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Variety in destruction of andesitic lava domes, which were built during the 1998-2017 unrest at Volcán de Colima, México, and the general development of the eruption: Insight from associated seismic signals

Vyacheslav M. Zobin[1]

Abstract

The 1998-2017 unrest at Volcán de Colima, México showed a variety in destruction of andesitic lava domes that were formed during seven episodes of the lava-dome eruption. The destructions of the lava domes during six eruptive episodes (1 to 5 and 7) were realized with a sequence of Vulcanian explosions. Another type of destruction of the lava dome, because of a partial collapse of the southern sector of the crater, was recorded during episode 6. This study is based on the seismic signals and video images of destructive events, which were recorded by the networks of Colima University, and demonstrated regularity in the general process of this 20-year eruption. The explosive destruction of the lava domes was studied according to the two-phase conceptual model of explosive process proposed by Zobin *et al.* (2006a). There were estimated values of durations of the initial phase of the seismic signal, $D = t_2 - t_1$, proportional to the length of the way of the magma bubbles from the fragmentation level in the conduit to the surface, where the explosion occurring, and the energy of explosions, E. The temporal variations of these two parameters from episode to episode (in the case of episode 6 with collapse of the lava dome without large destructive Vulcanian explosion, E and D were taken equal to 0) allowed to recognize three destructive periods in development of the eruption. The change in the depth of the feeding magma reservoir was proposed as the decisive element in the change of process of the lava dome destruction. It allows to reconstruct the development of the 1998-2017 eruptive activity as a turbulence of magma deposit with its consumption with every episode of lava dome destruction.

Key words: Volcán de Colima, Lava dome eruption, Episode of the lava dome building-destruction, Destructive period.

Resumen

Las erupciones del domo de lava, ocurridas en el andesítico Volcán de Colima, México, durante 1998-2017, demostraron variedad en el proceso de la destrucción de los domos de lava que fueron formaron durante los siete episodios de la erupción. Las destrucciones de los domos de lava durante seis episodios eruptivos (1 a 5 y 7) se realizaron con una secuencia de explosiones Vulcanianas. Otro tipo de destrucción del domo de lava, debido a un colapso parcial del sector sur del cráter, se registró durante el episodio 6. Este estudio se basa en las señales sísmicas e imágenes de video de eventos destructivos, que fueron grabados por las redes de la Universidad de Colima, y demostró la regularidad en el proceso general de esta erupción. La destrucción explosiva de los domos de lava se estudió de acuerdo con el modelo conceptual de dos fases del proceso explosivo propuesto por Zobin *et al.* (2006a). Se estimaron los valores de las duraciones de la fase inicial de la señal sísmica, $D = t_2 - t_1$, proporcionales a la longitud del paso de las burbujas de magma desde el nivel de fragmentación en el conducto, hasta la superficie donde las explosiones son generadas, y la energía de las explosiones, E. Las variaciones temporales de estos dos parámetros de un episodio a otro (en el caso del episodio 6 con colapso del domo de lava sin una gran explosión Vulcaniana destructiva, se tomaron E y D iguales a 0) permitieron reconocer tres períodos destructivos en el desarrollo de la erupción. El cambio en la profundidad de la cámara magmática, de donde magma realizó la construcción de cada domo, se propuso como el elemento decisivo en el cambio del proceso de destrucción del domo de lava. Esto permite reconstruir el desarrollo de la actividad eruptiva de 1998-2017 como una turbulencia del depósito de magma con su consumo con cada episodio de destrucción del domo de lava.

Palabras clave: Volcán de Colima, erupción del domo de lava, episodio de la construcción -destrucción del domo de lava, periodo destructivo.

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* Corresponding author: Vyacheslav Zobin, vzobin@ucol.mx
[1] Centro Universitario de Estudios Vulcanológicos, Universidad de Colima, Colima, México.

Vyacheslav Moisseevitch Zobin

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1. Introduction

Lava domes are mounds of viscous lava and rocks that pile up and accumulate around a volcanic vent. Processes of the lava dome-building in the crater of a volcano and their following destructions are characteristic for the sequences of eruptive activity at andesitic and dacitic volcanoes. Active lava domes are typically made of an inner, somewhat ductile lava core and a cooler, brittle outer rock carapace. Some lava domes do not extrude large volumes of lava but instead form dome-shaped plugs or caps at the top of magma conduits within a crater. They are often associated with systems that have relatively frequent explosive eruptions, so they can be short-lived. After an explosion removes the dome and conduit magma, the magma's free surface rises again (Fink, 1990; Miller *et al.*, 1998; Moran *et al.*, 2008; Okada *et al.*, 1981; Zobin *et al.*, 2002; Calder *et al.*, 2015; Rhodes *et al.*, 2018).

The edifices of active volcanoes are characterized by instability and may experience also lateral collapses at a range of scales, from relatively minor rockfalls consisting of a few hundreds of cubic meters of pyroclasts to the great pyroclastic density currents (PDCs).

PDCs are generated when the bulk density of the current exceeds that of the ambient atmosphere and can be emplaced by several eruption styles, including directed blasts, dome collapse, column collapse, and boiling-over eruptions (McGuire, 2003; Dufek *et al.*, 2015; Zobin, 2018).

In this article we discuss the variety in destruction of the sequence of andesitic lava domes that were built during the 1998-2017 unrest at Volcán de Colima, México, and demonstrate the application of this variety to reconstruct of the development of the total eruption process.

2. Volcán de Colima and the specific features of its 1998-2017 unrest

The 3860-m-high andesitic stratovolcano Volcán de Colima, México, is situated at the western end of the Trans-Mexican Volcanic Belt within the Colima Volcanic Complex (CVC) (Figure 1A). It is the most historically active volcano in México (Luhr and Carmichael, 1980). Volcán de Colima displays a wide spectrum of eruption styles, including small phreatic explosions, major block-lava effusions, and large explosive events followed by pyroclastic flows and lahars (Breton González *et al.*, 2002).

The recent 1998-2017 eruptive unrest was based on the new-formed shallow magma storage zone, feeding the eruption. This storage zone, which was formed at depths between 4 and 12 km beneath the crater, was filled with magma after a sequence of five swarms of volcano-tectonic (VT) earthquakes recorded below Volcán de Colima from November 1997 to November 1998 (Luhr, 2002; Zobin *et al.*, 2002).

The following 20-year lava dome-building eruption developed into two cycles and consisted of seven episodes of the lava dome-building and following destructions (Figure 1B). The first cycle lasted from November 1998 to June 2011 and included four episodes of the lava dome growth. The second cycle, which began after the one and half-year repose and developed from January 2013 to March 2017, consisted of three episodes. During the two cycles of eruption at Volcán de Colima, the equal volumes of products (about $75 \times 10^6\,m^3$) were erupted with a difference in the mean magma discharge rates (approximately $5 \times 10^6\,m^3$ and $18 \times 10^6\,m^3$ per year for cycles 1 and 2 respectively) (Zobin and Tellez, 2019).

