



## Short communication

# Quantification of volcanic explosions from tilt records: Volcán de Colima, México

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## Abstract

During the 2004–2005 explosive sequence at Volcán de Colima, México, impulses with a duration of several minutes were recorded by a two-component tiltmeter installed at a distance of 1.6 km from the crater for 46 Vulcanian explosions. The correlation between the amplitudes of tilt impulses  $A = \sqrt{(A_{\text{rad}}^2 + A_{\text{tang}}^2)}$  and the energy of explosions  $E$  estimated from the broadband seismic records is significant at the 99% confidence level. The regression equation can be used to estimate the energy of explosions at Volcán de Colima from the tilt records.

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## 1. Introduction

Recent monitoring of the andesitic Volcán de Colima, México, shows that the tiltmeter with a sample rate of 30 counts/h may record rather large (order of up to 100–150  $\mu\text{rad}$ ) tilt changes with few-minute lengths associated with the Vulcanian explosions (Fig. 1). These few-minute impulses appear on the tilt records when the explosion is large enough to generate an explosive shock that exceeds the minimum sensitivity of the instrument. The tilt impulse is recorded simultaneously with the seismic record shown in Fig. 1B. The energy classification of the 2004–2005 explosive sequence at Volcán de Colima from broadband seismic records (Zobin et al., 2006b) is used to

study the dependence of tilt amplitude on the energy of explosions. In this short communication, we show the characteristics of the tilt variation, with a duration of several minutes, associated with the Vulcanian explosions at Volcán de Colima and propose the application of tilt amplitudes for the rapid energy estimation of volcanic explosions.

## 2. Volcán de Colima and its activity in 2004–2005

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. 2). 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). The 1998–2005 unrest at

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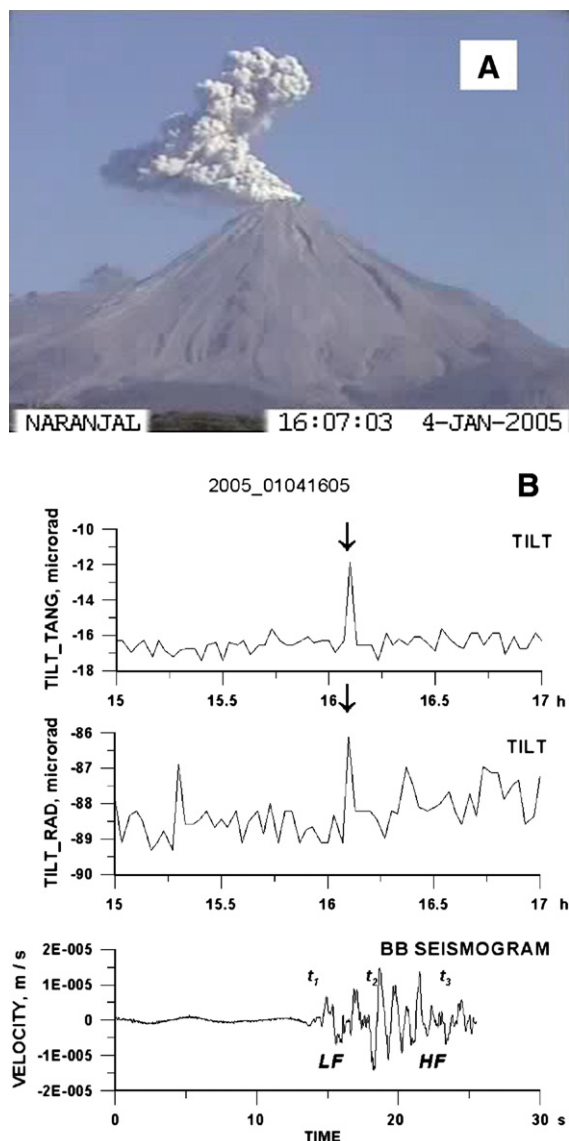


Fig. 1. (A) The Vulcanian explosion at Volcán de Colima recorded on 4 January 2005 at 16:05 GMT (code 2005\_01041605) by a video station NAR (shown in Fig. 2B) and (B) the two-component two-hour tilt records at station AGL situated at a distance of 1.6 km from the crater (shown in Fig. 2B) and the unfiltered broadband seismic record corrected for instrument response (vertical component of velocity) of the same explosion at station EZ5 situated at a distance of 4 km from the crater (shown in Fig. 2B). Clear impulses can be seen for both components of the tilt record (marked by arrows) coincident with the onset of the explosion. The moments of the beginning of the low-frequency impulse ( $t_1$ ), and of the beginning ( $t_2$ ) and the end ( $t_3$ ) of the high-frequency impulse are indicated on seismogram. LF is a low-frequency impulse; HF is a high-frequency impulse.

