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RESEARCH ARTICLE

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Seismic quantification of the explosions that destroyed the dome of Volcán de Colima, Mexico, in July–August 2003

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Abstract In July–August 2003, the andesitic lava dome at Volcán de Colima, México, was destroyed by a sequence of explosions that replaced the 2×10^6 m^3 dome with a crater 200 m across and 30 m deep. The two strongest explosions occurred on July 17 and August 28. The initial low-frequency impulses that they produced, which were recorded on broadband seismic records, allowed an estimation of the counter forces of the initiating process as being equal to 0.3×10^{11} N and 1×10^{11} N for the July and August events, respectively. The seismic characteristics follow the Nishimura-Hamaguchi scaling law for volcanic explosions, reflecting self-similarity in the processes initiating explosive events. The results also show that counter forces can discriminate between the sizes of explosive eruptions that are assigned the same magnitude by conventional methods of classification such as the Volcanic Explosivity Index. The increasing use of broadband seismometers may therefore provide the basis for using counter forces to determine the magnitude of explosive eruptions.

Keywords Volcano seismology · Volcán de Colima · Volcanic explosion · Counter force · Eruption magnitude

Introduction

The goal of quantifying the size of explosive volcanic eruptions has produced several magnitude and intensity scales, including the eight-grade Volcanic Explosivity Index, or VEI (Newhall and Self 1982; Carey and Sigurdsson 1989; Pyle 2000). These scales are based primarily on the size of the volcanic deposit and, as a result, their principal subdivisions cover large ranges of values (e.g., ranges in volume by about a factor of 10 for each VEI unit). In addition, they are commonly applied to the total products of an eruption, as opposed to those of specific phases during a related sequence of explosive events. An alternative approach to quantifying size is to use the seismic signals induced by volcanic explosions. Although such an approach is necessarily restricted to eruptions that are being monitored, it has the potential advantage of discriminating the magnitudes of events with greater precision.

The models proposed for volcanic explosions (Chouet et al. 1997, 2003; Ripepe et al. 2001; etc) indicate that they are produced by an unsteady flux of gas released from magma. The small bubbles move upwards and grow in the melt, causing the magma conduit to oscillate. When the bubbles explode close to the magma's free surface, they generate a seismic signal that may be used to quantify the size of the event.

Field observations at the basaltic volcano Stromboli have provided the basis for describing the seismic signals associated with volcanic explosions (Chouet et al. 1997; Ripepe et al. 2001). The observations of small explosions by seismic and acoustic sensors (Chouet et al. 1997) showed that a seismic signal generally consists of a low-amplitude low-frequency impulse followed by a high-amplitude, high-frequency signal. The onset of the high-frequency impulse coincides with the arrival of infrasonic waves that interfere with the initial low-frequency signal. An acoustic signal appears some seconds after the arrival of high-frequency signal. The visible explosion, indicated by a sharp increase in light sensitive recording, appears after the recording of the high-frequency impulse.

To explain the origin of the low- and high-frequency impulses, Ripepe et al. (2001) carried out laboratory experiments in which air bubbles were pumped at a constant flow rate into the bottom of a water-filled, cylindrical Plexiglass tank that was connected above to a pipe representing a magma conduit. Gas foam was observed to accumulate at the roof of the tank, which then collapsed into a large bubble inside the pipe, in a

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manner similar to that described by the foam-collapse model of Jaupart and Vergniolle (1990). The bubble began to flow in the pipe and then broke at the liquid surface. An acoustic sensor in the tube, but not in the water, recorded a low-frequency signal during bubble ascent and a high-frequency signal when the bubble broke at the surface. At the same time, a sensor inside the water recorded a strong decompression signal throughout bubble ascent. By analogy with the laboratory experiments, therefore, Ripepe et al. (2001) inferred that low-frequency seismic signals are generated by the rapid expansion of gas in a magma conduit, whereas high-frequency signals are generated by explosions at the magma's free surface.

