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Revisiting short-term earthquake triggered volcanism

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Abstract

It has been noted for centuries that earthquakes appear to trigger the eruption of volcanoes. For example, analyses of global volcanic and seismic records since 1500 AD have shown that explosive eruptions with Volcanic Explosivity Index (VEI) values ≥2 are preceded within days by nearby major earthquakes (magnitude M8 or larger) about 4 times more often than expected due to coincidence, suggesting that large earthquakes can trigger eruptions. We expand the definition of a triggered eruption to include the possibility of M6 or greater earthquakes within 5 days and 800 km of a VEI 2 or greater eruption. Removing pre-1964 records, to ensure complete and accurate catalogs, we find 30 volcanoes that at some point experienced a potentially triggered eruption and define these volcanoes as “sensitive” volcanoes. Within this group of sensitive volcanoes, normalized distributions of volcano-centric factors such as tectonic setting, dominant rock type, and type of volcano are practically indistinguishable from those of sensitive volcanoes in which the time of eruption is randomized. Comparisons of sensitive volcanoes and insensitive volcanoes (i.e., volcanoes that have never experienced a triggered eruption) reveal that sensitive volcanoes are simply more active than insensitive volcanoes: They erupt more frequently, are located solely in subduction zones, and erupt primarily andesites and basaltic-andesites. The potentially triggered eruptions do not show the magnitude-distance relationship expected for seismically induced responses (e.g., hydrologic responses), and eruptions that do occur within days of nearby earthquakes do so within rates expected by random chance. There is, however, a 5–12% increase in the number of explosive eruptions in the 2 months to 2 years following major earthquakes. We conclude that short-term seismically triggered explosive eruptions occur less frequently than previously inferred, an important conclusion when considering volcanic hazards and for understanding the nature of earthquake-volcano interactions.

Keywords

Earthquake, Eruption, Seismic triggering, Earthquake-volcano interactions, Induced volcanism

Introduction

It has long been proposed that earthquakes may trigger the eruption of volcanoes (Darwin 1840; Yokoyama 1971; Nakamura 1975), dating as far back as Pliny the Younger’s account of the violent tremors that preceded the eruption of Mount Vesuvius in 79 CE (Pliny, circa 106 CE). A connection is not unexpected: Large earthquakes can remotely alter the stress field and induce seismicity or hydrologic responses at distances of many hundreds of kilometers (e.g., Hill et al. 1993; Wang and Manga 2010; Nishimura 2017) and even globally (Velasco et al. 2008; Pollitz et al. 2012), especially in geologically active regions (Langbein et al. 1993). Indeed, there is growing evidence for global increases in volcanic unrest and degassing following earthquakes (Delle Donne et al. 2010; Avouris et al. 2017). Earthquakes can also indirectly trigger eruptions of very proximal volcanoes by mass wasting of their flanks (Lipman et al. 1985).

Linde and Sacks (1998) performed a quantitative assessment by defining a triggered eruption as a VEI 2 or larger eruption that occurred within 5 days and 800 km of a M8 or larger earthquake. They showed that since 1500 AD, these types of eruptions have occurred about 4 times more often than expected by chance. Of the 11 eruptions triggered by M8 or larger earthquakes listed by Linde and Sacks (1998), 7 occurred in Chile and 3 belonged to Villarrica, an andesitic-basaltic stratovolcano in central Chile with an intermittent open vent. This prompts the following questions:

Are some volcanoes more sensitive to triggering than others?

If so, what characteristics of the volcano might make it more sensitive to triggering?

Investigating these relationships is important for two reasons (National Academies 2017): They provide an opportunity to assess whether a volcano is poised to erupt and allow us to understand some of the processes that lead to eruptions.

We find here that modern records indicate that no triggered eruptions occurred within days of $M \geq 9$ earthquakes, even when the earthquakes were located in regions of active volcanism (M9.2 Alaska, 1964; M9.1 Sumatra, 2004; M9.0 Tohoku, 2011). Additionally, when we consider only post-1900 database records, the anomalous increase in eruptions within days of major earthquakes is no longer apparent, suggesting that either short-term triggered volcanism was more prevalent prior to the 1900s or that improved monitoring and careful record keeping has led to a decrease in reported short-term earthquake triggered eruptions.

Background

Earthquake-volcano interactions can be divided into three categories based on how stress is transferred by the earthquake to the volcano (Hill et al. 2002): static stress, quasi-static stress, and dynamic stress. Triggering may also arise from a superposition of these three mechanisms (Sulpizio and Massaro 2017).

