New Clues to Untangle the Question: Was the Volcanic Eruption Triggered by the Earthquake?

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Abstract

Understanding the cause/effect relationship between tectonic earthquakes and volcanic eruptions is a striking topic in Earth Sciences. Volcanoes may erupt due to the impact of seismic waves (i.e. dynamic stress) and changes in the stress field (i.e. static stress) with variable reaction times. In 2012, three large (M_w≥7.3) subduction earthquakes struck Central America within ten weeks; some volcanoes in the region erupted days after, meanwhile for others it took months to years to erupt. Here we show that the three earthquakes contributed to the increase in the number of volcanic eruptions during the seven years that followed. We found out that only those volcanoes that were already in a critical state of unrest effectively erupted, indicating that the earthquakes only prompted the eruptions. We recommend the permanent monitoring of active volcanoes to reveal which are more susceptible to culminate into eruption when the next large-magnitude earthquake hits a region.

Introduction

“Was the volcanic eruption triggered by the earthquake?” The answer to this question usually is “maybe”, or “it could be a coincidence”. These ambiguous answers are due to the lack of observational data and/or clear scientific evidence that relates the two processes. Darwin[1], in his expedition to Chile in 1835, experienced the Concepción earthquake in February of that year, with some volcanoes increasing their activity on the same day and others during the subsequent months. Observed cases of volcanic eruptions supposedly caused by tectonic earthquakes are reported for different tectonic settings. For example, the Plinian eruption at Fuji volcano (arc volcano along the subduction front of Japan), was preceded by a gigantic megathrust earthquake M_w=8.7 (Hoei earthquake in 1707), 49 days before[2]. In the extension zone of Iceland, Grimsvötn volcano erupted in 1996, preceded by an earthquake M_s=5.4 less than one day before[3]. In the case of a hot spot volcano, the M_w=7.7 Kalapana earthquake (Hawaii) in 1975 promoted rift-zone intrusions in Kilauea volcano and consenquently unleashed the 1977 eruption[4]. Understanding tectonic earthquake as the movement related to a fault in the crust, it releases tectonic stress and generates elastic waves.

The changes in volcanic activity can be observed after an increase in seismicity at a short distance to the epicenter (< 100 km), or at long distances (> 500 km)[5–8]. Other manifestations related to seismic events observed at volcanoes include variations in deformation rate[5,9,10], degassing and heat flux[11–13] and phreatic activity[14–17].

Some examples suggested that the reaction of volcanoes after a tectonic earthquake can be on the short term, such as hours or days after the earthquake[18]. These reactions are assumed to be triggered by the dynamic stress caused by the seismic waves transmitted through the volcanic system[5,8,14].

Other studies discussed that volcanoes could erupt in medium to long term (e.g. such as months, some years or even decades) after the earthquakes[5,7, 19–21]. These longer reaction times can be explained (1) by the co-seismic pressure change in the stress field around the volcano or in the magma system, called static stress[5–7] and/or (2) in the case of giant megathrust earthquakes in convergent tectonic systems, by the viscoelastic relaxation of the mantle and its effect on the magmatic system. An example of these long reaction times is the increase in the number of eruptions per year in the Cascades (western North America), for a period of more than one century after the M_w=9.0 giant earthquake of 1700 AD that occurred in the same region[5]. Recently, some studies have suggested that giant earthquakes can create the subsidence instigating the horizontal movement of magma bodies, such as for the M_w=8.8 Maule (Chile) and M_w=9.0 Tohoku (Japan) earthquakes in 2010 and 2011, respectively[9,10].

Nevertheless, it is not clear why some volcanoes change their behavior after a tectonic earthquake, although the majority of them do not. Recent research has proposed that the earthquake alone is not enough to trigger an eruption, if the magmatic system is not ready to erupt[6,22,23].

This study investigates if the rather unique occurrence of three major earthquakes in Central America, generated by the subduction of Cocos plate beneath Caribbean plate, in a time span of only 72 days in 2012 (August 27, El Salvador, M_w=7.3; September 5, Costa Rica, M_w=7.6; November 11, Guatemala, M_w=7.4) affected the state of unrest or eruption of the volcanoes in the region. We here conduct a statistical analyses (Monte Carlo approach[24]), and numerical modeling of the stress regime of selected volcanoes that erupted after this series of earthquakes, and demonstrate that only those that were in a clear state of unrest before the arrival of the seismic waves erupted.

Tectonic earthquakes and volcanic activity in Central America

This study focusses on Central America, a region with the necessary “ingredients” for our purpose: large earthquakes and dozens of active volcanoes. The historical record of earthquakes and volcanic eruptions are available since 1528 and 1524, respectively. However, this historical information available is inconsistent regarding location and magnitude of the earthquakes, and incomplete in the number of volcanic eruptions, which inhibits sound statistical analyses.

Nevertheless, for the last two decades, the available data set for the region is complete because each country (Guatemala, El Salvador, Nicaragua and Costa Rica) have their own seismic and volcano observatory agencies and offices of Civil Protection. Globally, seismic and volcanism programs and data bases are available, and social networks and news share information quickly. With this in mind, our study is anchored on 2012, when three large earthquakes of magnitudes M_w=7.3 (August 27), M_w=7.6 (September 5), and M_w=7.4 (November 11) struck El Salvador, Costa Rica, and Guatemala, respectively, within a period of only 10 weeks (Fig. 1). After the first two earthquakes, some volcanoes resumed volcanic unrest (Fig. 1). In particular, the San Cristóbal (Nicaragua) and Fuego (Guatemala) volcanoes had large eruptions a few days after the two events, causing the evacuation of some population around these volcanoes. Both eruptions generated pyroclastic density currents (PDC) that burned vegetation and livestock[25]. Other volcanoes that already were erupting, such as Santa María and Fuego, the number of eruptions and explosivity increased after the 2012 earthquakes. Notably, the number of paroxysmal explosions in Fuego increased drastically after the 2012 earthquakes (21 paroxysmal event between 1999–2012 to more than 55 paroxysmal eruptions in a period 2012-2018[26,27]).