The destructions of the lava domes during six eruptive episodes (1 to 5 and 7) were realized with a sequence of Vulcanian explosions. Another type of destruction of the lava dome, because of a partial collapse of the southern sector of the crater, was recorded during episode 6.

In this article, we study the specific characteristics of the processes of the lava-dome destructions of both types. At first, we will analyse the process of destruction of the lava domes with Vulcanian explosions. Then, the episode with destruction of the lava dome with a partial collapse will be considered.

The study is based on the seismic signals and video images of destructive events, which were recorded by the networks of Colima University and collected during 1998 to 2017. Figure 2 shows the position of the broadband digital seismic station, EZ5, situated at 4 km SE from the crater of volcano, whose signals were used in this study. It was installed in 2002 and equipped with a three-component GURALP CMG-40TD sensor with corner period of 30 s and GURALP DM24 multi-channel digitizer with sampling rate of 100 samples per second. For identification of seismic signals of explosive events, the video images of station *NEV*, installed at 5.5 km N of the crater of volcano in 1998 (Figure 2A), were used. The station was equipped with camera of Sony Hi8 having resolution of 320×240 pixels and focal length of 3.6-72 mm (Bretón-González *et al.*, 2013).

The short-period (T=1.0 s) vertical-component analogue seismic station EZV3, equipped with the KINEMETRICS RANGER SS1 analogue sensor and installed at a distance of 5.3 km N from the crater (Figure 2A), was used to count of seismic events, associated with explosive events and pyroclastic density currents (PDC).

Within the text of this article, the seismic signals and video images are indicated with the UTC time used in monitoring systems.

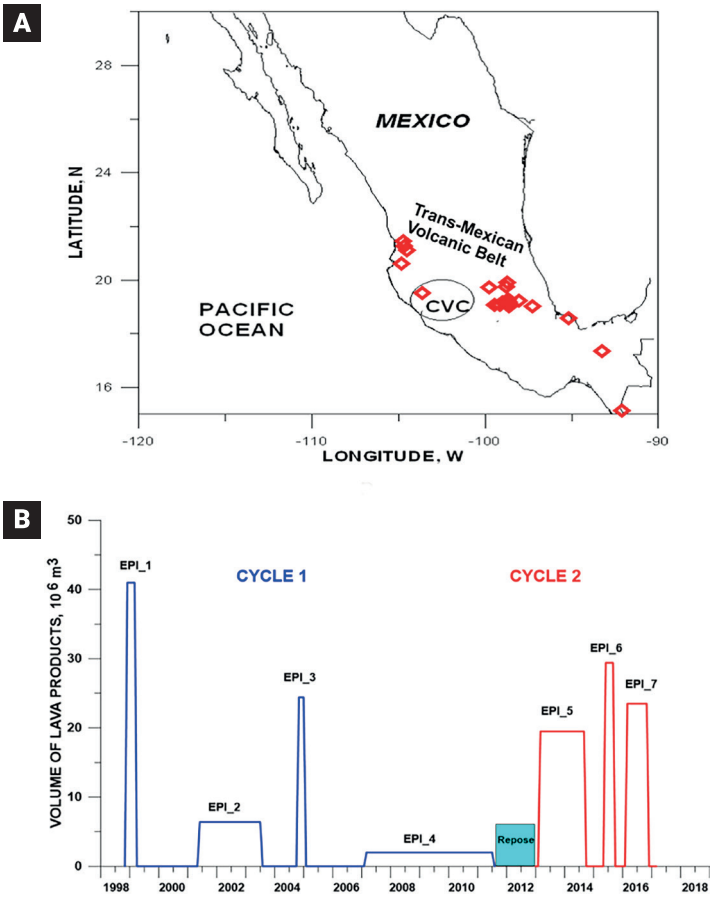


Figure 1. Position of Volcán de Colima within the Trans-Mexican Volcanic Belt (A) and the seven episodes (EPI_1 to EPI_7) of the lava dome-building activity at Volcán de Colima, occurring during the 1998-2017 activity (B). The active volcanoes of the Trans-Mexican Volcanic Belt are shown in A with diamonds. The episodes are shown according to the temporal variations of volumes of lava products, erupted during each of them. The volumes of lava products, including lava domes and lava flows, were determined using the mapped areal extents of units, obtained from visual monitoring and aero-photos. Deposit thicknesses were measured from photographs and video images. The color difference (blue or red) separates the episodes within two cycles (1 and 2 respectively). The period of intra-cycles repose is shown. Modified from Zobin *et al.*, 2020.

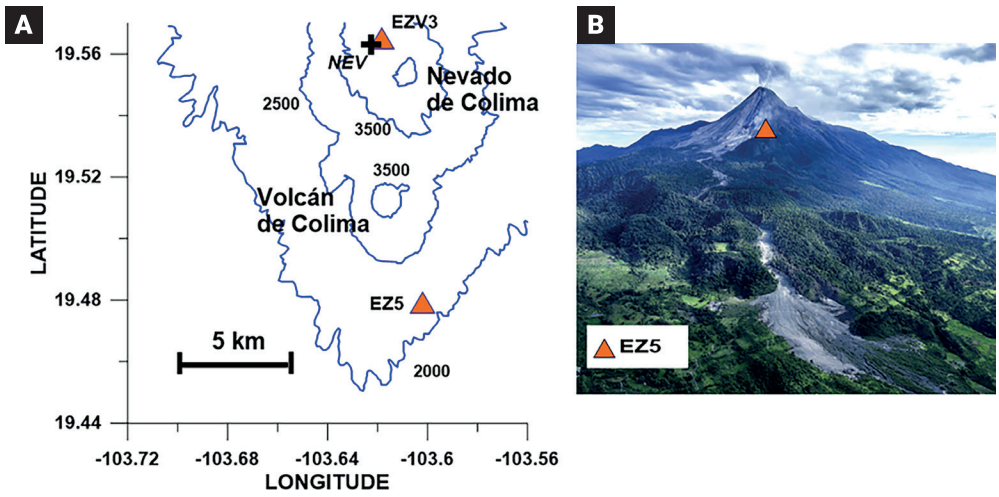


Figure 2. The system of monitoring around Volcán de Colima used in this article. In A, the seismic stations EZ5 and EZV3 (red triangles) and video station *NAR* (black cross), used in the article, are shown. In B, the position of station EZ5 is especially shown on the photo of the slope of Volcán de Colima. The contour lines 2000 m, 2500 m, and 3500 m show the relief of the volcanoes of Nevado de Colima and Volcán de Colima.