Volcán de Colima began on 28 November 1997 with a sharp increase in seismic activity and a significant shortening of geodetic lines around the volcano. This

then developed into three stages of effusive–explosive activity (Zobin et al., 2002, 2006a,b).

The most recent stage of eruptive activity at Volcán de Colima began on 30 September 2004 (Zobin et al., 2006b). The extrusion of andesitic lava, that occurred during September–November 2004, formed two lava flows from the summit lava dome, one with a length and width of about 2400 m and 300 m and the other, 600 m and 200 m, on the N and WNW flanks, respectively. The lava effusion was accompanied and followed by intermittent explosive activity represented mainly by small steam-and-ash Vulcanian explosions. With the termination of lava effusion, the number of small explosions gradually decreased during December 2004–January 2005, remaining at a rather stable low level during February–June, 2005. A series of large explosions began on 10 March and concluded 27 September 2005. The largest of them, accompanied by pyroclastic flows, were particularly vigorous from 24 May to 5 June. Some of these explosions issued material that reached an altitude as high as 10 km asl. The March–September explosive sequence removed the 2004 lava dome, and left a crater 260 m across and 30 m deep having emitted volcanic material with a volume of about  $2 \times 10^6 \text{ m}^3$ .

### 3. System of monitoring

Fig. 2B shows the position of the monitoring system from which observations used in this paper was obtained: a tiltmeter site AGL, a broadband seismic station EZ5 and a video monitoring station NAR. An Applied Geomechanics and Sobetra AGI701-2 dual-axis tiltmeter was installed at a distance of 1.6 km from the crater of Volcán de Colima in 1999. This resistive bubble-type tiltmeter with a resolution of  $0.1 \mu\text{rad}$  and a sampling rate of 30 samples/h includes a temperature sensor sealed in its body. Its radial component is oriented from the crater of the volcano ( $313^\circ$ ) and the tangential component is oriented in the direction of  $43^\circ$ . The seismic station EZ5 situated at a distance of 4 km from the crater on the southern flank of the volcano was equipped with a broadband three-component GURALP CMG-40TD sensor with a corner frequency of 30 s and a digitizer DM24 with a sampling rate of 100 samples/s. Sony model CCD-TRV118 videocamera was situated at a distance of 15 km from the crater (NAR).

### 4. Quantification of the 2004–2005 explosions from the broadband seismic records

The energy quantification of the 2004–2005 explosions was based on the broadband seismic records of