The force system equivalent to a volcanic eruption may be represented by a single force and volumetric tensor (Kanamori et al. 1984). Applied to the foam-collapse model (Jaupart and Vergniolle 1990; Ripepe et al. 2001), the low-frequency decompressive impulse may be attributed to a vertical force directed downward (induced by gas moving up through the magma conduit), and the high-frequency impulse related to volumetric tensors describing the oscillation of the magma column and deflation of the conduit during the explosion (Chouet et al. 1997).

Chouet et al. (2003) observed these explosion characteristics at Stromboli with a network of broadband seismic stations distributed around the volcano. They showed that the peak-to-trough amplitude of the force contributes roughly 5% of the signal amplitude relative to the contribution from the moment tensor. Therefore, a counter force represents only a small part of the total force system for the explosion. Nevertheless, it is a characteristic feature of the initial process of explosive eruptions and so it is reasonable to assume that it is systematically related to the total size of an explosion. Accordingly, the size of the counter force may be a reliable quantitative indicator of explosion magnitude.

The counter force was estimated for a range of eruption magnitudes, including those for Mount St. Helens (Kanamori et al. 1984), Asama (Nishimura and Hamaguchi 1993), Tokachi (Nishimura 1995), and Popocatépetl (Cruz-Atienza et al. 2001). This paper presents new data on the seismic characteristics of the two 2003 explosions at Volcán de Colima. Because only one broadband seismic station was available, the volumetric tensor could not be be evaluated and so analyses have focussed on the counter force alone. The results yield counter forces of 0.3×10^{11} N and 1×10^{11} N, respectively, for the July 17 and August 28 explosions.

Volcán de Colima and its recent activity

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

Colima's most recent unrest began on November 28, 1997 with a sharp increase in seismic activity and a significant shortening of geodetic lines around the volcano. It developed in two stages. The first stage began with the initial deformation of the volcanic edifice lasting for 12 months and culminated in the production of a block-lava flow that began on November 20, 1998 and ended about 80 days later in early February, 1999, producing 3.9×10^7 m^3 of lava (Navarro-Ochoa et al. 2002). Activity then became explosive and continued as such for the next two years (Zobin et al. 2002).

The second stage of activity began in May 2001 with the growth of a new lava dome in the crater. The crater was filled by February 2002 and, during the following year, eight block-lava flows, accompanied by a few pyroclastic flows and thousands of rockfalls, were directed down the volcano's western and southwestern flanks. Effusion