In terms of the first mechanism, earthquakes can change the static stress field around volcanoes, leading to one of two scenarios. The first is compression that will push the magma upwards (Feuillet et al. 2011), and the second is extension that will depressurize magma bodies, allowing the exsolution of volatiles (e.g., La Femina et al. 2004; Walter and Amelung 2007; Fujita et al. 2013), and unclamping of magmatic conduits (e.g., Nostro et al. 1998; Walter et al. 2007; Bonali et al. 2013, 2015; Bonini et al. 2016). There may be a delay of weeks to months between the earthquake and the eruption for this type of interaction. This was suggested for the 1991 eruption of Mount Pinatubo that occurred 11 months after a magnitude 7.5 earthquake 185 km away in Luzon (Bautista 1996). An increase in eruption rate was also observed in the Andean volcanic arc for about 12 months following $M > 8$ earthquakes in 1906 and 1960 (Watt et al. 2009).

Quasi-static strains due to viscous relaxation of the crust after very large mega-thrust earthquakes could also lead to long-term regional increases in eruption rates (Hill et al. 2002). Effects from these types of strains may not manifest in volcanism for months or years, and enhanced volcanic activity could last for years or even decades. Notable possible examples include a peak of volcanic activity in the Cascadia subduction zone in the mid-1800s following a 1700 AD megathrust earthquake, as well as an increase from 1965 to the late 1990s in the Aleutian Islands after the 1964 magnitude 9.2 megathrust earthquake off the coast of Alaska (Hill et al. 2002). Analyses of regional changes in eruption rates following megathrust earthquakes have shown that historically inactive or somewhat active volcanoes appear to be the most sensitive to this kind of quasi-static strain interaction (Walter and Amelung 2007).

The third category of hypothesized triggering mechanisms involves changes within magma bodies caused by dynamic stresses from the passage of seismic waves. These temporary stress changes must be made permanent in order to sustain the pressures needed to induce volcanism. Mechanisms to explain dynamic triggering were reviewed by Manga and Brodsky (2006), and are briefly summarized here. Bubbles within the magma chamber can drive eruptions either by increasing the overpressure in the magma chamber or by making the magmatic body more buoyant (Huppert and Woods 2002). Nucleation of bubbles could be triggered by pressure changes from passing seismic waves, according to classical bubble nucleation theory (Hirth et al. 1970). Advection of overpressure can occur if bubbles, mobilized by seismic waves, rise through an undeformable environment and transport their relatively high internal pressures to the top of the magma body, leading to the pressures needed for an eruption (e.g., Steinberg et al. 1989; Sahagian and Proussevitch 1992; Linde et al. 1994; Woods and Cardoso 1997). Passing seismic waves could also dislodge dense crystal mush from the walls or ceilings of magma bodies into the magma, encouraging both heterogenous bubble nucleation and magmatic overturn (Sumita and Manga 2008). Magma rising to replace the sinking mass could vesiculate during its ascent, thus increasing overpressure and possibly triggering an eruption (Johnson and Fletcher 1994; Marsh 2000; Hill et al. 2002). Laboratory experiments suggest that oscillations from seismic waves could enhance the mobility of bubbles within the magmatic melt, thus increasing pressures within the chamber and promoting eruptions (Namiki et al. 2016).

Regardless of the specific mechanism for triggering an eruption, many studies suggest that seismic triggering is more likely to occur when the volcano is already poised to erupt (e.g., Barrientos 1994; Marzocchi et al. 2002; Manga and Brodsky 2006; Eggert and Walter 2009; Watt et al. 2009). A stochastic analysis by Bebbington and Marzocchi (2011) supported this supposition, indicating that seismicity most likely initiates an already looming eruption.

