forecast the time of failure in a process of rupture, and is observed with the growth of the accumulated seismic energy. In

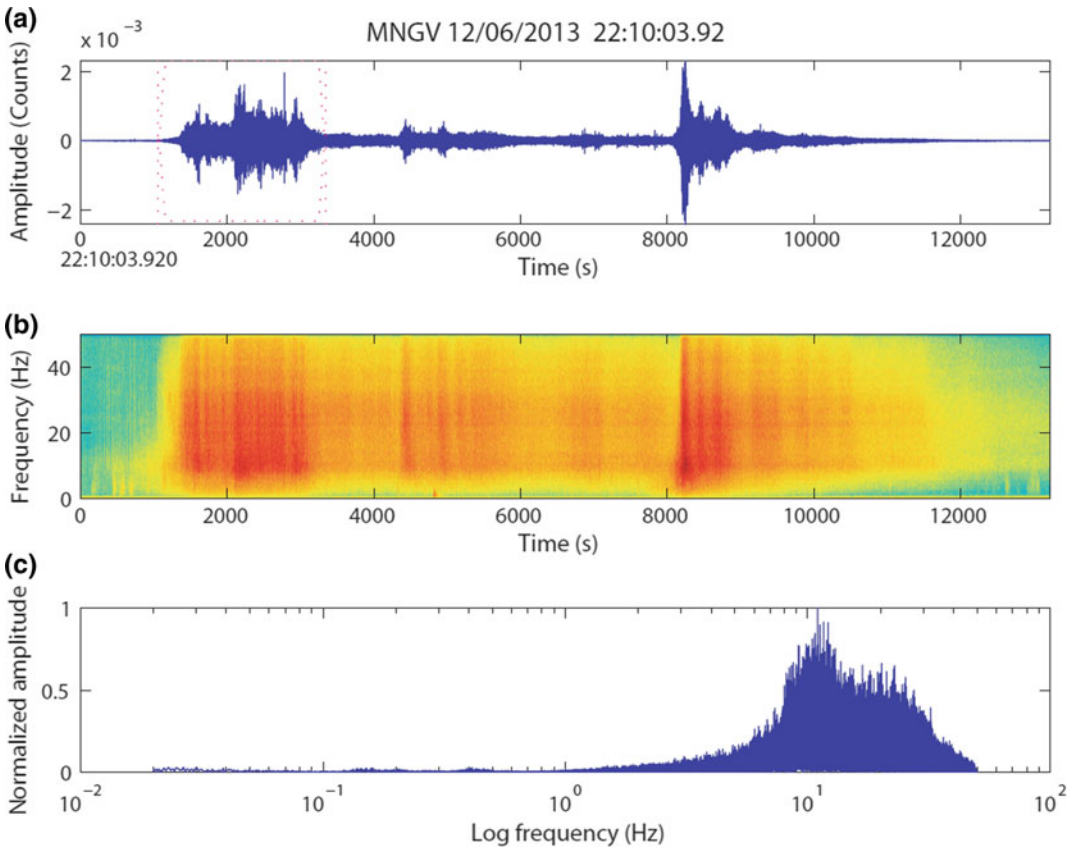


Fig. 14 Lahar recorded at MNGR (vertical component), on 12 June 2013; **a** velocity signal. Many pulses can be observed reflecting the variation of mass flow rate within the Montegrande ravine; **b** spectrogram; **c** normalized amplitude spectrum

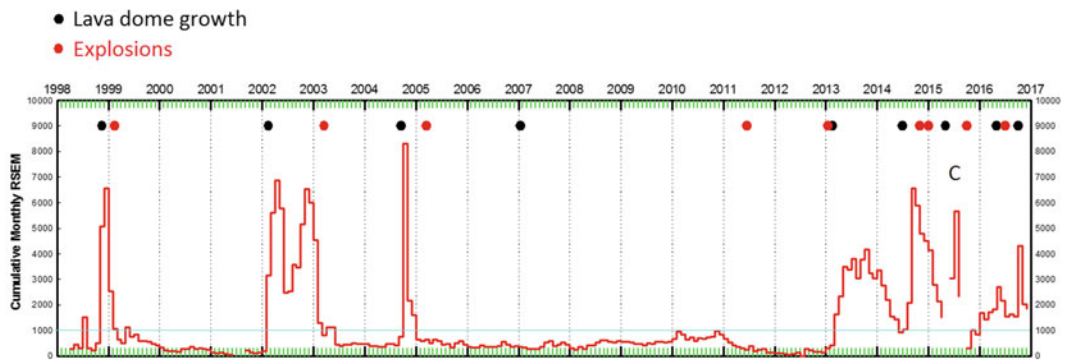


Fig. 15 Seismic activity observed at the short-period station EZV4 with RSEM, from 1998 to 2016. The black dots represent lava dome growth with lava flows (effusive stages), and the red dots represent destruction of lava domes (explosive stages). ‘C’ refers to lava dome collapses in July 2015

