**Solid Earth
Discussions**

Quantification of magma ascent rate through rockfall monitoring at the growing/collapsing lava dome of Volcán de Colima, Mexico

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Abstract

The most recent eruptive phase of Volcán de Colima, Mexico, started in 1998 and was characterized by episodic dome growth with a variable effusion rate, interrupted intermittently by explosive eruptions. Between November 2009 and June 2011, growth at the dome was limited to a lobe on the western side where it had previously started overflowing the crater rim, leading to the generation of rockfall events. This meant that no significant increase in dome volume was perceivable and the rate of magma ascent, a crucial parameter for volcano monitoring and hazard assessment, could no longer be quantified via measurements of the dome's dimensions. Here, we present alternative approaches to quantify the magma ascent rate. We estimate the volume of individual rockfalls through the detailed analysis of sets of photographs (before and after individual rockfall events). The relationship between volume and infrared images of the freshly exposed dome surface and the seismic signals related to the rockfall events was then investigated. Larger events exhibited a correlation between the previously estimated volume of a rockfall and the surface temperature of the freshly exposed dome surface as well as the mean temperature of rockfall masses distributed over the slope. We showed that for larger events, the volume of the rockfall correlates with the maximum temperature at the newly formed cliff as well as the seismic energy. By calibrating the seismic signals using the volumes estimated from photographs, the count of rockfalls over a certain period was used to estimate the magma extrusion flux for the period investigated. Over the course of the measurement period, significant changes were observed in number of rockfalls, rockfall volume and hence averaged extrusion rate. The extrusion rate was not constant: it increased from $0.008\,\mathrm{m^3\,s^{-1}}$ to $0.02\,\mathrm{m^3\,s^{-1}}$ during 2010 and dropped down to $0.008\,\mathrm{m^3\,s^{-1}}$ again in March 2011. In June 2011, magma extrusion had come to a halt. The methodology presented represents a reliable tool to constrain the growth rate of domes that are repeatedly affected by partial collapses. There is a good correlation between thermal and seismic energies and rockfall volume. Thus it is possible to calibrate the seismic records associated with the rockfalls

(a continuous monitoring tool) to improve both volcano monitoring at volcanoes with active dome growth and hazard management associated with rockfalls specifically.

1 Introduction

Volcán de Colima is located in Mexico at 19°51′ N and 103°64′ W (Fig. 1). The altitude
5 of the dome during the observation period January 2010 to June 2011 was 3850 m. The volcano is located at the western extreme of the Trans – Mexican Volcanic Belt and is characterized by calc-alkaline magma, generated as a result of the subduction of the Riviera – Cocos Plates beneath the North American Plate.

The behaviour of Volcán de Colima has shown cyclicity over several different orders
10 of magnitude of time. The last eruptive cycle ended with a Plinian eruption in 1913. After a period of quiescence, discrete effusive events formed summit domes with the first flank lava flows commencing in 1961 and ending in 1962 (Luhr and Carmichael, 1980). The most recent eruptive period started in 1998 and was primarily effusive (lava flows and domes). It has shown a great variability in magma extrusion rates. The current
15 dome started growing in early 2007 (Varley et al., 2010) and stopped in June 2011. It has been characterized by exceptionally slow growth rates throughout. Once the dome reached the crater rim it began to overflow mainly down the western flank and to minor extent the southern and northern rims. This is due to the growth within the crater being offset from the centre (Fig. 2).

20 Many other lava domes have been observed to grow in cycles. At Soufrière Hills Volcano on Montserrat, West Indies, episodes of growth were monitored to last between three and four years since 1995, when the last period of activity started (Loughlin et al., 2010). A detailed case study of the 2005–2008 dome growth cycle on Soufrière Hills Volcano was carried out both by Ryan et al. (2010) and Loughlin et al. (2010). Another
25 case of cyclic dome growth and collapse was observed at Mount St. Helens, USA, between 2004 and 2008 (Smith et al., 2011). Further periodic dome growth behaviour was studied at the Santiaguito dome, Guatemala, which has been continuously active since

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

1922 (Rose, 1972). Also Mount Unzen, Japan, and Shiveluch volcano, Kamtchatka showed cyclic behaviour (Barmin et al., 2002).

The magma effusion rate at Volcán de Colima has frequently varied: 1998–1999 and 2004 were characterized by a fast rate ($> 5\,\mathrm{m}^3\,\mathrm{s}^{-1}$) whereas it was low in 2001–2003 and 2007–2011 ($< 1\,\mathrm{m}^3\,\mathrm{s}^{-1}$) (Varley et al., 2010). In comparison to other volcanoes, the Volcán de Colima extrusion rate between 2007 and 2011 was unusually low: the average magma extrusion rate at Soufriere Hills Volcano, Montserrat, during the 2005–2008 dome growth period was $5.6\,\mathrm{m}^3\,\mathrm{s}^{-1}$ (Ryan, 2010). The Mount St. Helens extrusion rate during the 2004–2008 dome growth period describes a typical dome that started fast ($6\,\mathrm{m}^3\,\mathrm{s}^{-1}$ in 2004) and then gradually decreased to less than $1\,\mathrm{m}^3\,\mathrm{s}^{-1}$ in 2008 (Smith, 2011).

Since 2003, Volcán de Colima has been characterized by daily Vulcanian explosions as a result of crystallization, pressurization and subsequent explosions (Varley et al., 2010). Each eruptive event at Volcán de Colima since 1998 has been followed by more acute explosive activity. In 2005, a series of larger Vulcanian eruptions took place during a period with elevated effusion rate. Varley et al. (2010) studied in detail these events that occurred between February and September 2005; at least 30 pyroclastic flows were produced from column collapse. Each eruption event was characterized by a preceding swarm of low magnitude long-period events.

2 Dome growth and rockfalls

Magma rises due to buoyancy differences with the surrounding country rock. At high viscosities, the erupted magma tends to remain close to the vent rather than forming lava flows, leading to small aspect ratio bodies. The shape of a dome is controlled by the interplay of ascent rate (affecting the cooling history and thereby the viscosity) and magma properties (composition, bubble and crystal content, each affecting the rheological properties). Degassing, cooling and compaction may lead to the formation of a

dense plug with a greatly reduced permeability. The consequent reduction of degassing potential leads to an increased risk of explosions.

Dome growth can take place either endogenously or exogenously. Endogenous growth happens by magma intruding into the dome interior, exogenously growth by extrusion as new surface lobes (Fink et al., 1990). The type of dome growth may have an important bearing on volcanic hazard issues. Exogenous growth usually builds steeper and more unstable domes; this can lead to the generation of block-and-ash flows or rockfalls and makes them more prone to collapse (Nakada, 1996). Endogenous growth, on the other hand, may increase gas accumulation within the edifice, thus enhancing the chance of violent, explosive eruptions (Rose et al., 1977; Fink et al., 1990; Nakada et al., 1995). Activity at lobate domes, like the one at Volcán de Colima, can fluctuate between exogenous and endogenous; this was observed for example during the 1980–1986 Mount St. Helens dome growth period (Fink et al., 1990). A similar, more recent study has been carried out at Unzen volcano, Japan; fluctuation between endogenous and exogenous growth was observed during the 1991–1995 eruption (Kaneko et al., 2002) and was explained by variations in the rate of extrusion.

The four dome growth episodes at Volcán de Colima during the last period (1998 onwards) mainly took place endogenously, partly exogenously; a similar situation is described by Major et al. (2009) who describe the 2004–2008 lava spine extrusion and mainly endogenous growth at Mount St. Helens, USA. The most recent exogenously growing period at Volcán de Colima though was from 2009 to 2011, during which the dome was overflowing the Western crater rim and a lobe formed.