3. Process of destruction of lava domes with Vulcanian explosions

During the 1998-2017 eruption, the lava domes, each of them with volume of about 2×10^6 m^3, were destroyed in the explosive manner during six episodes, leaving every time an empty crater of 200-260 m across and 30-50 m deep (Zobin *et al.*, 2006a; Zobin *et al.*, 2006b; Smithsonian Institution (s.f.)).

The effects of destruction processes of the lava domes with Vulcanian explosions are illustrated in Figure 3. Figure 3A shows the crater, filled with a lava dome, that was built in January 2013 during episode 4. In two hours after taking the photo, the Vulcanian explosions, the largest of which is shown in Figure 3B, began to destroy the lava dome. After the 25-day sequence of explosions, the dome was destroyed, and the crater became empty (Figure 3C).

3.1. Seismic waveforms, generated by Vulcanian explosions, and their informativity

The characteristic seismic signal of an explosion event, occurring on 3 February 2017, is shown in Figure 4B together with the video image of this explosion (Figure 4A). The signal represents the two-phase waveform and is characterized with the high-amplitude high-frequency explosive main phase (*MP*) which is preceded with low-amplitude low-frequency (*LF*) phase.

The process of parametrization of Vulcanian explosions, based on corresponding seismic signals, is considered in this article according to the conceptual two-stage model, developed by Zobin *et al.* (2006; 2009; 2015). A volcanic explosion is supposed to be the result of magma fragmentation that transforms magma from liquid with dispersed gas bubbles to gas with dispersed liquid drops or isolated solid particles (Cashman *et al.*, 2000; Melnik and Sparks, 2002). In the case of Volcán de Colima, the process of explosion generation is proposed to occur within a dyke filled with magma which connects at a depth of about 2000 m beneath the crater with the cylindrical volcanic conduit. The depth of feeding dyke was taken according to the results of modeling of the 2003–2011 sources of deformation at Volcán de Colima associated with the magma storage volumes and obtained from the tilt and INSAR observations (Pinel, 2011; Zobin *et al.*, 2011). Magma enters the conduit, passes the fragmentation zone, moves to the surface (stage 1) and produces a subsequent explosion near the surface at explosion level (stage 2). The depths of the level of the initial ascent of magma bubbles were estimated by Zobin *et al.* (2015) in the range between 400 and 1000 m beneath the crater.

According to the conceptual model, one may consider the following elements of the two-stage explosive processes. The pre-explosive phase *LF* may serve as indicator of the way of generation and ascent of magma bubbles, triggering the explosion (stage 1). The duration of this phase $D = t_2 - t_1$ (Figure 4B) is proportional to the length of the way of the magma bubbles from the fragmentation level in the conduit to the surface.

The seismic energy of the *MP* phase defines the energy of volcanic explosion, *E*, at stage 2. The energy of explosion, *E*, is estimated from the seismic energy of explosion $E_{seismic}$ determined from Fourier spectra of the main seismic phase *MP*, taken between t_2 and t_3 (Figure 2), as

$$E = E_{seismic} \times 10^5 \text{ J (Pyle, 2000).} \quad (1)$$

The errors in estimation of $E_{seismic}$ may reach about ±10%.

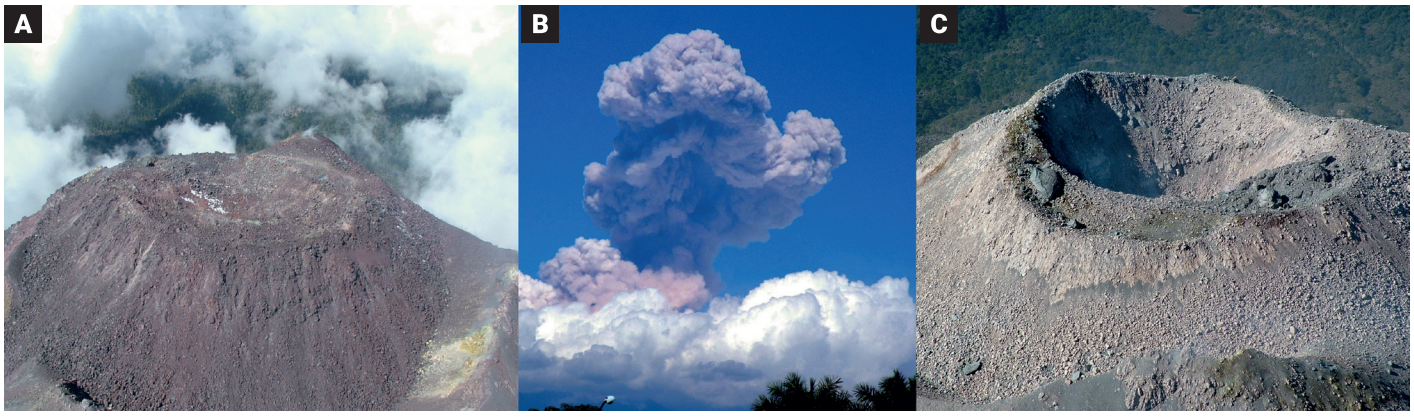


Figure 3. (A-D) Photos, illustrating different moments of the 2013 eruptive episode with destruction of the lava dome with Vulcanian explosions. (A) 6 January, the crater 2 h before the first explosion. View of the 2007–2011 lava dome looking southeast. (B) 6 January, the first and the largest Vulcanian explosion. View from Colima city, 32 km to south from the volcano. (C) 31 January, the new crater that was formed after the sequence of explosions. View of crater looking southeast. These photos were taken by C. Navarro during the flights of the Civil Protection of Jalisco state.

3.2. The parameters of Vulcanian explosions obtained based on the two-stage conceptual model

The explosive events during this eruption varied from small steam-and-ash to moderate-to-large Vulcanian explosions. A characteristic distribution of explosive events of different energy during an eruptive episode is shown in Figure 5. It was recorded for episode 3 (2004-2005) (Zobin *et al.*, 2010). As is seen, at the level of $E = 10^{11}$ J, there was a separation in type of distribution for large ($E \geq 10^{11}$ J) and small ($E<10^{11}$ J) explosive events.

Considering that the large explosions may be taken as destructive and will be useful for the special research, the Table 1 gives the catalog of the 26 large Vulcanian explosions, recorded during the total eruption, with estimated elements of two-stage explosive processes. The energy of large explosions, E, varied from 1.2×10^{11} to 1.5×10^{13} J.