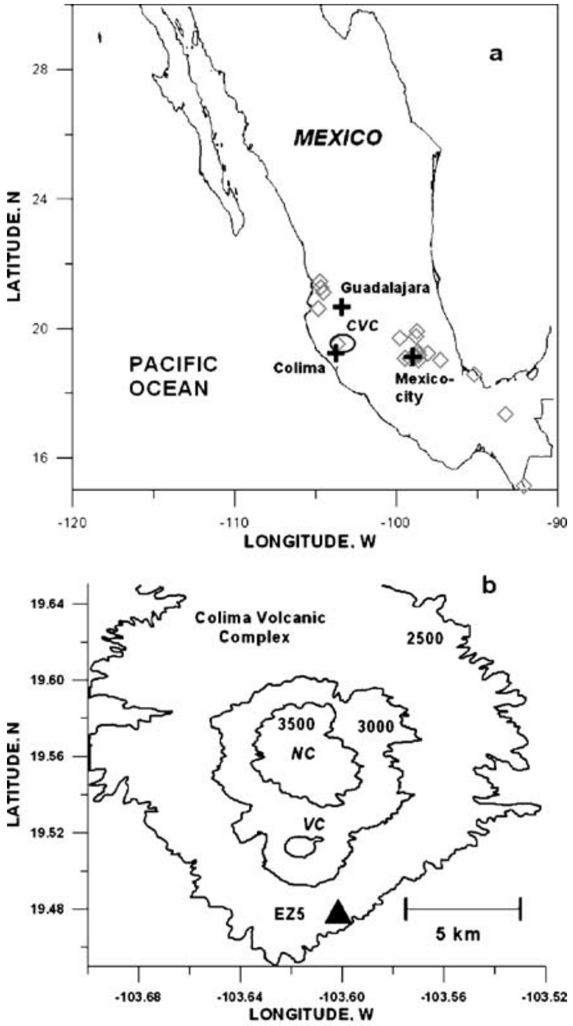

Fig. 1 **a** Position of Colima Volcanic Complex (CVC; *oval*) within the TransMexican Volcanic Belt (*diamonds* show active volcanoes). **b** The CVC consists of Volcán de Colima (VC) and Nevado de Colima (NC). The *triangle* is the location of seismic station EZ5. Contours in m

ceased at the end of February 2003, forming a new lava dome (Fig. 2a), and thousands of small explosions and degassing occurred beneath the dome during March–June (Fig. 3).

This activity culminated in July–August, 2003 with two large explosions (BGVN 1980–2004). The first large explosion occurred at 05:28 local time on 17 July. While blocks from the lava dome were expelled to heights of about 500 m, the ash-fraction of the column rose beyond 3,000 m. The explosion was accompanied by five pyroclastic flows and about 20 rockfalls on the W–SW slopes of the volcano, with the lengths of pyroclastic flows estimated to be up to 2 km. The second large explosion, at 23:52 on 28 August, formed an ash column at least 3,000 m high and distributed ash up to 60 km to the W–NW. It was accompanied by a series of pyroclastic flows up to 2.5 km long that covered practically the whole volcano.

The explosion sequence of March–August, 2003 produced a new summit crater, 200 m across and 30 m deep (Fig. 2b). About 2×10^6 m^3 of the former lava dome was ejected as volcanic bombs to distances of about 1–2.5 km. Based on erupted volume and column height, the 2003 March–August explosive eruption at Volcán de Colima had a VEI of 1–2.

Fig. 2 Explosive activity at Volcán de Colima in 2003. **a** July 9, 2003, before the explosions (*Photo*: M. Bretón); **b** February 12, 2004, after the explosions (*Photo*: A. Cortés). Courtesy of Colima Volcano Observatory

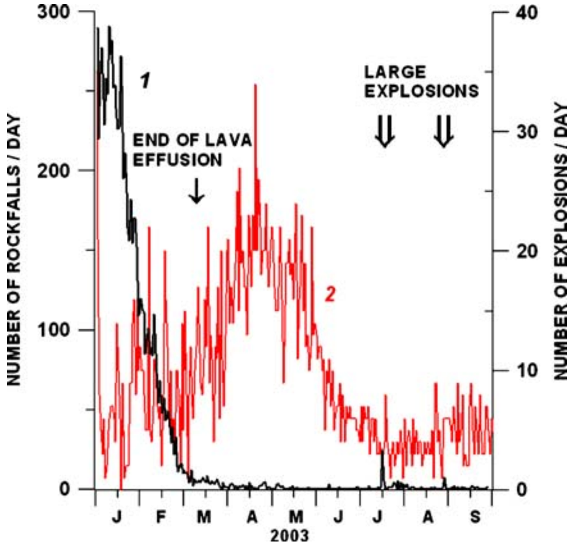

Fig. 3 Seismic activity at Volcán de Colima in January–September 2003. The variations in the daily number of seismic signals produced by rockfalls (*1*) and explosive events (*2*) are shown. The *single arrow* shows the end of lava effusion; the *double arrows* show the large explosions of July 17 and August 28

Seismic data

Figure 3 shows the sequence of seismic events that occurred at Volcán de Colima in 2003. Two types of signal can be distinguished: those produced by rockfalls (Curve 1) and those triggered by explosive events (Curve 2). The rockfalls ceased at the end of dome growth in March 2003 and were replaced by small explosive events, accompanied by small ash falls, related to the degassing of the lava dome. The daily number of small explosive events reached a maximum of 35 per day in April and then gradually decreased to 1–5 per day in July–September. The two large explosions of July–August occurred against this background of low-level activity.