Methods

Here, we recreate the histograms produced by Linde and Sacks (1998) by reanalyzing records from the same databases used in their study and adopting their definition of an “earthquake triggered eruption” (i.e., VEI 2 or greater eruptions preceded within 5 days of a M8 or larger earthquakes). In doing so, we find that the majority of short-term earthquake triggered eruptions are reported between 1500 AD and 1900, and that post-1900, there is no indication that short-term triggering is taking place (Fig. 1). To minimize potential biases due to incomplete records, we thus adjusted our study period to consider only 1964–2016. Eruption rates are relatively stable in this time period (Fig. 2). Prior to 1964, seismic records are incomplete, especially for depth measurements (Northern California Earthquake Data Center 2014). To account for the smaller sample size, we expand the definition of a triggered eruption to include the possibility of a VEI 2 or greater eruption within 5 days and 800 km of a M6 or greater earthquake and remove duplicate triggered eruptions so that each eruption is associated with only one earthquake (Fig. 3). When considering time spans of up to 5 days between earthquakes and volcanoes, we adopt the following “declustering” method. We choose the earliest (which is always the largest) earthquake to be the main “triggering” earthquake. All “aftershocks” of this main earthquake are removed so that only a single earthquake is associated with each eruption. For example, if earthquake A occurs on day 1, earthquake B on day 2, the eruption on day 3, and earthquake C on day 4, we count only earthquake A as a triggering earthquake and remove earthquakes B and C from consideration. This method skews our results in favor of eruptions occurring after the earthquake, since we are systematically removing earthquakes that are more likely to have happened after the eruption. For this reason, the results give a biased view in favor of triggered volcanism. For longer time frames (> 5 days) the compounded results become too skewed to be meaningful. For that reason, we do not decluster earthquakes when considering time frames longer than 5 days.

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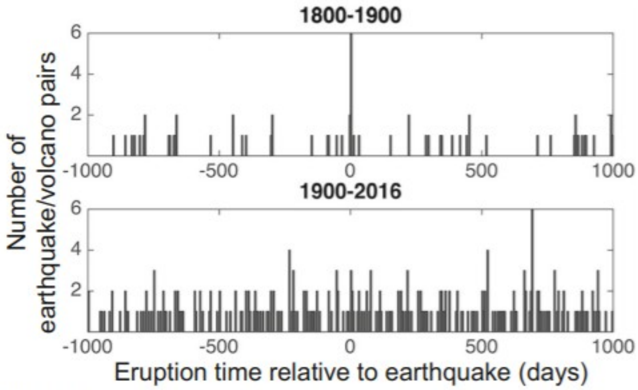

Fig. 1 Histograms of VEI ≥ 2 eruptions and their time of eruption relative to M ≥ 8 earthquakes within 800 km, recreating the analysis performed by Linde and Sacks (1998). Bin width is 5 days. The absence of a peak above background levels near day 0 in the bottom panel that is present in the top panel shows that the majority of possible short-term triggered eruptions were recorded prior to 1900

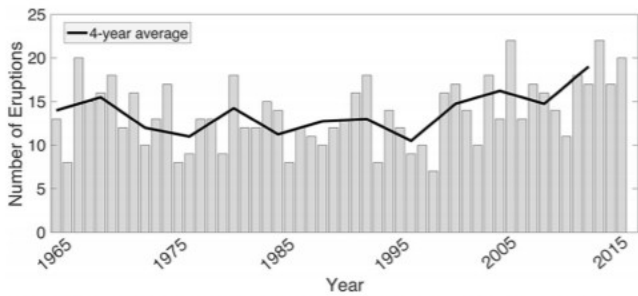

Fig. 2 VEI ≥ 2 eruptions during study period (1964–2016) in 1-year bins, along with 4-year running average