As is seen in Table 1, the number and maximum values of large destructive explosions were different from episode to episode: one large explosion ($E = 1.5\text{-}2.6\times10^{11}$ J) in the case of episodes 4 and 5, three (maximum second event, $E = 2.2\times10^{12}$ J) in the case of episode 2, 12 (maximum tenth event, $E = 1.5\times10^{13}$ J) in the case of episode 3, and 6 large explosions (maximum first event, $E = 9.4\times10^{11}$ J) in the case of episode 7.

Considering the parameters $D = t_2 - t_1$, which are proportional to the length of the way of magma bubbles from the fragmentation level in the conduit to the surface, their durations varied from 2.1 to 6.8 s (Table 1).

3.3. Interrelations between the lengths of the magma bubble paths D, from the fragmentation level in the conduit to the surface, where explosions occur, and the energy of the following explosions, E

Figure 6 presents the relation between E and D for explosions with $E \geq 10^{11}$ J, which may be separated into two groups.

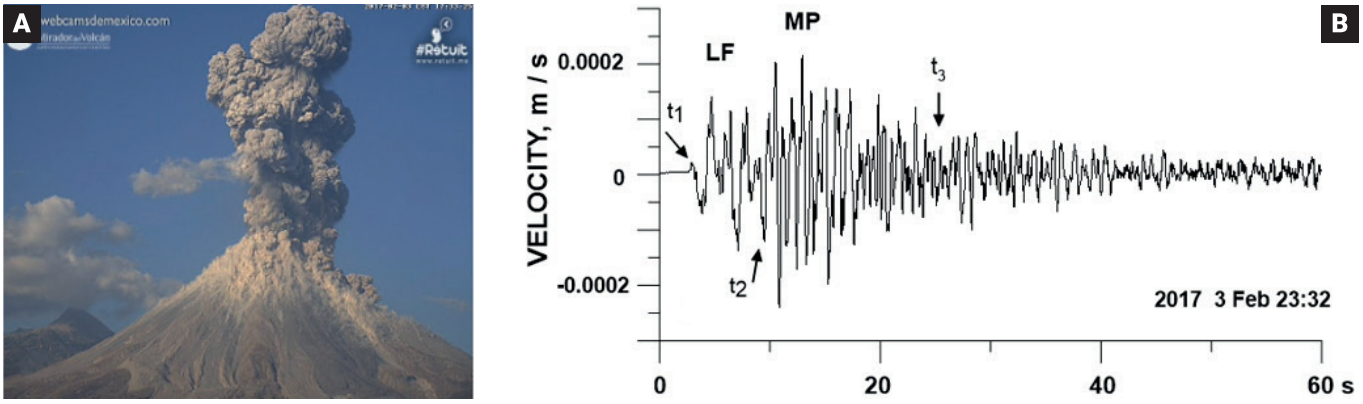


Figure 4. Video image of explosive plume of Vulcanian explosion of 3 February 2017, recorded at video station *NEV* in one minute after its initial appearance (A), and corresponding broadband seismic velocity waveform, generated by explosive event and recorded at station EZ5 (B). Arrows, marked as t_1, t_2, and t_3, indicate the initial and final steps of the phases *LF* and *MP* (see text). Video image of explosive event was recorded at station *NEV*. Here and later the seismic signals are corrected for instrument sensitivity.

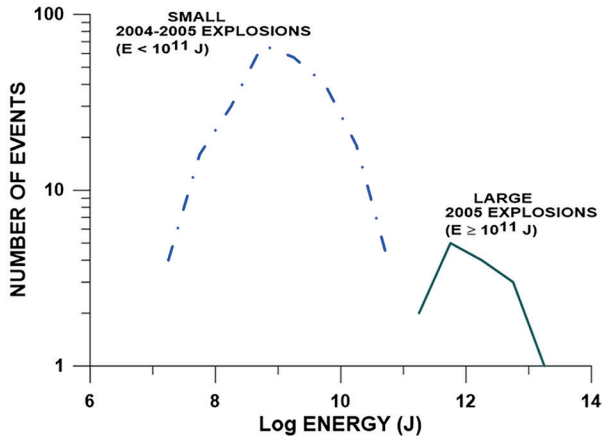


Figure 5. Distribution of explosive events of different energy, recorded during episode 3 (2004-2005). Two curves of events, separated at the level of energy of $E = 10^{11}$ J, are represented. Modified from Zobin *et al.*, 2010.

The group 1 includes the explosive events, characterizing with Log $E \geq 11.5$. The explosive events with Log $E < 11.5$ are included in group 2.

The events of group 1 are characterised by a tendency of dependence of the Log $E \geq 11.5$ on the depth, or the value of parameter D of the initial movement of magma to the surface, where the explosion is occurring and their least-square log-normal regression is

$$Log\ E\ (J) = 0.21D\ (s) + 11.26 \quad (2)$$

with a coefficient of correlation $R = 0.53$ ($R_{crit95\%} = 0.5324$).

This indicates that the larger explosions occur when the way of the magma bubbles from the fragmentation level in the conduit to the surface is longer, or the depth of initial generation of magma bubbles is deeper (low-most magma degassing). The group 2 represents the lower energy events, which are out of the relationship 1 (upper-most magma degassing).

As shown in Figure 6, the largest destructive explosions of episodes 2, 3, and 7 belong to group 1, while the largest destructive explosions of episodes 4 and 5, to group 2.

4. Process of destruction of lava dome with a partial collapse of the crater

The partial collapse of the crater sector at Volcán de Colima, which was accompanied with destruction of the lava dome, began on July 10, 2015 and continued on July 11 (episode 6) (Reyes-Davila *et al.*, 2016; Zobin, 2018). The process of destruction of the lava dome with a partial collapse of the crater is illustrated in Figure 7. The lava dome, that filled the crater in the beginning of June 2015, and was then destroyed during the crater collapse, is shown in Figure 7A. The following collapse of the crater was

Table 1. List of large explosions (energy $E \geq 10^{11}$ J) that destructed the lava domes at Volcán de Colima during 2002-2017.