The dome of Volcán de Colima itself is shaped as a truncated cone that has filled most of the summit crater (Fig. 2). Its carapace consists of variably sized blocks of cooled and crystallized lava. The flanks of the dome exhibit a slope angle of approximately 38°. After Blake (1990), who describes four kinds of domes (upheaved plugs, lava domes, low lava domes and coulees), Volcán de Colima dome would not fit in any of the four, typical categories. It is positioned between the lava dome and the low lava dome. Volcán de Colima dome has the typical dome slope angle (∼ 38°) of a lava dome

and was usually observed to be degas through the dome, which is typical for low lava domes. On the other hand, it doesn't have a typical spine like the most current dome at Mount St. Helens; also the typical flat slope angle (10–15°) of low lava domes is not demonstrated. A typical low lava dome was the dome at Soufriere de St. Vincent, West Indies.

Domes can lose volume by Eq. (1) gravitational instabilities, Eq. (2) explosive eruptions or Eq. (3) collapsing vesicles (Kennedy et al., 2012). Obviously, one can trigger the other. The style with which material is transported away from the dome in case of gravitational instabilities is a function of the growth conditions of the dome (pressure and temperature distribution) and the volume of dome collapse. Small volume collapses or collapses from slowly growing domes will most commonly lead to rockfall events. Larger volumes or if larger portions of a dome are affected, block-and-ash flows may be generated. If the collapse event takes place from an active or fast growing dome, pyroclastic flows will likely take place. Generally speaking, the transport properties may change as a response to the morphology along the path. The deposition of coarse material and/or entrainment of ambient air will significantly increase the mobility of the density current.

Monitoring rockfalls is important because this can contribute to real time hazard assessment and help in examining the activity of a volcano. Increasing or decreasing rockfall activity at volcanoes correlates directly with the effusion rate.

Rockfalls can lead to many threatening situations to mankind or the environment. Moran et al. (2008) describe an unusually large rockfall at Mount St. Helens, which occurred in May 2006. The rockfall resulted in an column that rose to 6000 m, which could possibly have affected air traffic. At Volcán de Colima, pyroclastic flows in October 2004 travelled as far as 6.1 km in the La Lumbre ravine. Simulations have shown that large dome collapses would threaten many of the ranches that surround the volcano (Sulpizio et al., 2010). The last major pyroclastic flow was generated by an explosion in September 2005 and marked the end of the 2004–2005 period of activity (Varley et al., 2010). At Merapi Volcano, Indonesia, continuous monitoring of dome

S. B. Mueller et al.

activity has been carried out since 2001. Due to its proximity to the City of Yogyakarta, the dome activity status is crucial for hazard mitigation. Hort et al. (2005), set up a microwave Doppler system which is not hampered by weather conditions such as cloud coverage. They determined both the velocity of material breaking off and the approximate amount of material passing through the radar beam. As a result, these authors described two different types of dome instabilities: those of purely gravitational nature and gravitational instabilities immediately followed by explosions.

Several studies have recently investigated the characteristics of the seismicity generated by rockfalls. Hibert et al. (2011), analysed seismic signals (shape, duration and frequency) associated with rockfalls at Piton de la Fournaise, Réunion. Signals were cigar shaped, did not show clear peak amplitude and P and S waves could not be distinguished. Their duration varied between 50 s and more than 200 s; frequency usually ranged between 2 and 10 Hz and was centred at 5 Hz. Rockfall signals were registered on four short period stations located between 600 m and 2100 m from the centre of the crater. A link between deflation of the summit dome, following crater floor collapse, and rockfall activity was found. The feasibility and validity of using seismicity for estimating fundamental rockslide event parameters has also been described by Dammeier et al. (2011). They characterized the seismic signals of alpine rockslides by taking five simple metrics (signal duration, peak value of the ground velocity envelope, velocity envelope area, risetime and average ground velocity) and used them for an estimation of rockslide volume, runout distance, drop height, potential energy and gradient of the slope. Norris (1994) studied Mount St. Helens, Mount Adams and Mount Rainier volcanoes in the Cascade Range and characterized the link between seismicity and rockfall parameters like source volume, source materials, track materials and failure modes for rockfalls.

More general studies regarding relations between rockfall properties and seismicity have been done by various others: a rockfall analysis at Soufrière Hills Volcano by Calder et al. (2005), describes a link between changing rate of growth of the 1995–1997 lava dome and both the frequency of occurrence of rockfalls and their

Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

duration determined using the seismic signals. A similar study to this was also carried out during the 2004 andesitic block – lava extrusion at Volcán de Colima: finding a link between seismic signal duration of rockfalls, energy of explosions and temporal variations in the number of rockfalls and explosions was the field of interest of Zobin et al. (2008). They compared it with both the rate of magma discharge and SO_2 emission; the rockfall appearance and subsequent disappearance was found to clearly indicate the beginning and the end of the extrusion.

Feasibility and validity of using seismicity for detection, localization and size determination of rockfalls at Montserrat, Catalonia, Spain has been described by Vilajosana et al. (2008). Rockfall volume was in a first instance obtained by using a laser scanner and then correlated to the seismic signals. One step further to laser scanner methods has been done by Jongmans and Garambois, (2007) who used 2-D and 3-D geophysical imaging methods for investigating structures of rockfall areas.

Rockfalls at Volcán de Colima during the recent activity were small, due to a very low effusion rate and occurred up to 20 times a day within the monitored timeframe for this paper (March and April 2011). The section of the dome observed from the Playón observation point to the West of the volcano has a diameter of approximately 298 m, which had not varied since the end of 2009. Up to 60 rockfalls a day were recorded in 2010, when the effusion rate was larger.

Active domes have been investigated by seismic, Doppler – radar and photographic methods; e.g. the growth rate of Soufrière Hills lava dome was assessed for the period of 2005–2008 using four different approaches: terrestrial photos, ground based LIDAR, ground based radar and an empirical method using photographs of dome profiles (Ryan et al., 2010). Only the photographic method was used regularly being the most simple. However, as it was only possible to take photos from two locations around the dome, systematic errors arose. Photo-based dome monitoring was first carried out by Sparks et al. (1998), for the first episode of lava dome growth within the current eruption at Soufriere Hills Volcano.

Full Screen / Esc

The situation at Volcán de Colima was different; since growth of the dome essentially stopped after November 2009, when the dome reached the western crater rim and magma input into the dome was immediately compensated in the form of rockfalls, a different approach to determine the magma extrusion rate had to be developed. A photographic method is still applicable, though not by correlating different dome profiles, but by examination of dome images showing variation of the surface features due to removal of material through rockfalls.

3 Seismicity at Volcán de Colima

In general, limited work on rockfall seismicity has been done. Much of the previous work (Hibert et al., 2011; Dammeier et al., 2011; DeRoin and McNutt, 2012; DeRoin et al., 2012) deals mainly with the seismic analysis of rockfall or block-and-ash flow events. Even less work has been done on the analyses of the frequency of rockfalls, Calder et al. (2005), examined rockfall frequencies during an andesite lava dome eruption at Soufriere Hills Volcano, Montserrat and described repose intervals between rockfalls correlating with log logistic survivor distributions. A detailed seismic analysis of rockfall signals has not been included in this paper.

Beneath Volcán de Colima Volcano Tectonic (VT) swarms, Long Period (LP) events and Hybrids have been detected. VT swarms were mainly detected prior to the 1998–1999 effusive eruption; however, during and after the eruption the seismicity changed to LP and Hybrid events (Zobin et al., 2002). During the recent eruptive episode, four types of signals dominated: tremor, which sometimes was harmonic, small magnitude LP events, larger magnitude isolated LP events or LP events with a diminishing coda (Varley et al., 2010), similar to tornillos which are defined for Galeras (Gil Cruz and Chouet, 1997) and explosion quakes.