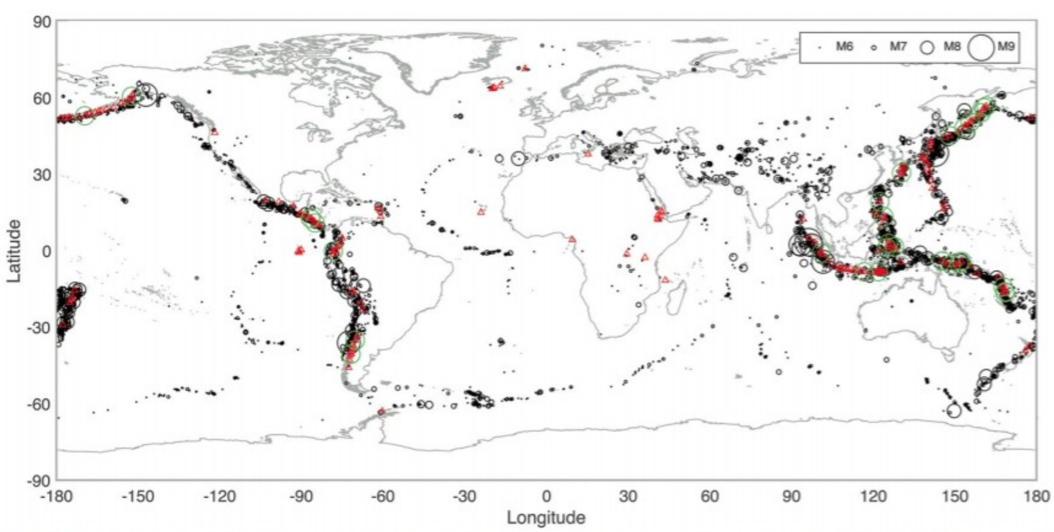

Fig. 3 Magnitude ≥ 6 earthquakes (black circles, scaled by magnitude) and VEI ≥ 2 eruptions (red triangles) from 1964 to 2016. Green circles indicate when an eruption was preceded within 5 days by an earthquake (these define what we term "sensitive" volcanoes)

We exclude eruptions smaller than VEI 2 because records appear to be incomplete for eruptions below that magnitude (Manga and Brodsky 2006;

Siebert et al. 2015). Earthquakes of M6 represent the lower limit of seismicity that could reasonably be expected to induce volcanic activity (Manga and Brodsky 2006), and 800 km has been noted as the distance beyond which seismically triggered eruptions are expected not to occur (Linde and Sacks 1998), although we acknowledge that large earthquakes may have global effects on volcanism (Delle Donne et al. 2010; Avouris et al. 2017). Here, we focus on triggering that takes place only after a few days, because the close temporal coupling of eruptions and earthquakes makes these events straightforward to identify in global databases (Selva et al. 2004) and allows us to confidently compare volcano-centric attributes that may be associated with triggered volcanism. These volcano-centric attributes come from the Global Volcanism Program, as administered by the Smithsonian Institution, Washington, DC, USA (Venzke 2013). We discard eruption entries that have unknown or uncertain VEIs and/or start times. Our 1964–2016 seismic data are from the Advanced National Seismic System (ANSS) composite catalog provided by the Northern California Earthquake Data Center (NCEDC). Data were accessed April 22, 2016.

For M8 or larger earthquakes beginning 1500 AD, we use the Significant Earthquake Database (National Geophysical Data Center/ World Data Service). This is because the ANSS database begins in 1898 and the National Geophysical Data Center database does not consistently include earthquakes with magnitudes 7.5 or smaller.

We define a “sensitive” volcano as one that has erupted at least once within 5 days and 800 km of a M6 or greater earthquake, and an “insensitive” volcano as one that has never experienced such a triggered eruption. Volcanoes that are not within 800 km of any M6 or greater earthquakes since 1964 are not included in our analysis. Our aim is to investigate differences in characteristics between sensitive and insensitive volcanoes with the aim of elucidating underlying physical mechanisms involved in seismic triggering of eruptions. To assess whether the timings of eruptions are indeed influenced by earthquakes, we employ a 1000-run Monte Carlo simulation in which we randomize only the dates of each eruption. We leave individual volcano locations, magnitudes, and total number of eruptions, as well as all aspects of the earthquakes, untouched. We are thus assuming that earthquakes might trigger eruptions, but that eruptions do not cause large (i.e., M6 or larger) earthquakes.

Results

After expanding our parameters to include M6 or larger earthquakes and narrowing our period of study to 1964–2016, we find that 33 of the 738 explosive eruptions (~ 4%) can be classified as potentially triggered eruptions. These eruptions occur from 30 different volcanoes, which represent ~ 15% of the 202 volcanoes that have explosively erupted since 1964 (Venzke 2013). We classify these 30 volcanoes as sensitive to seismic triggering; all other volcanoes are classified as insensitive. Figure 4 is a comparison of volcano-centric attributes between sensitive and insensitive volcanoes. Sensitive volcanoes reside solely in subduction zones and tend to be associated with less-evolved magmas. The randomly generated sensitive volcanoes exhibit these characteristics as well, and the randomly generated potentially triggered eruptions also represent on average about 4% of all eruptions. Overall, the differences between observed sensitive volcanoes and randomly generated sensitive volcanoes are negligible.