In the following years, other volcanoes increased their level of unrest, or included events that culminated into large volcanic eruptions (Telica, Rincón de la Vieja, Poás, Turrialba). Some volcanoes, which passed decades of volcanic quiescence, resumed magmatic activity after the earthquake series: San Miguel, Momotombo, Rincón de la Vieja, Poás, and Turrialba erupted after 37, 110, 18, 62 and 148 years of volcanic quiescence, respectively.

The present research aims at explaining whether the three large subduction earthquakes of 2012 promoted the increase of volcanic activity in Central America on the short- and long-term. Here, we considered the earthquake characteristics and the activity of each volcano prior to the earthquake series as key parameters to unravel why some volcanoes erupted, and some others did not.

Results

Increase in volcanic activity after the 2012 earthquakes

In the period from 2000 to 2019, 50 volcanic eruptions with a Volcanic Explosive Index[28] (VEI) ≥ 2 occurred in Central America, of which, 22 volcanic eruptions were before the 2012 three large earthquakes and 28 were after (Fig. 2a; see supplementary material table 5). This observation corresponds to an increment in eruption rate from 1.6 to 4.6 eruptions per year before and after the 2012 earthquakes, respectively (Fig. 2b). From a visual qualitative comparison, the observed change in cumulative eruption rate is unlikely caused by a random process. We hence applied the Monte Carlo simulation[24] to discriminate whether the increase in the number of volcanic eruptions could have been a random process or linked to a cause/effect relationship (see methods). We ran 10,000 random simulations and only 15 of them (or 0.15%) resulted similar to our observed data. Thus, the testing hypothesis can be rejected at standard confidence levels (e.g. 0.01), suggesting that the observed acceleration in the number of volcanic eruptions was not a simple coincidence, instead, reflects a significant change induced by an external factor: the earthquakes occurred exactly at the moment when the curve of the cumulative number of volcanic eruptions changes its slope.

Stress changes caused by the earthquakes

The San Cristóbal and Fuego volcanoes erupted three and nine days after the Costa Rica earthquake, respectively. This quick reaction may be caused by the disturbance in the system prompted by the dynamic stress. We calculated the dynamic stress (σ_D) using the seismic waveform and the static stress differential (σ_{sdiff}), maximum (σ_{smax}) and minimum (σ_{smin}) by each analyzed volcanoes in response to the three large earthquakes (see supplementary material table 1–2 and Fig. 1). The San Cristóbal volcano received σ_D = 0.022 MPa and 0.255 MPa and Fuego volcano σ_D = 0.013 MPa and 0.031 MPa by El Salvador and Costa Rica earthquakes, respectively. In the case of static stress, only the El Salvador earthquake produced more than 1 kPa to San Cristóbal volcano, that had a change of σ_{sdiff} = 2.5 kPa, σ_{smax} = 1.5 kPa and σ_{smin}= -1.2 kPa in the N-S alignment. The static stress produced by Costa Rica earthquake was less than 1 kPa for both earthquakes, this magnitude could be considered a neglected change.

After the August 27, El Salvador earthquake, San Miguel volcano received the maximum dynamic stress (0.16 MPa). This volcano also received the most significant change in the static stress with a σ_{sdiff} = 3 kPa, σ_{smax} = 2 kPa and σ_{smin}= – 2 kPa considering an alignment of 160°. For the September 5, Costa Rica earthquake, Rincón de la Vieja volcano was subjected to 1.25 MPa of dynamic stress. By Costa Rica earthquake, Rincón de la Vieja had the largest change in static stress regime with a σ_{diff} = 55 kPa, σ_{smax} = 40 kPa σ_{smin}= -15 kPa, with W-E alignment. Santa María volcano, instead, underwent a maximum σ_D = 0.39 MPa produced by the November 11, Guatemala earthquake. The earthquake caused the largest change in static stress, with a σ_{sdiff} = 0.1 MPa, σ_{smax} = 80 kPa and $\sigma_{smin=}$ -30 kPa, and an alignment of 60°.

Discussions And Conclusions

Volcanic eruptions in 2000–2019

As demonstrated in Fig. 2a-b, after the 2012 earthquakes, the number of volcanic eruptions effectively increased along the Central American Volcanic Arc (CAVA hereafter). Some volcanoes increased the number of eruptions and explosivity compared with previous years (Santa Marían and Fuego), while others began to erupt such as San Miguel, Momotombo, Rincón de la Vieja, Poás and Turrialba. The eruption rate increased by a factor of 2.88. Similar trend was also observed after the M_w=9.3 Andaman-Sumatra earthquake (December 24, 2004), with an increment of four times in the eruption rate in the same region[20]. However, after the 2012 Central America earthquakes, the volcanic eruptions after occurred diachronously: some shortly after (days), and some months to years after the earthquakes. Moreover, we cannot recognize a migration of the volcanic eruption based on the location and time.