The large explosions produced earthquakes that were recorded by the broadband digital seismic station EZ5. This station is situated on the southern flank of the volcano, 4 km from the crater (Fig. 1b). It is equipped with a three-component GURALP CMG-40TD sensor, with a corner frequency of 30 s, and a DM24 digitizer with a sampling rate of 100 samples per second. The earthquake records (velocities) are shown in Fig. 4. The low-frequency seismic signals, inferred to have been generated by the rapid expansion of gas in the magma conduit (Ripepe et al. 2001), are shown in the ovals at the start of each record. The elliptical form of their particle orbits (Fig. 5) indicates that these signals were formed by Rayleigh surface waves.

Modelling of seismic signals

Kanamori and Given (1982, 1983) have shown that the seismic records of volcanic explosions can be interpreted as Lamb pulses. Lamb (1904) computed the transient re-

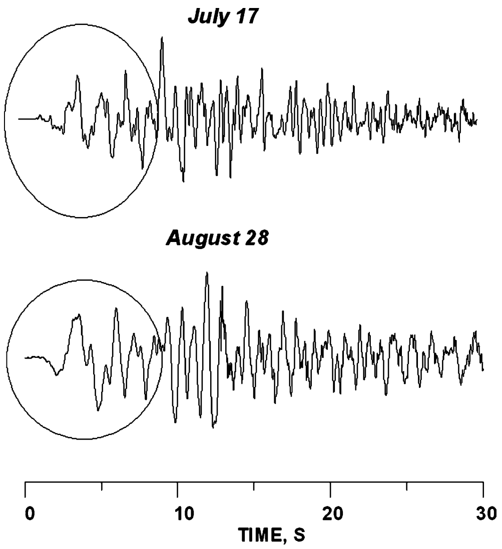

Fig. 4 The seismic records (velocity, vertical component) of the explosions on July 17 and August 28, 2003, measured by the broadband seismic station EZ5 4 km from the crater. The ovals show the low-frequency impulses used for calculating the counter force

sponse of a homogeneous elastic half space to a single force and showed that a pronounced pulse propagates along the free surface with the Rayleigh-wave velocity. This pulse is preceded by minor pulses which propagate with P- and S-wave velocities.

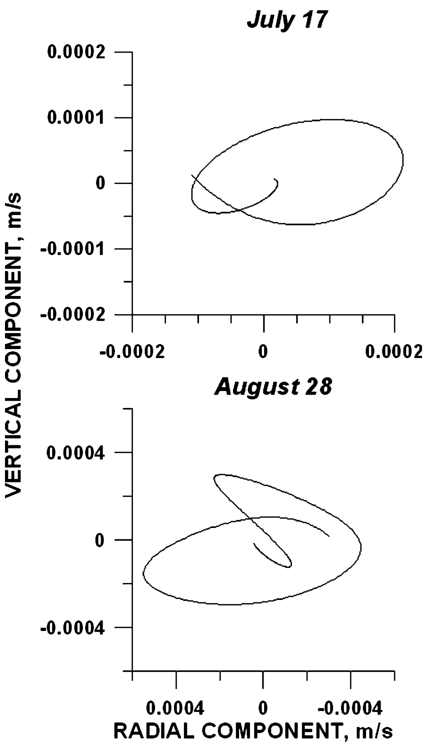

Fig. 5 The particle motions of low-frequency impulses of seismic records of volcanic explosions. The seismic records were low-pass filtered at 0.5 Hz

The groups of Lamb pulses were observed by Kanamori and Given (1983) for the seismic records associated with the 1980 explosions at Mount St. Helens. They showed that the similarity between the theoretical Lamb pulses and the observed seismic records of explosions allowed the calculation of a vertical single force F, which represents the counter force of the eruption.

To determine the counter forces of explosive eruptions of Volcán de Colima, we calculated the time domain synthetic seismograms (vertical and radial components) excited by a vertical single impulse of unit force F (1 N) originating at a depth of 0.5 km below the crater of the volcano and recorded at a distance of 4.0 km (the location of seismic station EZ5).