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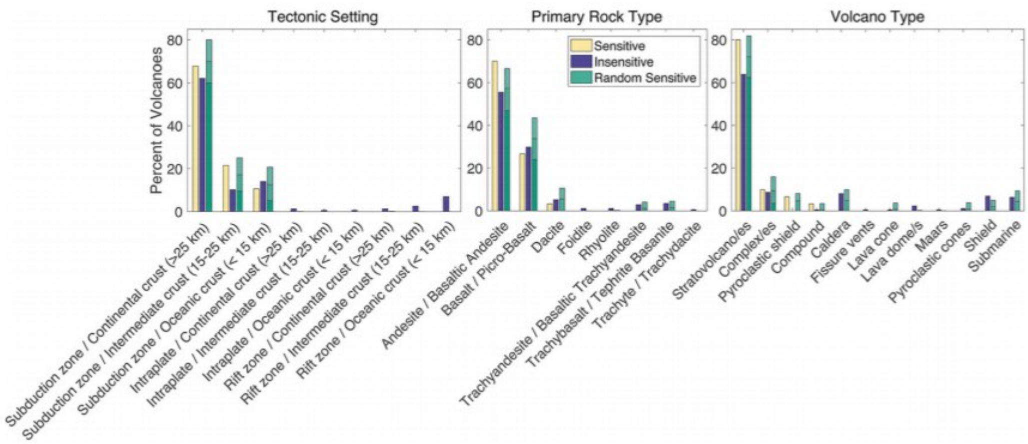


Fig. 4 Volcano-centric characteristics for sensitive volcanoes (i.e., volcanoes that have erupted within 5 days and 800 km of a $M \geq 6$ earthquake), insensitive volcanoes, and sensitive volcanoes generated via Monte Carlo simulation. The uppermost and lowermost divisions for the random sensitive volcanoes designate the 90th and 10th percentiles of the Monte Carlo-generated data, respectively

Figure 5 shows that one notable difference between sensitive volcanoes and insensitive volcanoes is that a larger proportion of sensitive volcanoes have shorter time intervals between explosive eruptions than insensitive volcanoes. This indicates that sensitive volcanoes erupt more frequently than insensitive volcanoes. Additionally, Fig. 5 shows that explosive eruptions are clustered in time (although not necessarily space).

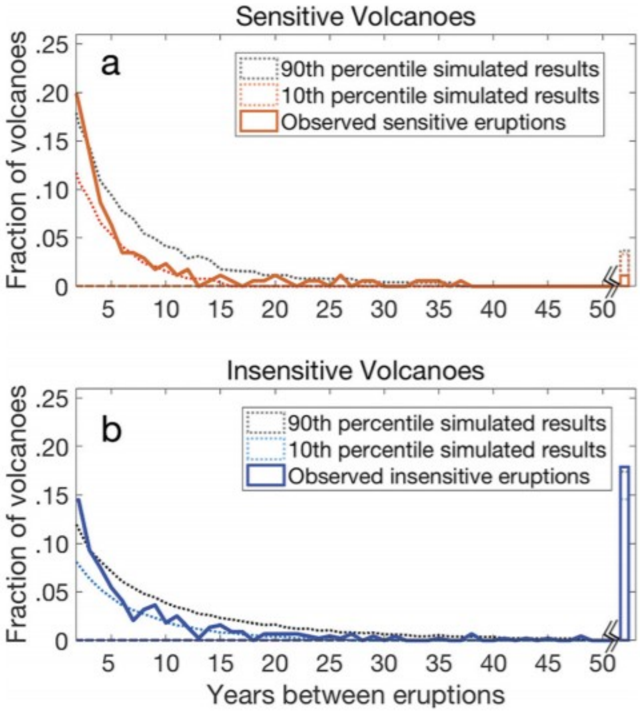


Fig. 5 Eruption frequency for sensitive (**a**) and insensitive (**b**) volcanoes. The 90th and 10th percentiles of results from Monte Carlo simulation are also reported. Right sides of histograms show the fraction of eruptions from volcanoes with only one eruption between 1964 and 2016

Figure 6 shows that large magnitude earthquakes occur in the vicinity of many sensitive volcanoes that do not erupt within 5 days of the earthquake. Volcanoes that did erupt within 5 days do not exhibit the magnitude-distance relationship expected from seismically induced responses (i.e., their distance from the earthquake does not increase with increasing earthquake magnitude). We do acknowledge, however, that any relationship is difficult to accept or reject when using so few data points.

