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# The relationship between large earthquakes and volcanic eruptions: A global statistical study

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## Abstract

It is now generally accepted that large earthquakes can promote eruptions at nearby volcanoes. However, the prevalence of "triggered" eruptions, as well as the distance and timescale over which triggering occurs, remain unclear. Here, we use modern global earthquake and eruption records to compare volcanic eruption rates before and after large earthquakes with the time-averaged background eruption rate. We quantify the significance of observed deviations from the average eruption rate using Monte Carlo simulations. To integrate our findings with previous eruption triggering studies, we systematically vary the earthquake magnitudes we consider, as well as the distances and timescales used to calculate eruption rates. We also investigate the effects of earthquake depth and slip orientation. Overall, we find that post-earthquake eruption rates are around 1.25 times the average eruption rate within 750 km and one year following $M_w \geq 7$ earthquakes, with above-average post-earthquake eruption rates possibly lasting for two to four years. By contrast, pre-earthquake eruption rates are around 0.9 times the average eruption rate within 750 km and 182 days before $M_w \geq 7$ earthquakes. Furthermore, deep earthquakes (≥70 km) appear to more strongly affect eruption rates than shallow earthquakes, while earthquake slip orientation is also important. Further study of the relationships reported here represents a good opportunity to improve our understanding of tectono-magmatic relationships.

Keywords: Earthquake; Volcano; Eruption; Triggering; Statistics.

## 1 Introduction

The potential for large earthquakes to trigger eruptions at nearby volcanoes has long been noted [e.g. Darwin 1840]. However, systematic global recording of earthquakes and eruptions only began in the mid-twentieth century [Siebert et al. 2010; Storchak et al. 2015], therefore limiting detailed statistical analyses of the relationship between earthquakes and eruptions until more recently. Since the 1990s, numerous studies have investigated how earthquakes affect volcanic eruption rates (i.e. the number of eruptions per unit time), at scales from individual volcanoes [Nostro et al. 1998; Walter and Amelung 2006], through regional correlations [Eggert and Walter 2009; Watt et al. 2009; Bebbington and Marzocchi 2011; Bonali et al. 2013], to globally [Linde and Sacks 1998; Marzocchi 2002; Manga and Brodsky 2006; Walter and Amelung 2007; Nishimura 2017; Sawi and Manga 2018]. These studies generally find that volcanic eruptions occur more often than expected by chance following nearby large earthquakes. Consequently, it is now mainly accepted that earthquakes can trigger volcanic eruptions, and various triggering mechanisms have been proposed [Hill et al. 2002; Seropian et al. 2021].

However, the prevalence of triggered eruptions, as well as the distance and timescale over which eruption triggering occurs, remain unclear. Although previous studies have considered these factors, their findings vary markedly; eruption triggering has been associated with greatly increasing eruption rates during the first few days following earthquakes [Linde and Sacks 1998], to producing only minor increases in eruption rates over the following months to several years [Sawi and Manga 2018]. These variable findings can likely be attributed to the use of different earthquake and eruption records, as well as different definitions for triggered eruptions in terms of the minimum earthquake magnitude required and the maximum distance and timescale between earthquakes and triggered eruptions. On the other hand, potentially important factors such as earthquake depth and slip orientation have not yet been studied. Addressing these issues in quantifying how earthquakes affect eruption rates is important for assessing volcanic risk, as well as for understanding the processes that lead to volcanic eruptions.

Determining if an earthquake triggered a given volcanic eruption is challenging, as most earthquakes and eruptions occur in regions with high rates of seismic and volcanic activity, predominantly at subduction zones. Furthermore, it is widely believed that earthquakes can only trigger eruptions at volcanoes that are already close to erupting anyway [Barrientos 1994; Manga and Brodsky 2006; Walter and Amelung 2007; Nishimura 2017]. For these reasons, we prefer to avoid the term eruption triggering. Instead, we use modern global earthquake and eruption records to investigate how large earthquakes promote, or perhaps sometimes inhibit, volcanic eruptions [e.g. Marzocchi 2002]. To achieve this, we calculate volcanic eruption rates before and after nearby large earthquakes and compare these against the time-averaged background eruption rate. We then use Monte Carlo simulations with randomised eruption dates to quantify the significance of observed deviations from the average eruption rate. To thoroughly characterise how earthquakes affect eruption rates, we systematically vary the earthquake magnitudes we consider, as well as the distances and timescales over which we calculate eruption rates. We also investigate the effects of previously unconsidered factors such as earthquake depth and slip orientation.

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## 2 Summary of previous studies

As there is now a wealth of literature concerning the relationship between earthquakes and eruptions, we restrict this brief review to studies investigating the statistical relationship between large earthquakes and volcanic eruptions at the global scale (Table 1). Perhaps the first attempt at this was provided by Carr [1977], who produced time-series for great thrust earthquakes and volcanic eruptions along the circum-Pacific subduction zones from 1820 to 1976. Using these time-series, Carr [1977] suggested that subduction zones often exhibit a period of decreased eruption rates for several years to a few decades before great earthquakes, followed by a period of increased eruption rates beginning a few years before or after great earthquakes. In contrast to later studies, Carr [1977] highlighted the decrease in eruption rates prior to large earthquakes as the most characteristic finding, although the statistical significance of this result was not tested.

The first truly global eruption triggering study was performed by Linde and Sacks [1998] using earthquake records from the USGS National Earthquake Information Centre Compendium (NEIC) and eruption records from the Smithsonian Global Volcanism Program (GVP) for the past several hundred years. Investigating both great ($M \geq 8$) and large ($7 \leq M < 8$) magnitude earthquakes, Linde and Sacks [1998] identified a peak in VEI $\geq$ 2 eruption rates lasting for a few days within 750 km following great earthquakes and within 250 km following large earthquakes. Simulations using randomised earthquake catalogues showed that the probability of the observed eruption rate peaks occurring by chance was $\ll$1 %. No enhanced eruption rates were identified beyond 750 km, or for timescales longer than a few days following earthquakes. Manga and Brodsky [2006] later recreated the Linde and Sacks [1998] study using an updated earthquake catalogue and observed a similar peak in VEI $\geq$ 2 eruption rates within five days and 800 km following $M > 8$ earthquakes. While this provided further evidence for short-term eruption triggering, Manga and Brodsky [2006] also highlighted the absence of short-term triggered eruptions following the most recent large earthquakes.

More recently, Sawi and Manga [2018] also recreated the Linde and Sacks [1998] study but using only earthquakes and eruptions from 1964 through 2016, taken from the Advanced National Seismic System Composite Catalogue (ANSS) and the GVP respectively. To offset their decreased number of earthquakes and eruptions caused by removing all events prior to 1964, Sawi and Manga [2018] lowered their earthquake magnitude threshold to include $M \geq 6$ earthquakes. To quantify eruption triggering, Sawi and Manga [2018] compared VEI $\geq$ 2 eruption rates within 800 km and five days following $M \geq 6$ earthquakes with VEI $\geq$ 2 eruption rates within 800 km and five days before $M \geq 6$ earthquakes. By performing simulations with randomised eruption dates, Sawi and Manga [2018] showed that eruption rate changes within five days of earthquakes agreed with those expected by random chance, suggesting that the short-term eruption triggering reported by Linde and Sacks [1998] was caused by using incomplete historical records. However, Sawi and Manga [2018] also calculated eruption rate changes over longer timescales and reported a borderline statistically significant increase in eruption rates of 5–12 % during the two months to two years following $M \geq 6$ earthquakes.

Also recently, Nishimura [2017] and Jenkins et al. [2021] used similar methods to Sawi and Manga [2018] to further investigate how eruption triggering over longer timescales depends on earthquake magnitude and the distance from earthquakes. Using earthquake records from the Global Centroid Moment Tensor catalogue (CMT) from 1976 to 2010 and eruption records from the GVP from 1966 to 2015, Nishimura [2017] calculated eruption rate changes for distances of up to 1000 km from earthquakes in increments of 200 km. From this, Nishimura [2017] found an approximately 50 % increase in VEI $\geq$ 2 eruption rates within 200 km and five years following $M_w \geq 7.5$ earthquakes. Simulations using randomised earthquake dates showed that the probability of this increase occurring by chance was <1 %. However, no significant increases in eruption rates were found at larger distances or greater timescales, or for earthquakes with $7 \leq M_w < 7.5$. Additionally, of the 52 volcanic eruptions within 200 km and five years following $M_w \geq 7.5$ earthquakes, 20 came from only two volcanoes (Bezymianny and Ulawun), although excluding repeat eruptions from a single volcano still produced 20–60 % increases in eruption rates. By contrast, Jenkins et al. [2021] found increases of only around 10 % in VEI $\geq$ 2 eruption rates within 1000 km and one to five years following $M_w \geq 7$ earthquakes, using earthquake records from the International Seismological Centre catalogue (ISC) from 1960 through 1975 and from the CMT from 1976 through 2019, along with eruption records from the GVP for 1955 through 2019. Jenkins et al. [2021] found no strong evidence for eruption triggering using distances of 200 or 2000 km, or for $M_w \geq 6$ earthquakes.