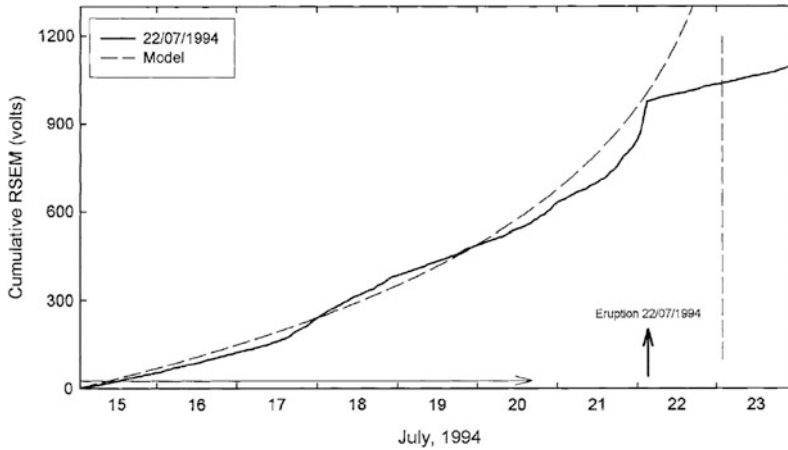


Fig. 16 The heavy curve represents cumulative RSEM data in volts for the period 15-23 July 1994, at Volcán de Colima. A 'forecast' was made in hindsight from part of the observed cumulative curve by trial fitting. The dashed curve is the prediction of the model, calculated from the cumulative data of the first 5.76 days as indicated by the

horizontal arrow, counted from the beginning of the swarm on 15 July 1994. The dashed vertical line is the time of failure given by the model prediction from the data in that interval (After Reyes-Dávila and De la Cruz-Reyna 2002)

this case the Seismic Spectral Energy Measurement (SSEM), was utilized, which is the RSEM filtered between 1 and 3 Hz. The inverse SSEM was calculated, giving a straight line. This was extrapolated to a zero value, which provided a posteriori forecast of the time of the explosion that could be compared with that observed. For the 2005 data, a systematic delay of a few hours between the actual time of occurrence of the explosions and the estimated time was observed, which leads to the suggestion that more complex processes than a simple disruption of a volcanic plug occur prior to each event. For the 2005 activity, 53% of the major explosions could be forecast. This methodology has been utilised at many volcanoes around the world, with some degree of success for forecasting explosions (Ortiz et al. 2003; De la Cruz-Reyna et al. 2010). It seems that forecasting can be improved by first classifying the seismicity (Boué et al. 2015).

In Fig. 17, the accumulated RSEM of the precursory seismicity can be observed in the principal explosions of 1999, 2001, 2003, 2005, 2011 and 2013. This seismicity can be intense with many LPs, HFs or tremor, or discrete with few events, and can last a few hours or up to

several days. In many cases, a notable increase in the seismic energy and number of events was seen a short time prior to the explosions, sometimes with harmonic or spasmodic tremor. This behaviour indicates that the associated seismicity can be complex, due to multiple magma pathways, leading to different vents, or variations in any combination of the following factors: gas contents, permeability, or rheology (Lavallée et al. 2008; Lavallée et al., this volume).

New techniques of seismic monitoring are being tested at Volcán de Colima. Automatic recognition of volcanic seismic signals based on Hidden Markov Models (HMMs; Benitez et al. 2009; Cortés et al. 2009) is one such technique. The classification of each seismic signal is done automatically, the program based on HMMs can recognize the signals without help from the operator. First, however, the system must be trained with many examples of each seismic event, then, a process of recognition and evaluation of the system is performed, until the program classifies with a high level of accuracy. The HMMs have the capacity to work in a continuous way, unlike other algorithms. The use of automatic recognition systems is very useful during