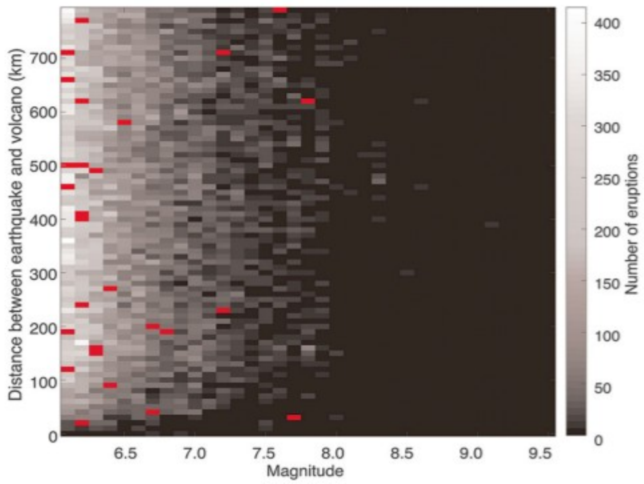


Fig. 6 Density map of distance between earthquakes and volcanoes that did not have a VEI ≥ 2 eruption within 5 days of the earthquake, against earthquake magnitude. Red boxes are potentially triggered eruptions

We use a 1000-run Monte Carlo simulation to investigate a possible increase in explosive eruptions following major earthquakes (Fig. 7). Because earthquakes are reported to the second, whereas eruptions are reported only to the day, we are unable to determine which preceded which when they occur on the same day, that is, on "day 0." For this reason, we include two possibilities: Events on day 0 are either excluded in Fig. 7b or included in Fig. 7c in the "after" bin. We define the fractional increase in eruptions as the change of number eruptions following earthquakes divided by the number of eruptions preceding earthquakes. Thirty-three percent of randomized trials have a higher fractional increase in eruptions than the actual data, regardless of whether day 0 is excluded or included.

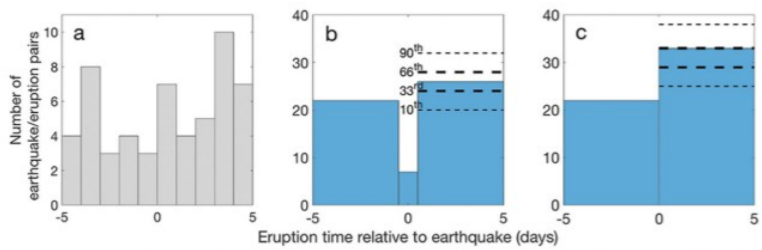


Fig. 7 Histogram of VEI ≥ 2 eruptions relative to the dates of M ≥ 6 earthquakes, binned in single days (**a**) and five days "before" or "after" bins, either excluding or including day 0 events in the "after bin" (**b**, **c**, respectively). Dashed lines show the 90th, 66th, 33rd, and 10th percentiles of results from Monte Carlo simulations

Figure 8 shows the increase in the number of eruptions for time spans of 30, 60, and 120 days, with 5-day bins superimposed over the "before" and after bins. Here, as for all time spans greater than 5 days, we employ no declustering of the earthquake catalog (described in "Methods"). For all time spans, 33% of randomized trials have a higher fractional increase in eruptions than the actual data. Going beyond an analysis of short-term seismic triggering, we expand the time period considered for a triggered eruption to 5 years and compare the eruption record with the results from the 1000-run Monte Carlo simulations for time intervals of 10 days to 5 years (Fig. 9). Because earthquakes may not be randomly distributed in time and space, we normalize our results by subtracting the 50th percentile values of the Monte Carlo simulation results. We define the fractional change in the number of eruptions following an earthquake as

$$A = \frac{N_{before} - N_{after}}{N_{before}} - PR_{50}\left(\frac{M_{before} - M_{after}}{M_{before}}\right)$$

$$B_x = PR_x\left(\frac{M_{before} - M_{after}}{M_{before}}\right) - PR_{50}\left(\frac{M_{before} - M_{after}}{M_{before}}\right)$$

where for a given timespan, PR_x denotes the *x*th percentile of the argument in parentheses, *A* is the normalized data, and B_x is the normalized *x*th percentile of the simulation results, *N* is the number of eruptions observed before or after a given earthquake, and *M* is the number of simulated eruptions before or after a given earthquake. Figure 9 shows that at 60 days, there is a ~ 12% increase in eruptions following major earthquakes. Not until 2 years following the earthquakes do eruption rates return to pre-earthquake levels. The increase in eruption frequency of 5–12% between 60 days and 2 years is significant at the one-sigma level, but not the two-sigma level.