Overall, the recent studies of Nishimura [2017], Sawi and Manga [2018], and Jenkins et al. [2021] provide contrasting views regarding the prevalence of eruption triggering, despite their similar methods. This variation could be caused by the different earthquake and eruption records utilised, but all three studies used reliable global catalogues. Instead, the different parameter ranges investigated (Table 1) are likely responsible for the variable findings. Reconciling these differences to accurately understand the prevalence of eruption triggering, as well as how this varies with factors such as earthquake magnitude and the distance from earthquakes, is an important issue which we now address.

## 3 Data and methods

### 3.1 Data

Following recent global statistical studies on eruption triggering [Nishimura 2017; Sawi and Manga 2018; Jenkins et al. 2021], we use only modern global earthquake and eruption records compiled since the mid-twentieth century. In doing this, we aim to minimise the impact of potentially biased data. In particular, it has been suggested that apparent eruption triggering can be attributed to large earthquakes inducing a state of temporarily heightened awareness within local populations, resulting in increased reporting of volcanic eruptions [Manga and Brodsky 2006]. While we consider this unlikely for our

Table 1: Reported parameter ranges investigated by previous global statistical studies of eruption triggering. Parentheses indicate parameters that were studied but did not show evidence for significant eruption triggering.

| Study | Earthquake magnitude | Distance from earthquake (km) | Timescale following earthquakes (days) |
|---|---|---|---|
| Linde and Sacks [1998] | $M \geq 8$<br>$7 \leq M < 8$ | 0–250<br>0–500<br>0–750 | 1000, in daily bins |
| Manga and Brodsky [2006] | $M > 8$ | 0–800 | 1000, in daily bins |
| Nishimura [2017] | $M_w \geq 7.5$<br>($7 \leq M_w < 7.5$) | 0–200<br>(200–400)<br>(400–600)<br>(600–800)<br>(800–1000) | 0–1826<br>(1826–3652) |
| Sawi and Manga [2018] | $M \geq 6$ | 0–800 | (0–5)<br>(0–30)<br>0–60<br>0–120<br>0–365<br>0–730<br>(0–1825) |
| Jenkins et al. [2021] | ($M_w \geq 6$ )<br>$M_w \geq 7$<br>$M_w \geq 8$ | (0–200)<br>0–1000<br>(0–2000) | 0–365<br>0–1826 |

data, we note that volcanic eruptions sometimes have uncertain reported start dates, even during the late-twentieth and early-twenty-first centuries. Only since around 2010 has the number of uncertain start date eruptions fallen dramatically, probably due to increased remote sensing.

We use earthquake times, locations, and moment magnitudes ($M_w$) from the Global Centroid Moment Tensor catalogue, from its inception in 1976 through 2020 [CMT: Dziewonski et al. 1981]. The CMT catalogue is reported to be complete above $M_w$ 5.5 [Dziewonski et al. 1981; Ekström et al. 2012], so we use a minimum $M_w$ of 6 to obtain a total of 5418 earthquakes over the 45 year catalogue. We further divide these events into 4885 $M_w$ 6 earthquakes, 506 $M_w$ 7 earthquakes, and 27 $M_w \geq 8$ earthquakes (Table 2). We also classify these earthquakes by their depth and slip orientation. For depth, we use a threshold depth of 70 km to separate shallower crustal earthquakes from deeper earthquakes within subducted slabs [e.g. Pacheco et al. 1993; Heuret et al. 2011]. For slip orientation, we analyse the slip rake angles from the CMT focal mechanism solutions, using both nodal planes as the true fault plane is generally unknown. We define normal faulting earthquakes as those with at least one rake between $-70°$ and $-110°$, reverse earthquakes as those with at least one rake between 70° and 110°, and strike-slip earthquakes as those with at least one rake either between $-20°$ and 20°, $>160°$, or $<-160°$. Visual inspection of the focal mechanism solutions reveals that this method classifies slip orientations well and few earthquakes cannot be classified due to satisfying multiple categories.

We use volcanic eruption start dates, locations, and explosivity (VEI) from the Global Volcanism Program [GVP: Global Volcanism Program 2013]. In order to calculate eruption rates up to five years before and after nearby earthquakes, we consider eruptions from 1971 through 2020. The completeness of the GVP for smaller eruptions is unclear, but for explosive eruptions (VEI $\geq$ 2) the eruption record is likely complete since 1971 [e.g. Newhall and Self 1982; Mead and Magill 2014; Papale 2018]. The GVP notes where eruption magnitudes are uncertain, but we take the VEI value for each eruption as given. The GVP lists the initiation of 924 VEI $\geq$ 2 eruptions from 216 individual volcanoes over the 50 years from 1971 through 2020, including 182 eruptions with an uncertain start date (Table 3). We experiment with including or excluding these uncertain start date eruptions in our analyses, as well as with using different minimum VEI thresholds.

## 3.2 Methods

### 3.2.1 *Eruption rates before and after earthquakes*

To calculate volcanic eruption rates before and after nearby large earthquakes, we first specify the earthquake parameters ($M_w$, depth, slip orientation) and eruption parameters (VEI, include/exclude uncertain start date eruptions) to study. We also specify the distance and timescale from the earthquakes over which to calculate the eruption rates. Here, we investigate surface distances of up to 1000 km from the earthquake centroid locations in increments of 250 km, over timescales of 30, 91, 182, 365, 730, 1096, 1461, and 1826 days (one month to five years). These distances and timescales can either be considered cumulatively (i.e. 1000 km and 1826 days gives the

Table 2: Classification of earthquakes from the 1976–2020 CMT catalogue used in this study.

| $M_w$ | Depth | Reverse | Normal | Strike-slip | Oblique* | Unclassified** | Total |
|---|---|---|---|---|---|---|---|
| $6 \leq M_w < 7$ | <70 | 1635 | 388 | 1337 | 449 | 13 | 3822 |
| | ≥70 | 214 | 290 | 197 | 325 | 37 | 1063 |
| $7 \leq M_w < 8$ | <70 | 213 | 32 | 87 | 37 | 2 | 371 |
| | ≥70 | 28 | 43 | 23 | 38 | 3 | 135 |
| $M_w \geq 8$ | <70 | 12 | 3 | 5 | 4 | 0 | 24 |
| | ≥70 | 0 | 3 | 0 | 0 | 0 | 3 |
| | Total | 2102 | 759 | 1649 | 853 | 55 | 5418 |

* Oblique refers to earthquakes that do not satisfy any slip category.
** Unclassified refers to earthquakes which satisfy multiple slip categories.

Table 3: Classification of volcanic eruptions from the 1971–2020 GVP catalogue used in this study.

| VEI | Start date | |
|---|---|---|
| | Certain | Uncertain |
| 0 | 118 | 55 |
| 1 | 467 | 145 |
| 2 | 510 | 142 |
| 3 | 191 | 38 |
| 4 | 36 | 2 |
| ≥5 | 5 | 0 |

eruption rates within 0 to 1000 km and one to 1826 days either before or after earthquakes) or as individual bins (i.e. 1000 km and 1826 days gives the eruption rates within 750–1000 km and 1462–1826 days either before or after earthquakes). For statistical analyses, the individual bins approach is preferred as it provides independent results for each distance and timescale considered. However, with the earthquake and eruption numbers currently available from modern global records, the cumulative approach is often used instead in order to include sufficient eruptions to perform meaningful statistical analyses [e.g. Nishimura 2017; Sawi and Manga 2018; Jenkins et al. 2021]. For this reason we primarily use the cumulative approach, although we show that, without careful interpretation, this can cause anomalous eruption rates at short distances or timescales to appear smeared out over longer distances or timescales.

For a given set of input parameters, we select all of the earthquakes and eruptions that meet the specified criteria from our databases. Earthquakes that occurred less than the specified timescale before the end date of the database (31st December 2020) are automatically rejected, and potential foreshocks and aftershocks can optionally be filtered out. Where we apply foreshock and aftershock filtering, we use a variation of the filtering method described by Nishimura [2017], whereby earthquakes that occurred within a certain distance and time period of a larger earthquake are deemed to be foreshocks or aftershocks and are discarded. Although we explore several filtering parameters, we note that filtering cannot fully resolve the potentially complex effects of multiple earthquakes on volcanic eruption rates, due to the interplay between earthquakes with different magnitudes, distances, and timescales from eruptions.