Rockfalls at Volcán de Colima can be readily identified by their seismic signal; surface processes at volcanoes in general, like lahars, pyroclastic flows or rockfalls produce seismic signals that typically show a slowly increasing and then decreasing, long

Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

duration seismic waveform. They can last up to several minutes and have a high peak frequency (> 5 Hz) (Shearer, 2009). For accurate rockfall monitoring at Volcán de Colima the seismic network RESCO is sufficient. The network consists of four short-period and four broadband stations. The signals of the EZV4 station were used, it being the closest station to the volcano (1.9 km from the crater). The short-period signals are telemetered to the observatory and digitized with a 16 bit A/D converter, whereas the broadband sensor is using a 24 bit A/D converter and digital transmission. Signals have a sampling frequency of 100 Hz. During the visual observation period of this study, all rockfalls originated at the same location from the dome. Accordingly, the path dependence of the seismic signal was considered minor and not taken into consideration.

A seismic signal study has already been carried out at Volcán de Colima by Arámbula et al. (2011). They investigated the 2004–2005 period of large eruptive activity, including cross correlation of LP's and autoregressive analysis of monochromatic LP's. Seismic activity at Volcán de Colima for this period mainly contained LP's, tremor, explosion signals, rockfalls or pyroclastic flows and few lahars. Rockfall signals always showed a clearly identifiable seismic waveform and had a high frequency range between 1 and 15.

4 Thermography used in volcano monitoring

Thermography is applicable for many monitoring problems: the spatial distribution of temperatures related to degassing and/or eruptive activity or the detection of anomalies in time series; and they can be used for deriving heat fluxes and effusion rates (Hutchinson et al., 2012; Calvari et al., 2007). Higher gas flux is usually caused by more intense magmatic activity; an increase of fumaroles gas temperature has been commonly observed prior to eruptions or shallow magma intrusions (e.g. Menyailov et al., 1986).

At Volcán de Colima, thermal images are obtained from flights, handheld ground-based observations and temporary fixed stations. These images are not only used for

rockfall monitoring, but also for thermal surveys of growing domes, fumaroles or for the thermal gradient of ash plumes. Fumaroles on the crater rim have been routinely monitored from a fixed location at Volcán de Colima since 2004 (Stevenson and Varley, 2008). Trends like a sharp drop in fumarole heat fluxes coincided with the emergence of a lava dome in the summit crater in 2007. Also a general, long term drop of fumarole temperatures between January 2006 and August 2007 coincided with a decrease in the explosivity of the volcano (Varley and Reyes, 2013). For this study, thermal images were used to investigate the thermal signature of rockfalls at Volcán de Colima.

5 Methodology

A field campaign to monitor rockfalls at Volcán de Colima was conducted in 2010 and 2011. This paper presents data of a total of 86 rockfall events, from the period March to April 2011. Observations were made from a base to the west of the volcano, within the Playón, the relatively flat floor of a collapse caldera (Figs. 1 and 2), about 2.3 km from the crater.

5.1 Direct observation

The volume of individual rockfall events was estimated through a comparison of sets of high-resolution photos of the dome before and after (Fig. 3). The goal was to identify blocks or entire dome sections that were quantifiable in size before a rockfall and had been removed during an event. For obvious reasons, this technique only works during daylight. Additionally, the image quality was negatively affected by the sun position behind the volcano (morning) and reduced visibility due to meteorological or volcano degassing conditions. As a consequence, we used the data of 23 out of 86 recorded events for this study.

A Nikon D90 SLR (single lens reflex camera) with a resolution of 12.2 megapixels and a 300 mm lens was used. The raw photos were digitally sharpened, which allowed blocks larger than 20 cm to be easily recognized and defined. Where possible, the rocks in question were marked on the before and after pictures (Fig. 3).

5   In order to calculate the volume of a block on the dome, one needs to define three orthogonal axes (Fig. 4c): axis y is parallel to the slope; x is perpendicular to the gradient; axis z is perpendicular to the surface of the slope (Fig. 4). For further calculations, rocks are assumed to have an ideal cuboid shape with 6 faces. The true length along the x-axis could be simply measured because the geometrical line of sight between

10   viewer and rock did not influence it. The line of sight did, however, influence the measurement of the length along the y-axis. The horizontal distance between observer and dome was 2300 m; the vertical distance was 1050 m. Therefore the oblique angle of view had to be taken into consideration. The apparent length h along the y-axis can be used to calculate the true length l as shown in Fig. 4a and b. The thick, black line on the

15   dome represents the block in question. Lines a and b (Fig. 4b) are approximately parallel; with a being the line between observer and the top of the rock, b the line between observer and the bottom of the rock. The rock itself is part of the dome surface with an average slope angle of $\gamma = 38° \pm 3°$, estimated from photos from flights obtained at the same altitude as the dome. As rocks are supposed to be cuboids, they show the

20   same gradient as the dome slope. Rocks on the dome carapace of Volcán de Colima are angular due to dome growth and cooling processes. Figure 4 shows the geometry; l is the real length of the rock, but what is measured using the photos taken before and after is the apparent length h, l can be calculated as follows:

$$l = \frac{h}{\sin\beta} = \frac{h}{\sin(\sigma - \gamma)} \tag{1}$$

25

$$as\, \beta \approx \delta \text{ and } \tan\sigma = \frac{2300}{1050}. \tag{2}$$

with δ being 27°. Finally the length of the block along the z-axis, normal to the dome surface and in some cases hard to detect in the pictures taken from Playon needs to be determined. Photos from flights were evaluated, when all three axes of the rocks could be seen. We found that the length along the z-axis is always the shortest one.

5　The length pointing downwards along axis y is always the longest one.

Taking the average values of the axes of the rocks in the photos, the following empirical relationships were found:

$$x = 2.11\,z\,(\rho = 0.9) \text{ and } y = 3.02\,z\,(\rho = 1.3) \tag{3}$$

with ρ being Standard Deviation SD. These ratios provide an alternative method to
10　estimate the length of the z-axis. For calculating the volume of individual blocks, a near-vertical face that was generated during the rockfall was measured if possible; scaling this face with the ratios of the axes gives us the most accurate possible length of each individual z-axis. The rock volume was estimated based upon the resulting calculation of all three lengths and using the known dome diameter (298 m viewed
15　from the observation base in the West) as a scale.

5.2　Thermal imagery

For thermal imagery, a VarioCam hr from InfraTec[®] GmbH (Germany) with a 640×480 array was used in this study. Based on the distance, this allowed for a detailed analysis of the entire visible dome surface ($28\,000\,\text{m}^2$) as each pixel had the dimensions
20　of $4.5 \times 4.5\,\text{m}$ ($20.25\,\text{m}^2$). Results were obtained for all 86 rockfalls events within the observation period.

The camera was set up at the observation site, where it recorded an image of the dome every two seconds continuously, leading to an excellent database for every rockfall during the 12 field days. The thermal images were used for analysing the exposed
25　area on the dome surface after a rockfall and to investigate the mean temperature of rockfall masses spread over the volcano slope. It should be noted that temperatures

stated are the average temperatures within the pixels of the infrared image. The thermal images were analysed with the software IRBIS Professional from InfraTec GmbH.