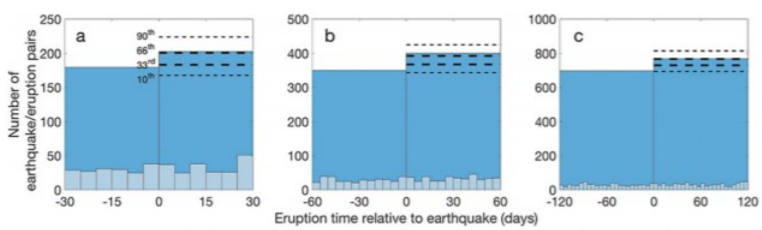
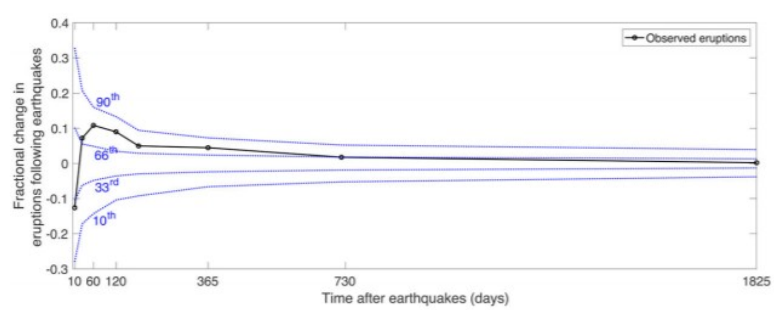


Fig. 8 Histograms showing the number of VEI ≥ 2 before and after M ≥ 6 earthquakes, binned by 5 days (light blue) and by 30, 60, or 120 days (blue; **a**, **b**, **c**, respectively). Eruptions on day 0 are counted as having occurred after the earthquake and included in the right-hand bin. Dashed lines show the 90th, 66th, 33rd, and 10th percentiles of results from Monte Carlo simulations

Fig. 9 Fractional change in number of VEI ≥ 2 eruptions following M ≥ 6 earthquakes, in time span specified by *x*-axis. Dashed lines show the various percentiles of results from Monte Carlo simulations. All data normalized by the 50th percentile simulation results



Discussion

Our analysis of 30 sensitive volcanoes (that is, volcanoes that have erupted within 5 days and 800 km of a M6 or larger earthquake between 1964 and 2016) shows that such volcanoes are located only in subduction zones. Sensitive volcanoes also typically erupt andesites and basaltic andesites and erupt more frequently than insensitive volcanoes. This suggests that sensitive volcanoes are in fact not responsive to triggering due to static, volcano-centric properties. Instead, this class comprises frequently or persistently active volcanoes located in regions of high seismicity, meaning that a number of coincident earthquake-eruption events will occur. Another indication that these volcanoes are not being triggered by seismicity is a seemingly random magnitude-distance relationship between earthquake-eruption pairs (Fig. 6). By randomizing the dates, but not the locations, of eruptions on record, we would expect fewer triggered eruptions and a change in the distribution of volcano-centric characteristics. However, the differences between attributes of the actual and randomly generated sensitive volcanoes are practically indistinguishable. Most notably, randomly generated sensitive volcanoes still reside solely in subduction zone settings. This supports the theory that some apparently triggered eruptions are actually just coincidentally occurring after a nearby major earthquake. Additionally, a comparable number of volcanoes were triggered whether the times of the eruptions were randomized or not. On average, 4% of eruptions were triggered in the randomized catalogs, as well as in the actual data. This also suggests that apparent short-term triggered eruptions could have occurred by chance.

It does appear, however, that over longer timespans (2 months to 2 years), there is a statistically significant increase in volcanism following M6 or greater earthquakes, with the number of eruptions increasing by 5–12% within 2 years of a major earthquake. This fractional increase in eruptions following earthquakes is higher than 66% of the results from Monte Carlo simulations, suggesting that the observed increase in eruptions is not occurring randomly. This finding is consistent with previous studies that also found that rates of volcanism can increase during a 1 to 5-year period following major earthquakes (e.g., Walter and Amelung 2007; Watt et al. 2009; Nishimura 2017).