For each selected earthquake ($E_i = E_1 \ldots E_n$), we search the selected volcanic eruptions to determine the number of eruptions that occurred within the specified distance and timescale before the earthquake ($B_i$), as well as the number of eruptions that occurred within the specified distance and timescale after the earthquake ($A_i$). Eruptions that occurred on the same day as the earthquake are not counted; the GVP does not list eruption times, so it is unknown whether the eruption initiated before or after the earthquake. To account for frequently erupting volcanoes, there is an option to exclude repeat eruptions from the same volcano. Where we apply this option, each volcano is limited to contributing at most one eruption to $B_i$ and one eruption to $A_i$. As $B_i$ and $A_i$ give the number of eruptions during the specified timescale, they represent the pre-earthquake and post-earthquake eruption rates respectively for each earthquake.

### 3.2.2 *Time-averaged eruption rates*

Recent global statistical studies have quantified eruption triggering by comparing post-earthquake eruption rates with pre-earthquake eruption rates calculated over the same distance and timescale [Nishimura 2017; Sawi and Manga 2018; Jenkins et al. 2021]. Although we use this method to compare our results with previous studies, we primarily use an alternative approach whereby we compare post-earthquake eruption rates with long-term time-averaged eruption rates [e.g. Walter and Amelung 2007]. Using time-averaged eruption rates provides a more stable reference to compare post-earthquake eruption rates with, while also allowing us to compare pre-earthquake eruption rates with time-averaged eruption rates [e.g. Carr 1977]. More importantly, using time-averaged eruption rates increases the amount of data that we use from the earthquake and eruption catalogues. This is because we consider all earthquakes that occurred within the specified distance of an active volcano (i.e. a volcano with at least one eruption between 1971–2020), as opposed to only earthquakes that occurred within the specified distance and timescale of an eruption.

For a given set of input parameters, we would ideally calculate the time-averaged eruption rate within the specified distance of each selected earthquake using a long eruption record prior to the eruption record used to determine $B_i$ and

$A_i$. However, the completeness of the global eruption record much before 1971 is unclear [e.g. Jenkins et al. 2021]. Therefore, we instead calculate the time-averaged eruption rate for each selected earthquake by searching the selected volcanic eruptions to determine the number of eruptions that occurred within the specified distance of the earthquake over our entire eruption record ($N_i$: 1971 through 2020), excluding the five years either side of the earthquake. Excluding the five years either side of the earthquake helps to ensure that $N_i$ is independent of any changes to eruption rates caused by the earthquake itself. If repeat eruptions from the same volcano were excluded when calculating $B_i$ and $A_i$, eruptions are also excluded from contributing to $N_i$ if they occurred within the specified timescale of the previous eruption that contributed to $N_i$ from the same volcano. $N_i$ is then converted to give the average eruption rate within the specified distance and timescale of the earthquake,

$$\mu_i = t\frac{N_i}{T}, \tag{1}$$

where $t$ is the specified timescale and $T$ is the timescale used to calculate $N_i$ (40 years, except for earthquakes that occurred between 2016–2020). Although using time-averaged eruption rates could smooth out inherently clustered underlying eruption data (Supplementary Material 1), the suitability of our averaging method is shown by the fact that observed eruption rates tend towards the average eruption rate at long timescales before and after earthquakes (e.g. Figure 1B).

### 3.2.3 *Combined relative eruption rates*

For any given individual earthquake, the eruption rates $B_i$ and $A_i$ are generally low (<10 eruptions) over our timescales of up to five years. Statistical analyses on such small sample sizes are limited, so evidence for eruption triggering is unlikely to be found by analysing earthquakes individually. Therefore, to provide more meaningful results, we follow the approach of previous studies by summing the eruption rates from all of the selected earthquakes [Nishimura 2017; Sawi and Manga 2018; Jenkins et al. 2021]. For $n$ selected earthquakes, the combined eruption rates associated with those earthquakes are therefore given by

$$B = \sum_{i=1}^{n} B_i, \tag{2}$$

$$A = \sum_{i=1}^{n} A_i, \tag{3}$$

$$\mu = \sum_{i=1}^{n} \mu_i. \tag{4}$$

From these, we calculate the combined pre-earthquake eruption rate relative to the average eruption rate ($B/\mu$) and the combined post-earthquake eruption rate relative to the average eruption rate ($A/\mu$). Relative eruption rates <1 represent below-average eruption rates and relative eruption rates >1 represent above-average eruption rates.

### 3.2.4 *Quantifying statistical significance*

To quantify the significance of observed deviations of pre-earthquake or post-earthquake eruption rates from average eruption rates, we use 1000-run Monte Carlo simulations. In each simulation, we calculate the relative eruption rates associated with large earthquakes using the same parameters and methods as for the real data but with randomised eruption dates instead. The simplest way to randomise the eruption dates is to assign each selected eruption a completely random date within the catalogue boundaries [e.g. Sawi and Manga 2018]. However, this generates simulated eruption catalogues with different time distributions of eruptions than the observed eruption catalogue. Therefore, we randomly permutate the selected eruption dates instead (i.e. pool together the selected eruption dates and then randomly redistribute them back to the selected eruptions). Random permutation maintains the time distribution of the observed eruption catalogue and is therefore a more robust test of the statistical significance because it accounts for any global eruption rate variations unrelated to eruption triggering [e.g. Jenkins et al. 2021]. A potential issue with both randomly permutating the eruption dates and completely randomising the eruption dates is that the time distributions of eruptions at any given volcano are not maintained, which could result in unrealistically clustered simulated eruptions (e.g. two eruptions recorded on consecutive days at the same volcano, which in reality would be classified as a single eruption). However, by imposing limits on the recurrence of eruptions at any one volcano, we show that this does not significantly affect the results (Supplementary Material 1).

Using randomised simulations, the significance of an observed relative eruption rate ($B/\mu$ or $A/\mu$) is shown by its percentile score ($P$) relative to the $j = 1000$ simulated relative eruption rates ($B_j/\mu_j$ or $A_j/\mu_j$),

$$P = 100\left(\frac{\sum_{j=1}^{1000} 1[(B/\mu) \geq (B_j/\mu_j)]}{1000}\right), \tag{5}$$

$$P = 100\left(\frac{\sum_{j=1}^{1000} 1[(A/\mu) \geq (A_j/\mu_j)]}{1000}\right), \tag{6}$$

where a percentile score of 100 represents the case where the observed relative eruption rate is greater than or equal to all of the simulated relative eruption rates, and a percentile score of 0 represents the case where the observed relative eruption rate is lower than all of the simulated relative eruption rates.

Relative eruption rates associated with earthquakes can be >1 (above-average eruption rates) or <1 (below-average eruption rates), so percentile scores close to either 100 (significantly above-average eruption rates) or 0 (significantly below-average eruption rates) are considered significant. As we test a range of parameters and timescales, some percentile scores are expected to be significant purely by chance. For this reason, we focus on relationships where the percentile scores consistently indicate a significant result across a range of timescales or parameter choices.