Earthquakes characteristics

The three large earthquakes occurred within ten weeks, almost equidistant from each other (420–450 km), but at different hypocenter depths (Fig. 3). The hypocenter depth of El Salvador earthquake (August 27, week – 1, M_w=7.3) was 11.8 km and had low high-frequency (HF) energy radiation and a long period, which are classical characteristics of “tsunamogenic earthquakes”[29–33]. Nine days later, the Costa Rica earthquake (September 5, week 0, M_w=7.6) struck with a moderate HF energy radiation and with a hypocenter depth of 15.8 km[30,32,33]. The Guatemala earthquake hypocenter depth (November 7; week 9;

M_w=7.4) was 24 km, where conditionally stable areas surround small patchy in the slab that, at failure, produce moderate slip and high HF radiation[30,32,33].

The spectra of the El Salvador and Costa Rica earthquakes range from 0.07 to 1.2 Hz, with a frequency domain between 0.07–0.1 Hz in broadband stations. It is important to consider both, the resonance frequency of the fluids[34] (i.e. magma, gas, vapour, or liquid) as well of the volcanic edifice[35], to evaluate if Fuego and San Cristóbal volcanoes could enter in resonance and squeeze out the magma after crack opening. We calculated a resonance frequency of a theoretical fluid (magma) filled conduit as a dyke (f_{rd}) with a hypothetical width of 100 m and 10 m is 0.09 and 0.28 Hz, respectively. The resonance frequency of the volcanic edifices calculated (f_{rv}) for Fuego volcano is around 0.16 Hz and for San Cristóbal volcano is 0.27 Hz (more details of these calculation in the supplementary material). These resonance frequencies of fluid filled and volcanic edifices of Fuego and San Cristóbal volcanoes are in the or close of the range of the frequency domain of the earthquakes, which means, that it is possible to considered this could be a mechanism that prompted these eruptions.

Dynamic stress is generally considered for time intervals of a few seconds. However, in the El Salvador earthquake case, Telica volcano experienced around of 120 seconds (vs the general 20–50 seconds[12]), of continuous frequency seismicity and, correspondingly, continuous dynamic stress; this can promote the sloshing mechanism in the hydrothermal and/or magmatic plumbing system[34,36].

In addition, sloshing depends on the viscosity[34,36], considering a higher viscosity for silicic magmas with respect to mafic magmas. For San Cristóbal and Fuego volcanoes, the predominant magmas in recent eruptions are basaltic-andesitic, which means that the overpressure needed to trigger an eruption is lower than for dacitic/rhyolitic magmas.

Volcanic eruptions shortly after the earthquakes

On September 8 and 13, the San Cristóbal (VEI = 2) and Fuego (VEI = 3) volcanoes had paroxysmal eruption, respectively. To evaluate if these eruption were possibly triggered by the earthquakes, we calculated a lithostatic pressure in the reservoir[22], of 98 MPa (4000 m magma chamber depth) and 73.5 MPa (3000 m magma chamber depth), respectively (see supplementary material). The total change in the pressure by σ_D of the Costa Rica earthquake was < 0.26% for San Cristóbal, and 0.02% for Fuego of the lithostatic pressure. This estimate implies that the earthquake itself could not have triggered the eruptions. Nevertheless, the disturbance in the stress regime created by the earthquake could have favored other mechanisms (such as rectified diffusion, bubble growing, increment the gas dissolved, magma migration, etc[5,14,23,37]) to facilitate the eruptions. Regarding the role of static stress the respective alignment system could be crucial[38]. In the case of San Cristóbal, the σ_{sdiff} = 2.5 kPa, located around the zone of high and low rigidity, i.e. the contact between the country-rock and magma chamber boundary (3000 m depth), respectively (more details in the methodology and supplementary material table 3–4). The σ_{sdiff} is hence a potential parameter to predict crack opening and could have induced crack propagation and consequent fluid migration. Contrarily to San Cristóbal, the static stress of Fuego volcano was less than 1 kPa, arguably too low to create crack opening and fluid migration. Nevertheless, some studies suggest that a change in stress of a few kPa can trigger volcanic eruptions, such as for Etna and Stromboli (both in Italy)[39,40], and Merapi (in Indonesia)[41], three of the world's most frequently erupting volcanoes. In the case of the 2006 Merapi eruption, geological evidence shows that the preceding December 24, 2004 Andaman-Sumatra earthquake added xenoliths from the carbonate basement to the magma chamber, causing an internal pressure increase generated by CO_2, before eventually culminating in an eruption[42].

Volcanic eruptions long after the earthquakes

For the August 27, El Salvador earthquake, the static stress applied was low, in the order of ± 2 kPa in three volcanoes (San Miguel, San Cristóbal and Telica). In the case of the September 5, Costa Rica earthquake, the σ_{sdiff} was from 5 kPa for Turrialba to 55 kPa for Rincón de la Vieja. The σ_{sdiff} in the November 11, Guatemala earthquake was from 12 kPa for Pacaya to 0.1 MPa for Santa María. The static stress in Karymsky volcano (in Kamchatka, Russia), produced by a tectonic earthquake (M_w=7.1) promoting a dyke intrusion and triggering the 1996 eruption, was 0.2 MPa[39], which means that it is difficult to explain with our results that only static stress could have opened cracks and generated a dyke intrusion. Quantifying the stress regime around each single volcano is a necessary constraint to determine whether the static stress reduces or increases the country-rock strength. An example of how the static stress changes according to the different alignment is provided by Rincón de la Vieja volcano; this stress regime had at least three directions (N-S, W-E and 45°). The largest σ_{sdiff} (55 kPa) occurred in the deepest part of the magma chamber with a W-E alignment. This differential in the pressure could cause magma rise towards the shallow reservoir, creating an overpressure, and superheating of the shallow magma chamber.