Estimating the source depth of low-frequency impulses is problematic. According to Ripepe et al. (2001), the impulse is triggered by vibration of a magma conduit during ascent of a collapsed foam layer (transformed into a slug of gas), so that the effective source depth is expected to change with time. Here we take the source depth to be the position of initial slug ascent, rather than the depth of the resulting explosion. The duration of slug movement can be estimated from the duration of the low-frequency impulse, which was 7.5 s for both Colima events. We have no direct estimate of a gas slug's rate of ascent through an andesitic magma. However, an upper limit is available from the velocity of about 60 m s^{-1} estimated for conditions in basaltic magma (Ripepe et al. 2001). Applying this value, the minimum distance travelled by the slug is about 0.4–0.5 km. A mean depth of 0.5 km has also been estimated for similar sources associated with the explosive destruction of an andesitic lava dome at México's Popocatépetl volcano (Cruz-Atienza et al. 2001). Accordingly, we infer that 0.5 km is a reasonable first estimate of source depth.

The synthetic seismograms were calculated using the codes of Nishimura (1995), which apply the discrete wave number method of Bouchon (1979, 1981) and reflection and transmission coefficient matrixes (Kennett and Kerry 1979). The source time function was taken as a triangle with a pulse width of τ. The triangular form of the source function for vertical force is based on the results of the inversion realized by Chouet et al. (2003) for the explosions at Stromboli. The three-layer crustal structure for Colima was simplified from Núñez-Cornú et al. 1994.

Figure 6 shows a set of synthetics (Green's functions) calculated for vertical and radial components using values for τ of 1, 2, and 3 s. These synthetics are presented in terms of velocity for easier comparison with the field seismograms. They have durations of about five seconds and consist of a group of large amplitude signals that, from Lamb's theory, may be considered as Rayleigh waves (Kanamori and Given 1983). They model only the initial part of the low-frequency signal that characterizes the beginning of the upward movement of the gas slug. This means that the influence of interfering waves appearing during the continuous movement of the slug can be avoided.

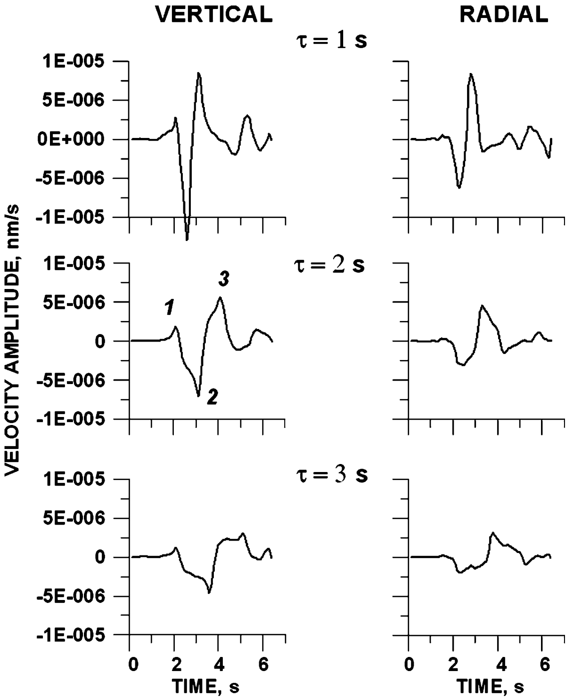

Fig. 6 Theoretical Green functions (velocity) calculated for the vertical single force of 1 N acting with the triangular source-time function with pulse widths τ of 1, 2 and 3 s. The inferred source depth is 0.5 km below the crater of the volcano. The calculations were made for the distance of 4.0 km. *1*, *2* and *3* indicate the first three amplitudes of the Rayleigh wave impulse used to calculate the counter force

Determination of the counter force of eruptions

The counter force of eruptions was calculated by normalizing the average of the three first peak amplitudes by their synthetic equivalents. The procedure of Nishimura (1995) does not include any inversion technique (such as least-square iterations) for precise comparison of the synthetic and observed records. Nevertheless, the simple form of the synthetics allows a visual comparison (Fig. 7).