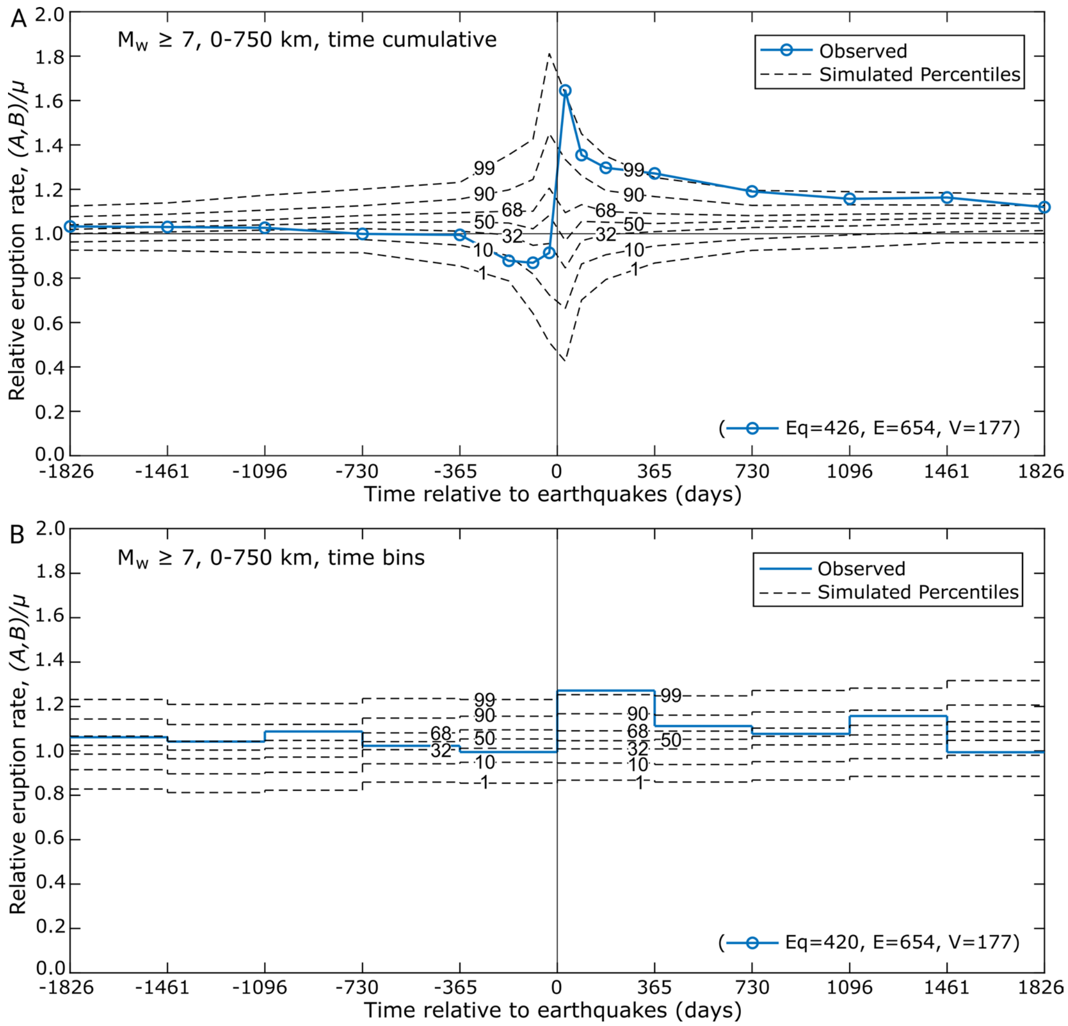


Figure 1: Combined VEI ≥ 2 eruption rates within 750 km and up to five years before and after $M_w \geq 7$ earthquakes, relative to average eruption rates. This includes repeat eruptions from a single volcano but excludes eruptions with an uncertain start date. No foreshock or aftershock filtering is applied. The percentiles of the simulated eruption rates calculated using random permutation of the observed eruption dates are shown. The amount of data used to calculate the eruption rates are also shown (Eq gives the number of earthquakes, E gives the number of unique eruptions, V gives the number of unique volcanoes; see Supplementary Material 2 for more detail). [A] Relative eruption rates over cumulative timescales. [B] Relative eruption rates over yearly binned timescales.

# 4 Results

## 4.1 Principal results

For simplicity, the results given in the main text consider only VEI ≥ 2 eruptions, with repeat eruptions from a single volcano included but eruptions with uncertain start dates excluded, and no foreshock or aftershock filtering of earthquakes applied. Sensitivity testing shows that changing these parameters does not affect the main findings (Supplementary Material 1). Overall, we find that volcanic eruption rates deviate significantly from average eruption rates within 750 km and up to several years of earthquakes with a minimum $M_w$ of 7 (Figure 1A). This primarily consists of above-average post-earthquake eruption rates, with relative eruption rates of 1.64 within 750 km and 30 days following $M_w \geq 7$ earthquakes, decreasing to 1.27 at one year, and 1.19 to 1.12 at two to five years. There are also below-average pre-earthquake eruption rates, with relative eruption rates of 0.87 to 0.91 within 750 km and 30 to 182 days before $M_w \geq 7$ earthquakes. These deviations from average eruption rates are only recorded at subduction zones, as all of the $M_w \geq 7$ earthquakes that occurred near active volcanoes between 1976–2020 were located in subduction zones (Supplementary Material 1).

To understand the significance of the observed eruption rates, Figure 1A also shows the percentiles of the simulated eruption rates calculated by randomly permutating the eruption dates. Compared to the simulations, the above-average post-earthquake eruption rates have percentile scores of >99 % over timescales of 30 days and one year, suggesting that it is very unlikely that these above-average eruption rates occur by chance. The above-average post-earthquake eruption rates over all of the other timescales also have percentile scores of >95 %, except at five years. For the below-average pre-earthquake eruption rates, the percentile score of 7 % over a timescale of 182 days suggests that there is a reasonably low chance that this below-average eruption rate occurs by chance. However, the below-average pre-earthquake eruption rates over timescales of 30 days, 91 days, and one year have percentile scores of 17–31 %, suggesting that these below-average eruption rates are more consistent with those expected by chance.

Figure 1A shows eruption rates over cumulative timescales, so deviations from the average eruption rate over short timescales before or after earthquakes could appear smeared out over longer timescales. Therefore, Figure 1B shows eruption rates in one year bins instead. The binned post-earthquake relative eruption rates are 1.27 over a timescale of one year, 1.08 to 1.15 over one to four years, and close to 1 over four to five years. However, compared to the simulations, the binned post-earthquake eruption rates over timescales of one to four years have percentile scores of 56–81 %, suggesting that eruption rates over timescales of one to four years are actually more consistent with those expected by chance than is shown when using the cumulative timescales approach.

### 4.2 Effects of $M_w$, distance, and time

The main parameters considered by previous eruption triggering studies were earthquake magnitude and the distance and timescale between earthquakes and eruptions. As previous studies have produced contrasting results, we now provide a systematic investigation into how these key parameters affect eruption rates associated with earthquakes. Figure 2 shows eruption rates over cumulative timescales of up to five years before and after earthquakes as a function of earthquake magnitude ($M_w$ 6, $M_w$ 7, and $M_w \geq 8$) and the distance from earthquakes (0–250 km, 250–500 km, 500–750 km, and 750–1000 km). Within five years of $M_w$ 6 earthquakes, relative eruption rates are generally between 1 and 1.10, regardless of distance and timescale. However, the eruption rates associated with $M_w$ 6 earthquakes exhibit few high or low percentile scores compared to the simulated eruption rates. Due to the lack of consistently significant percentile scores, the eruption rates associated with $M_w$ 6 earthquakes are likely consistent with those expected by random chance.

By contrast, post-earthquake eruption rates within 750 km and one to five years of $M_w$ 7 earthquakes are consistently above average, with relative eruption rates between 1.10 to 1.35. Post-earthquake eruption rates within 750 km and less than one year of $M_w$ 7 earthquakes are also mostly above average, although there is more variation, including very high relative eruption rates of 2.44 within 30 days and 250–500 km and very low relative eruption rates of 0.56 within 0–250 km and 30 days. This variation likely reflects the lower numbers of eruptions being counted over short timescales, which limits the statistical analysis (Supplementary Material 2). Nonetheless, the generally above-average post-earthquake eruption rates within 750 km of $M_w$ 7 earthquakes have consistently high percentile scores compared to the simulations, often being >95 %. It is therefore unlikely that these above-average eruption rates occur by chance. By contrast, pre-earthquake eruption rates within 750 km of $M_w$ 7 earthquakes are more variable as a function of distance and timescale, while beyond 750 km, eruption rates associated with $M_w$ 7 earthquakes are generally close to average.

$M_w \geq 8$ earthquakes exhibit variable post-earthquake eruption rates as a function of distance and timescale, with relative eruption rates ranging from 0.71 to 1.78 within one to five years and 750 km. This variability likely reflects the much lower numbers of $M_w \geq 8$ earthquakes in the record, which limits the statistical analysis (Supplementary Material 2). The variable post-earthquake eruption rates following $M_w \geq 8$ earthquakes display variable percentile scores compared to the simulations, suggesting that these eruption rates are consistent with those expected by chance. However, pre-earthquake eruption rates within 500 km of $M_w \geq 8$ earthquakes are generally below average, especially within 0–250 km, where relative eruption rates are 0 to 0.22. The below-average pre-earthquake eruption rates within 500 km of $M_w \geq 8$ earthquakes have low percentile scores, often being <10 %. It is therefore relatively unlikely that these below-average eruption rates occur by chance. By contrast, pre-earthquake eruption rates within 500–1000 km of $M_w \geq 8$ earthquakes are more variable and have less significant percentile scores, suggesting that they are consistent with eruption rates expected by chance.

### 4.3 Effects of earthquake depth and slip orientation

The effects of earthquake depth and slip orientation on eruption rates associated with earthquakes have not previously been studied. Therefore, we investigate how these parameters affect our principal results. Figure 3 compares eruption rates within 750 km of shallow (<70 km) and deep (≥70 km) $M_w \geq 7$ earthquakes. While shallow and deep earthquakes show similar eruption rates, deep earthquakes exhibit both greater magnitude deviations from the average eruption rate and more significant percentile scores than shallow earthquakes. In particular, below-average pre-earthquake eruption rates within 30 to 182 days and within two years before deep earthquakes have percentile scores of <5 % relative to the simulations, so these below-average eruption rates are unlikely to occur by chance. Deep earthquakes also generally have more significant percentile scores for the above-average post-earthquake eruption rates than shallow earthquakes, although the post-earthquake percentile scores are most significant when considering earthquake of all depths.