The possible response of volcanoes on the long term (months to years) to the earthquakes depend on the degree of the critical stage of each volcano, explaining why some volcanoes that received more stress (dynamic and static) than others responded later, or not at all. For example, Rincón de la Vieja and Poás volcanoes erupted in 2017, and received more stress change compared to Turrialba volcano that already erupted in 2014. Volcanic processes, such as magma migration from the mantle to the crust or magma mixing, can occur on various time scales, from months to years to even centuries[43,44]. In addition, the presence of a mush zone, of which part of it could be an eruptable melt at crustal depth, a seismic event or some other processes, like the addition of a mafic melt can trigger eruptions years after (e.g. the deadly phreatic eruption of Ontake volcano in 2014[45]).

Another hypothesis in favor of the increase in the number of eruptions years after the earthquakes, is the post-seismic activity in Central America. The region is well known for the occurrence of post-seismic slow slip earthquakes, as also manifested for the El Salvador and Costa Rica 2012 earthquakes[46,47]. An example is provided by San Miguel volcano, which erupted in December 2013, after 37 years of quiescence. According to GPS data, the horizontal displacement by co-seismic slip at San Miguel was around 1.2 cm[46]. Nevertheless, almost one year after the three earthquakes, the horizontal displacement was 2 cm by post-seismic slip[46].

Some of the 19 studied volcanoes were already erupting prior to the 2012 earthquakes, but the number of eruptions increased after the earthquakes. For Poás volcano, the number of eruptions and the magnitude of phreatic explosions increased after the January 8, 2009 Cinchona earthquake[15–17], a M_w=6.2 tectonic event with an epicenter 10 km from Poás and also after 2012 earthquakes. On April 10, 2014, a M_w=6.1 tectonic earthquake hit near Momotombo volcano (Nicaragua), triggered seismic swarms[48] and resumed explosive activity in December 2015. The most impressive change in the increase in the number of eruptions occurred at Fuego volcano. In three years (2015–2018), 50 paroxysmal eruptions occurred, including the deadly eruption of June 3, 2018, while between 1999 to 2012, Fuego volcano generated 21 paroxysmal eruptions[27] (Note: the Fuego eruption is still ongoing, but the most recent data are not included in this study).

Volcanic unrest 2007–2012

The change in volcanic activity beyond background behavior to worrisome levels (i.e. volcanic unrest) sometimes escalates into volcanic eruptions or triggers other hazardous events[49–52]. This research classified the information available on volcanic activity in three different "degrees of unrest", based on the energy release of volcanoes[53] from lowest (unrest 1), to intermediate (unrest 2) to the highest (unrest 3) degree. Each degree of unrest means: *Unrest 1* = increase in the seismicity of the volcanic system (green color in the Fig. 4); *Unrest 2* = increase in the temperature, deformation, degassing, phreatic activity, or small explosions (yellow color in the Fig. 4); *Unrest 3* = occurrence of large eruptions with considerable ashfall, explosions with ballistics and paroxysmal events (red color in the Fig. 4). Between September 2007 and September 2017, 19 volcanoes in the CAVA showed signs of unrest before and/or after the earthquakes of 2012 (Figs. 1 and 4). Before the 2012 earthquakes, 13 volcanoes were in a state of unrest (Santa María, Pacaya, Fuego, San Miguel, San Cristóbal, Telica, Momotombo, Masaya, Concepción, Rincón de la Vieja, Arenal, Poás and Turrialba; Fig. 4), and among these Santa María, Fuego, Pacaya, San Cristóbal, Telica, Masaya, Concepción, and Arenal were erupting. After the earthquakes and until 2017, Concepción, and Arenal ceased their eruptions. Concepción volcano had a phreatomagmatic event in May 2011[25,54]. The magnitude of the explosions in Arenal volcano was in a constant decrease since 2007[25], and the last explosion occurred in October 2010. After the 2012 earthquakes, these volcanoes decreased their level of unrest to 1 or 2 (Fig. 4). A possible reason why these volcanoes did not erupt after the 2012 earthquakes could lie on the fact that the magma volume erupted in the previous eruptions already released its internal pressure and both volcanoes are close-conduit system. The other volcanoes in eruption prior to September 2012, Santa María, Fuego, Pacaya, San Cristóbal, Telica and Masaya, are very active open-conduit systems and/or are in permanent unrest, for which internal pressure constantly reaches the threshold to trigger eruptions.

Some of the other volcanoes experienced decades without magmatic eruptions, but they already had unrest degrees of 1 and 2 (San Miguel, Momotombo, Rincón de la Vieja, Poás and Turrialba; Figs. 1 and