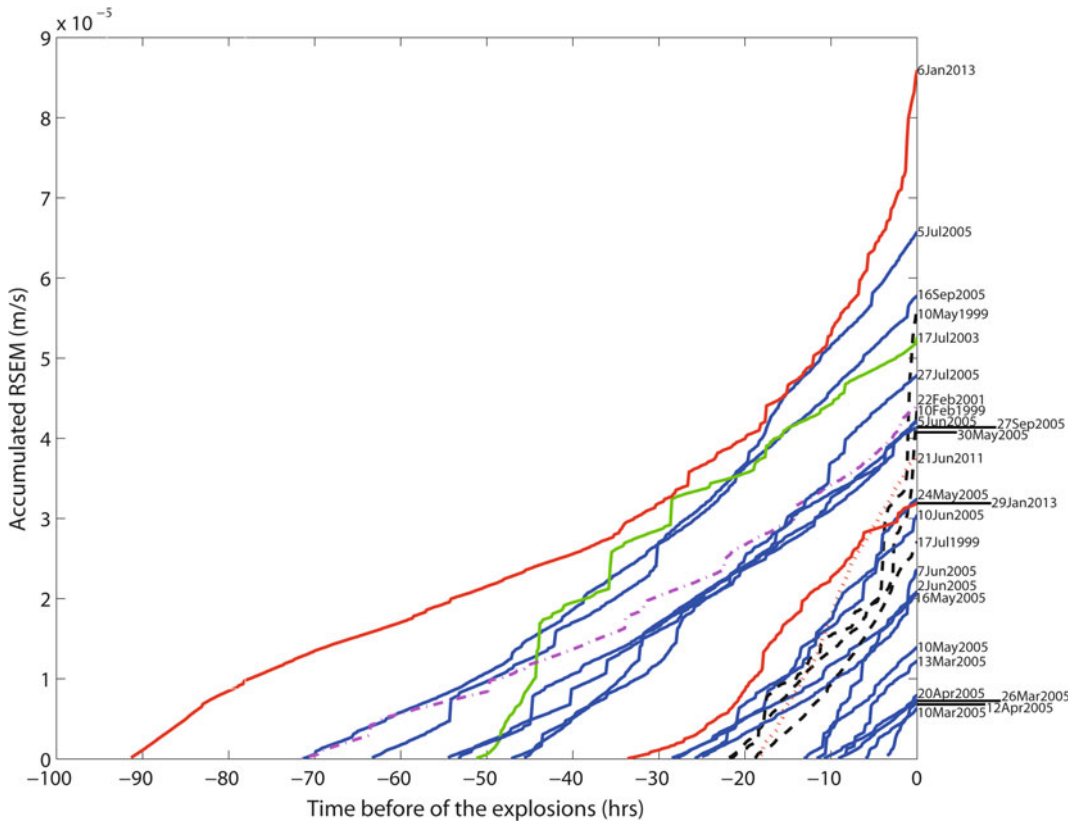


Fig. 17 Precursory seismicity (RSEM calculated each 10 min) before each of the main explosions observed at the short-period station EZV4 during the most recent explosion episodes. Zero is the onset of each explosion, the start time being taken as the occurrence of a notable increase in the RSEM associated with the initiation of a

swarm. The explosions observed were: 10 Feb, 10 May, 17 Jul. 1999; 22 Feb. 2001; 17 July 2003; 10 Mar., 13 Mar., 26 Mar., 12 Apr., 20 Apr., 10 May, 16 May, 24 May, 30 May, 2 June, 5 June, 7 June, 10 June, 5 July, 27 July, 16 Sep., 27 Sep. 2005; 21 June 2011; 6 Jan., 29 Jan. 2013

times of crisis. It allows a fast evaluation of the activity, thus allowing time to be spent on other analysis.

Currently the system is run continuously at Volcán of Colima, whereby the software generates a seismogram with various colours representing different types of events (Fig. 18). The implementation of the software in RESCO has allowed the characterization of the last two periods of volcanic activity: 2007–2011 (Fig. 19) and the ongoing period of activity that began in January 2013. This system is still in development and currently its accuracy is about 82% (Arámbula-Mendoza 2011a), when compared with manual event picking.

The level of seismicity, as illustrated by the RSEM, at Volcán de Colima can be variable and depends mainly on the effusion rate. Eruptive periods with a low effusion rate generate low numbers of rockfalls per hour, and low explosive activity as in 2001–2003 and 2007–2011. The maximum extrusion rate during recent activity, prior to July 2015 was between 6 and $8 \text{ m}^3 \text{ s}^{-1}$ for the last days of September and first few days of October, 2004 (Varley et al. 2010a). With an effusion rate at this level, large volume rockfalls and small pyroclastic density currents are commonplace. For the most recent eruptive period (2013–present), the maximum daily number of rockfalls has been between 250 and 350 events,