Figure 4 shows eruption rates within 750 km of $M_w \geq 7$ earthquakes depending on their slip orientation. As the orientation of the earthquake fault planes are generally unknown, our purpose for dividing earthquakes by slip orientation is to investigate the effects of different subduction zone stress regimes, rather than the effects of earthquake-driven stress changes. The focal mechanisms of deep earthquakes within subducted slabs might not reflect the crustal stress regime, so Figure 4 only includes shallow (<70 km) earthquakes. Figure 4 shows that, over all timescales, shallow reverse earthquakes generally display above-average eruption rates with high percentile scores, while shallow normal earthquakes generally display below-average eruption rates with

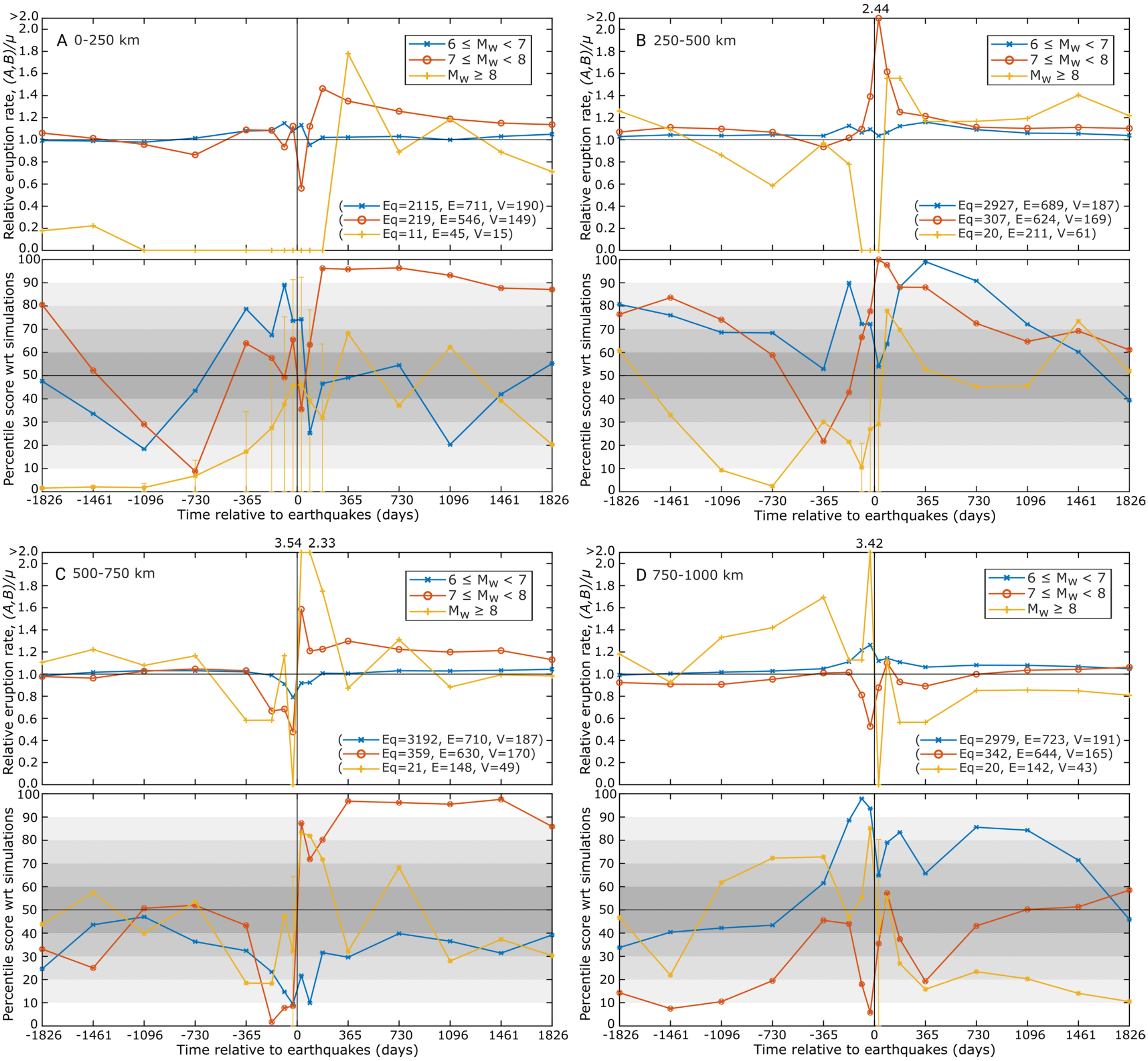


Figure 2: Top panels: Observed combined VEI ≥ 2 eruption rates over cumulative timescales up to five years before and after earthquakes as a function of earthquake magnitude, relative to average eruption rates. This includes repeat eruptions from a single volcano but excludes eruptions with an uncertain start date. No foreshock or aftershock filtering is applied. Relative eruption rates of >2 are indicated by labelling. The amount of data used to calculate the eruption rates are also shown (Eq gives the number of earthquakes, E gives the number of unique eruptions, V gives the number of unique volcanoes; see Supplementary Material 2 for more detail). Bottom panels: the corresponding percentile scores for the observed eruption rates with respect to simulations using random permutation of the observed eruption dates. Lighter shading for percentile scores near 0 % or 100 % suggests significant deviations from average eruption rates. Error bars show where the observed eruption rate is equal to the simulated eruption rates across multiple percentiles. Each pair of panels shows a different distance range from earthquakes over which eruption rates are calculated: [A] 0–250 km, [B] 250–500km, [C] 500–750km, and [D] 750–1000 km.

low percentile scores. By contrast, shallow strike-slip earthquakes generally show below-average pre-earthquake eruption rates but above-average post-earthquake eruption rates. The greater variability in the eruption rates associated with shallow normal and strike-slip earthquakes likely reflects the lower numbers of these earthquakes in the record, compared to shallow reverse earthquakes.

### 4.4 Eruption rates after versus before earthquakes

To facilitate more direct comparison with previous eruption triggering studies [Nishimura 2017; Sawi and Manga 2018; Jenkins et al. 2021], we also compare post-earthquake eruption rates with pre-earthquake eruption rates calculated over the same timescale (i.e. $A/B$). Figure 5 shows that, within 750 km and up to five years of $M_w \geq 7$ earthquakes, the post-