4) prior to the 2012 earthquakes. From the 19 volcanoes in a state of unrest in the period 2007–2017, eleven volcanoes erupted after the 2012 earthquakes and these were already in unrest before the 2012 earthquakes. A question to pose is why the other eight did not erupt? Different answers can be suggested (Fig. 4): 1) two of them had already released their energy upon large eruptions or prolonged periods, as explained before (Concepción and Arenal). 2) five volcanoes that previously did not show any sign of unrest switched into unrest only after the Costa Rica earthquake occurred (Apoyeque, Miravalles, Tenorio, Platanar and Irazú; Fig. 4). Among the latter five, only one volcano had erupted in historical times (Irazú, 1963–1965), while the other four are far from the recurrence period for a potential new eruption. These five volcanoes only showed unrest degree 1 (increased seismicity) some hours or a few days after the Costa Rica earthquake. This response can be linked to the dynamic stress that triggered some seismic swarms in the fault systems around these volcanoes[6,8,55]. 3) One volcano (Cerro Negro) had large explosions in August 1999, and unrest degree 1 was reached on June 4, 2013. All nine volcanoes showed evidence that the earthquakes themselves were insufficient to trigger volcanic eruptions, despite the fact that the earthquakes caused an increase in the degree of unrest for some of them. However, the same seismic energy transmitted to other volcanoes that were already in an advanced state of unrest was able to trigger a new eruption. In consequence, we postulate, according to the data presented and the obtained results, that dormant volcanoes or volcanoes with low activity did not change significantly their state just because of the earthquake's shaking, or the change in the stress field regime. The earthquakes were not able by themselves to bring the volcanoes from equilibrium to eruption.

From our findings stemming from the fortunate occurrence of three subduction tectonic earthquakes in a time span of 10 weeks in an active volcanic arc at Central America, we conclude that the postulated cause/effect relationship between tectonic earthquakes and volcanic eruptions is only valid when volcanoes are already in a high state of unrest prior to the earthquake. The energy supplied by the seismic shock may constitute the additional energy contribution necessary to trigger an eruption in a high stage of pre-eruption volcanic activity. The fact that the volcano may react shortly, or long term after the seismic input, does not seem to depend on the magnitude of the earthquake itself, but on the processes that occurred inside the volcano (type of magma, gas content, viscosity, strength of the hots rock, etc). Other earthquake characteristics in addition to magnitude and location (i.e. energy radiated, frequency, duration, etc) could also play a role on how tectonic earthquakes may contribute to volcanic eruptions. Nevertheless, this external energy supply, regardless of the distance between the earthquake epicenter and the volcano, and the magnitude of the event, is not sufficient to raise the state of a volcano from quiescence directly into eruption. Our results confirm the need to monitor all active volcanoes to know their degree of unrest at any time and hence prior to the next large earthquake, and to establish future scenarios of possible increased volcanic activity, and eventually volcanic eruption on the short (days) or long term (years). This kind of surveillance can be a useful forecasting tool for future eruptions, and will help the Civil Protection offices and decision makers to timely adopt strategies to disaster risk reduction at the regional or local scales.

Methodology

Statistical analysis

The starting observation is that it seems that there is an acceleration in the number of eruptions after the large earthquakes of 2012 (Fig. 2b). Our question is if this distribution can be casual or if it differs significantly from a random distribution of the eruptions in the time. To answer this question we investigated what is a random distribution by using Monte Carlo simulations[24]. We computed the probability that a random distribution has this point with a value below the observed one, i.e. if at the time of the earthquake the number of volcanic eruptions could be lower that the observed 22 value (testing hypothesis). The simulation considered that: a) the number of eruptions from 2000 to 2019: a total of 50 volcanic eruptions occurred in 7305 days (20 years); b) the second of the three earthquakes, the M_w=7.6 Costa Rica earthquake struck on September 5, 2012 (day 4632): at this moment 22 out of 50 volcanic eruptions had already occurred; and c) 28 out of 50 eruptions occurred after the second earthquake (i.e., between day 4632 and 7305). We run 10,000 simulations, following the law of large number and we found that only 0.15% of these simulations satisfies the testing hypothesis. Our results shows that it is likely that the observed acceleration in the number of volcanic eruptions is not due to chance, but instead, it is a significant change induced by the earthquake.

Dynamic stress

The pressure change inside a geological system by the passing of the seismic waves is called dynamic stress (σ_D). This can be calculated using the Eq. (1)[56]:

$$\sigma_D = \frac{PGV * G}{Vph} \qquad (1)$$

where *PGV* is the peak ground velocity of the seismic wave (km/s), *G* is shear modulus with a value of 30 GPa for the region[30] and *Vph* is the velocity phase of the wave (km/s). The dynamic stress considers the maximum peak-to-peak velocity of the waveform (see supplementary material table 1–2 and Fig. 1).

Static stress

The static stress is the change in the local stress field resulting after the earthquake. The software used to calculate the static stress was "Advance FrontSTR", which is based on a finite element method[6,57]. We simulated each magma chamber with spherical shape and with 1000 m of diameter with a rigidity of 1 kPa, the depth location and alignment is based in the publication available, more details are in supplementary material table 3–4.

The calculation of static stress is governed by the equations (2–3):

$$\frac{\partial \sigma_{ij}}{\partial x_j} + f_i = 0 \qquad (2)$$

$$\sigma_{ij} = D\varepsilon_{ij} \quad (3)$$

where σ_{ij} is the stress tensor, and f_i is the external force vector applied, D is the matrix of elastic constants, and ε is the strain.

Volcanic eruptions 2000–2019

We recognized volcanic eruptions in the Central American region with a Volcanic Explosive Index[28] (VEI) ≥ 2, and reported with its day, month, and year of occurrence from January 1, 2000 to December 31, 2019. For phreatic explosions, the lack of volcanic deposits and some confusing reports are usual. That is why this research only considered eruptions with a well-defined VEI, despite the occurrence of phreatic eruptions at some volcanoes in the region (e.g. Poás, Turrialba) during the period of observation.

Volcanic unrest between 2007–2017

This research delimited a period of five years before and five years after the earthquakes[7] to determine whether the earthquakes that occurred in 2012 increased volcanic unrest. The catalog compiled for the states of volcanic unrest of the 19 volcanoes included a weekly report of the Global Volcanism Program (GVP)[25], information from internal reports by the local observatories, scientific papers, and personal data.