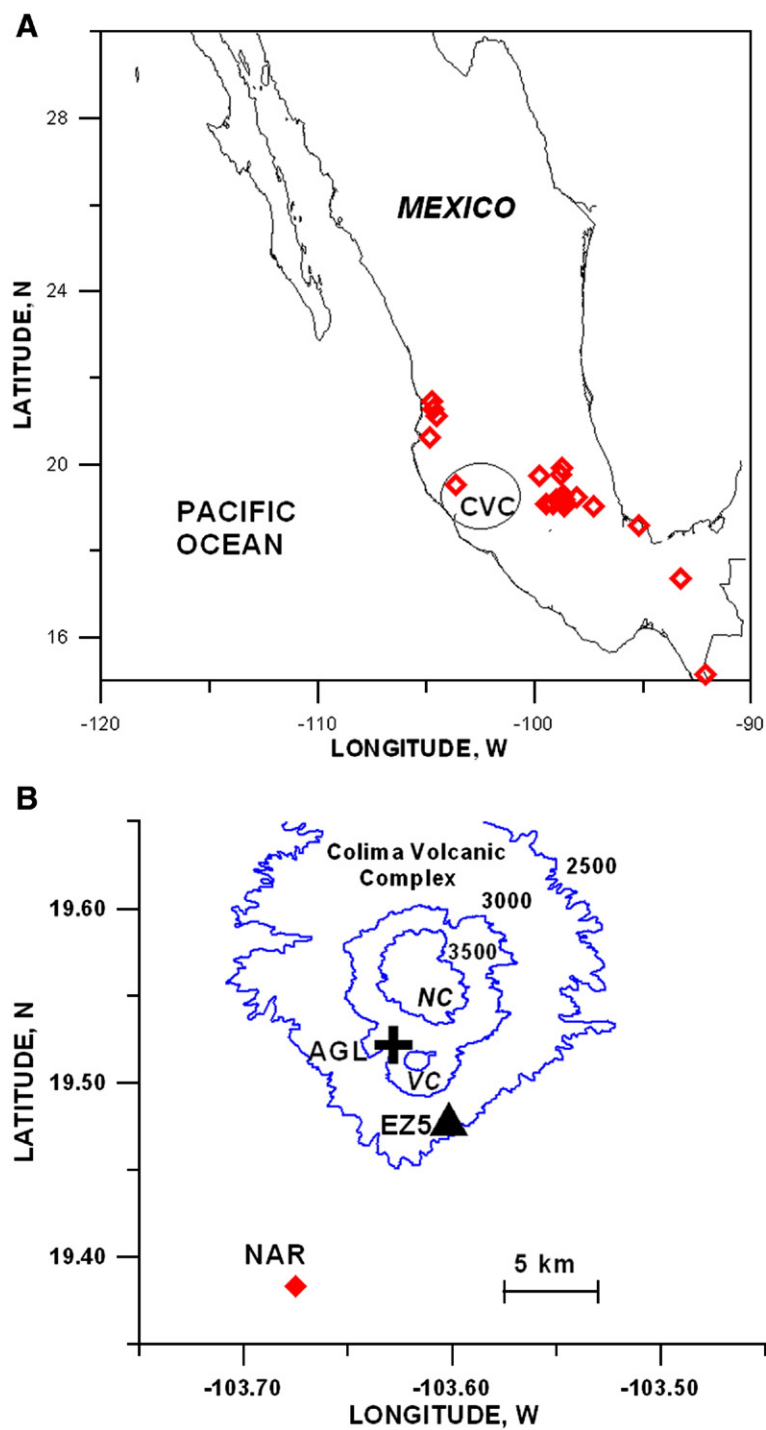


Fig. 2. Position of Colima Volcanic Complex (CVC) within the TransMexican Volcanic Belt (A) and the monitoring system (B). In A, the active volcanoes are shown by open diamonds. The oval shows the position of CVC. In B, the contour lines at 2500, 3000 and 3500 m show the relief of the Colima Volcanic Complex. VC is Volcán de Colima; NC is Nevado de Colima. The seismic station EZ5 is shown as a triangle; the video station NAR is shown as diamond; the tiltmeter AGL is shown as cross.

explosions at seismic station EZ5 (Fig. 2B). A typical seismic record of a Vulcanian explosion is shown in Fig. 1B. This unfiltered broadband signal, observed also at Stromboli and Popocatepetl volcanoes (Neuberg et al., 1994; Chouet et al., 1997; Ripepe et al., 2001; Zobin et al., 2007), consists of two impulses, of low-frequency (LF) and high-frequency (HF) contents. The conceptual model proposed by Zobin et al. (2006b) and based on the field and laboratory experiments of Ripepe et al. (2001), states that the low-frequency seismic signal was generated by the pre-explosion magma movement in the conduit, while the high-frequency seismic signal was generated by the explosion. The energy of the seismic impulse recorded on EZ5 was calculated from the Fourier spectrum of HF impulse, being multiplied by a coefficient including a correction for the seismic portion of the total energy of an explosion and the effective attenuation of seismic energy with distance. The 2004–2005 Colima explosions spans 7 orders of energy magnitude, ranging from  $4 \times 10^7$  J to  $1.5 \times 10^{13}$  J (Zobin et al., 2006b).

### 5. Tilt impulses associated with explosions

Fig. 3 demonstrates characteristic records of tilt at a distance of 1.6 km from the crater during volcanic explosions, together with the values of energy of these explosions. These records form the bi-modal or uni-modal impulses with a duration of 3 to 6 min. The radial component of impulses has a positive polarity (away from the crater) for all events; the tangential components have both positive and negative polarities. The difference in polarities of the tangential components and their large amplitudes indicate that the location of the explosion source was not constant and did not coincide with the formal direction between the instrument site and the crater.