Our analysis is hindered by limitations and biases in the global record of volcanic eruptions. We have chosen to focus on VEI 2 or greater eruptions because the catalog is complete for that magnitude of eruption (Manga and Brodsky 2006; Siebert et al. 2015). This, however, excludes subtler manifestations of triggered activity that are not classified as explosive eruptions. Such manifestations include temperature and volume flux anomalies, increased fumarole temperatures, and degassing of SO_2, as well as increases in discharge rate during effusive eruptions (e.g., Harris and Ripepe 2007; Fattori Speranza and Carniel 2007; Walter et al. 2007; Avouris et al. 2017). Additionally, many volcanoes are located far from populations with extensive scientific or monitoring infrastructure, which can lead to a geographic bias in favor of intensely monitored regions. For example, although the USA was home to about 11% of VEI 2 or greater eruptions between 1964 and 2016, it represents only about 6% of the triggered eruptions in the same time frame. Volcanoes in Papua New Guinea, on the other hand, are responsible for 15% of triggered eruptions, despite representing only 6% of all explosive eruptions in the same time period. This could perhaps suggest that robust monitoring decreases the number of reported triggered eruptions. Satellite-based monitoring offers solutions to both issues of non-explosive manifestations of triggering and geographic bias (Carn et al. 2016). For that reason, instituting long-term, satellite-based observations that are incorporated into global databases should continue to be a priority for the volcano science community (National Academies 2017). Temporal observational biases may also be introduced if reporting rates increase following major geologic events due to heightened public awareness (Siebert et al. 2015). It is possible that this phenomenon could have inflated the number of early (pre-1900) recorded instances of triggered volcanism before eruptions were more systematically monitored and, more recently, confirmed by satellite observations. A more sophisticated analysis could take into account changes in eruption reporting rates. Although eruption reporting rates increased dramatically since the 1800s, especially for low-intensity (VEI 1 or smaller) eruptions, modern (post-1960s) reporting rates of VEI 2 or greater eruptions are reliable enough that we neglect changes in reporting rates in our analysis (Fig. 3; Siebert et al. 2015).

Another limitation of our study is that the global catalog of eruptions does not include the time of eruption. If an earthquake and an eruption happen on the same day, it may not be possible to determine which preceded which. Including the times of eruptions in global databases would give a more accurate view of earthquake-volcano interactions, though we acknowledge that the relevant start time is not well defined (e.g., initiation of unrest that leads to eruption vs initiation of surface eruption).

While this paper was in the proof stage, on May 17, 2018, Kilauea erupted to a height of 10 km. Twelve days earlier, there was a M6.9 earthquake 30 km from the vent. Both events are presumably part of the same eruption and manifestations of the ongoing activity that began in 1983. Although this pair of events falls narrowly outside our definition of a sensitive volcano, the eruption highlights some limitations in our analysis and conclusions. First, we assumed that earthquakes generated by magmatic and volcanic processes would not exceed M6. Second, had our time window for sensitive volcanoes been longer, this would be an example that resides outside a subduction zone.

Because of the infrequent nature of explosive volcanic eruptions and large earthquakes, and the limited time period over which we conduct our analysis, it could be that our study period has not captured the full scope of earthquake-volcano interactions. For example, shaking-induced volcanism was implicated as a cause for mass extinction events. Richards et al. (2015) and Byrnes and Karlstrom (2018) suggested that shaking produced by the Chicxulub impact triggered some of the Deccan large igneous province eruptions and increased magmatism at mid-ocean ridges, respectively. With a longer period of study, it is possible that we would see stronger indications of short-term earthquake-induced volcanism.

Conclusion

We define a “short-term earthquake triggered eruption” as a VEI 2 or greater eruption within 5 days and 800 km of a magnitude 6 or larger earthquake. Given the most recent and reliable data from global databases of seismic and volcanic events, it appears that apparent earthquake triggered eruptions are likely occurring due to chance. Compared to insensitive volcanoes (volcanoes that have never been triggered), sensitive volcanoes (volcanoes that have been triggered at least once) have a higher eruption frequency and are concentrated in subduction zones. This suggests that sensitive volcanoes are not actually sensitive to seismicity, but rather just frequently active volcanoes in regions that experience frequent earthquakes so that, by chance, from time-to-time, an eruption coincides with an earthquake. Randomizing the timing of eruptions does not change these results, implying that instances of short-term eruption triggering could simply be due to the frequency with which eruptions and earthquakes occur in close proximity within subduction zones, rather than (or possibly, in addition to) actual triggering phenomena. However, expanding the timeframe in which an eruption could be considered triggered results in a 5–12% increase in eruptions in the 2-month to 2-year-long period following a major earthquake. Our results indicate that short-term seismically triggered explosive eruptions thus occur less frequently than previously inferred.

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