Declarations

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Author contributions

G.G. conceived the idea and led the data analysis. G.G., D.R., J.M., and E.F. wrote the manuscript. G.G., E.F., B.S., T.H., G.Chiodini, I.Y., F.L., K.N., J.M. and D.R., worked in the data analysis. G.G., R.M-A., A.M. and G.Chigna, support with the data acquisition. All the authors participated in the discussion and final version of this manuscript.

Competing interest

The authors declare no competing interest.

Data available (Supplementary material)

The authors declare that the data supporting the findings of this study are available within the supplementary information files.

Competing financial interests

The authors declare no competing financial interests.

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Figures

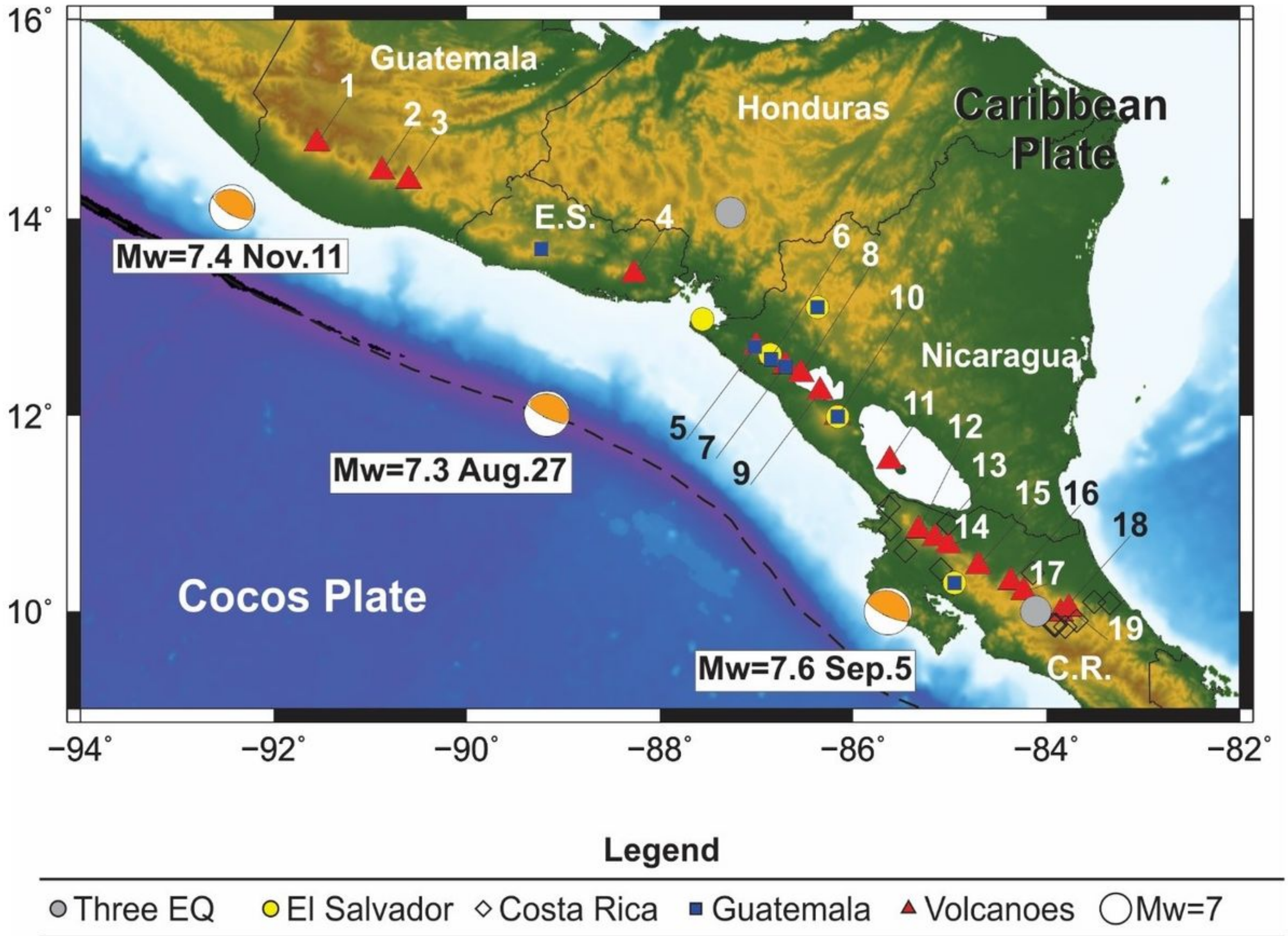

Figure 1

Epicenter of the 2012 earthquakes, volcanoes with unrest, and location of the seismic stations used to obtain the waveform to calculate the dynamic stress of the earthquakes in Central America (more information in the supplementary material). The dashed line corresponds to the Mesoamerican trench along which the Cocos plate subducts below the Caribbean plate. Three EQ (gray circle) indicate stations available for the three earthquakes of 2012 (August 27, El Salvador; September 5, Costa Rica; November 11, Guatemala). Yellow circle, black diamond, and blue square are seismic stations used for the El Salvador, Costa Rica, and Guatemala earth-quakes, respectively. Orange/white circle are the focal mechanism of each earthquake from Global CMT. The volcanoes analyzed in this study are: 1. Santa María, 2. Fuego, 3. Pacaya, 4. San Miguel, 5. San Cristóbal, 6. Telica, 7. Cerro Negro, 8. Momotombo, 9. Apoyeque, 10. Ma-saya, 11. Concepción, 12. Rincón de la Vieja, 13. Miravalles, 14. Tenorio, 15. Arenal, 16. Pla-tanar, 17. Poás, 18. Irazú and 19. Turrialba.