The relatively low sampling rate of the tilt records (1 sample/120 s) does not allow a direct comparison with the seismic signal with the total duration of less than 100 s. It is not possible to say if any part of the tilt record coincides with the LF or HF seismic impulses. Nevertheless, it is seen (Fig. 3) that the amplitudes of the tilt signal depend on the energy of explosions estimated from the HF impulses; they are larger for the events of higher energy. Therefore, it is possible to consider, in the frame of our conceptual model (Zobin et al., 2006b), that the amplitudes of the tilt records are associated with the energy release during the explosion. This assumption allows us to study the empirical relationship between tilt amplitudes and energy of the explosions. The tilt records were examined for 120 explosions that oc-

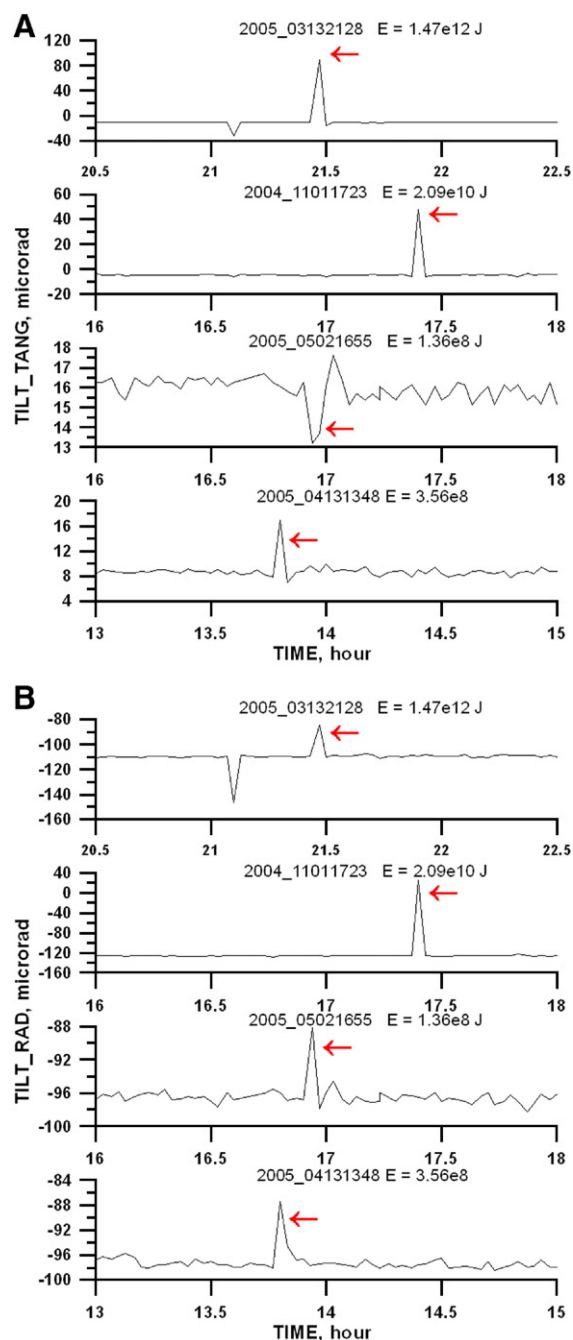


Fig. 3. Examples of two-hour tilt records (A, tangential component; B, radial component). Arrows show the impulses that were associated with explosions. The codes of records are the same as in Fig. 1. The energy of explosion  $E$  was estimated from the broadband seismic records at station EZ5 (Fig. 2B).

curred from October 2004 to September 2005 and whose energy was estimated from the broadband seismic records by Zobin et al. (2006b). The impulses of tilt were recognized for 46 events only; they are listed in

**Table 1.** The remaining 74 explosions had no response within the tiltmeter records or were recorded with the initial part of signal missing. Impulses were recorded only for 17% of the explosions with energy of  $10^7$  to  $10^8$  J but for 51% of the explosions with energy of  $10^9$  to  $10^{10}$  J and for 87% of the explosions with energy of  $10^{11}$  to  $10^{13}$  J. The energy threshold of  $10^9$  to  $10^{10}$  J is

assumed to be limited by the sensitivity of the instrument. The registering of impulses produced by explosions with energy lower than  $10^9$  J may depend upon conditioned by their position being closer to the instrument site.