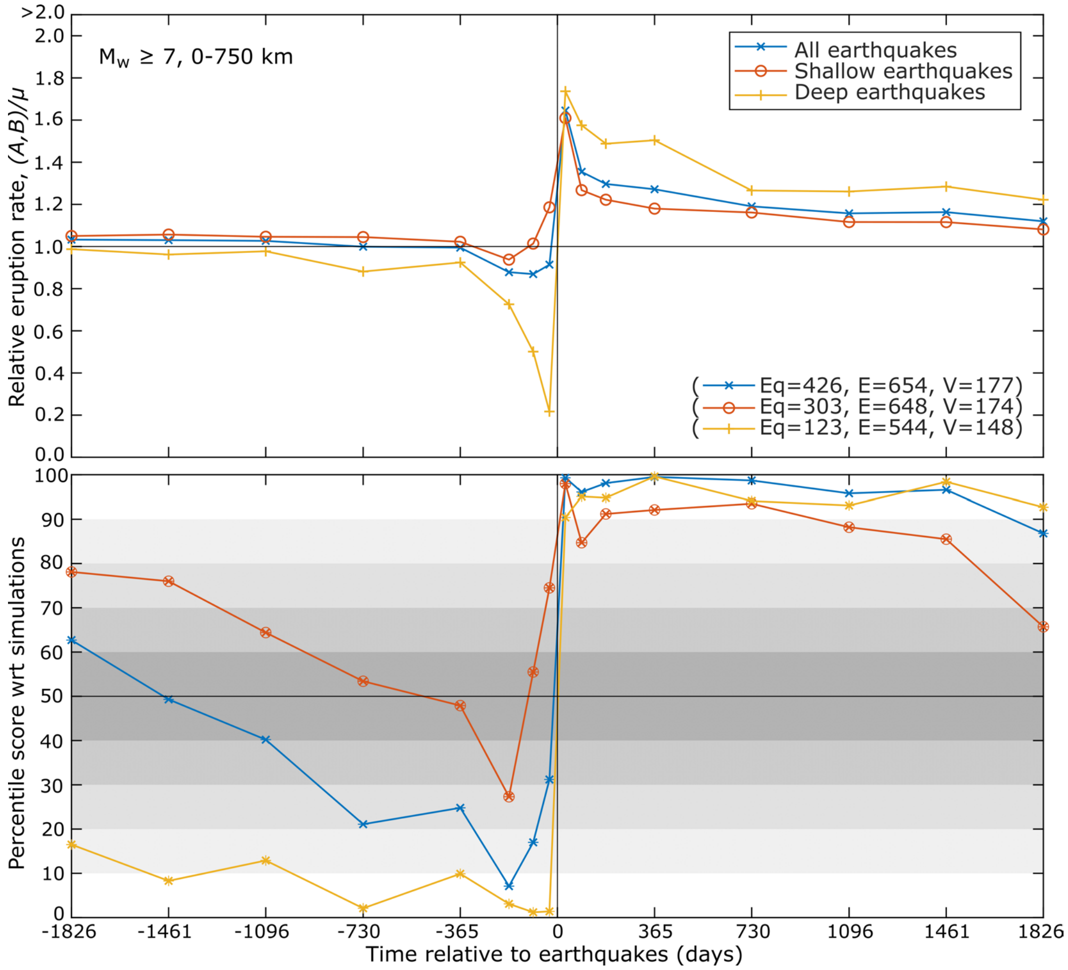


Figure 3: Top panel: Observed combined VEI ≥ 2 eruption rates within 750 km and cumulative timescales of up to five years before and after $M_w \geq 7$ earthquakes, relative to average eruption rates. Eruption rates are shown for all earthquakes, shallow earthquakes (<70 km), and deep earthquakes (≥70 km). This includes repeat eruptions from a single volcano but excludes eruptions with an uncertain start date. No foreshock or aftershock filtering is applied. The amount of data used to calculate the eruption rates are also shown (Eq gives the number of earthquakes, E gives the number of unique eruptions, V gives the number of unique volcanoes; see Supplementary Material 2 for more detail). Bottom panel: the corresponding percentile scores for the observed eruption rates with respect to simulations using random permutation of the observed eruption dates. Lighter shading for percentile scores near 0 % or 100 % suggests significant deviations from average eruption rates.

earthquake eruption rates relative to pre-earthquake eruption rates show similar values to the post-earthquake eruption rates relative to average eruption rates (Figure 1). In particular, post-earthquake eruption rates are 1.28 times the corresponding pre-earthquake eruption rates within 750 km and one year, with a percentile score of 98 % compared to simulations with randomly permutated eruption dates. By comparison, post-earthquake eruption rates are 1.27 times the average eruption rate within 750 km and one year, with a percentile score of 99 %.

## 5 Discussion

### 5.1 Effects of $M_w$, distance, and timescale

Given the variability in the calculated eruption rates associated with earthquakes across the studied parameter space, we now consider whether the observed eruption rates show physically realistic behaviours as a function of $M_w$, distance, and timescale. Specifically, the mechanisms responsible for eruption triggering invoke stress changes imparted to volcanoes by earthquakes, either due to the static elastic relaxation of the crust or the dynamic passage of seismic waves [Seropian et al. 2021]. For both static and dynamic triggering mechanisms, the stress changes experienced by volcanoes are greater for larger magnitude earthquakes and for smaller distances from the earthquake. Therefore, larger magnitude earthquakes at smaller distances should have a greater effect on eruption rates. By contrast, the importance of the timescale between earthquakes and eruptions is more complicated, as the timescales over which eruptions initiate are variable [Chamberlain et al. 2014; Kilgour et al. 2014; Metcalfe et al. 2021], and earthquake-related processes such as afterslip and visco-elastic relaxation can alter the crustal stress field over timescales far longer than the earthquake rupture [Wang et al. 2012; Copley 2014].

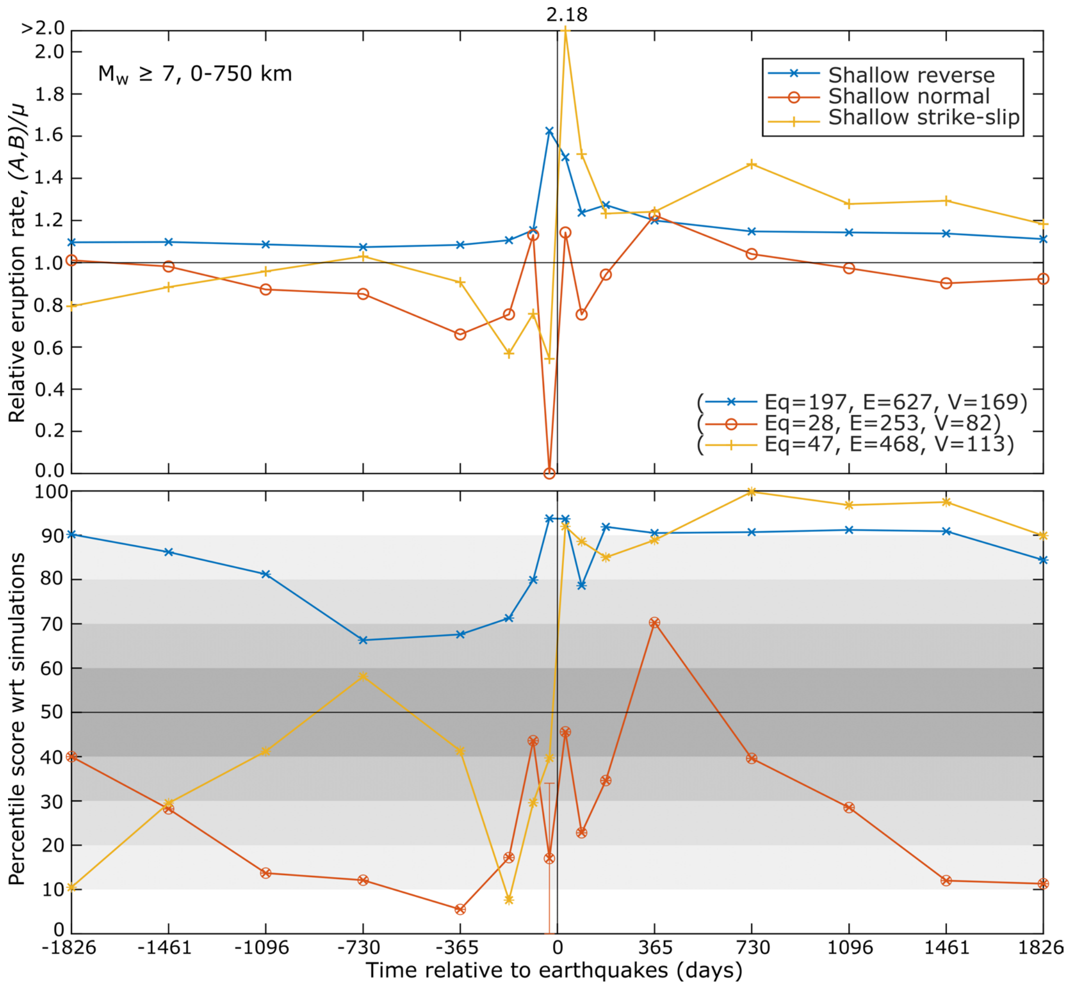


Figure 4: Top panel: Observed combined VEI ≥ 2 eruption rates within 750 km and cumulative timescales of up to five years before and after $M_w \geq 7$ earthquakes, relative to average eruption rates. The eruption rates are shown for shallow depth (<70 km) reverse, normal, and strike-slip earthquakes. This includes repeat eruptions from a single volcano but excludes eruptions with an uncertain start date. No foreshock or aftershock filtering is applied. Relative eruption rates of >2 are indicated by labelling. The amount of data used to calculate the eruption rates are also shown (Eq gives the number of earthquakes, E gives the number of unique eruptions, V gives the number of unique volcanoes; see Supplementary Material 2 for more detail). Bottom panel: the corresponding percentile scores for the observed eruption rates with respect to simulations using random permutation of the observed eruption dates. Lighter shading for percentile scores near 0 % or 100 % suggests significant deviations from average eruption rates.

Figure 2 shows that eruption rates associated with $M_w$ 6 earthquakes do not show significant deviations from average eruption rates, whereas post-earthquake eruption rates within 750 km and several years of $M_w$ 7 earthquakes deviate significantly from average eruption rates. However, post-earthquake eruption rates following $M_w \geq 8$ earthquakes do not show significant deviations from average eruption rates, although pre-earthquake eruption rates for $M_w \geq 8$ earthquakes are consistently below average. The lack of significant post-earthquake eruption rate deviations following $M_w \geq 8$ earthquakes might be explained by the low number of $M_w \geq 8$ earthquakes in our record (Supplementary Material 2). Consequently, eruption rates may follow the expected behaviour with earthquake magnitude, but more data for $M_w \geq 8$ earthquakes is needed to test this.