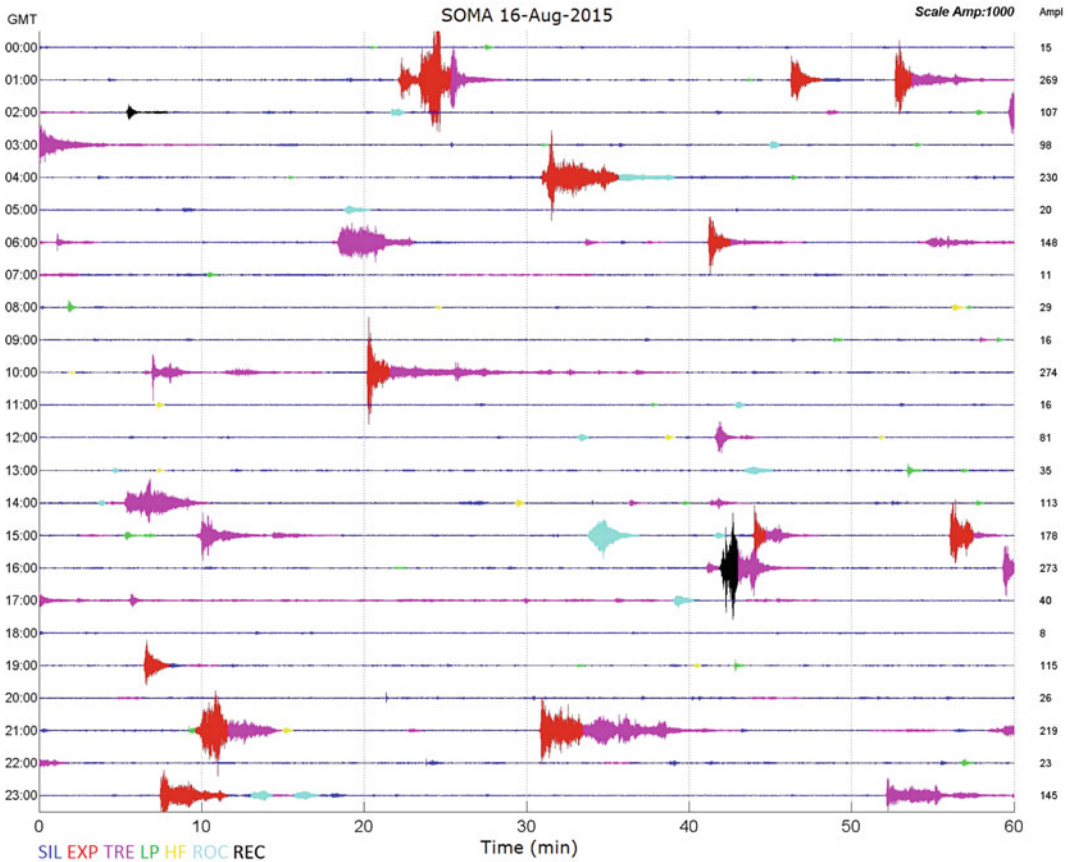


Fig. 18 Automated seismogram classified with Hidden Markov Models (HMMs), the colours indicate the type of seismic event; explosions (red), LPs (green), HFs (yellow), rockfalls (cyan), tremor (magenta), regional tectonic event (black) and silence (blue). The station used is a

broadband sensor SOMA, located at 1.7 km from the crater; the seismic signal is filtered between 0.5 and 50 Hz. Taken from Arámbula-Mendoza et al. (2017), submitted

with an extrusion rate within the range $0.1\text{--}1\text{ m}^3\text{ s}^{-1}$. The mean number of explosions was 8.5 per day up to December 2014, with some days having up to 30 events. Considering the activity over the past century, the most important period of explosive activity was between February and September 2005 (see Varley, this volume). During that time, the number of explosive events per day was actually lower than certain other periods, but the mean energy release by the explosions was greater, indicating a variation in the generation mechanism of the explosions, which remains undefined.

4 Discussion and Conclusions

Seismic monitoring is vital in the surveillance of a volcano. Since 1989, when the first seismic station was installed at Volcán de Colima, many thousands of signals (VTs, LPs, explosions, tremors, rockfalls and lahars) have been recorded by the seismic network. These signals represent different physical and geological processes, which can happen both inside and outside the volcano.

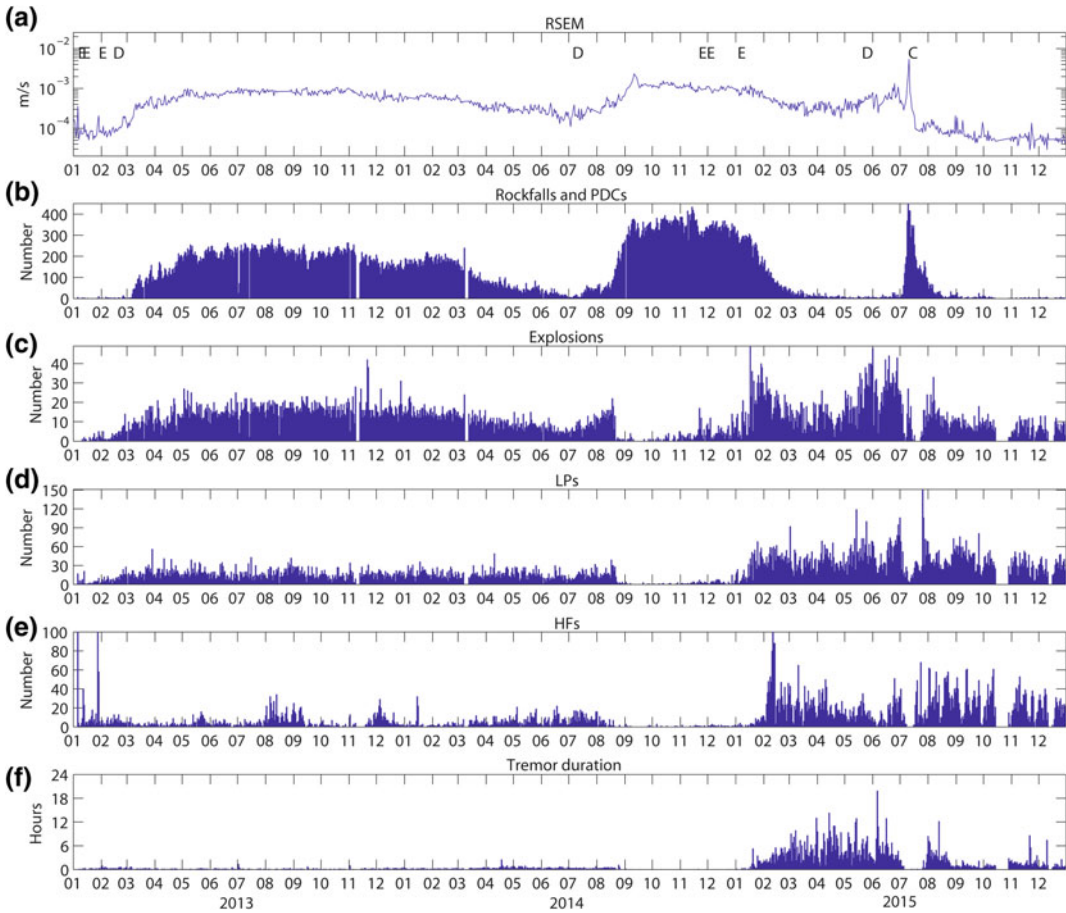


Fig. 19 a Daily RSEM, daily number of b rockfalls and pyroclastic density currents (PDCs), c explosions, d LPs, and e HFVs, f tremor, duration in hours. ‘E = moderate

explosion’, ‘D = start of lava dome growth’ and ‘C = lava dome collapse’. Taken from Arámbula-Mendoza et al. (2017), submitted