Fig. 4 shows the relationship between the amplitudes of tilt  $A = \sqrt{A_{\text{rad}}^2 + A_{\text{tang}}^2}$  and the energy of explosions E.

Table 1  
Catalog of explosions with recorded tilts

| Date, yyyy_mmddhhmm | Energy of explosion from BB seismic record, J | Tilt amplitude, tangential component, microrad | Tilt amplitude, radial component, microrad |
|---------------------|-----------------------------------------------|------------------------------------------------|--------------------------------------------|
| 2004_10181257       | 3.62E+09                                      | −3.32                                          | 3.91                                       |
| 2004_11011723       | 2.09E+10                                      | 54.6                                           | 150.95                                     |
| 2004_11031310       | 1.72E+09                                      | 1.32                                           | 1.56                                       |
| 2004_11231818       | 9.19E+08                                      | 2.07                                           | 3.33                                       |
| 2004_12010007       | 3.18E+09                                      | 1.266                                          | 10.23                                      |
| 2005_01021356       | 2.78E+08                                      | −1.79                                          | 2.33                                       |
| 2005_01040015       | 1.03E+09                                      | 2.01                                           | 3.33                                       |
| 2005_01041605       | 1.55E+09                                      | 4.46                                           | 2.98                                       |
| 2005_01081807       | 9.29E+08                                      | −7.108                                         | 3.92                                       |
| 2005_01082121       | 1.38E+09                                      | −0.86                                          | 7.35                                       |
| 2005_01090321       | 3.15E+09                                      | −1.57                                          | 5.11                                       |
| 2005_01181605       | 1.03E+10                                      | 1.57                                           | 3.22                                       |
| 2005_02010612       | 1.90E+10                                      | −1.86                                          | 5.68                                       |
| 2005_02071800       | 5.23E+09                                      | 0.954                                          | 11.581                                     |
| 2005_02082040       | 2.80E+10                                      | 2.267                                          | 10                                         |
| 2005_02132202       | 2.30E+10                                      | 1.079                                          | 8.24                                       |
| 2005_03022200       | 1.27E+09                                      | 10.46                                          | 2.73                                       |
| 2005_03101409       | 1.37E+12                                      | −1.24                                          | 4.55                                       |
| 2005_03132128       | 1.47E+12                                      | 101.61                                         | 24.96                                      |
| 2005_03260340       | 3.15E+11                                      | −11.4                                          | 42.57                                      |
| 2005_04011237       | 4.09E+08                                      | 5.77                                           | 2.36                                       |
| 2005_04012357       | 1.04E+09                                      | 0.47                                           | 7.67                                       |
| 2005_04042149       | 2.90E+08                                      | 4.44                                           | 0.79                                       |
| 2005_04061714       | 1.11E+09                                      | −3.22                                          | 0.32                                       |
| 2005_04082002       | 2.06E+09                                      | −1.37                                          | 9.79                                       |
| 2005_04091545       | 1.00E+09                                      | −1.32                                          | 3.45                                       |
| 2005_04102136       | 5.33E+09                                      | 3.56                                           | 0.87                                       |
| 2005_04122204       | 1.02E+09                                      | −0.53                                          | 4.12                                       |
| 2005_04131348       | 3.56E+08                                      | 9.17                                           | 10.76                                      |
| 2005_04151908       | 3.00E+09                                      | −3.58                                          | 4.66                                       |
| 2005_04200156       | 7.34E+11                                      | −5.41                                          | 18.34                                      |
| 2005_04292302       | 2.82E+09                                      | 4.32                                           | 4.13                                       |
| 2005_05021655       | 1.36E+08                                      | −3.81                                          | 8.69                                       |
| 2005_05081133       | 9.35E+08                                      | 7.08                                           | 9.6                                        |
| 2005_05140156       | 1.37E+08                                      | 2.22                                           | 1.34                                       |
| 2005_05160201       | 2.07E+12                                      | −1.38                                          | 15.25                                      |
| 2005_05160832       | 1.52E+08                                      | −3.25                                          | 5.99                                       |
| 2005_05240009       | 5.44E+12                                      | −101.72                                        | 105.33                                     |
| 2005_05300826       | 7.22E+12                                      | 138.46                                         | 105.85                                     |
| 2005_06020449       | 3.63E+12                                      | −7.99                                          | 26.76                                      |
| 2005_06051920       | 1.46E+13                                      | −12.97                                         | 16.42                                      |
| 2005_06070404       | 1.06E+12                                      | −17.04                                         | 50.16                                      |
| 2005_06100254       | 3.01E+11                                      | 13.65                                          | 17.53                                      |
| 2005_07270913       | 9.60E+10                                      | 103.51                                         | 24.95                                      |
| 2005_09161547       | 8.57E+11                                      | 40.51                                          | 1.39                                       |
| 2005_09271008       | 5.78E+11                                      | 14.63                                          | 13.41                                      |