Every rockfall exposed a new surface with a specific mean and maximum temperature; large volume rockfalls produced pixel temperatures up to 200 °C hotter than the local pre-rockfall dome exterior. In contrast, in the case of very small rockfalls (volume of only a few cubic meters) it was not always possible to constrain a temperature difference ΔT; those events were noted with a $\Delta T = 0$ °C. Furthermore, for every rockfall the number of pixels at elevated temperatures on the slope of the volcano in the resulting thermal image could be quantified by a pixel precise edging of the areas of interest. The mean temperatures of the analyzed mass distributed on the slope were calculated in Irbis and compared to the estimated volumes. The mean temperatures where taken when the hottest pixels where revealed on the slope.

By correlating the estimated rockfall volume derived from the photographic images with the ΔT of the exposed face and the mean temperature of the rockfall masses, it was possible to obtain a relationship which could be used to estimate the rockfall volume solely by using thermal images in the end.

Here we demonstrate the approach for defining the temperature of the exposed face. The rockfall event of 8 March 2011 between 15:07 and 15:11 Colima Standard Time (21:07 and 21:11 GMT) will be used as an example.

Figure 5 shows a series of three images of the dome (a) prior to, (b) during and (c) after the rockfall event. On the images are two circles, C1 and C2; C1 marks the spot where the exposed face will be generated during the rockfall, C2 marks a spot on the slope, where the rockfall will pass during the event. The maximum temperature for C1 refers to the pixel with the maximum temperature within the circle C1 and in this case it was 105.7 °C before and 305 °C after the rockfall, giving a difference of 199.3 °C. C2 shows a maximum temperature of more than 400 °C whilst the rocks were within the region. In picture (b), C1 and C2 show relatively low temperatures due to ash generation which occured due to a combination of impacts on the slope and from the dome during each rockfall event. This created a barrier reducing measured temperatures. The

temperature differences of the exposed dome area before and after each rockfall were then correlated to volume of rockfalls estimated from the photographic pairs (Fig. 6).

In Fig. 5c, the hot trace of the rockfall moving down the slope can be seen. The thermal emission from hot rocks rolling down the slope was measured as a time series. The mean temperatures of the analyzed rockfall traces in Irbis were then again compared to the rockfall volume (Fig. 7), as estimated from photographs.

5.3 Energy of associated seismic signals

The seismic investigation of rockfalls, however, brought an additional challenge: the fact that some rockfalls occur together with small eruptive events. In these cases the rockfall and eruption signals were superimposed. 15 out of the 23 events with their volume estimated using pairs of photographs, however, occurred not simultaneously with an eruption, allowing straightforward analysis of the seismic signal.

Because rockfall signals are complex, it is not possible to calculate precisely the corresponding energy release. Thus we used the integral of the squared signal, or the sum of the squares of the samples multiplied by the sampling interval, as a proxy of the energy release. Analysis and calculations were carried out with the Matlab package *Seismo_volcanalysis* (Lesage, 2009). Figure 8 shows a typical seismic rockfall signal of Volcán de Colima together with its spectrogram.

5.4 Comparison between the rockfall volume and thermal monitoring

The volume estimated from the photographs was compared with the measured ΔT values of the exposed face on the dome and to the mean temperature of the rockfall masses distributed over the slope. A first order correlation between ΔT and volume $V\,(\mathrm{m}^3)$ yields the result ($R^2 = 0.88$, Fig. 6):

$$V = 0.84\,\Delta T \tag{4}$$

The mean temperature of the rockfall mass on the slope correlated very well with the volume of the event. Figure 7 shows estimated volume V vs. mean temperature T of 15 rockfall events. Only 15 of the total 23 estimated rockfalls were easily compared because the 8 remaining rockfalls were associated with an explosive event; in this case measurement of the mean temperature was difficult due to strong ash generation. A new correlation ($R^2 = 0.85$; Fig. 7) was observed with the exception of two events. The outlier (a) represents a rockfall that occurred shortly after another large rockfall. Thus it started in an area of the dome with lava exposed that is hotter than average surface temperatures. The second outlier (b) marks a rockfall that broke off at the NW edge of the dome where rockfall activity was low and accordingly the involved blocks had cooled over a more substantial time.

The ratio between volume and mean temperature of rockfall traces has been calculated and the following relationship has been found:

$$V = 1.25\,T \tag{5}$$

Using this relationship, an estimation of the volume of rockfalls is possible based solely on thermal images.

5.5 Comparison between rockfall volume and seismic energy

The proxy of energy E' was estimated for the signals associated with 15 rockfalls. A remarkably good correlation was observed between E' and V (Fig. 9) meaning that E' can be used to estimate rockfall volume V at Volcán de Colima.

The correlation between estimated volume of rockfalls V and pseudo − energy E' gives the following empirical relationship:

$$V = 1.21^{-7}\,E' \tag{6}$$

with V in m^3 and E' in arbitrary units of the seismic network. This analysis was only possible for rockfalls without simultaneous eruptive or ash-venting events.

5.6 Magma extrusion rate

After the dome at Volcán de Colima started overflowing the western crater rim in November 2009, no significant increase in volume was perceivable. For this reason, rockfalls generated at the lobe between November 2009 and June 2011 are assumed to be equivalent in their volume to represent the total extrusion of magma.

Two approaches for constraining the magma extrusion rate were employed using the calibrated seismic data. In the first, rockfalls for the whole year of 2010 were classified into three classes depending upon the associated level of seismic signal. In the second, individual seismic energies E' were estimated for March 2011 events. After analysing and comparing the results of the two methods, unsurprisingly the estimation of individual seismic energies E' proved to be much more accurate and efficient, though more time consuming.

For the first method, the average volumes of rockfalls for the three classes were assigned while counting the number of rockfalls per day. Taking the mean of all 23 estimated volumes resulted in 56.6 m^3 per rockfall. The three categories were: small, medium and large. A volume was assigned to each type based upon the estimated volumes from the photographs. It needs to be emphasized that all rockfalls were of a small volume when compared to other volcanoes with higher rates of extrusion.

The first step in this approach was evaluating the seismic records of each day in 2010 to obtain the total number of rockfalls that year (Fig. 10). The duration of the small rockfalls usually is less than one minute and the amplitude is about 33 % of the saturation threshold of the seismic signal. The volume of six small events was estimated amongst the photographic events. Clearly estimating missing rock volumes from the photographs is far less accurate for small volumes. For those six events the maximum exposed face temperature difference was 20°; the average volume of this rockfall type was 8.7 m^3.

Medium rockfalls were defined by duration (less than 3 min) and an amplitude between 33 % and 66 % of the maximum from the seismic signal. The exposed face

temperature difference of these events usually was between 20 °C and 100 °C, their volume was less than 100 m^3. The volume of 12 medium events was estimated and the average value was 43 m^3.

Large rockfalls can last for at least 5 min and the seismograms can reach saturation. ΔT at the exposed face of these events is always more than 100 °C, the hottest temperature difference measured for the 23 rockfalls was 200 °C. The volume of five large events was estimated, giving an average of 147 m^3. These events are relatively rare.

Taking July 2010 as an example, there were in total 897 rockfall events recorded. 591 of them were of the small type, 222 medium and 84 of the large rockfall type. So the total volume of magma extruded in July 2010 was 27 000 m^3 giving an average magma extrusion rate of 0.010 m^3 s^{-1}. In comparison, taking the mean volume of all 23 calculated events (56.59 m^3) instead of classifying them by size, the magma extrusion rate resulted at 0.019 m^3 or 90 % greater. For the year 2010, an average magma extrusion rate of 0.011 m^3 s^{-1} (40.68 m^3 h^{-1}) has been established; taking the error of 31 % (see discussion) into account, it ranges between 0.008 m^3 s^{-1} and 0.014 m^3 s^{-1}. As shown in Fig. 11, the variation was between 0.008 m^3 s^{-1} and 0.019 m^3 s^{-1} in 2010 with an initial increase in February followed by a general decline.