VTs are usually the first seismic signals that show up, indicating the beginning of a new period of volcanic activity, for example prior to the 1991, 1994 and 1998 eruptions. During these periods, the system is considered as closed or partially closed after a long period of quiescence. The origin of the VTs is related to changes in the stresses within the volcano, as a consequence of the migration of magma to the surface. At Volcán de Colima, the tensional tectonic regimen associated to the Colima Graben can also produce VTs without a clear relationship to the ascent of magma.

Usually, the next type of event to occur are LPs. However, for the 2001, 2004, 2007 and 2013 periods, LPs were the first seismic signals

of reactivation. Evidence exists to indicate that LPs are generated by the fracturing of magma during its ascent to the surface. The occurrence of LP events in swarms can be a precursor of the emplacement of a lava dome and/or major explosions. 2005 was a year with extensive LP activity associated with magma ascent that ended with moderate-large Vulcanian explosions (Varley et al. 2010a, b; Arámbula-Mendoza et al. 2011b). Civil Protection authorities were warned a few hours before several explosions occurred, with the information based on the occurrence of LPs.

Volcanic tremor is another seismic signal that is often observed at Volcán de Colima. During

explosive episodes in 1999, spasmodic tremor appeared a few hours before the occurrence of large explosions. During the 2001–2003 effusive period, we observed a lengthy period of harmonic tremor in 2002, probably associated with degassing processes or interaction of groundwater. This tremor was of low amplitude, which could be associated with phreatic eruptions (Benoit et al. 2013), a reflection of a small diameter volcanic conduit (McNutt and Nishimura 2008), or a low gas content of the magma (Nadeau et al. 2011).

Rockfalls and pyroclastic flows are also common events at Volcán de Colima, occurring after the crater is filled with new material and begins to overflow. The size and number of rockfalls are both related to the emission rate. Explosions can be accompanied by a large energy release, with major events generating pyroclastic flows due to column collapse. The seismicity associated with explosions can be complex. With the increase in the number of broadband seismometers, VLPs have also been observed during explosions, most likely resulting from the liberation of gravitational energy during a volcanic jet. Finally, during the rainy season, lahars can occur due to remobilization of the non-consolidated material on the volcano's slopes. The size of these events depends of the amount of rain and the available material on the volcano (see Capra et al. this volume). As the occurrence of this type of event endangers the people that live close to, or even within, the ravines, seismic monitoring is a vital tool in reducing the risk. The moment that a lahar event is identified, state civil protection authorities are notified. The message is then relayed to the municipal civil protection offices who will advise the people that live near to the rivers or ravines and if necessary, carry out evacuations of the most vulnerable population.

At Volcán de Colima many successful forecasts of volcanic activity have been carried out. Seismic monitoring has been the vanguard of the network since its introduction 27 years ago. However, improvements in the observations of others seismic parameters in real time such as Q value (attenuation of the seismic waves for

changes in the medium; Domínguez et al. 2003), b value (statistical relationship between the magnitude and occurrence of VTs; Zobin et al. 2002a, b, c, anisotropy (variations in the fractures associated with magmatic activity; Johnson and Savage 2012), seismic noise (variations in the velocity of the medium; Lesage et al. 2014), etc., could help to better our knowledge about the process that accompanies the eruptions.

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References

- Arámbula-Mendoza, R.: Clasificación automática de eventos sísmicos volcánicos y análisis de la actividad reciente en el Volcán de Colima. Ph.D. Thesis. Instituto de Geofísica, UNAM, México, 176 pp (2011a)
- Arámbula-Mendoza, R., Lesage, P., Valdés-González, C., Varley, N.R., Reyes-Davila, G., Navarro, C.: Seismic activity that accompanied the effusive and explosive eruptions during the 2004–2005 period at Volcán de Colima, Mexico. *J. Volcanol. Geoth. Res.* **205**, 30–46 (2011)
- Arámbula-Mendoza, R., Reyes, D.G., Vargas, B.D., González, A.M., Navarro, O.C., Velásquez, M.A., Ariel, R.C.: Seismic monitoring of effusive-explosive activity and large lava dome collapses during 2013–2015 at Volcán de Colima, Mexico. Submitted to *J. Volcanol. Geoth. Res.* (2017)
- Arciniega-Ceballos, A., Chouet, B., Dawson, P.: Very long-period signals associated with vulcanian explosions at Popocatepetl Volcano, Mexico. *Geophysical Res. Lett.* **26**, 3013–3016 (1999)
- Battaglia, J., Aki, K.: Location of seismic events and eruptive fissures on the Piton de la Fournaise volcano using seismic amplitudes. *J. Geophys. Res.* **108**(B8). <https://doi.org/10.1029/2002jb002193> (2003a)
- Benitez, M.C., Lesage, P., Cortés, G., Segura, J.C., Ibáñez, J.M., De la Torre, A.: Automatic recognition of volcanic-seismic events based on continuous hidden markov models. In: Bean, C.J., Braidon, A.K., Lokmer, I., Martini, F., O'Brien, G.S. (eds.) *The Volume Project, Volcanoes: understanding Subsurface Mass Movement*, pp. 130–139 (2009)