Episode	Date, year, month, day	Time, hour, min	$t_2 - t_1$, s	Energy, J
2	2003 July 17	10 28	4.5	1.7×10^{11}
	2003 August 2	20 40	6.6	2.2×10^{12}
	2003 August 29	04 52	3.8	8.5×10^{11}
3	2005 March 10	14 09	3.4	1.4×10^{12}
	2005 March 13	21 28	3.9	1.5×10^{12}
	2005 March 26	03 40	3.5	7.3×10^{11}
	2005 April 20	01 56	7	3.0×10^{11}
	2005 May 10	14 15	5.7	7.1×10^{11}
	2005 May 16	02 01	5.5	2.1×10^{12}
	2005 May 24	00 09	5.8	5.4×10^{12}
	2005 May 30	08 26	4.1	7.2×10^{12}
	2005 June 2	04 49	5.7	3.6×10^{12}
	2005 June 5	19 20	6	1.5×10^{13}
	2005 June 7	04 04	4.6	1.1×10^{12}
	2005 June 10	02 54	6	3.0×10^{11}
4-5	2013 January 29	09 45	2.3	1.5×10^{11}
5	2014 November 30	07 31	2.1	2.6×10^{11}
7	2017 January 12	23 15	4.4	9.4×10^{11}
	2017 January 16	16 12	3.4	4.5×10^{11}
	2017 January 18	06 16	2.7	1.6×10^{11}
	2017 January 19	10 18	3.8	1.4×10^{11}
	2017 January 20	04 09	2.4	1.4×10^{11}
	2017 February 3	23 19	6.8	1.2×10^{11}

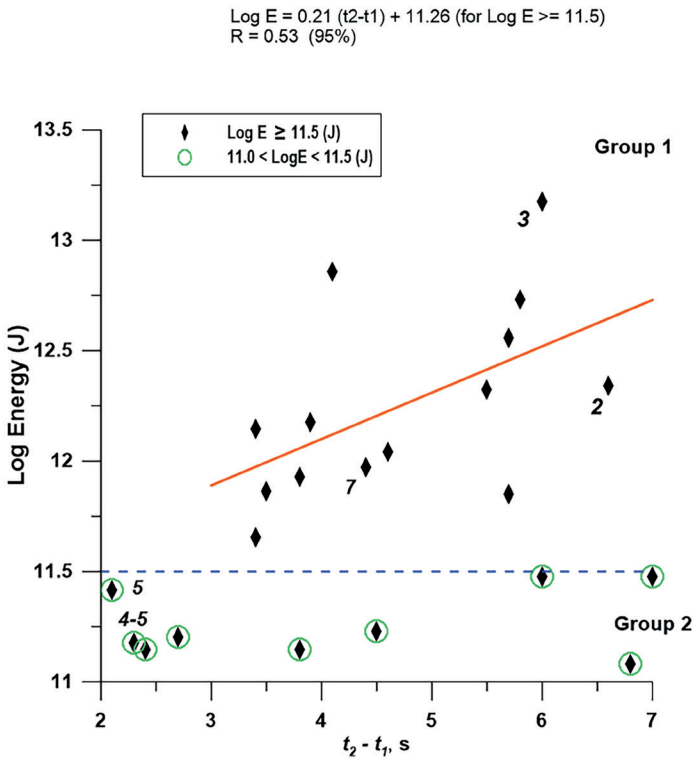


Figure 6. Relationship between the energy of large explosive events and the parameter $D = t_2$-t_1, proportional to the length of the path of collected magma bubbles from the fragmentation level in the conduit to the surface, for two groups of events: with Log E>=11.5 and 11.0<Log E<11.5, separated with a dashed line. A linear approximation for the events of group 1 is shown.

accompanied with two multiple PDC sequences, occurring on 10 and 11 July, and moving with runout distances of 9.1 and 10.3 km, respectively. The absence of any explosive column during occurrence of the PDC sequences is clearly evident in the image of Figure 7B, taken on 11 July (Reyes-Davila *et al.*, 2016). As a result of the crater collapse, the dome was destroyed, and an amphitheatre-shaped crater, opened towards the south, was formed (Figure 7C).

The sequences of PDCs, emplaced on 10 and 11 July, were characterized by the volumes of $2.4\times10^6\,m^3$ and $8\times10^6\,m^3$, respectively (Reyes-Dávila *et al.* 2016). The studies of the lava domes, formed in the crater of Volcán de Colima in 2003 and 2004 (Zobin *et al.* 2006; 2008), showed that the volume of the lava dome, when it filled completely the crater, was estimated to be equal to about $2.0\times10^6\,m^3$. Therefore, each of the 10 and 11 July 2015 collapses were able to remove the typical-size lava dome from the crater.

4.1. Seismic waveforms, generated by collapse of crater, and their informativity

Figure 8A shows a 20-h sequence of broad-band seismic signals, associated with two PDCs sequences, which followed two collapses of crater. The first (Sec1) and the second (Sec2) of the multiple PDCs sequences are clearly seen in the seismogram with sharp increases in amplitudes of the combined groups of signals. Figure 8 (B and C) show the seismic signals of both sequences with more details. They are characteristic for multiple PDCs and consist of a combined sequence of at least six waveforms of different amplitudes and durations at sequence 1 and of at least eight waveforms at sequence 2. The waveforms of both PDC sequences are marked with numbers.

4.2. Characteristic parameters of moving PDCs

The radiated seismic energy, $E_{seismic}$, of moving PDCs was estimated assuming a point-source and considering the medium as isotropic and homogeneous. It was assumed also that surface waves dominate the seismic signal of PDCs (Deparis *et al.* 2008; Hibert *et al.*, 2017; Levy *et al.* 2015). The estimated radiated seismic energy of moving PDCs varied between 1.7×10^7 and 1.1×10^8 J at the emplacement 1 and between 9.0×10^6 and 3.3×10^8 J at the emplacement 2 (Zobin, 2018).

Comparison with the radiated seismic energy of explosions which destroyed the lava domes, generated during other episodes of the unrest, shows that the radiated seismic energy



Figure 7. Photos, illustrating different moments of the 2015 eruptive episode of destruction of the lava dome with a sequence of partial collapses. (A) Aerial view of a new dome that was built in the crater before the 10 July collapse (7 July 2015). A view from SE to NW. (B) Photograph of the second PDCs on July 11. A view from East. (C) Aerial view of the crater that was opened after eruptions of 10-11 July (11 August 2015). A view from SE to NW. A, Courtesy of C. Suarez, Universidad de Guadalajara; B, Taken from Reyes-Dávila *et al.*, 2016. Photograph by R. Arámbula. C, Modified from publication in a newspaper of Universidad de Colima *El Comentario* on 13 August 2015 (http://elcomentario.ucol.mx/).