For the second and more accurate method of extrusion rate calculation, rockfalls occurring during an eruption have been excluded as the superposition of the rockfall and explosion signal prevents an estimation of the volume. The integrated velocity squared value E' of the seismic signal was calculated, which as discussed, is related to the energy of the rockfall. In an attempt to include a consideration of rockfalls coinciding with explosions, the duration of the rockfalls was considered. Employing the frequency spectrogram of the seismic signals and by using differences in frequency content between explosion and rockfall allowed a precise determination of the duration parameter for the majority of superimposed events. Plotting duration against E' of pure rockfalls showed only a moderate correlation (Fig. 12).

Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

After applying Eq. (4), Eq. (5) results, which allowed the constraint of the volume of eruption related rockfalls using their duration:

$$V = 0.1\,21D \tag{7}$$

The plot of volume versus duration resulted in an R^2 value of 0.8; for this analysis, nine days of observation in March 2011 were used. When rockfalls occurred during an eruption, the duration was used to estimate E'. There were 701 rockfalls in March 2011, giving an average of 23 per day. During the nine field days an average of 11 rockfalls a day were observed, a reduced number since observation was not carried out throughout the night.

Applying Eq. (4) and Eq. (5), the total magma extruded in March 2011 was $21\,000\,\mathrm{m}^3 \pm 7000\,\mathrm{m}^3$. The total magma extrusion rate can be divided between $20\,000\,\mathrm{m}^3$ for isolated rockfalls and $1000\,\mathrm{m}^3$ of rockfall volume generated during an explosion. The magma extrusion rate at Volcán de Colima during March 2011 was estimated at $0.0078\,\mathrm{m}^3\,\mathrm{s}^{-1} \pm 0.0027\,\mathrm{m}^3\,\mathrm{s}^{-1}$. This result agrees reasonably with the result shown in Fig. 11, where the magma extrusion rate shows a decrease at the end of 2010 at $0.009\,\mathrm{m}^3\,\mathrm{s}^{-1}$. Also observations, both in the field and of the seismicity, showed that effusive activity gradually decreased after November 2010 until it finally stopped in June 2011.

5.7 Discussion

Rockfalls occur frequently during lava emplacement at active volcanoes; at Volcán de Colima the number and magnitude increased significantly between November 2009 and June 2011 when the summit dome overflowed the western crater rim. In this study, an estimation of rockfall volume through photographic observation was performed. At the outset we note that whereas seismic stations are running constantly, the acquirement of thermal images currently requires operator intervention. Of 86 rockfalls recorded visually, 23 were suitable for volume estimates; these were then used for comparison with other measured parameters.

19

Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

Volume estimation from photographs and subsequent magma extrusion rate calculations include some inherent error: possible error sources are the dome slope angle, due to a large variation of the slope on different parts of the dome; the manually measured rock dimensions from photographs; or the assumption of rocks being perfect cuboids. For our calculations, we assumed an error of 3° for the slope angle, 1 mm (20 cm true length) for the length of individual rock axes (in the zoomed photograph) and took into account that rocks are usually not all parallelepiped. A further source of error is the minimum rock size detectable, which is estimated to be 20 cm. However, a rock of these dimensions is still quite small, and even considering a large number of small rocks, the impact on the volume estimation would be negligible. The final error for the volume estiamted from photographs is the following: ±1 mm of measured rock lengths translates to an average error of 25 %; ±3° error of dome slope angle produces 12 %, the minimum detectable rock size might lead to a further 3 % error and assuming rocks to be a cuboid results in an error of 13 %. Then calculating the root mean square we get 31 %.

Calculations using correlations can be assumed to have a minimal error when the correlation coefficient R^2 is high; it is assumed that there are no significant systematic errors. In the case of estimating rockfall volume from superimposed events (rockfall and explosion) with the seismic records, R^2 (0.8, Fig. 13) is worse. However, only 5 % of the total extruded volume in March 2011 is affected by this correlation coefficient and thus the overall impact should be minimal. Finally, errors arise due to uncertainties on energy estimations: seismic rockfall signals are picked manually, hence there can be minimal errors regarding the picked and true length of rockfalls which affects the resulting energy. The Highpass filter removes background noise (mainly oceanic noise) but it can't be regarded as a filter which deletes everything except of rockfalls. An average error of 16 % is assumed here and has been added to the photographic error estimations. After application and consideration of all possible error sources, a maximum possible error of 35 % in the magma extrusion rate has been determined when applying the Volcanalysis script. For explosion related rockfalls the volume – duration

relation is useful, although less precise than the estimation using E'. The relationship between rockfall volume and the thermal emission of either the exposed dome face or the material on the flank was less precise, and can easily contain additional error sources.

For estimating rockfall volumes over long periods the continuous seismic data stream is available. With the relations between rockfall volume, duration and pseudo – energy, a final minimum magma extrusion rate of $0.0078 \pm 0.0027\,\mathrm{m^3\,s^{-1}}$ for March 2011 and a maximum of $0.019 \pm 0.007\,\mathrm{m^3\,s^{-1}}$ for February 2010 have been constrained. This result fits very well with observations of the period 2007–2010 by Lavallée et al. (2012). In March 2011 the rate decreased and finally reached zero in June 2011.

Of course photographic methods for dome monitoring have already been used (e.g. at Soufriere Hills; Sparks et al., 1998; Ryan et al., 2010), however, in these cases changes in the dome profile was monitored. In our study, the extraordinary observation conditions permitted an unprecedented opportunity to look in detail at small rockfalls, which represented the only new material being emplaced. Sparks et al. (1998) and Ryan et al. (2010) estimated their error in volume calculations to be 15 %, but it has to be noted that they concentrate on dome profile lines which can be more accurate than our presented three dimensional calculations on two dimensional images. Since they were observing much larger effusion rates for the 2005–2007 active dome growth period at Soufriere Hills, the extrusion rate was $5.6 \pm 0.9\,\mathrm{m^3\,s^{-1}}$ (Ryan et al., 2010), the absolute error was much larger.

The relationship between pseudo–energy and volume of rockfalls has, in a different way, also been described by Hibert et al. (2011). By studying the connection between seismic and potential energy in granular flow and combining an analytical approach with experimental work on moving granular flows, they defined a methodology for estimating rockfall volumes at Piton de la Fournaise, Reunion. They also suggest their method could be used for real-time rockfall volume monitoring at active volcanoes.

The methodology developed in this study could be used for future periods of effusive activity at Volcán de Colima. In particular the correlation between seismicity and

volume is limited to Volcán de Colima because E' is dependent on volcano-specific parameters such as dome slope angle, density of rock material, run-out distance and slope angle and the distance between seismic station and dome. Nevertheless, the technique itself is applicable for other volcanoes exhibiting similar phenomena pro-
5 vided a calibration is obtained in each case. A further complication would be inherent if rockfalls were to occur in more than one direction. The applicability for the presented method at Colima requires a decentralized slow growing dome in the summit crater which produces small rockfalls on the western flank of the volcano. If the dome has a different relative position within the summit crater, the recorded seismicity would have
10 different characteristics because of new parameters (slope gradient, distance to EZV4 seismic station). Furthermore, different magma properties (volatile-contents, temperature, chemical composition, crystal-contents) or a different effusion rate would lead to different dome growth characteristics and hence variation in the generation of rockfalls. If direct observation is possible, further rockfall volume estimation could be performed
15 to freshly calibrate the associated seismic signal. During late 2009–2011 at Volcán de Colima, almost all rockfalls descended the western flank following an almost identical path. Rockfalls descending a volcano on different flanks would introduce further complications for interpretation of the seismicity. But with careful calibration and under the right circumstances, the presented methodology could prove suitable.