- Benoit, J.P., McNutt, S.R., Barboza, V.: Duration-amplitude distribution of volcanic tremor. *J. Geophys. Res.* **108**(B3), 2146. <https://doi.org/10.1029/2001jb001520> (2003)
- Boatwright, J.: A spectral theory for circular seismic sources: simple estimates of source dimension, dynamic stress drop, and radiated seismic energy. *Bull. Seismol. Soc. Am.* **70**(1), 1–27 (1980)
- Boué, A., Lesage, P., Cortés, G., Valette, B., Reyes-Dávila, G.: Real-time eruption forecasting using the material failure forecast method with a Bayesian approach. *J. Geophys. Res. Solid Earth* **120**(4), 2143–2161 (2015)
- Cortés, G., Arámbula, R., Álvarez, I., Benítez, C.M., Ibáñez, J.M., Lesage, P., González, A.M., Reyes, D.G.: Analysis of Colima, Popocatepetl, and Arenal volcanic seismicity using an automatic Continuous Hidden Markov Model-based recognition system. In: Bean, C.J., Braiden, A.K., Lokmer, I., Martini, F., O'Brien, G.S. (eds.) *The Volume Project—Volcanoes: understanding Subsurface Mass Movement*, pp. 150–160 (2009)
- Chouet, B.: Volcano seismology. *Pure. Appl. Geophys.* **160**, 739–788 (2003)
- D'Auria, L., Giudicepietro, F., Martini, M., Peluso, R.: Seismological insight into the kinematics of the 5 April 2003 vulcanian explosion at Stromboli volcano (southern Italy). *Geophys. Res. Lett.* **33**, L08308 (2006). <https://doi.org/10.1029/2006GL026018>
- Dawson, P.B.A., Chouet, B.A., Power, J.: Determining the seismic source mechanism and location for an explosive eruption with limited observational data: Augustine Volcano, Alaska. *Geophys. Res. Lett.* **38**, L03302. <https://doi.org/10.1029/2010gl045977> (2011)
- De Barros, L., Lokmer, I., Bean, C.J.: Origin of spurious single forces in the source mechanism of volcanic seismicity. *J. Volcanol. Geotherm. Res.* **262**, 1–6 (2013)
- De la Cruz-Reyna, S., Reyes-Dávila, G.A.: A model to describe precursory material failure phenomena: application to short-term forecasting at Colima volcano, Mexico. *Bull. Volcanol.* **63**, 297–308 (2001)
- De la Cruz-Reyna, S., Tárrega, M., Ortiz, R., Martínez-Bringas, A.: Tectonic earthquakes triggering volcanic seismicity and eruptions. Case studies at Tungurahua and Popocatepetl volcanoes. *J. Volcanol. Geotherm. Res.* **193**, 37–48 (2010)
- Domínguez, T., Zobin, V.M., Reyes-Dávila, G.A.: The fracturing in volcanic edifice before an eruption: the June–July 1998 high-frequency earthquake swarm at Volcán de Colima, México. *J. Volcanol. Geoth. Res.* **105**, 65–75 (2001)
- Domínguez, R.T., Flores, C.F., Reyes, D.G.: Temporal change in coda wave attenuation observed at Volcán de Colima, México before the 1998 eruption. *J. Volcanol. Geoth. Res.* **125**, 215–223 (2003)
- Haney, M.M., Chouet, B.A., Dawson, P.A., Power, J.A.: Source characterization for an explosion during the 2009 eruption of Redoubt Volcano from very-long-period seismic waves. *J. Volcanol. Geotherm. Res.* <https://doi.org/10.1016/j.jvolgeores.2012.04.018> (2012)
- Goto, A.: A new model for volcanic earthquake at Unzen volcano: melt rupture model. *Geophys. Res. Lett.* **26**, 2541–2544 (1999)
- Green, D.N., Neuberg, J.: Waveform classification of volcanic low-frequency earthquake swarms and its implication at Soufriere Hills Volcano, Montserrat. *J. Volcanol. Geoth. Res.* **153**, 51–63 (2006)
- Jiménez, Z., Reyes, G., Espíndola, J.M.: The July 1994 episode of seismic activity at Colima Volcano, Mexico. *J. Volcanol. Geoth. Res.* **64**, 321–326 (1995)
- Johnson, J.B., Aster, R.C.: Relative partitioning of acoustic and seismic energy during Strombolian eruptions. *J. Volcanol. Geotherm. Res.* **148**, 334–354 (2005)
- Johnson, J.H., Savage, M.K.: Tracking volcanic and geothermal activity in the Tongariro Volcanic Centre, New Zealand, with shear wave splitting tomography. *J. Volcanol. Geotherm. Res.* **223**, 1–10 (2012)
- Konstantinou, K.I., Schlindwein, V.: Nature, wavefield properties and source mechanism of volcanic tremor: a review. *J. Volcanol. Geoth. Res.* **119**, 161–187 (2003)
- Kumagai, H., Chouet, B.A.: The complex frequencies of long-period seismic events as probes of fluid composition beneath volcanoes. *Geophys. J. Int.* **138**, F7–F12 (1999)
- Kumagai, H., Nakano, M., Maeda, T., Yepes, H., Palacios, P., Ruiz, M., Arrais, S., Vaca, M., Molina, I., Yamashima, T.: Broadband seismic monitoring of active volcanoes using deterministic and stochastic approaches. *J. Geophys. Res.* **115**, B08303 (2010). <https://doi.org/10.1029/2009JB006889>
- Kumagai, H., Palacios, P., Ruiz, M., Yepes, H., Kozono, T.: Ascending seismic source during an explosive eruption at Tungurahua volcano, Ecuador. *Geophys. Res. Lett.* **38**, L01306 (2011). <https://doi.org/10.1029/2010GL045944>
- Lavallée, Y., Meredith, P., Dingwell, D.B., Hess, K.U., Wassermann, J., Cordonnier, B., Gerik, A., Kruhl, J. H.: Seismogenic lavas and explosive eruption forecasting. *Nature* **453**, 507–510 (2008)
- Lesage, P., Reyes-Dávila, G., Arámbula-Mendoza, R.: Large tectonic earthquakes induce sharp temporary decreases in seismic velocity in Volcán de Colima, Mexico. *J. Geophys. Res. Solid Earth* **119**, 4360–4376. <https://doi.org/10.1002/2013jb010884> (2014)
- McNutt, S.R., Nishimura, T.: Volcanic tremor during eruptions: temporal characteristics, scaling and constraints on conduit size and processes. *J. Volcanol. Geoth. Res.* **178**(1), 10–18 (2008)
- Mueller, S.B., Varley, N.R., Kueppers, U., Lesage, P., Reyes-Dávila, G., Dingwell, D.B.: Quantification of magma ascent rate through rockfall monitoring at the growing/collapsing lava dome of Volcán de Colima, Mexico. *Solid Earth* **4**, 201–213 (2013)
- Nadeau, P.A., Palma, J.L., Waite, G.P.: Linking volcanic tremor, degassing, and eruption dynamics via SO₂ imaging. *Geophys. Res. Lett.* **38**(1), L01304 (2011)