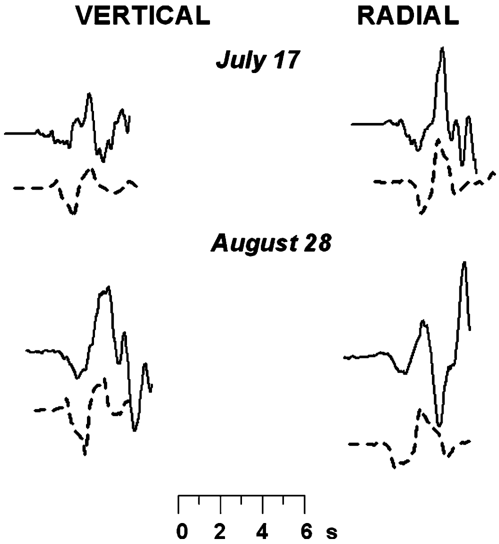

Fig. 7 Comparison of observed and synthetic (*dashed lines*) records. See text for details

Table 1 Characteristics of the 2003 explosion earthquakes of Volcán de Colima

Date of event	τ, s	F_{vert}, N	F_{rad}, N	F, N
17 July	1.7	0.17×10^{11}	0.26×10^{11}	0.3×10^{11}
28 August	2.5	0.42×10^{11}	0.94×10^{11}	1.0×10^{11}

Figure 7 shows a good agreement between the vertical and radial components of the observed and synthetic records. Although the vertical component of the first small positive impulse is almost invisible, especially for the August 28 event, the following large negative and positive impulses are well fitted by the synthetics. The counter forces calculated from the inversions for vertical (F_{vert}) and radial (F_{rad}) components (Table 1) show that the radial components are systematically larger, indicating that the counter force was inclined. The full counter force F for each event was calculated as

$$F = \left(F_{vert}{}^2 + F_{rad}{}^2\right)^{1/2} \tag{1}$$

yielding values of 0.3×10^{11} N and 1×10^{11} N, respectively, for the explosions on July 17 and August 28. The estimated errors are ±30–50%, produced by uncertainties in the manual fitting of the synthetic and observed records.

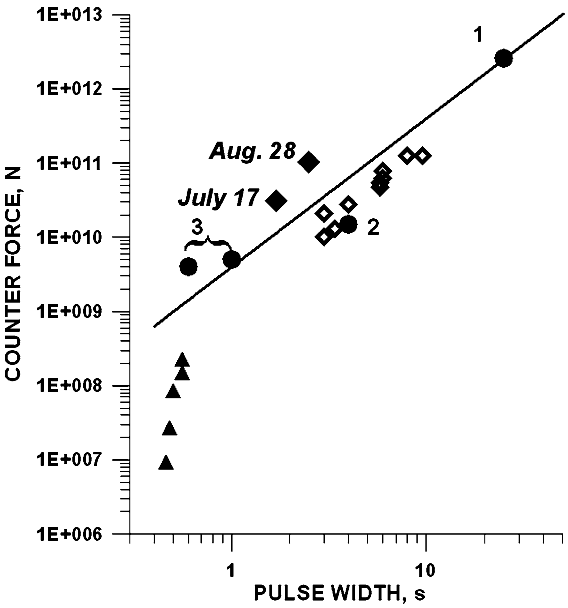

Fig. 8 The relation between the counter force of explosions and the pulse width of source-time function. The *filled diamonds* show the 2003 Colima data. Other data: Mount St. Helens, May 18, 1980 (*filled circle 1*; Kanamori et al. 1984); Asama, April 7, 1983 (*filled circle2*; Nishimura and Hamaguchi 1993); Tokachi, Jan. 27 –Feb. 7, 1989 (*filled circle 3*; Nishimura et al. 1995); 1997–1998 explosions of Popocatépetl (*open diamonds*; Cruz-Atienza et al. 2001); Tokachi (*filled triangles*; Nishimura 1995). The *line* shows Nishimura-Hamaguchi scaling law (Eq. 2)

