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A NEW PATHWAY TO UNTANGLE THE QUESTION: WAS THE VOLCANIC ERUPTION TRIGGERED BY THE EARTHQUAKE?

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ABSTRACT

The relationship between tectonic earthquakes and volcanoes is one of the most striking, but yet less well-understood topics in earth sciences, due to the lack of observational data. When this interaction occurs, volcanoes may react in the short term (hours to days) to long term (months to decades), causing an eruption, which suggests that what happens inside the volcano to trigger this new eruption needs time. In 2012, three large earthquakes struck Central America, and some volcanoes erupted days after, while others took erupted months to years after the earthquakes to enter into an eruption. This poses to the question: was the eruption triggered by the earthquakes? Here I show that the large earthquakes contributed to the increment in the number of volcanic eruptions in the region. I found that only volcanoes were already undergoing a certain degree of unrest and without large eruptions previous to the large tectonic earthquakes erupted, thus suggesting that the volcanoes were nearly ready to erupt and that the earthquakes helped, but not necessarily caused the volcanic eruptions. The present research can become a tool for forecasting volcanic activity when a large earthquake hits a region if the volcanic activity is previously well monitored and to communicate and prepare the population and to reduce the volcanic risk if the protocols are well established.

Keywords: Earthquake and volcano interaction, volcanic eruptions, volcanic unrest, stress, Monte Carlo method.

1. 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 can be the result of the lack of observational data and/or clear scientific evidence that relates both processes. Darwin (1838), 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 during the subsequent months. Some studies suggested that the reaction of volcanoes after a tectonic earthquake can be on the short term, such as hours or days after the earthquake (Linde and Sacks, 1998; Manga and Brodsky, 2006) or the medium-long term, such as months or some years or even decades after the earthquakes (Hill et al., 2002; Walter and Amelung, 2007).

Recently, in 2012, three large earthquakes of magnitudes Mw=7.3 (August 27), Mw=7.6 (September 5), and Mw=7.4 (November 11) struck El Salvador, Costa Rica, and Guatemala, respectively, occurred within a period of only 72 days (Figure 1). After the first two earthquakes, some

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volcanoes resumed volcanic unrest (Figure 1). Two volcanoes (San Cristóbal and Fuego) had large explosions a few days after the first two earthquakes. Years later, other volcanoes changed their behavior; some entering in a state of unrest to eventually escalate into large volcanic eruptions (i.e. San Miguel, Telica, Momotombo, Rincón de la Vieja, Poás, Turrialba volcanoes). With this perspective in mind, the present research tries to explain whether the three megathrust earthquakes of 2012 promoted the increment of the volcanic activity in Central America on the short- and long-term.