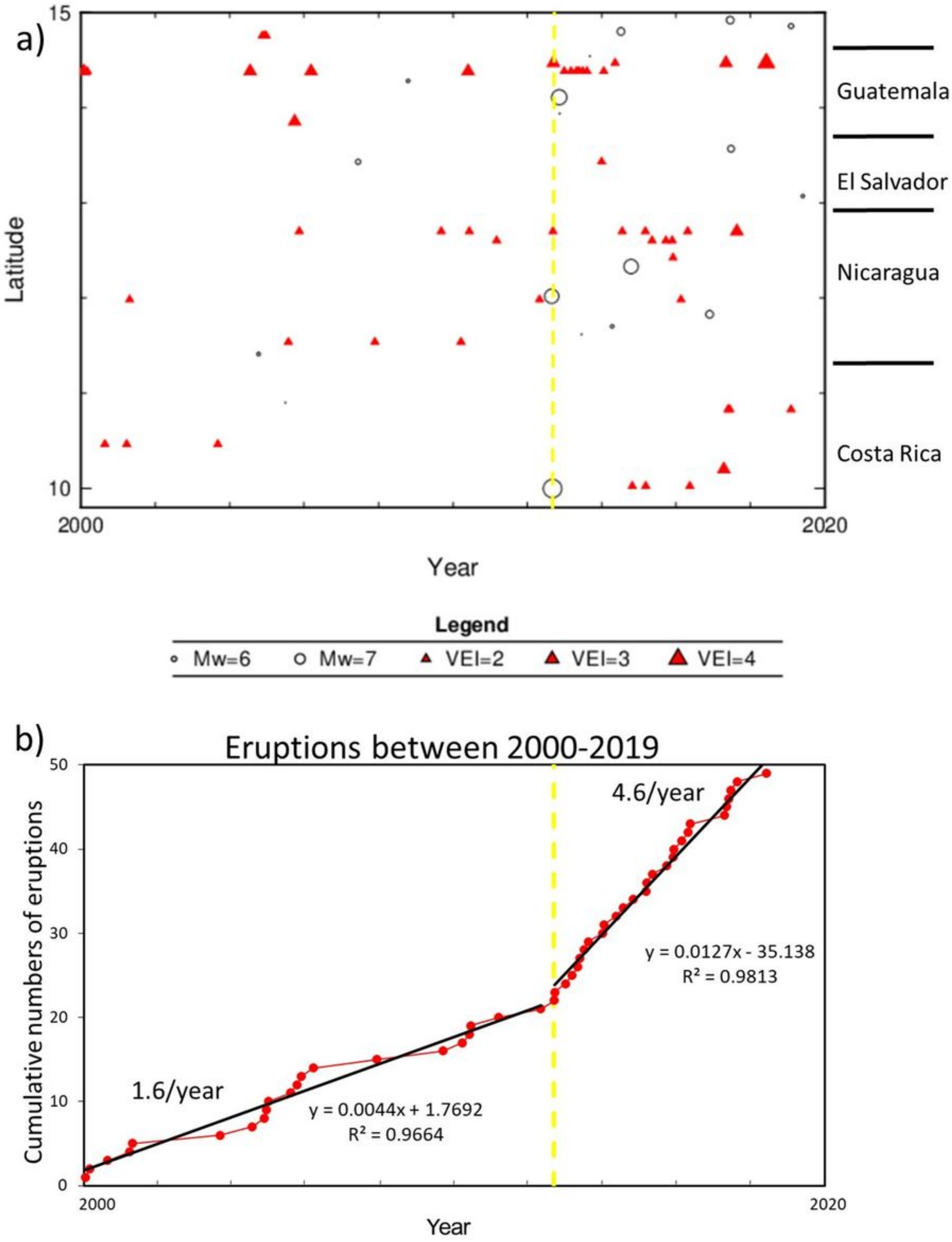

Figure 2

Volcanic eruptions in Central America during the period 2000-2019 (for reference see supple-mentary material table 5). a) Volcanic eruptions by size and locations in Central America. b) The cumulative number of volcanic eruptions showing the increase in eruption rate increase after the 2012 earthquakes. The yellow dashed lines correspond to the Costa Rica earthquake on Sep-tember 5, 2012.