- Neuberg, J., Luckett, R., Baptie, B., Olsen, K.: Models of tremor and low frequency earthquake swarms on Montserrat. *J. Volcanol. Geoth. Res.* **101**, 83–104 (2000)
- Neuberg, J.W., Tuffen, H., Collier, L., Green, D., Powell, T., Dingwell, D.: The trigger mechanism of low-frequency earthquakes on Montserrat. *J. Volcanol. Geoth. Res.* **153**, 37–50 (2006)
- Núñez-Cornú, F., Nava, F. A., De la Cruz-Reyna, S., Jiménez, Z., Valencia, C., García-Arthur, R.: Seismic activity related to the 1991 eruption of Colima Volcano, Mexico. *Bull. Volcanol.* **56**, 228–237 (1994)
- Ortiz, R., Moreno, H., García, A., Fuentealba, G., Astiz, M., Peña, P., Sánchez, N., Tarraga, M.: Villarica volcano (Chile): characteristics of the volcanic tremor and forecasting of small explosions by means of a material failure method. *J. Volcanol. Geotherm. Res.* **128**, 247–259 (2003)
- Palo, M., Ibáñez, J.M., Cisneros, M., Bretón, M., Del Pezzo, E., Ocaña, E., Orozco-Rojas, J., Posadas, A. M.: Analysis of the seismic wavefield properties of volcanic explosions at Volcán de Colima, México: insights into the source mechanism. *Geophys. J. Int.* **177**, 1383–1398 (2009)
- Petrosino, S., Cusano, P., La Rocca, M., Galluzzo, D., Orozco-Rojas, J., Breton, M., Del Ibáñez, J., Pezzo, E.: Source location of long period seismicity at Volcán de Colima, México. *Bull. Volc.* **73**, 887–898 (2011)
- Powell, T., Neuberg, J.: Time dependent features in tremor spectra. *J. Volcanol. Geoth. Res.* **128**, 177–185 (2003)
- Reyes-Dávila, G.A., De la Cruz-Reyna, S.: Experience in the short-term eruption forecasting at Volcán de Colima, México, and public response to forecasts. *J. Volcanol. Geoth. Res.* **117**, 121–127 (2002)
- Reyes-Dávila, G.A., Arámbula-Mendoza, R., Espinasa-Pereña, R., Pankhurst, M.J., Navarro-Ochoa, C., Savov, I., Vargas-Bracamontes, D.M., Cortés-Cortés, A., Gutiérrez-Martínez, C., Valdés-González, C., Domínguez-Reyes, T., González-Amezcuca, M., Martínez-Fierros, A., Ramírez-Vázquez, A., Cárdenas-González, L., Castañeda-Bastida, E., Vázquez-Espinoza de los Monteros, D.M., Nieto-Torres, A., Campion, R., Courtois, L., Lee, P. D.: Volcán de Colima dome collapse of July, 2015 and associated pyroclastic density currents. *J. Volcanol. Geotherm. Res.* **320**, 100–106 (2016).
- Stix, J., Torres, R.C., Narváez, M.L., Cortés, J.G.P., Raigosa, J.A., Gómez, M.D., Castonguay, R.: A model of vulcanian eruptions at Galeras volcano, Colombia. *J. Volcanol. Geoth. Res.* **77**, 285–303 (1997)
- Takei, Y., Kumazawa, M.: Why have the single force and torque been excluded from seismic source models? *Geophys. J. Int.* **118**, 20–30 (1994)
- Tuffen, H., Dingwell, D., Pinkerton, H.: Repeated fracture and healing of silicic magma generates flow banding and earthquakes? *Geology* **31**, 1089–1092 (2003)
- Tuffen, H., Smith, R., Sammonds, P.R.: Evidence for seismogenic fracture of silicic magma. *Nature* **453**, 511–514 (2008)
- Uhira, K., Takeo, M.: The source of explosive eruptions of Sakurajima volcano, Japan. *J. Geophys. Res.* **99** (B9), 17775–17789 (1994)