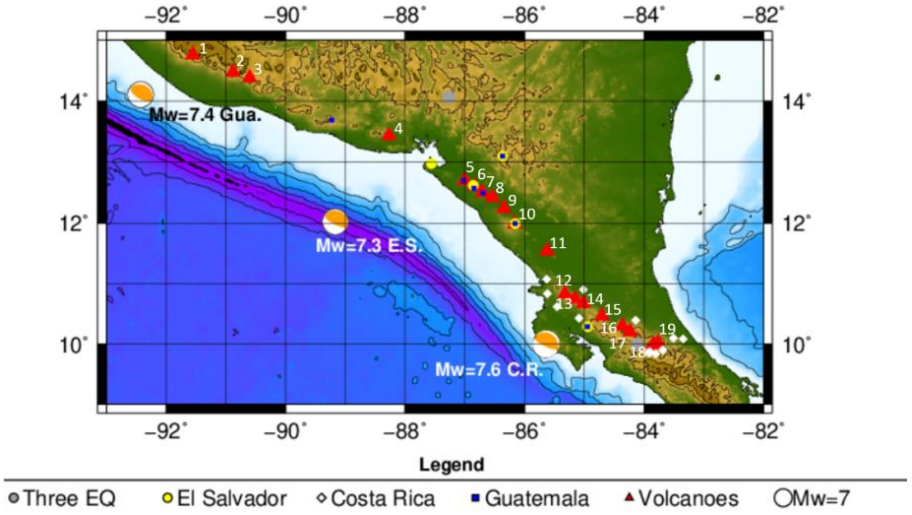

Figure 1. The epicenter of the earthquakes, volcanoes with unrest and location of the seismic stations used to obtain the waveform to calculate the dynamic stress of the 2012 three large earthquakes in Central America. The legend: Three EQ (gray circle) indicate stations available for the three earthquakes. Yellow circle, white diamond, and blue square are seismic stations used for the El Salvador, Costa Rica, and Guatemala earthquakes, respectively. The volcanoes analyzed here are: 1. Santa María, 2. Fuego, 3. Pacaya, 4. San Miguel, 5. San Cristóbal, 6. Telica, 7. Cerro Negro, 8. Momotombo, 9. Apoyeque, 10. Masaya, 11. Concepción, 12. Rincón de la Vieja, 13. Miravalles, 14. Tenorio, 15. Arenal, 16. Platanar, 17. Poás, 18. Irazú and 19 Turrialba.

2. METHODOLOGY

In order to determine why these volcanoes reacted either in a short or in the long term after the large earthquakes of 2012, I have considered the dynamic and static stress related to these tectonic shocks. Also, I applied the Monte Carlo statistical method, as explained below:

2.1 Dynamic stress

The pressure's change by the passing of the seismic waves is called the dynamic stress (σ_D). This can be calculated using the Eq. 1 proposed by Hill et al. (1993):

$$\sigma_D = \frac{PGV * G}{Vph} \tag{1}$$

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 based on Ye et al. (2016), and *Vph* is the velocity phase of the wave (km/s). The dynamic stress considers the maximum peak-to-peak velocity of the waveform.

2.2 Static stress

The static stress is the change in the local stress field after the earthquake. The software used to calculate the static stress was "Advance FrontSTR" and it is based on a finite element method, following the procedure described by Fujita et al. (2014).

The calculation of static stress considers the government equation, Eq. (2) and Eq. (3).

$$\frac{\partial \sigma_{ij}}{\partial x_j} + f_i = 0 \tag{2}$$

$$\sigma_{ij} = D\varepsilon_{ij} \tag{3}$$

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.

2.3 Statistical analysis

After the large megathrust earthquake of 2012, the number of volcanic eruptions in the region increased. To discriminate whether this increase in volcanic eruptions occurred by chance (i.e. temporal coincidence) or not (i.e. cause-effect relationship), I used the Monte Carlo simulation method (Metropolis and Ulam, 1949). To apply the Monte Carlo simulation, it is necessary to consider these following information: a) The number of eruptions from 2000 to 2019: a total of 50 eruptions occurred in 7305 days; b) The Mw=7.6 Costa Rica earthquake struck on day 4632, and at this moment, 22 eruptions had already occurred; c) The analysis yet aims to reveal how many random simulations prior to day 4632 result in 22 eruptions, to reach 50 eruptions in the 2673 days that followed (i.e., 4632-7305). To understand this, and following the law of the large numbers, the number of simulations was 10^4 times.

3. DATA

This research considered the large three tectonic earthquakes that occurred in 2012 in Central America and the volcanic unrest five years before and five years after these earthquakes. Volcanic eruptions with a VEI≥2 (Newhall and Self, 1987) from 2000 to 2019, were selected because the available data set in the region is complete.

3.1 Seismic waveforms of the 2012 earthquakes

In the case of the August 27, 2012 El Salvador earthquake, the first of the three, seven waveforms are available from IRIS (Figure 1). For the September 5, 2012 Costa Rica earthquake, two waveforms from IRIS and 16 accelerometer data from LIS-UCR are available (Figure 1). In the case of the November 11, 2012 Guatemala earthquake, nine waveforms are available from IRIS (Figure 1). In the case of IRIS data, usually broadband seismic signals are available.

3.2 Fault parameter of the 2012 earthquakes

To calculate the static stress it is necessary to set the fault parameters of each earthquake. The references used were the information published by USGS and Ye et al. (2016).

3.3 Volcanic unrest between 2007- 2017

This research delimitated a period of five years before and five years after the earthquakes to understand if the earthquakes that occurred in 2012 affected the volcanic activity, similar to the approach by Nishimura (2017). The catalog compiled included a weekly report of the Global Volcanism Program, information from internal reports from the local observatories, scientific papers, and personal data. This research classified the information available on volcanic activity in three different "degrees of unrest", based on the energy release of volcanoes from least (unrest 1), to intermediate (unrest 2) to the highest (unrest 3) degree, as discussed by Yokoyama et al. (1992). Each degree of unrest means: *Unrest 1*= increase in the seismicity of the volcanic system; *Unrest 2*= Increase in the temperature, deformation, degassing, phreatic activity, or small eruptions; *Unrest 3*= Large explosions with considerable ashfall/explosion with ballistic and paroxysmal events.