Above-average post-earthquake eruption rates associated mainly with $M_w$ 7 earthquakes are observed for all distances up to, but not beyond, 750 km (Figure 2). Similarly, below-average pre-earthquake eruption rates associated mainly with $M_w \geq 8$ earthquakes are observed up to 500 km, and possibly up to 750 km, but not beyond 750 km. Therefore, approximately 750 km from $M_w \geq 7$ earthquakes appears to be the limit to which significant deviations from average eruption rates occur. Given that static stress changes from earthquakes are typically viewed as important at distances of up to a few fault rupture lengths away [King et al. 1994; Stein 1999; Freed 2005], 750 km spans the range where static stress changes should be significant, and the range where static stress changes are insignificant and dynamic stress changes are more dominant. However, determining whether static or dynamic stress changes are responsible is challenging.

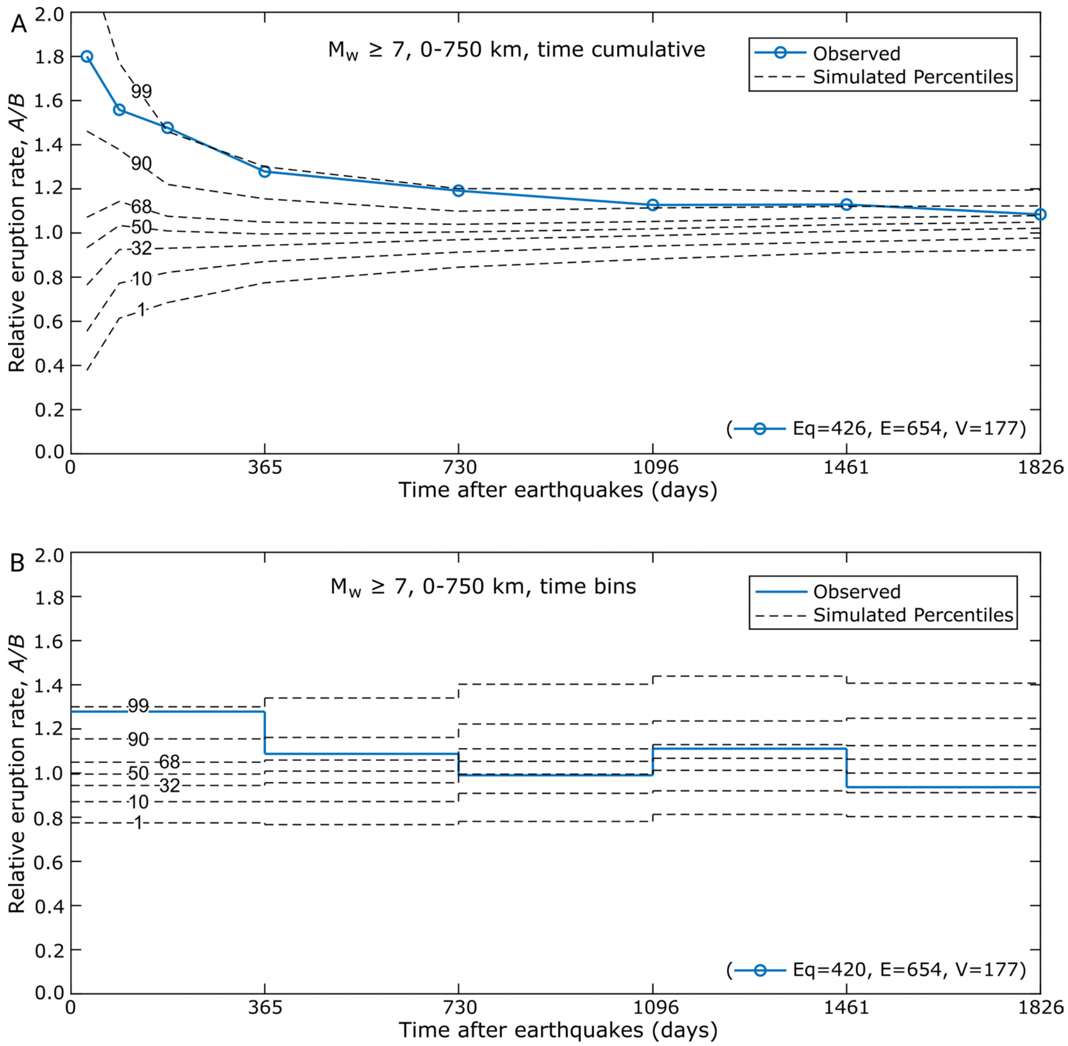


Figure 5: Combined VEI ≥ 2 post-earthquake eruption rates within 750 km and up to five years after $M_w \geq 7$ earthquakes, relative to combined pre-earthquake eruption rates calculated over the same distance and timescale. This includes repeat eruptions from a single volcano but excludes eruptions with an uncertain start date. No foreshock or aftershock filtering is applied. The percentiles of simulated eruption rates calculated using random permutation of the observed eruption dates are also shown. The amount of data used to calculate the eruption rates are also shown (Eq gives the number of earthquakes, E gives the number of unique eruptions, V gives the number of unique volcanoes; see Supplementary Material 2 for more detail). [A] Relative eruption rates over cumulative timescales. [B] Relative eruption rates over yearly binned timescales.

Furthermore, post-earthquake eruption rates following $M_w$ 7 earthquakes do not clearly follow the expected relationship with distance within 750 km; relative eruption rates following $M_w$ 7 earthquakes are generally greatest at 0–250 km, but the relative eruption rates at 500–750 km are generally both greater and more significant than those at 250–500 km.

Within 750 km of $M_w \geq 7$ earthquakes, post-earthquake eruption rates progressively decrease from a high of 1.64 times the average eruption rate within 30 days to 1.12 times the average eruption rate within five years (Figure 1). This suggests that the greatest deviations from average eruption rates occur within the shortest timescale of earthquakes. However, this result is not consistent for all distances and magnitudes (Figure 2). The low numbers of eruptions associated with earthquakes at shorter timescales (Supplementary Material 2) also means that large deviations from the average eruption rate do not always correspond to significant percentile scores. Constraining the timescales over which earthquakes affect eruption rates therefore remains challenging.

## 5.2 Effects of earthquake depth and slip orientation

Figure 3 shows that deep earthquakes (≥70 km) display greater deviations from average eruption rates than shallow earthquakes. This is true for both the above-average post-earthquake eruption rates and especially the below-average pre-earthquake eruption rates. The reasons for this are unclear, although because deep earthquakes are restricted to subducted slabs, there appears to be a link between deep subduction earthquakes and magmatism. This may relate to the location of deep earthquakes below volcanic arcs, which may cause them to have more impact on fluid and magma transport across the entire transcrustal magmatic system (Figure 6).

Similarly, Figure 4 hints at a potential relationship between the slip orientation of shallow earthquakes and the eruption rates associated with earthquakes. Overall, Figure 4 shows that post-earthquake eruption rates are generally greater than pre-earthquake eruption rates for all earthquake slip orientations. However, eruption rates are generally above average within several years of shallow reverse earthquakes and generally below average within several years of shallow normal earthquakes. Only shallow strike-slip earthquakes show the below-average pre-earthquake eruption rates and above-average post-earthquake eruption rates displayed by considering all earthquakes (Figure 1). Given that all of the $M_w \geq 7$ earthquakes that occurred near active volcanoes between 1976–2020 were located in subduction zones (Supplementary Material 1), there appears to be a relationship between the local to regional tectonic setting within the broader subduction zone environment and the eruption rates associated with large earthquakes (Figure 6). The reasons for this are unclear, and we note that using slip orientation as a proxy for the crustal stress regime is not perfect as earthquakes with different focal mechanisms can occur closely in time and space. Additionally, the relatively low numbers of shallow normal and strike-slip earthquakes in the record limit this analysis (Supplementary Material 2). The different spatial distributions of (static) stress changes caused by earthquakes with different slip orientations may also be important, although testing this is difficult due to ambiguity in the fault plane orientation from focal mechanism solutions.