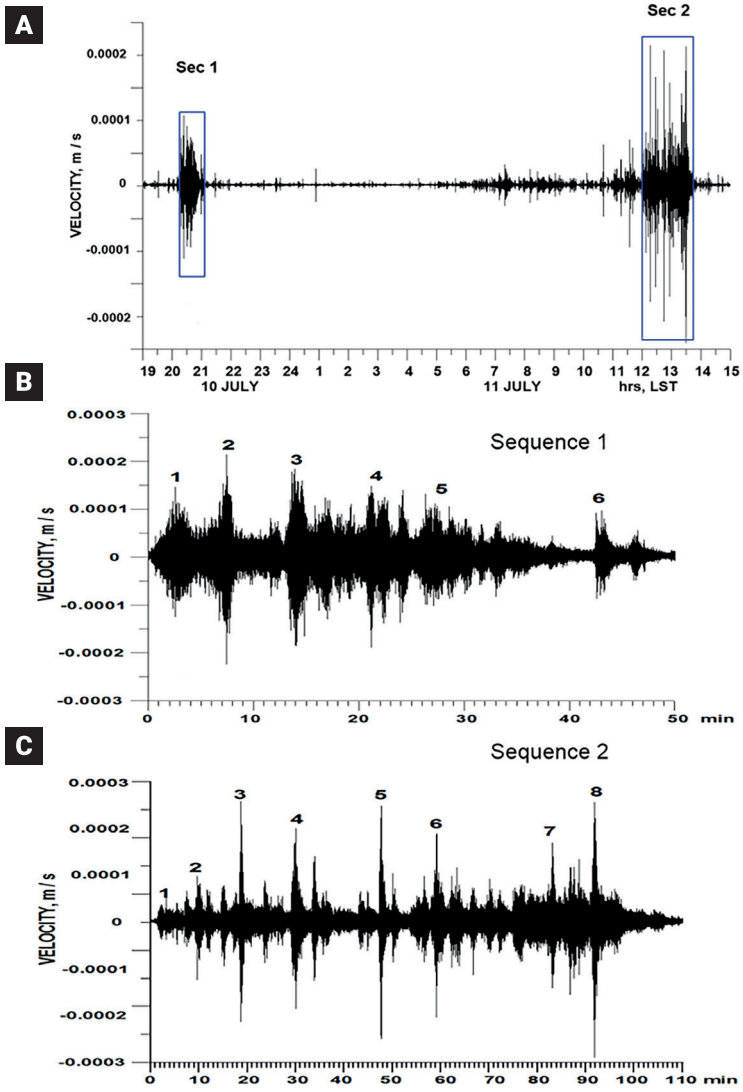


Figure 8. A 20-h record of the seismic signals (Station EZ5, velocity, vertical component), associated with two multiple PDCs sequences, occurring on 10 and 11 July 2015 at Volcán de Colima during the lava dome collapses (A) and the detailed presentation of seismic signals of the first (B) and second (C) sequences of the multiple PDCs. The seismic signals generated by two PDC sequences are selected in boxes in Figure A. Numbers in B and C indicate the multiple seismic records, comprising two sequences of the seismic signals of PDCs. LST, local summer time (UTM – 5).

of moving PDCs was within the same range. According to the equation (1), the radiated seismic energy $E_{seismic}$ of the large ($E >= 10^{11}$ J) destructive explosions may be considered equal to $E_{seismic} >= 10^{6}$ J. This means that the radiated seismic energy of moving PDCs was comparable with the radiated seismic energy of the large explosions which destroyed the lava domes during other episodes, and the collapse of crater was able to destroy the lava dome.

5. Discussion. Reconstruction of the general development of the volcanic unrest at Volcán de Colima in 1998-2017

Variety in destruction of andesitic lava domes during seven episodes of the 1998-2017 unrest at Volcán de Colima gives the possibility to reconstruct the general development of this volcanic unrest. In the previous sections there were shown the characteristic features of destructive elements as derived from the seismic signals radiated during the processes of destructions of the lava domes.

As was noted, the recent 1998-2017 eruptive unrest was based on the new-formed shallow magma storage zone, feeding the eruption. The VT earthquake swarms, occurring from November 1997 to November 1998, potentially constructed a way for juvenile magma to ascent into this magma storage, located at depths between 4 and 12 km beneath the crater (Luhr, 2002; Zobin *et al.*, 2002). Magma bubbles continued its way to the surface as the turbulent flows (Lanzafame *et al.*, 2017) and constructed the sequence of seven lava domes. Six of them were destroyed then by Vulcanian explosions, and one during the collapse of the crater sector, which, as was shown above, was able to destroy the dome also. The energy of large explosions, E, varied from 1.2×10^{11} to 1.5×10^{13} J. Parameters D, proportional to the length of the way of the magma bubbles from the fragmentation level in the conduit to the surface, varied for these explosions from 2.1 to 6.8 s. The temporal variations of these two parameters from episode to episode (in the case of episode 6 with collapse of the lava dome without large destructive Vulcanian explosion, there were taken E and D equal to 0) allowed to recognize the regularity in variety of the lava dome destructions.

In Figure 9 there are presented the values of the energies of the maximum explosions for each episode and corresponding values of D. It is seen a regularity in temporal development of these parameters. Three temporal destructive periods are separated.

The destructive period I includes the episodes 2 and 3 (maybe episode 1 also). Their destructive explosions were the most energetic (2.2×10^{12} and 1.5×10^{13} J) and had the deepest length of the ways of the magma bubbles till the level of explosion generation ($D = 6.6$ and 6 s).

The destructive period II began with episode 4. This episode was characterized with the longest process of the lava dome build-

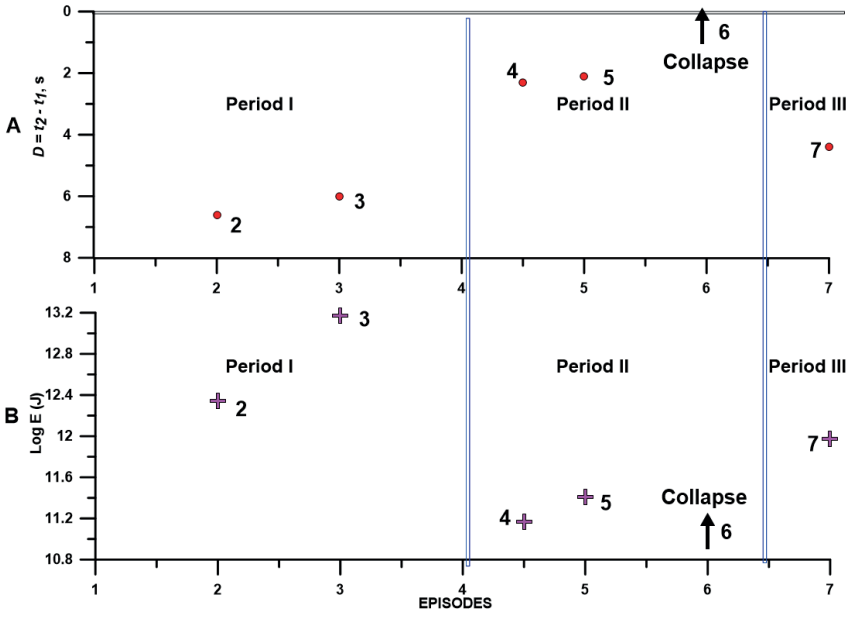


Figure 9. Temporal variations in the conditions of destructive situation of the lava domes during the 1998-2017 unrest at Volcán de Colima, presented in the terms of the parameter $D = t_2 - t_1$, proportional to the length of the way of collected gas bubbles in the conduit to the surface (A), and the energy of these explosions, E (B). Numbers indicate the numbers of episodes. Arrow indicates the episode with the collapse-type destruction of the dome. Vertical lines separate the sequences of episodes characterizing the different periods of destructive situation of the lava domes. Destructive periods I, II, and III are indicated.