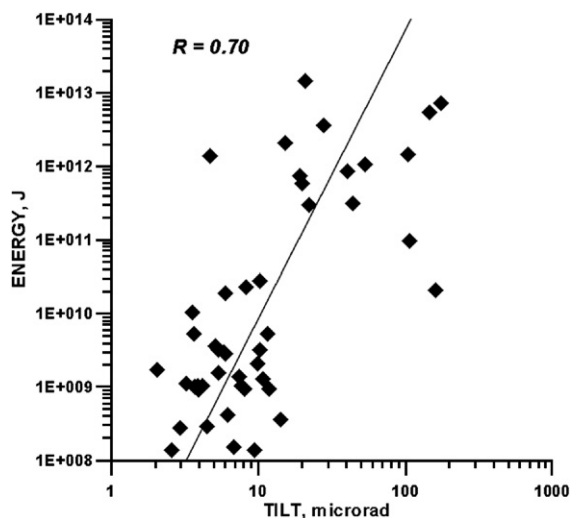


Fig. 4. Relationship between tilt amplitudes  $A = \sqrt{A_{\text{rad}}^2 + A_{\text{tang}}^2}$  and energy of explosions estimated from the broadband seismic records at station EZ5 (Fig. 2B). The regression line corresponding to Eq. (1) is shown.  $R$  is the coefficient of correlation.

The maximum likelihood regression between these two parameters is:

$$\begin{aligned} \text{Log } E(J) = & (3.938 \pm 0.116) \text{Log } A(\mu\text{rad}) \\ & + (5.980 \pm 0.252) \end{aligned} \quad (1)$$

$$R = 0.70 (R_{\text{crit}99\%} = 0.37).$$

Here  $R$  is the coefficient of correlation. Therefore, we have a significant correlation (at the 99% confidence level) between the amplitude of tilt and the energy of the explosion.

## 6. Physical basis of Eq. (1)

The obtained empirical correlation between the explosion energy and the tilt amplitude is not a formal only. It logically follows from the nature of Vulcanian explosion and the physics of an elastic medium. According to the models of Vulcanian explosions, the overpressure release in the conduit may initiate the upward flow of a gas slug (basaltic volcanoes, Ripepe et al., 2001) or produce downward fragmentation waves generating the upward moving fragmented magma (andesitic volcanoes, Alidibirov and Dingwell, 1996; Melnik and Sparks, 2002; Clarke et al., 2002). Both these types of upward magmatic flow produce an explosion in the upper part of the conduit. A Vulcanian explosion represents an extension source in the conduit which may cause the inflation-type deformation of the volcanic edifice recorded by the tiltmeter. This explosion is also

recorded by the seismic station. So, the seismic record and the tilt are produced by the same process.

In the terms of the physics of an elastic medium (e.g., Aki and Richards, 2002), the elastic body that possesses an internal energy  $W$  is characterized by a changing strain component  $\tau_{ij}$  of an elastic medium as  $\tau_{ij} = \delta W / \delta E_{ij}$ , where  $E_{ij}$  is the stress. Therefore, it can be expected that the deformation of a volcanic edifice is related to the energy of an explosion. Experimental studies of the dependence between the magnitude of a nuclear explosion and the deformation of the surrounding area showed that the deformation around the explosion site (length of fracturing along faults) increases when the magnitude (or yield in megatons) of explosions increases (McKeown and Dickey, 1969). Assuming that the process of energy release for volcanic and nuclear explosion is similar, we may expect a similar direct relationship between the energy release by volcanic explosions and the deformation of the surrounding volcanic region.

## 7. Application of Eq. (1) for quantification of volcanic explosions

Eq. (1) allows us to use the amplitudes of tilt impulses for the quantification of explosions at Volcán de Colima. Comparing the values of energy obtained from Eq. (1) with the values of energy obtained from seismic data produces a mean deviation  $\sigma = \pm 1.13$  log unit. Thirty one out of 46 events (67%) give a deviation less than  $\sigma$ , 3 events (or 6.5%) give a deviation larger than  $2\sigma$ .