20 **6 Conclusions**

We propose a methodology for the detailed monitoring of rockfall volume to estimate the magma extrusion rate of volcanoes with active domes. The example of Volcán de Colima illustrates that if dome growth is limited to rockfalls, the method alone succeeds in yielding the extrusion rate. Rockfall volume itself was obtained from comparing pho-
25 tographic images before and after the events. The relationship with two other parameters (thermal and seismic data) was shown and proven suitable to estimate rockfall volume once calibrated by using a number of direct estimates from photographic images.

The thermal emission recorded was either the mean temperature at the freshly exposed face on the dome directly after the rockfall or the mean rockfall temperature on the slope of the volcano. A better correlation was obtained between the volume and the mean rockfall slope temperature. The second and more important relationship that was used to estimate rockfall volumes was that with the seismic signals. The relationship between E' and the rockfall volume V showed an astonishingly good correlation coefficient (0.92). For this reason, seismic signals have been used to estimate the magma effusion rate at Volcán de Colima. Seismic monitoring can thus be used as a powerful tool for extrusion rate monitoring of certain erupting volcanoes. We recommend that these methods be considered for risk assessment at dome-building eruptive centres.

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Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

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Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Sulpizio, R., Capra, L., Sarocchi, D., Saucedo, R., Gavilanes-Ruiz, J. C., and Varley, N. R.: Predicting the block-and-ash flow inundation areas at Volcán de Colima (Colima, Mexico) based on the present day (February 2010) status, J. Volcanol. Geoth. Res., 193, 49–66, 2010.

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Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.
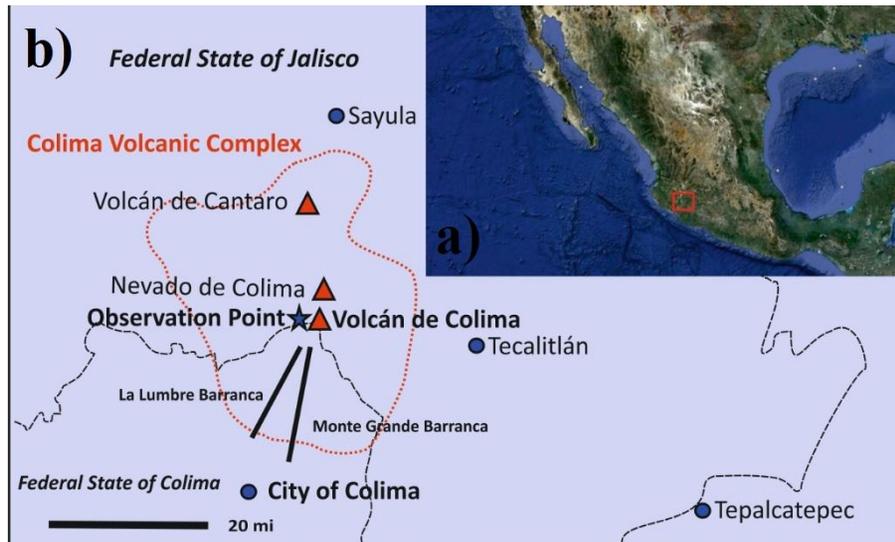
Fig. 1. (a) Position of Volcán de Colima in Mexico (Red box); **(b)** hand drawing shows the Colima Volcanic Complex with the extinct volcanoes Volcán de Cántaro and Nevado de Colima and the active Volcán de Colima (red triangles). Two black lines south of Volcán de Colima show the two main Barrancas leading towards the City of Colima; in case of a dome collapse events, twice barrancas guide pyroclastic flows. Also the observation point Playón to the west of Volcán de Colima where data for this study has been collected is shown (blue star).

Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

Fig. 2. Photograph shows Volcán de Colima and the observation camp within the Playón to the West of the volcano. Image shows the decentralized growing dome. The dome has a diameter of 298 m and can be used as a scale in photographs. The white dust track down the slope was triggered by an ongoing rockfall.
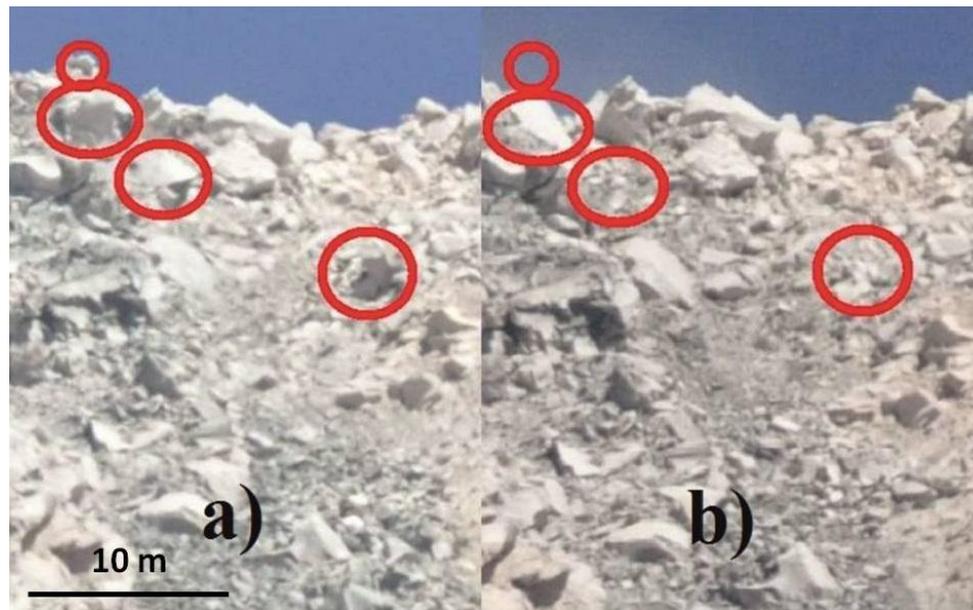
Fig. 3. View of the dome of Volcán de Colima **(a)** before the rockfall on 8 March 2011, 15:02 Colima Local Time (21:02 GMT) and **(b)** after the rockfall. Rocks that are missing after the rockfall are marked with a red circle.
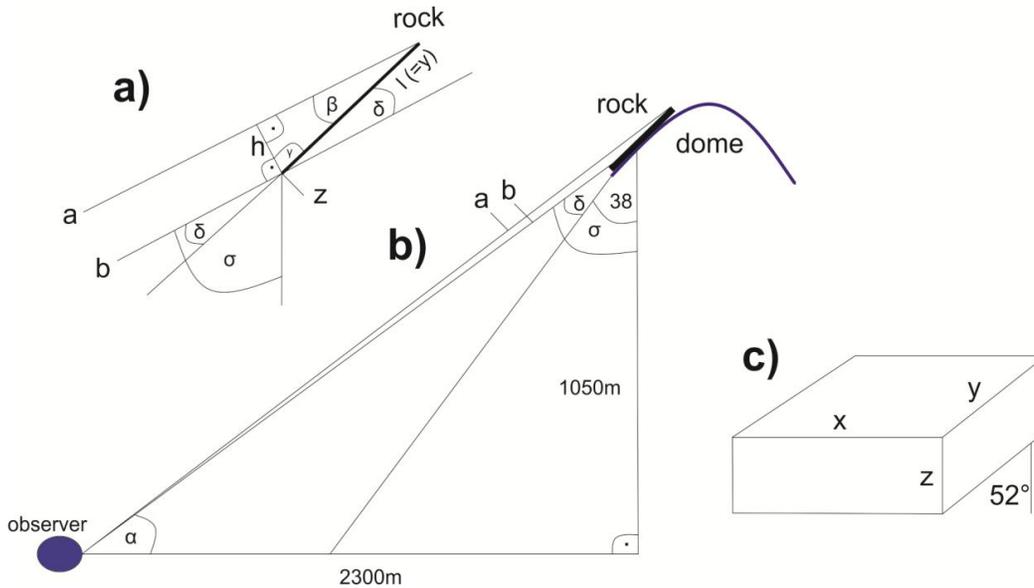
Fig. 4. Geometry between observer and rock on dome. **(c)** Shows rock axes x, y and z.
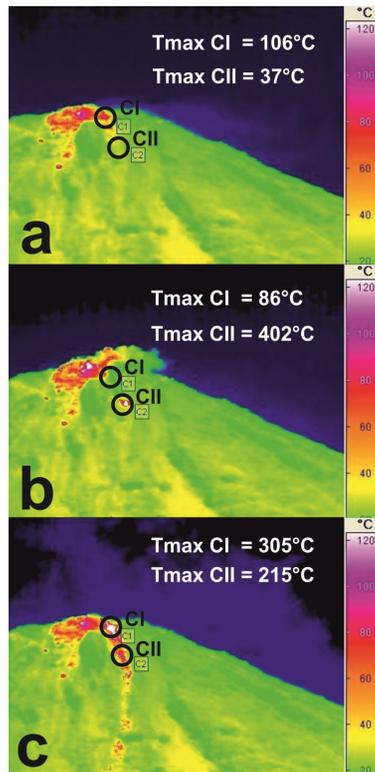
Fig. 5. Series of thermal images of a rockfall on 9 March 2011 at 21:07 GMT at Volcán de Colima before **(a)**, during **(b)** and after **(c)** a rockfall. The black circle C1 marks the exposed face on the dome; C2 marks a spot on the slope where the rockfall will pass by. Each picture shows the maximum temperature of each circle which is the base for the temperature difference measurements.