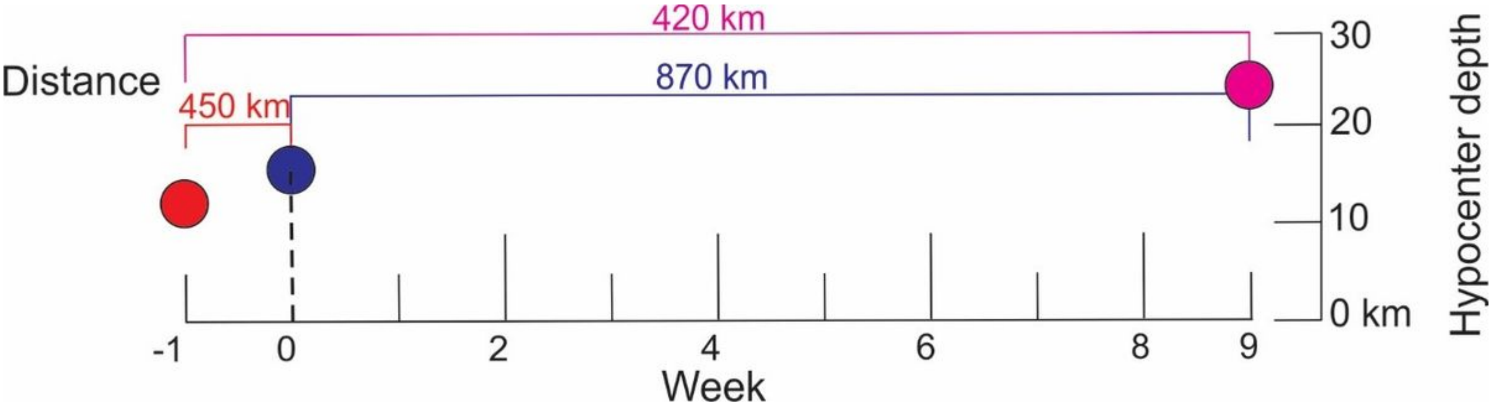

Figure 3

Distance, hypocenter depth and time occurrence of 2012 earthquakes in El Salvador (red), Costa Rica (blue) and Guatemala (cyan).

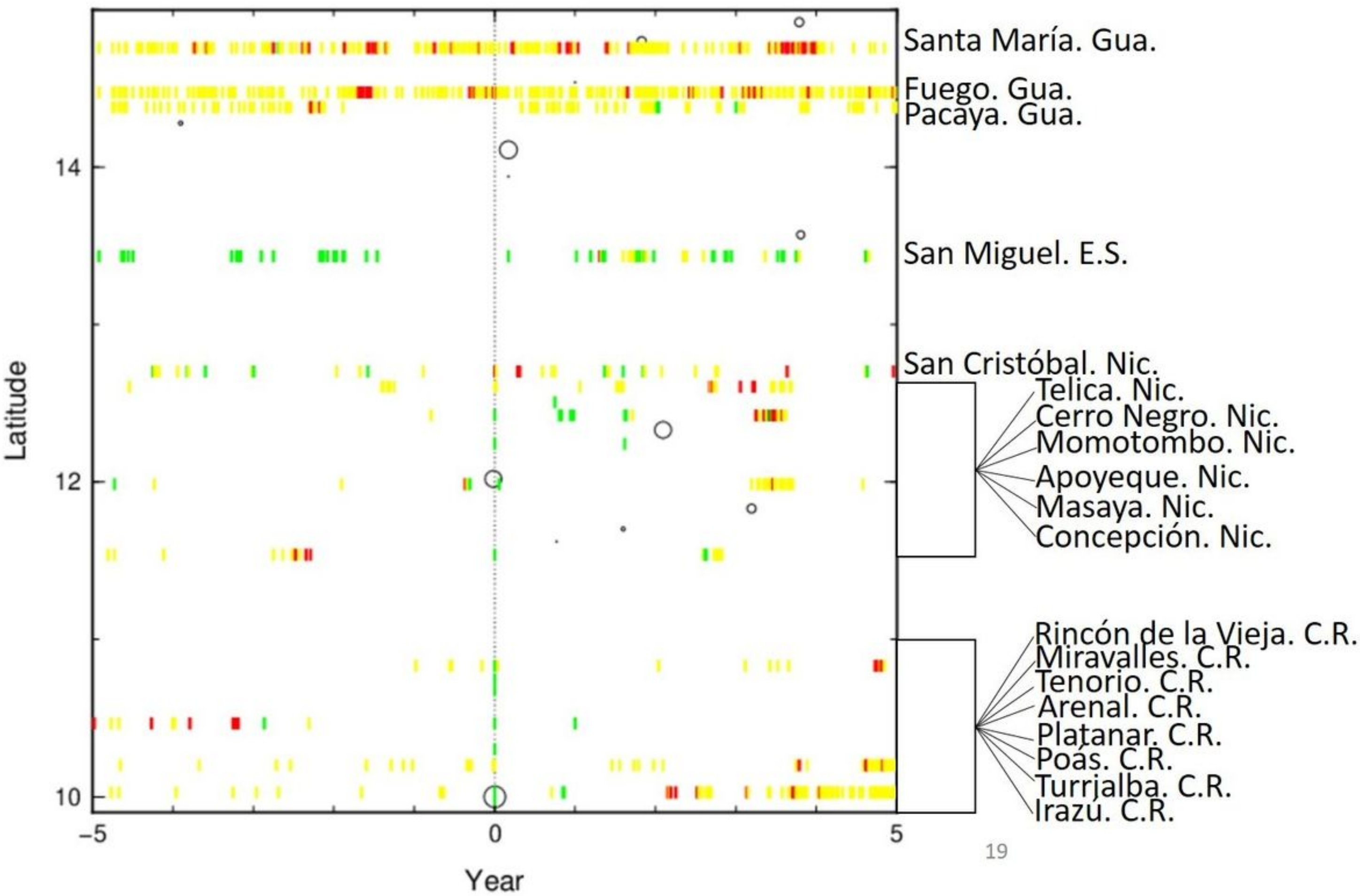

Figure 4

Volcanic unrest and earthquakes from 2007 (-5) to 2017 (5). Dotted line (0) corresponds to the Costa Rica earthquake on September 5, 2012. The green color represents the increase in the seismicity of the volcanic system. The yellow color means increasing in the temperature, de-formation, degassing, phreatic activity, or number of small explosions. The red color is related with the occurrence of large eruptions with considerable ashfall, explosions with ballistics and paroxysmal events.

Supplementary Files

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