4. RESULTS AND DISCUSSION

4.1 Increasing the number of volcanic eruptions after the 2012 earthquakes

In the period from 2000 to 2019, 50 volcanic eruptions occurred, of which, 22 eruptions (in approximately 12 years) were before the 2012 three large earthquakes in Central America, and 28

volcanic eruptions were after (in approximately 7 years). The increment rate was from 1.6 to 4.6 eruptions (three times more) per year before and after the 2012 earthquakes, respectively (Figure 2). From a visual qualitative comparison, it seems that the observed cumulative change in eruption rate is unlikely caused by a random process. In particular, at the time of the earthquake, the observed curve has a value lower than most of the simulated ones: this is when the curve changes its slope. In this case, I applied the Monte Carlo simulation to discriminate if the increment in the number of volcanic eruptions is by chance or not. I ran 10,000 random simulations, and only 15 simulations are the same or equal to our observed data, which means 0.15%. This 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.

4.2 Dynamic and static stress

The volcanoes San Cristóbal and Fuego erupted three and nine days after the Costa Rica earthquake, respectively. This quick reaction could be by the disturbance in the system promoted by the dynamic stress. The El Salvador earthquake (Mw=7.3) had low high-frequency energy radiation and a long period; this could have induced resonance and sloshing at the volcanoes internal system (Namiki et al., 2018). After, the Costa Rica earthquake (Mw=7.6) struck with a moderately high-frequency energy radiation. Both earthquakes could have disturbed these volcanoes in the short term.

The Costa Rica earthquake produced the largest stress change. Rincón de la Vieja volcano received 1.25 MPa of σ_D and 50 kPa of differential static stress (σ_{diff}). However, I found that the σ_{diff} increased depending on the alignment system. For example, the W-E alignment direction received more σ_{diff} compare with the N-S alignment direction. Also, the static stress increased drastically close to the zone between the high and low rigidity, which means, the country-rock and magma chamber, respectively. In the case of San Cristóbal volcano, σ_{diff} of 2 kPa occurred in the upper and lower part of the magma chamber, which could have induced cracks propagation.

4.3 Volcanic unrest 2007-2012

The change in the volcanic behavior (volcanic unrest) sometimes escalates into volcanic eruptions, but sometimes can trigger other hazardous events (Phillipson et al., 2013). This research considered the volcanic unrest of the Central American region from September 2007 to September 2017. The volcanic unrest is divided into three degrees according to the energy release (Yokoyama et al. 1992).

In this period analyzed, 19 volcanoes were showing signs of unrest before and/or after the earthquakes of 2012 (Figures 1 and 3). Before the earthquakes of 2012, 13 volcanoes were in unrest (Santa María, Pacaya, Fuego, San Miguel, San Cristóbal, Telica, Momotombo, Masaya, Concepción, Rincón de la Vieja, Arenal, Poás and Turrialba; Figure 3) and from these, the volcanoes Santa María, Fuego, Pacaya, Masaya, Concepción, and Arenal were erupting. After the earthquakes until 2017, the volcanoes Pacaya, Concepción, and Arenal did not erupt. In the case of the Pacaya volcano, a large eruption occurred in May 2010. Concepción volcano erupted in May 2011. The magnitude of the volcanic eruptions in Arenal volcano was in a constant decrease, and the last explosion was in October 2010. After the earthquakes of 2012, these volcanoes showed unrest degrees 1 and 2. A possible reason that these volcanoes did not erupt after 2012 earthquakes is that the magma volume erupted in the previous eruptions already released the internal pressure. In the opposite case, as Santa María and Fuego volcanoes are very active and open systems, for which internal pressure constantly reaches the threshold and triggers explosions.