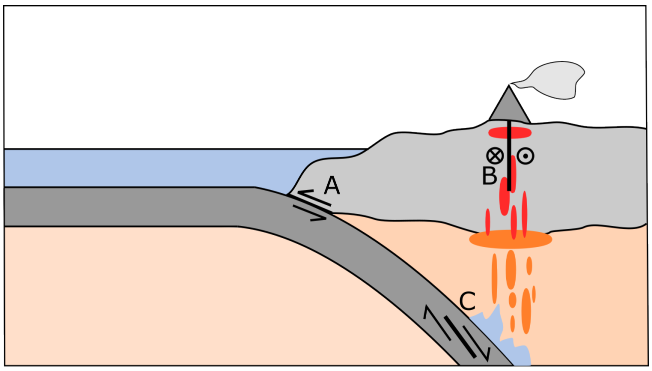


Figure 6: Schematic representation of the locations of earthquakes with different depths and slip orientations within subduction zones. For example, A represents shallow megathrust earthquakes at the plate interface, B shows earthquakes within volcanic arcs, such as major arc-parallel strike-slip faults, while C shows deep slab earthquakes, which often have normal or strike-slip focal mechanisms. These earthquake distributions may provide clues regarding the distinct eruption rates associated with different earthquakes.

### 5.3 Comparison with previous studies

Figures 1 and 2 show that volcanic eruption rates deviate significantly from average eruption rates within 750 km of earthquakes with a minimum $M_w$ of 7. This consists primarily of post-earthquake eruption rates that are around 1.25 times the average eruption rate over timescales of at least one year, and possibly to a lesser extent over two to four years, mainly following $M_w$ 7 earthquakes. However, we also find that pre-earthquake eruption rates are around 0.9 times the average eruption rate over timescales of at least 182 days, and possibly to a lesser extent over one year, mainly before $M_w \geq 8$ earthquakes and possibly also before $M_w$ 7 earthquakes. Although decreased eruption rates prior to earthquakes were first proposed by Carr [1977], we currently have no physical explanation for this borderline statistically significant finding. By contrast, Lemarchand and Grasso [2007] suggested that eruption rates increase during the six to ten days both before and after earthquakes, within a distance of up to ten times the earthquake rupture length. However, as Lemarchand and Grasso [2007] used a minimum earthquake magnitude of 4.8, their study likely included volcanotectonic earthquakes, for which a short-term correlation between earthquakes and eruptions is expected.

Compared with recent global statistical studies on eruption triggering, our post-earthquake eruption rates of around 1.25 times the average eruption rate (i.e. 25 % above the average eruption rate) are greater than the approximately 10 % increase found by Sawi and Manga [2018] but lower than the 50 % increase suggested by Nishimura [2017]. However, the parameter ranges investigated by Sawi and Manga [2018] and Nishimura [2017] were more restricted than we present here. Using our methodology and datasets with the parameters investigated by Sawi and Manga [2018] ($M_w \geq 6$ , <800 km between earthquakes and eruptions, two months to two years timescales), we find that post-earthquake eruption rates are 6–7 % above average. This is consistent with the 5–12 % increase in eruption rates reported by Sawi and Manga [2018]. However, when comparing post-earthquake eruption rates with pre-earthquake eruption rates using the parameters of Sawi and Manga [2018], we find eruption rate increases of only 3–4 %.

Using our methodology and datasets with the parameters reported by Nishimura [2017] ($M_w \geq 7.5$, <200 km between earthquakes and eruptions, five year timescale), we find that post-earthquake eruption rates are 23 % below average. We also find that post-earthquake eruption rates decrease by 4 % relative to pre-earthquake eruption rates over the same distance and timescale. These values differ significantly from the 50 % increase in post-earthquake eruption rates reported by Nishimura [2017]. Inspection of our results reveals that this discrepancy is mostly caused by differences in the earthquake locations used by up to half a degree of latitude and longitude; we obtain these values from the earthquake centroid location, whereas Nishimura [2017] used the earthquake epicentre location. For a small distance of 200 km from each $M_w \geq 7.5$ earthquake, these variations of several tens of kilometers significantly alter which eruptions are associated with each earthquake. By contrast, our principal results (within 750 km of $M_w \geq 7$ earthquakes) are not sensitive to which earthquake location is used (Supplementary Material 1).

While we do not disagree with the findings of Nishimura [2017] and Sawi and Manga [2018], our results argue for post-earthquake eruption rates intermediate between those reported by Nishimura [2017] and Sawi and Manga [2018]. However, by only investigating a smaller parameter range, Nishimura [2017] and Sawi and Manga [2018] were not able to fully characterise the volcanic eruption rates associated with large earthquakes. In particular, we show that calculated eruption rates can differ significantly as a function of the earthquake magnitudes, distances, and timescales considered (Figure 2). The difference between our results and those of Nishimura [2017], caused by using slightly different earthquake locations, also illustrates this point and highlights the importance of considering the whole parameter space in order to reach more reliable conclusions.

### 5.4 Implications for forecasting

Assuming a causative relationship between earthquakes and the observed deviations from average eruption rates, we find that $M_w \geq 7$ earthquakes promote eruptions at volcanoes up to 750 km away within the following year to several years, while eruptions are also inhibited for several months to half a year within 750 km before $M_w \geq 7$ earthquakes. Consequently, at the regional scale, below-average volcanic eruption rates correspond to an increased likelihood of a large earthquake occurring, while a large earthquake increases the likelihood of volcanic eruptions. However, the scope for using these relationships predictively is limited. For example, our finding that volcanic eruption rates are 1.27 times the average eruption rate within 750 km and one year following $M_w \geq 7$ earthquakes is derived from there being 248 observed eruptions compared to an average eruption rate of only 195 eruptions (Supplementary Material 2). In other words, there were 53 extra or potentially "triggered" VEI ≥ 2 eruptions within 750 km and one year of the $M_w \geq 7$ earthquakes in our catalogue. Given that our catalogue contains 533 $M_w \geq 7$ earthquakes, of which 426 occurred within 750 km of an active volcano, this corresponds to, on average, an extra 0.12 eruptions within one year following each $M_w$ 7 earthquake. As around 10 $M_w \geq 7$ earthquakes occur near active volcanoes annually at the global scale, on average only one or two eruptions may be promoted by earthquakes each year. For comparison, global VEI ≥ 2 eruption rates are around 20–40 eruptions each year.

## 6 Conclusions

Overall, we find that $M_w \geq 7$ earthquakes are associated with post-earthquake eruption rates of around 1.25 times the average eruption rate within 750 km and one year, as well as pre-earthquake eruption rates of around 0.9 times the average eruption rate within 750 km and half a year (Figure 1A). Randomised simulations show that the probability of the observed above-average post-earthquake eruption rates occurring by chance is very low (<1 %), while the probability of the observed below-average pre-earthquake eruptions rates occurring by chance is also low (<10 %). Post-earthquake eruption rates may also remain above average for two to four years following earthquakes, while pre-earthquake eruption rates may be below-average for up to one year before earthquakes, although these deviations are less statistically significant (Figure 1B). Over shorter timescales, quantifying the significance of eruption rates is challenging due to the small sample sizes currently available in modern global records (Figure 2 and Supplementary Material 2). However, we do find some preliminary evidence for short-term (30 to 182 days) increases in post-earthquake eruption rates following nearby $M_w \geq 7$ earthquakes (Figure 1).

Assuming a causative relationship between earthquakes and the observed deviations from average eruption rates, we conclude that large earthquakes promote eruptions at nearby volcanoes, while eruptions also appear to be inhibited shortly before nearby large earthquakes. However, this general observation may not apply to individual earthquakes, as we find that deep earthquakes more strongly affect eruption rates than shallow earthquakes, while earthquakes with different slip orientations affect eruption rates differently. Further study of these relationships represents a good opportunity to further our understanding of tectono-magmatic processes. Similarly, additional earthquake and eruption data gathered over the coming decades will help clarify the statistical relationships described here, such as whether eruption rates show physically realistic behaviours as a function of earthquake magnitude and distance from earthquakes. More data will also facilitate the use of a binned approach instead of the cumulative approach where data are currently sparse, such as for short timescales (less than one year) and $M_w \geq 8$ earthquakes. There is particular potential in this regard with the volcanic record, where increased remote sensing can provide more complete eruption records and also enable investigation into potential relationships between earthquakes and non-eruptive volcanic phenomena [e.g. Takada and Fukushima 2013; Hill-Butler et al. 2020].

## Author Contributions

AJ completed the formal analysis and writing of the original manuscript. AJ, AR, and JB contributed to the conceptualisation, methodology, and editing of the manuscript.

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## Data Availability

The data used in this study are freely available from the Global Centroid Moment Tensor Project ([Dziewonski et al. 1981]; https://www.globalcmt.org/) and the Global Volcanism Program (Global Volcanism Program [2013]; https://volcano.si.edu/). The MATLAB code EqVolc developed and used by this study and Jenkins et al. [2021] can be downloaded from github (https://github.com/ex18983/EqVolc).

## Copyright notice



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