Discussion

Figure 8 compares the counter forces for the 2003 Colima explosions with estimates from other eruptions world wide. The data follow two trends between counter force and pulse width, according to whether the counter force is greater or less than a threshold value of about 10^9 N. The Colima data follow the upper-force trend, defined by measurements from the 1989 explosion at Tokachi volcano, Hokkaido (4.7×10^9N; Nishimura et al., 1995) and the 1980 plinian eruption of Mount St. Helens, USA (2.6×10^{12} N; Kanamori et al., 1984). This trend is also followed by data from explosions Popocatépetl's andesitic dome during 1997–1998 (0.1×10^{11}–1.25×10^{11} N; Cruz-Atienza et al. 2001). The Popocatépetl explosions were very similar in nature to the 2003 Colima eruptions and, indeed, they share a similar range in values of counter force.

Nishimura and Hamaguchi (1993) proposed a scaling law for the counter force (F) and pulse width (τ) of the upper trend (Fig. 8)

$$Log\ F = 2\ \log\ \tau + 9.6 \tag{2}$$

The existence of a linear dependence on a Log–Log scale indicates a power law relation between F and τ and, hence, the events are self-similar. Such a relation in turn implies that the counter force may be used to quantify and compare explosions at different volcanoes, consistent with the earlier assumption that the initial impulse of an explosion can be used to characterize an explosive event.

The data for events smaller than 10^9 N (Fig. 8) follow a trend independent from the larger events. From the measurements available, it is uncertain whether the data belong to another power-law relation, or reflect variations in counter force from an essentially constant source width.

Comparison of estimates of VEI (BGVN 1980–2004) and F for volcanic explosions shows a better resolution of the explosion size based on the counter-force method. For the 1997–1998 Popocatépetl explosion sequence a value of VEI=3 was estimated from the total volume of magma expelled. At the same time, the seismic estimations of F give a variation of 1.5 orders of magnitude of F for individual explosions. Similarly, although the 1983 Asama and the 1989 Tokachi explosive eruptions are characterized by the same VEI=2, their counter forces show that the Asama explosion was a stronger event (Fig. 8). The counter force of an eruption has thus the potential to discriminate between explosive events that share the same magnitude according to conventional methods of classification.

The Nishimura-Hamaguchi scaling law (Eq. 2) is remarkable because it links explosive eruptions that range from impulsive explosions (as at Colima) to the onset of extended plinian eruptions, as at Mount St Helens (Fig. 8). A common feature of these events is that the eruption occurs in response to an effectively single force (or system of forces). Other types of volcanic process can also be modelled in terms of a response to a single force and examples include: lava-dome collapse (Uhira et al. 1994), volcanic landslides (Kawakatsu 1989), draining of lava lakes (Hamaguchi et al. 1992) and thermal energy flux (Kanamori and Mori 1992). For instance, the 1977 drainage of Nyiragongo's lava lake has been associated with an effective counter force of 10^9–10^{10} N (Hamaguchi et al. 1992). Estimates of counter force may thus prove valuable also for comparing the magnitudes of non-explosive volcanic events.

Conclusions

Counter forces of 0.3×10^{11} N and 1×10^{11} N have been determined by the inversion of broadband seismic signals for two large explosions from the sequence that destroyed the lava dome at Volcán de Colima, México in July–August 2003. The results follow the Nishimura-Hamaguchi scaling law for volcanic explosions (Nishimura and Hamaguchi 1993) reflecting that the volcanic explosions follow a self-similar behavior. Values of counter force are able to distinguish the relative sizes of explosive events that are assigned the same magnitude by conventional classification schemes such as the Volcanic Explosivity Index. Accordingly, the wider use of broadband seismometers in volcano monitoring would be a good basis for the uniform classification of explosive eruptions using the counter force as a quantitative measure of eruption magnitude.

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