Fig. 6. Relationship of rockfall volume and temperature measured at the area of origin; R^2 is 0.88.
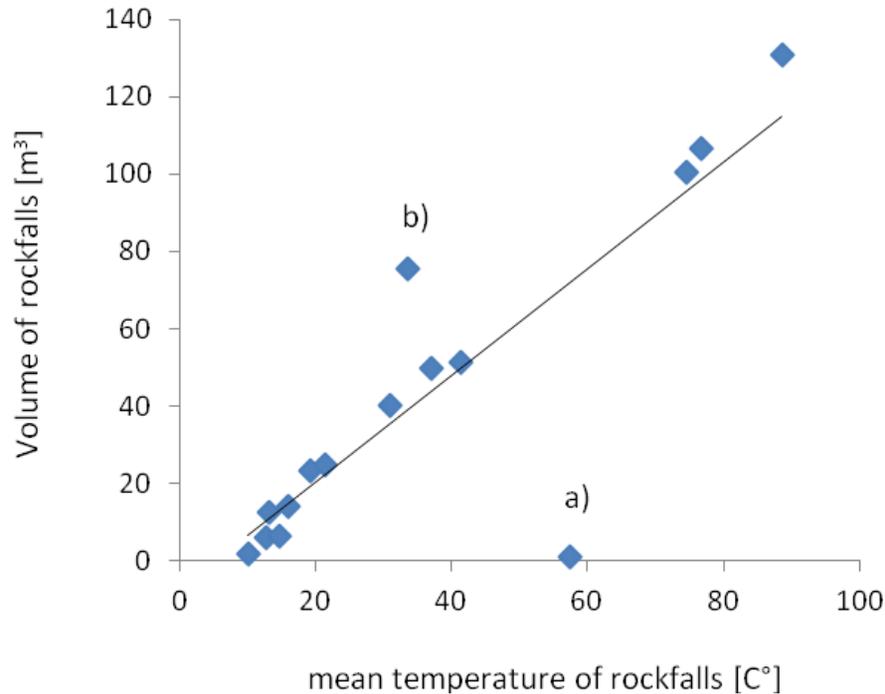
Fig. 7. Relationship between the volume of rockfalls and the mean temperature of the related deposits distributed over the volcano's slope. Two outliers can be observed: Point **(a)** marks a rockfall that happened shortly after a big one so the high average T for the observed small volume is not representative. Point **(b)** marks a rockfall that broke off from the NW edge of the dome. Here rockfall activity was very low; accordingly the involved mass had had more time for cooling, leading to the observed low value of average T.
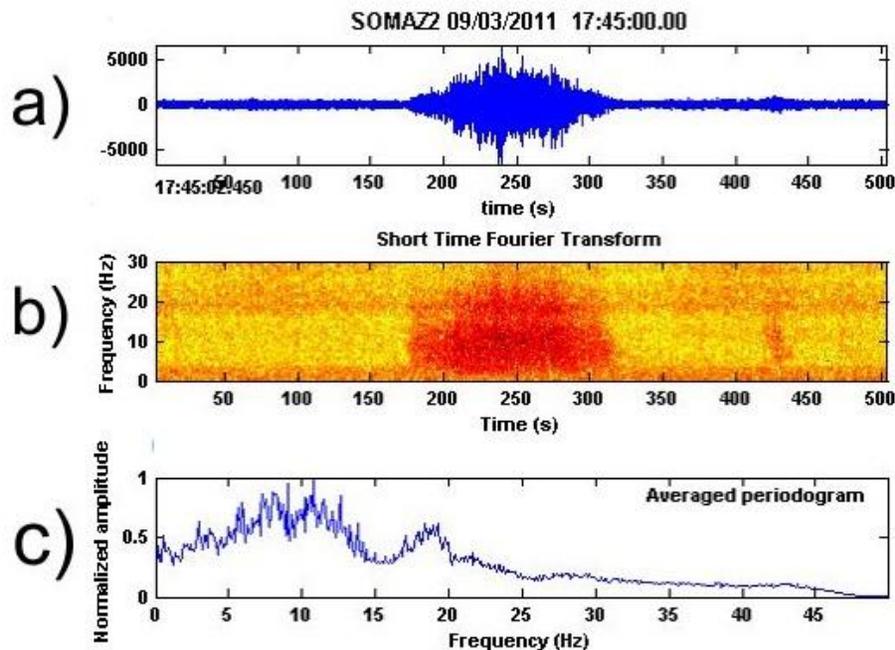
Fig. 8. Rockfall signal at Volcán de Colima with its frequency. Shown are **(a)** the seismogram and **(b)** its time – frequency spectrogram representation and **(c)** the averaged periodogram of the event. An order 2 – Highpass Filter was applied with a low corner frequency of 1 Hz. The rockfall was recorded at SOMA station at 17:48 GMT on 9 March 2011.
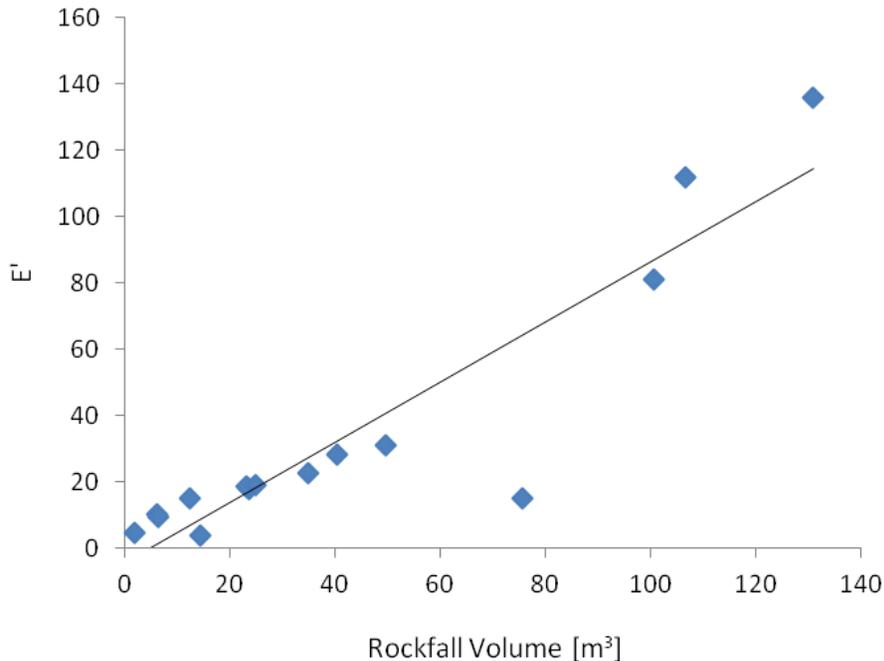
Fig. 9. Rockfall volume vs. seismic signal related energy with averaged trendline. Good correlation between estimated volume and seismic signal energy value E' which is a pseudo – energy and stands for a number that is approximately proportional to the actual seismic energy without units. R^2 between E' and rockfall volume is 0.92.