ing during about 4 years. When the lava dome was finally built in March 2011, its explosive potential became so low that no large explosion, able to destroy the dome, was generated. The repose in volcanic activity continued till January 2013, when the 2007-2011 dome was finally destroyed in the very beginning of episode 5. This time the destructive explosions became more superficial with $D = 2.3$ and 2.1 s for the dome of episode 4 and the new constructed dome of episode 5, which indicated the uplift of the feeding level of magma. Their energy decreased on one order, till 1.5×10^{11} J and 2.6×10^{11} J, respectively. This destructive period II was logically concluded with superficial non-explosive collapse of the lava dome during episode 6.

The destructive period III was characterized with relative increase in the energy of destructive explosion up to 9.4×10^{11} J for episode 7 and comparably increase of the depth of magma source of explosion generation ($D = 4.4$ s).

6. Conclusions

The 1998-2017 lava dome-building unrest at andesitic Volcán de Colima consisted of seven episodes of the lava dome-building and following destructions. Variety in destruction of andesitic lava domes during seven episodes gives the possibility to see the general development of this volcanic unrest. All eruptive processes were accompanied with seismic signals. Their application within the frame of two-stage conceptual model (Zobin *et al.*, 2006), allowed to quantify the characteristic elements of the lava dome destructions by explosions.

Two parameters were estimated for 26 large Vulcanian explosions: the values of durations of the initial phase of the seismic signal, $D = t_2 - t_1$, proportional to the length of the way or path of the magma bubbles from the fragmentation level in the conduit to the surface, and the energy of explosions, E. Three temporal intervals of destructions were proposed.

The destructive period I was characterized by the deepest magma bubble sources of destructive explosions. They were also the most energetic during this unrest. At the following destructive period II, the magma bubble sources of destructive explosions became more superficial, and this interval was concluded with non-explosive superficial collapse of the lava dome. The energy of destructive explosions, occurring during this interval, decreased on one order comparing with the events of destructive period I. The destructive period III was characterized by relative increase in the energy of destructive explosion and increase of the depth of its feeding magma reservoir.

Therefore, the decisive element in the change of process of the lava dome destruction may be considered the change in the depth of the feeding magma reservoir from episode to episode. This allows to reconstruct the development of the 1998-2017 eruptive activity as a turbulence of magma deposit with its consumption with every episode of lava dome destruction.

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8. Data availability

The RESCO seismic data and video images are available through the University of Colima.

9. References

Bretón González, M., Ramírez, J. J., and Navarro, C. (2002). Summary of the historical eruptive activity of Volcán de Colima, México 1519-2000. Journal of Volcanology and Geothermal Research, 117(1-2), 21-46. doi: **https://doi.org/10.1016/S0377-0273(02)00233-0**

Bretón-Gonzalez, M., Campos, A., León, Z., Plascencia, I., Ramírez, J. J. (2013). The 2007–2012 lava dome growth in the crater of Volcán de Colima, México, derived from Video Monitoring System. In: Zobin VM. (Ed.). Complex monitoring of volcanic activity: methods and results. (pp. 153–169). Nova Science Publishers.

Calder, E. S., Lavallée, Y., Kendrick, J. E., & Bernstein, M. (2015). Lava Dome Eruptions. In *The Encyclopedia of Volcanoes* (pp. 343–362). Elsevier. doi: **https://doi.org/10.1016/B978-0-12-385938-9.00018-3**

Cashman, K.V., Sturtevant, B., Papale, P., and Navon, O. (2000). Magmatic fragmentation. In "Encyclopedia of Volcanoes" (pp. 421-430). Academic Press, San Diego.

Deparis, J., Jongmans, D., Cotton, F., Baillet, L., Thouvenot, F. and Hantz, D. (2008). Analysis of rock-fall and rock-fall avalanche seismograms in the French Alps. Bulletin of the Seismological Society of America. 98(4), 1781-1796.

Dufek, J., Esposti Ongaro, T., Roche, O. (2015). Pyroclastic density currents: processes and models. In. Sigurdsson, H., Loughton, B., McNutt, S., Rymer, H., Stix, J. (Eds.), *The Encyclopedia of Volcanoes*. (pp. 617–629). Elsevier. doi: **https://doi.org/10.1016/B978-0-12-385938-9.00035-3**

Fink, J. H., Malin, M. C., Anderson, S.W. (1990). Intrusive and extrusive growth of the Mount St Helens lava dome. Nature, 348, 435-437. doi: **https://doi.org/10.1038/348435a0**

Lanzafame, G., Lezzi, G., Mancini, L., Lezzi, F., Mollo, S., Ferlito, C. (2017). Solidification and Turbulence (Non-laminar) during Magma Ascent: Insights from 2D and 3D Analyses of Bubbles and Minerals in an Etnean Dyke. Journal of Petrology, 58(8), 1511–1533. doi: **https://doi.org/10.1093/petrology/egx063**

Lesage, P. (2009). Interactive Matlab software for the analysis of seismic volcanic signal. Computers & Geosciences, 35(10), 2137–2144. doi: **https://doi.org/10.1016/j.cageo.2009.01.010**

Levy, C., Mangeney, A., Bonilla, F., Hibert, C., Calder, E. S., & Smith, P. J. (2015). Friction weakening in granular flows deduced from seismic records at the Soufrière Hills Volcano, Montserrat. Journal of Geophysical Research: Solid Earth, 120(11), 7536–7557. doi: **https://doi.org/10.1002/2015JB012151**

Luhr, J. F. (2002). Petrology and geochemistry of the 1991 and 1998–1999 lava flows from Volcán Colima, México. Journal of Volcanology and Geothermal Research, 117(1-2), 169–194. doi: **https://doi.org/10.1016/S0377-0273(02)00243-3**

Luhr, J. F., & Carmichael, I. S. E. (1980). The Colima Volcanic complex, Mexico: I. Post-caldera andesites from Volcan Colima. Contributions to Mineralogy and Petrology, 71(4), 343–372. doi: **https://doi.org/10.1007/BF00374707**

McGuire, W.J. (2003). Volcano instability and lateral collapse. Revista 1, 33-45.