The deviation between the two values does not depend on the energy of explosion. The main reason for these deviations may be due to variation in the location of the explosion sources from event to event in both depth and space indicated by the great variations in the size and polarity of the tangential component of tilt. The smaller deviations were observed when the amplitudes of radial and tangential components were close. Two of the three largest deviations (2.9 and 4.2 log units) were observed when the amplitudes of tangential and radial components had a difference of greater than 60  $\mu\text{rad}$ . Another reason for the deviation may be that a part of the impulse is missing during 2-min gap in the tilt record (one sample every 2 min).

The depth effect may be rather complicated. At first, the depth of an explosion needs to be defined. According to our conceptual model (Zobin et al., 2006b) we have at least two characteristic depths forming part of the explosive process: the depth of the beginning of the upward movement of fragmented magma (fragmentation level) and the depth of the explosion of this magma-

and-gas mixture. Recent estimations of explosion depths (Cruz-Atienza et al., 2001; Chouet et al., 2005) refer to a third definition of depth, the depth of the centroid of tensor, which describes the radiation of very long-period seismic waves. This approach is essentially taking an average of the whole volume involved in the process of an explosion beginning from the propagation of decompressed wave and terminating with the outlet of the magmatic material from the crater. For Volcán de Colima, we can constrain the depths of explosions using the duration  $D = t_2 - t_1$  of the LF impulses (Fig. 1B) which are proposed to be the time of simultaneous downward propagation of the fragmentation wave and the upward flow of the fragmented magma before the explosion. The values of  $D$  varied from 0 to 10 s for the Colima events (Zobin et al., 2006b). Therefore, considering the maximum velocity of the propagation of the fragmentation wave to be about one hundred m/s (Alidibirov and Dingwell, 1996), we can propose that the range of depths representing the fragmentation level generating the Colima explosions was from 0 to 1000 m within the upper part of the conduit. This large variation in the source depth for an explosion sequence may also have a significant influence on the energy estimation from tilt.

Eq. (1) is constructed as the empirical relationship of only two parameters, indicating the deformation as a function of the energy of the explosion. We understand that the deformation of a volcanic edifice may be affected by the mass of ejected explosion products, the conduit geometry, etc. Neglecting these factors may be a reason for the large value of  $\sigma$ , especially for complicated shallow explosions. At the same time, the energy of an explosion is the only well-determined characteristic, while the use of the additional characteristics would be strongly hypothetical.

Eq. (1) may be used for the preliminary estimation of explosion energy during real-time monitoring. To avoid large errors, we don't recommend using this equation when the amplitude of the tangential component significantly differs from the amplitude of the radial component. The values of tilt strongly depend on the site location, meaning that Eq. (1) must be recalibrated for other sites around Volcán de Colima and for other volcanoes.

## 8. Comparison with geological and geophysical scales of volcanic explosions

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 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 volume of products of an eruption, as opposed to those of specific phases during a related sequence of explosive events. The value of the VEI for the 2004–2005 explosive eruption at Volcán de Colima estimated from the altitude of the volcanic columns and the total volume of erupted material is equal to 2.

Our alternative approach is to quantify the explosion energy, which also offers the opportunity to quantify individual explosive events which would otherwise be averaged over an entire explosive sequence. The scaling of explosions using the counter force of an eruption  $F$  estimated from the modeling of low-frequency impulses of the broadband seismic records (see Fig. 1B) shows better a resolution for the explosion magnitude compared with the VEI for the entire sequence. For the 1997–1998 Popocatepetl explosion sequence a value of  $VEI=3$  was estimated from the total volume of magma expelled (BGVN, 1980–2004). At the same time, the seismic estimations of  $F$  varied by 1.5 orders of magnitude 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 (Zobin et al., 2006a).

As it was shown in Zobin et al. (2006b), the energy of the 2004–2005 Colima explosions estimated from the high-frequency impulses of the broadband seismic records spans 7 orders of magnitude with a resolution of about  $\pm 0.1$  log units. The estimation of explosive energy from the tilt impulses has less precision than that from the seismic records. At the same time, the explosive energy estimation from the tilt records may be useful when the seismic records are absent.

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