Other volcanoes had decades without magmatic eruption, but before the earthquakes, they were already in unrest degrees 1 and 2 (San Miguel, Momotombo, Rincón de la Vieja, Poás and Turrialba; Figure 1 and 3). From the 19 volcanoes in a state of unrest in the period of 2007-2017, 10 volcanoes erupted after 2012 earthquakes. These 10 volcanoes were already in unrest before the 2012 earthquakes. A question to pose is why the other nine did not erupt. Different answers can be given (Figure 3): 1) Three of them had large explosions, as explained before (Pacaya, Concepción, and Arenal). 2) Five

volcanoes reacted only when the earthquakes occurred, which means that previously they did not show any unrest (Apoyeque, Miravalles, Tenorio, Platanar and Irazú; Figure 2). From these, only one had eruptions in historical times (Irazú), and maybe, the other four are far from the recurrence period of new eruptions. 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. 3) One volcano (Cerro Negro) had large explosions in August 1999, and the unrest degree 1 was reached on June 4, 2013. These nine volcanoes showed evidence that the earthquake itself cannot trigger volcanic eruptions, but the earthquakes can promote eruptions by different mechanism only in volcanoes that are already in a state of unrest; this also implies that dormant volcanoes or volcanoes with low activity cannot erupt just for the earthquake's shaking/sake, or the change in the stress regime caused by the earthquake.

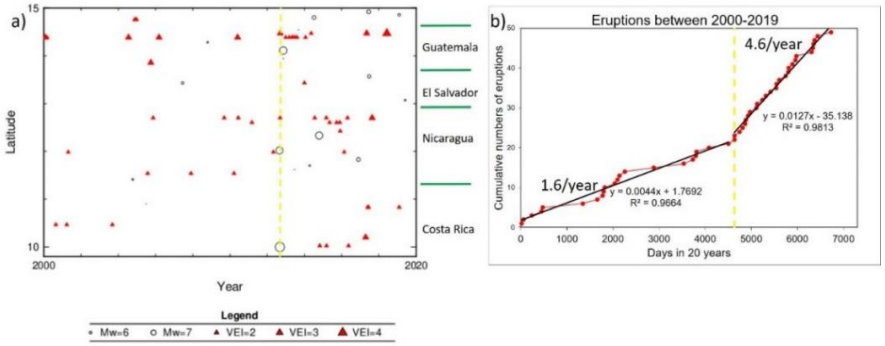

Figure 2. Volcanic eruptions in Central America during the period 2000-2019. a) Eruptions by size and locations in Central America. b) The cumulative number of eruptions and the eruption rate increase after the 2012 earthquakes. The yellow dotted lines correspond to the Costa Rica earthquake on September 5, 2012.

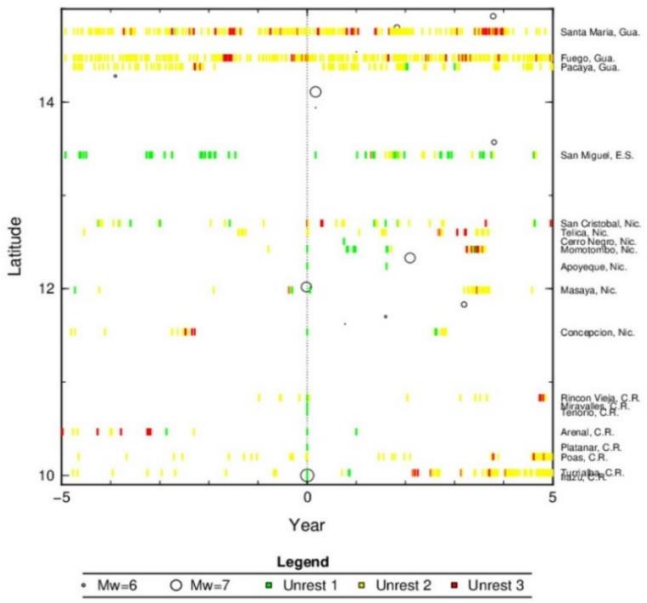

Figure 3. Volcanic unrest and earthquakes from 2007 (-5) to 2017 (5). Dot line (0) corresponds to the Costa Rica earthquake on September 5, 2012.

5. RECOMMENDATION

This study showed the necessity of monitoring all volcanoes to know the degree of unrest prior to the next large earthquake, to establish future scenarios of increment of volcanic activity and eventually volcanic eruption on the short (days) or long term (years) considering the previous state of unrest,

earthquake characteristics and geological history. This kind of surveillance can be a useful forecasting tool of volcanic unrest to prepare the Civil Protection office, local government, and the Central Government to take decisions to reduce the risk at different scales. However, it is important to work quickly with the most vulnerable populations that usually live close to the volcanoes and do not have enough information or time to prepare before the next volcanic eruption. At the date of submission of this synopsis, August 24, 2020, an Mw=6.0 struck Costa Rica and 10 min after, Rincón de la Vieja volcano located 165 km far from the epicenter, erupted. The previous days, the volcano was in unrest; this can be a possible case of earthquake and volcano interaction.

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