- Varley, N., Arámbula-Mendoza, R., Reyes-Dávila, G., Stevenson, J., Harwood, R.: Long-period seismicity during magma movement at Volcán de Colima. *Bull. Volc.* **72**, 1093–1107 (2010a)
- Varley, N., Arámbula-Mendoza, R., Reyes-Dávila, G., Sanderson, R., Stevenson, J.: Generation of Vulcanian activity and long-period seismicity at Volcán de Colima, Mexico. *J. Volcanol. Geoth. Res.* **198**, 45–56 (2010b)
- Vázquez, R., Capra, L., Caballero, L., Arámbula-Mendoza, R., Reyes-Dávila, G.: The anatomy of a lahar: Deciphering the 15th September 2012 lahar at Volcán de Colima, Mexico. *J. Volcanol. Geoth. Res.* **272**, 126–136 (2014)
- Voight, B.: A method for prediction of volcanic eruptions. *Nature* **332**, 125–130 (1988)
- Voight, B.: A relation to describe rate-dependent material failure. *Science* **243**, 200–203 (1989)
- White, R., McCausland, W.: Volcano-tectonic earthquakes: a new tool for estimating intrusive volumes and forecasting eruptions. *J. Volcanol. Geoth. Res.* (2015). <https://doi.org/10.1016/j.jvolgeores.2015.10.020>
- Zamora-Camacho, A., Espindola, J.M., Reyes-Dávila, G.: The 1997–1998 Activity of Volcán de Colima, Western Mexico: some aspects of the associated seismic activity. *Pure Appl. Geophys.* **164**, 39–52 (2007)
- Zobin, V.M., Luhr, J.F., Taran, Y.A., Bretón, M., Cortés, A., De La Cruz-Reyna, S., Domínguez, T., Galindo, I., Gavilanes, J.C., Muñiz, J.J., Navarro, C., Ramírez, J. J., Reyes, G.A., Ursúa, M., Velasco, J., Alatorre, E., Santiago, H.: Overview of the 1997–2000 activity of Volcán de Colima, México. *J. Volcanol. Geotherm. Res.* **117**(1–2), 1–19 (2002a)
- Zobin, V.M., González-Amezcuca, M., Reyes-Dávila, G. A., Domínguez, T., Cerda-Chacón, J.C., Chávez Alvarez, J.M.: Comparative characteristics of the 1997–1998 seismic swarms preceding the November 1998 eruption of Volcán de Colima, México. *J. Volcanol. Geoth. Res.* **117**, 47–60 (2002a)
- Zobin, V.M., González-Amezcuca, M., Reyes-Dávila, G. A.: Seismotectonic deformation of the volcanic edifice prior to the 1998 lava eruption of Volcán de Colima, México. *Bull. Volcanol.* **64**, 349–355 (2002b)

- Zobin, V.M., Navarro-Ochoa, C.J., Reyes-Dávila, G.A.: Seismic quantification of the explosions that destroyed the dome of Volcán de Colima, Mexico, in July-August 2003. *Bull. Volcanol.* **69**, 141–147 (2006a)
- Zobin, V.M., Navarro, C., Reyes-Dávila, G., Orozco, J., Bretón, M., Téllez, A., Reyes-Alfaro, G., Vázquez, H.: The methodology of quantification of volcanic explosions from broadband seismic signals and its application to the 2004–2005 explosions at Volcán de Colima, México. *Geophys. J. Int.* **167**, 467–478 (2006b)
- Zobin, V.M., Reyes, G.A., Guevara, E., Bretón, M.: Scaling relationship for Vulcanian explosions derived from broadband seismic signals. *J. Geophys. Res.* **114**, B03203 (2009). <https://doi.org/10.1029/2008JB005983>
- Zobin, V.M., Plascencia, I., Reyes, G., Navarro, C.: The characteristics of seismic signals produced by lahars and pyroclastic flows: Volcán de Colima, México. *J. Volcanol. Geoth. Res.* **179**, 157–167 (2009b)