Melnik, O., & Sparks, R. S. J. (2002). Modelling of conduit flow dynamics during explosive activity at Soufrière Hills Volcano, Montserrat. *Geological Society, London, Memoirs, 21*(1), 307–317. doi: **https://doi.org/10.1144/GSL.MEM.2002.21.01.14**

Miller, A. D., Steward, R. C., White, R. A., Luckett, R., Baptie, B. J., Aspinall, W. P., Latchman, J. L., Lynch, L. L., Voight, B. (1998). Seismicity associated with dome grows and collapse at Soufriére Hills volcano, Montserrat. Geophysical Research Letters 25(18), 3401–3404. doi: **https://doi.org/10.1029/98GL01778**

Moran, S. C., Malone, S. D., Qamar, A. I., Thelen, W. A., Wright, A. K., Caplan-Auerbach, J. (2008). Seismicity associated with renewed dome building at Mount St. Helens, 2004–2005. In: Sherrod DR, Scott WE, Stauffer PH (Eds.) A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006. (pp. 27–60.). U.S. Prof. Paper Washington.

Okada, H., Watanabe, H., Yamashita, H., Yokoyama, I. (1981). Seismological significance of the 1977–1978 eruptions and the magma intrusion process of Usu volcano, Hokkaido. Journal of Volcanology and Geothermal Research, 9(4), 311–334. doi: **https://doi.org/10.1016/0377-0273(81)90042-1**

Pinel, V. (2011). Influence of pre-existing volcanic edifice geometry on caldera formation. Geophysical Researcher Letters, 38(11). doi: **https://doi.org/10.1029/2011GL047900**

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-Amezcua, M., Martínez-Fierros, A., Ramírez-Vázquez, A., Cárdenas-González, L., Castañeda-Bastida, E., Espinoza, Vázquez, de los Monteros, D. M., Nieto-Torres, A., Campion, R., Courtois, L., Lee, P.D. (2016). Volcán de Colima dome collapse of July, 2015 and associated pyroclastic density currents. Journal of Volcanology and Geothermal Research, 320, 100–106. doi: **https://doi.org/10.1016/j.jvolgeores.2016.04.015**

Rhodes, E., Kennedy, B. M., Lavallée, Y., Hornby, A., Edwards, M., Chigna, G. (2018). Textural insights into the evolving lava dome cycles at Santiaguito lava dome, Guatemala. Frontiers in Earth Science Vulcanology, 6, 1-18, **https://doi.org/10.1016/10.3389/feart.2018.00030**

Smithsonian Institution. Global Volcanism Program. (s.f.). Volcán de Colima. Bulletin of Global Volcanism. **http://volcano.si.edu/volcano.cfm?vn=341040**

Zobin, V. M. (2018). Development of the 10-11 July 2015 two-stage sequence of multiple emplacements of pyroclastic density currents at Volcán de Colima, México: Insight from associated seismic signals. Journal of Volcanology and Geothermal Research, 351, 29–40. doi: **https://doi.org/10.1016/j.jvolgeores.2017.12.012**

Zobin, V. M., Bretón, M., Ramírez, J. J., Santiago, H. (2020). Transition from passive to pre-extrusion degassing of ascending andesitic magma before the lava dome-building eruption as derived from the seismic signals and tilt changes: Volcán de Colima, México, August–September 2004. Journal of Volcanology and Geothermal Research, 401, 1–17. doi: **https://doi.org/10.1016/j.jvolgeores.2020.106971**

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. (2002). Overview of the 1997–2000 activity of Volcán de Colima, Mexico. Journal of Volcanology and Geothermal Research, 117, 1–19. doi: **https://doi.org/10.1016/S0377-0273(02)00232-9**

Zobin, V. M., Melnik, O. E., Gonzalez, M., Macedo, O., Bretón, M. (2010). Swarms of micro-earthquakes associated with the 2005 Vulcanian explosion sequence at Volcán de Colima, México. Geophysical Journal International, 182(2), 808-828. doi: **https://doi.org/10.1111/j.1365-246X.2010.04647.x**

Zobin, V. M., Navarro-Ochoa, C. J., Reyes-Davila, G.A. (2006b). Seismic quantification of the explosions that destroyed the dome of Volcan de Colima, Mexico, in July–August 2003. Bulletin of Volcanology, 69, 141–147. doi: **https://doi.org/10.1007/s00445-006-0060-y**

Zobin, V. M., Navarro, C., Reyes-Dávila, G., Orozco, J., Bretón, M., Tellez, A., Reyes-Alfaro, G., Vázquez, H. (2006a). The methodology of quantification of volcanic explosions from broadband seismic signals and its application to the 2004–2005 explosions at Volcán de Colima, México. Geophysical Journal International, 167(1), 467–478. doi: **https://doi.org/10.1111/j.1365-246X.2006.03108.x**

Zobin, V. M., Ramírez, J. J., Santiago, H., Alatorre, E., Navarro, C. (2011). Relationship between tilt changes and effusive–explosive episodes at an andesitic volcano: the 2004–2005 eruption at Volcán de Colima,México. Bulletin of Volcanology, 73, 91-99. doi: **https://doi.org/10.1007/s00445-010-0405-4**

Zobin, V. M., Reyes, G. A., Guevara, E., Bretón, M. (2009). Scaling relationship for Vulcanian explosions derived from broad-band seismic signals. Journal of Geophysical Research Solid Earth, 114(B03203). doi: **https://doi.org/10.1029/2008JB005983**

Zobin, V. M., Tellez, A. (2019). Precursors to intra-eruptive reposes during the 1998–2019 lava dome-building eruption at Volcán de Colima, México. Bulletin of Volcanology, 81, 1–9. doi: **https://doi.org/10.1007/s00445-019-1307-8**

Zobin, V. M., Varley, N. R., González, M., Orozco, J., Reyes-Dávila, G., Navarro, C., Bretón, M. (2008). Monitoring the 2004 andesitic block-lava extrusion at Volcán de Colima, México from seismic activity and SO2 emission. Journal of Volcanology and Geothermal Research, 177(2), 367–377. Doi: **https://doi.org/10.1016/j.jvolgeores.2008.05.015**

Zobin, V. M., Peral, J. J, Nava, F, Bretón, M. (2015). Vulcanian explosions in the process of building-destruction of the lava dome of andesitic volcano: Insight from the seismic signals recorded at Volcán de Colima, México. Physics of the Earth and Planetary Interiors, 244, 1–10. doi: **https://doi.org/10.1016/j.pepi.2015.05.001**