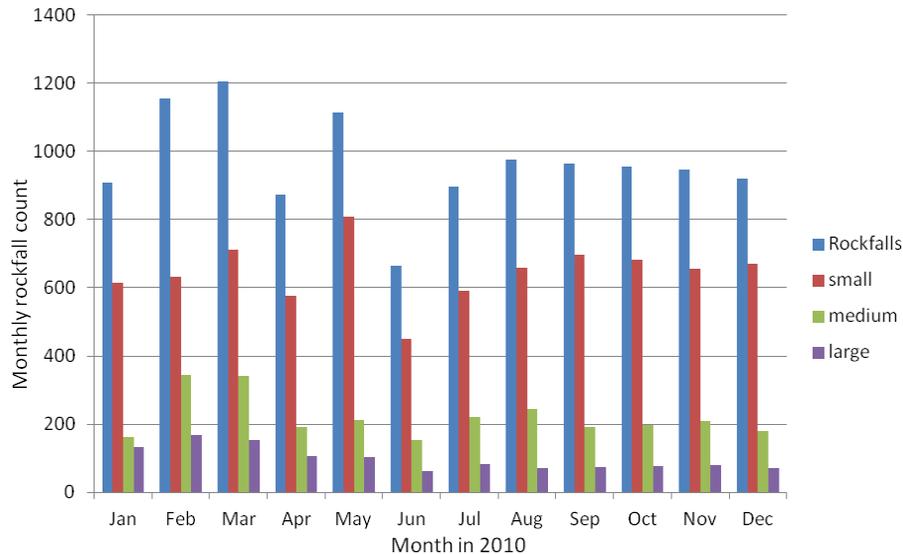
Fig. 10. Total amount of rockfalls at Volcán de Colima in 2010. The blue bar shows the monthly total, red shows the small, green the medium and purple the large rockfalls. The small category is defined by seismic amplitude smaller than 3 mm on the helicorder output. They are also usually shorter than 60 s in duration. The medium one have amplitudes smaller than 7 mm, their duration usually never exceeds 180 s. All rockfalls with greater amplitude than 7 mm count as large rockfalls. All the data shown in this figure is gained from the daily helicorder records for the year 2010 of the EZV4/SOMA station in the RESCO Volcán de Colima seismic network.
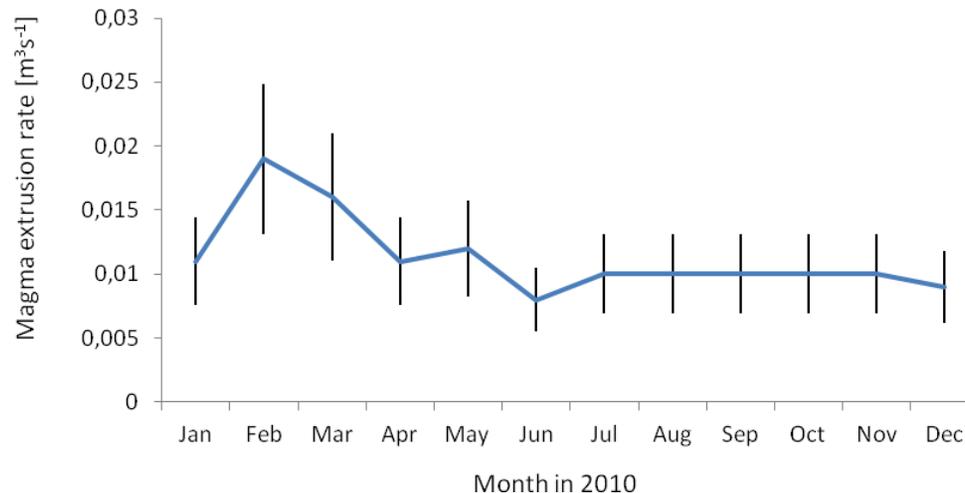
Fig. 11. Magma extrusion rate of Volcán de Colima in 2010, with error of 31 %; calculated with the seismic amplitude – photographic method. The maximum is in February 2010 with $0.019\,\mathrm{m^3\,s^{-1}}$, the minimum in June 2010 with $0.008\,\mathrm{m^3\,s^{-1}}$. The average extrusion rate in 2010 is $0.0113\,\mathrm{m^3\,s^{-1}}$. In November 2010 the decrease of activity starts and will finally stop in June 2011.
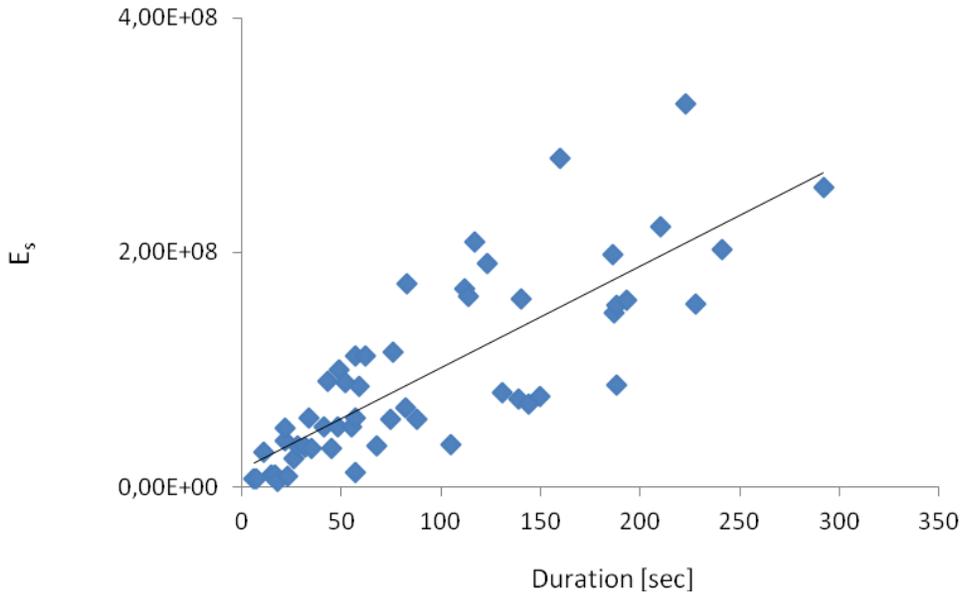
Fig. 12. Pseudo – energy E' vs. duration of rockfalls in seconds; R^2 is 0.8.

Quantification of magma ascent rate through rockfall monitoring

S. B. Mueller et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion