Supplementary Material 1 for 'The relationship between large earthquakes and volcanic eruptions: A global statistical study'

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Abstract

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S1 Suitability of time-averaged eruption rates

A potential issue with using long-term time-averaged eruption rates is that time-averaging could smooth out inherently clustered underlying eruption rates. To investigate this, Figure S1 shows the distribution of inter-eruption times within 750 km of $M_w \geq 7$ earthquakes, compared with simulated distributions of inter-eruption times calculated using randomly permutated eruption dates. The observed distribution of inter-eruption times deviates slightly from the average simulated distribution of inter-eruption times over inter-eruption times of around 1 to 2 years, showing that there is some clustering in the observed eruptions at inter-eruption times of 1 to 2 years. However, the observed distribution of inter-eruption times is not vastly different from a distribution that would be expected for random eruption dates, suggesting that this clustering effect is only minor. Therefore, we consider that our averaging method is likely suitable. Further evidence of the suitability of our averaging method is shown by the fact that observed eruption rates tend towards the average eruption rate over long timescales of 1826 days before and after earthquakes (e.g. Figure 1 in the main text).

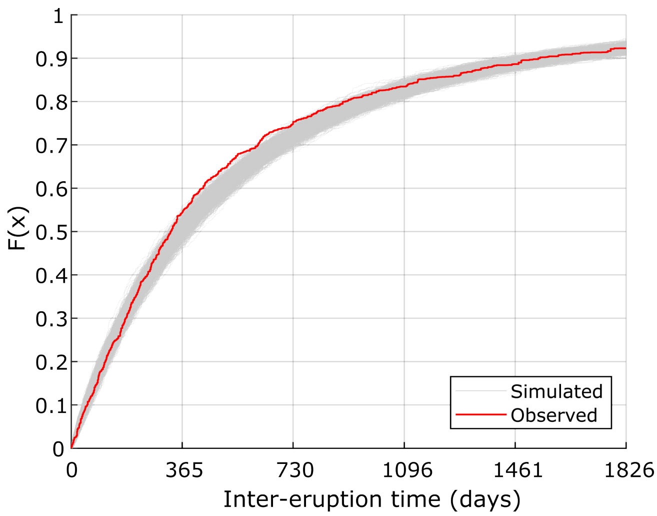

Figure S1: Cumulative distribution of inter-eruption times within 750 km of $M_w \geq 7$ earthquakes, compared with simulated cumulative distributions of inter-eruption times calculated using randomised eruption dates. The inter-eruption times are taken from the long-term time-average eruption rate calculation for each earthquake, which identifies all of the eruptions within the specified distance of each earthquake, before calculating the time between subsequent eruptions. To calculate these inter-eruption times, we allow repeat eruptions from a single volcano but exclude eruptions with an uncertain start date; for the inter-eruption times calculation, we also do not exclude the 5 years either side of the earthquake.

S2 Sensitivity testing of results

In the interests of robustly testing the results given in the main text, this section explores how varying the parameters that were fixed in the main text affects our principal results.

S2.1 Simulation method

In the main text, we use random permutation of the selected eruption dates with no limit on the recurrence of eruptions from a single volcano. However, this could potentially generate unrealistically clustered simulated eruptions at individual volcanoes, which could affect the percentile scores. Therefore, we modify our random permutation algorithm to impose a limit on the recurrence of eruptions from a single volcano within either 91 days or 1 year. To ensure successful permutation of all of the selected eruption dates while conforming with the recurrence limits, we reassign eruption dates to the volcanoes that have the most eruptions first; if a randomly chosen eruption date would violate the recurrence limit given the eruption dates already reassigned to a volcano, then the chosen date is returned to the pool and another eruption date is randomly chosen instead. Figure S2 shows that using eruption recurrence limits does not significantly affect the percentile scores of the observed eruption rates, suggesting that random permutation of the selected earthquake dates without a recurrence limit is appropriate.

Figure S2 also shows the percentile scores for the observed eruption rates calculated using completely randomised eruption dates instead of randomly permutated eruption dates [e.g. Sawi and Manga 2018]. Using completely randomised eruption dates increases the percentile scores for the observed eruption rates. This decreases the significance of

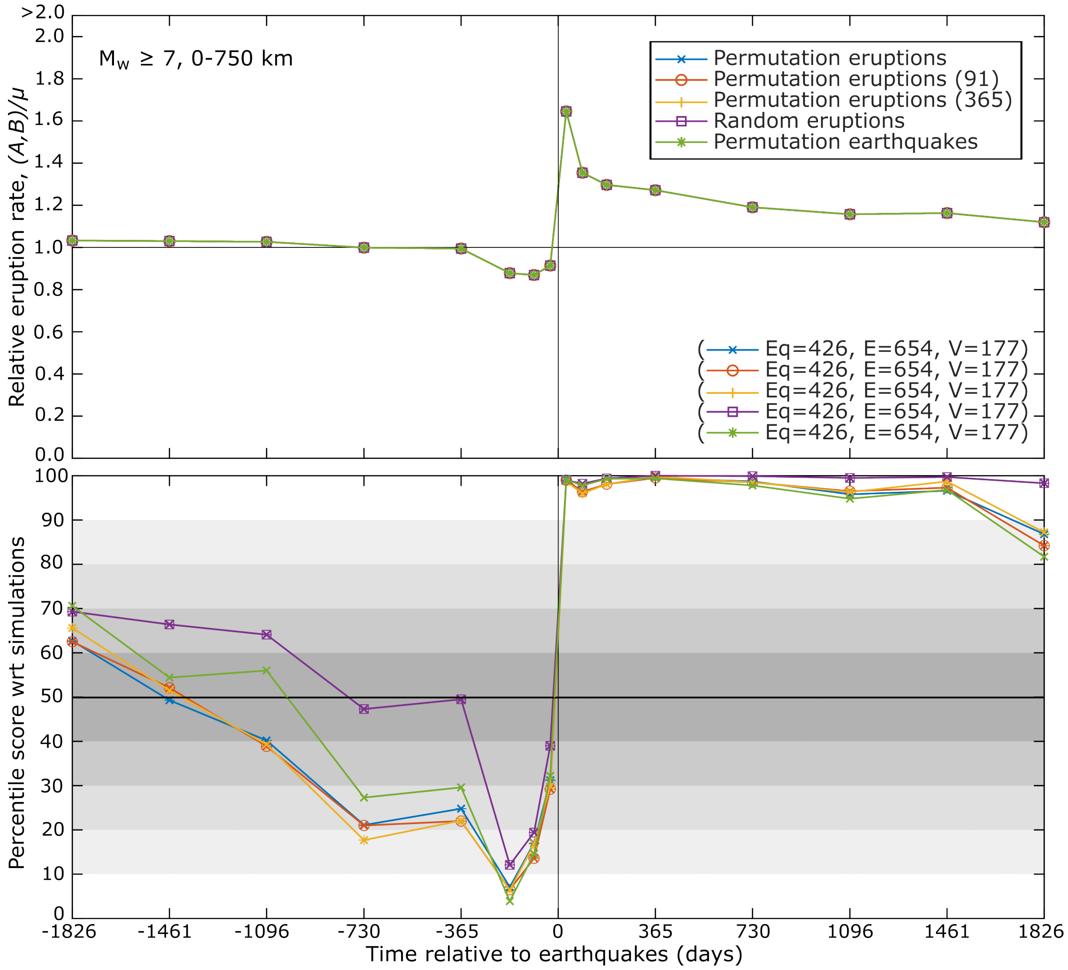

Figure S2: Top panel: Observed combined VEI ≥ 2 eruption rates within 750 km and cumulative timescales of up to 5 years before and after $M_w \geq 7$ earthquakes, relative to average eruption rates. This includes repeat eruptions from a single volcano but excludes eruptions with an uncertain start date. No foreshock or aftershock filtering is applied. The 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 different simulation methods: random permutation of the observed eruption dates; random permutation of the observed eruption dates with a recurrence limit on eruptions at a single volcano of 91 or 365 days; completely random eruption dates; and random permutation of the observed earthquake dates. Lighter shading for percentile scores near 0% or 100% suggests significant deviations from average eruption rates.

the below average pre-earthquake eruption rates, although not considerably for timescales of ≤182 days. By contrast, using completely randomised eruption dates increases the significance of the above average post-earthquake eruption rates, generating percentile scores of >99% for all timescales between 182 days and 4 years. Using completely randomised eruption dates produces higher percentile scores than random permutation of eruption dates because observed global rates of earthquakes and eruptions are correlated, likely due to factors other than eruption triggering [Jenkins et al. 2021]. Consequently, with random permutation of eruption dates, above average eruption rates associated with earthquakes are expected by chance to some degree. This is shown by the median percentile of the random permutation simulations exhibiting slightly above average eruption rates within 5 years of earthquakes (Figure 1- note that the peak and dip in the median percentile at timescales of 30 days before and after earthquakes respectively is likely an artefact caused by the low numbers of eruptions being counted at such short timescales, which highlights the difficulty in interpreting observed eruption rates at such short timescales). By contrast, with completely random eruption dates, earthquakes are associated with average eruption rates by chance.

Figure S2 also shows the percentile scores for the observed eruption rates calculated by using randomly permutated earthquakes dates instead of randomly permutated eruption dates. Figure S2 shows that using randomly permutated earthquakes dates does not significantly affect the percentile scores of the observed eruption rates.

S2.2 Foreshock and aftershock filtering

Large earthquakes trigger aftershocks, while large earthquakes themselves can occur in sequences [Freed 2005]. In the main text, we do not filter potential foreshocks or aftershocks from the selected earthquakes. However, because we calculate eruption rates for each selected earthquake, including multiple related earthquakes could skew the results by causing a single eruption to be counted for all of those earthquakes. Therefore, we use a simple method described by Nishimura [2017] to identify earthquakes that occur within a specified distance and time period of a larger earthquake as potential foreshocks and aftershocks. Figure S3 shows that removing potential foreshocks and aftershocks using the same distance and timescale as used for calculating eruption rates, or using the same distance and a timescale of 14 days, does not significantly affect the principal results.

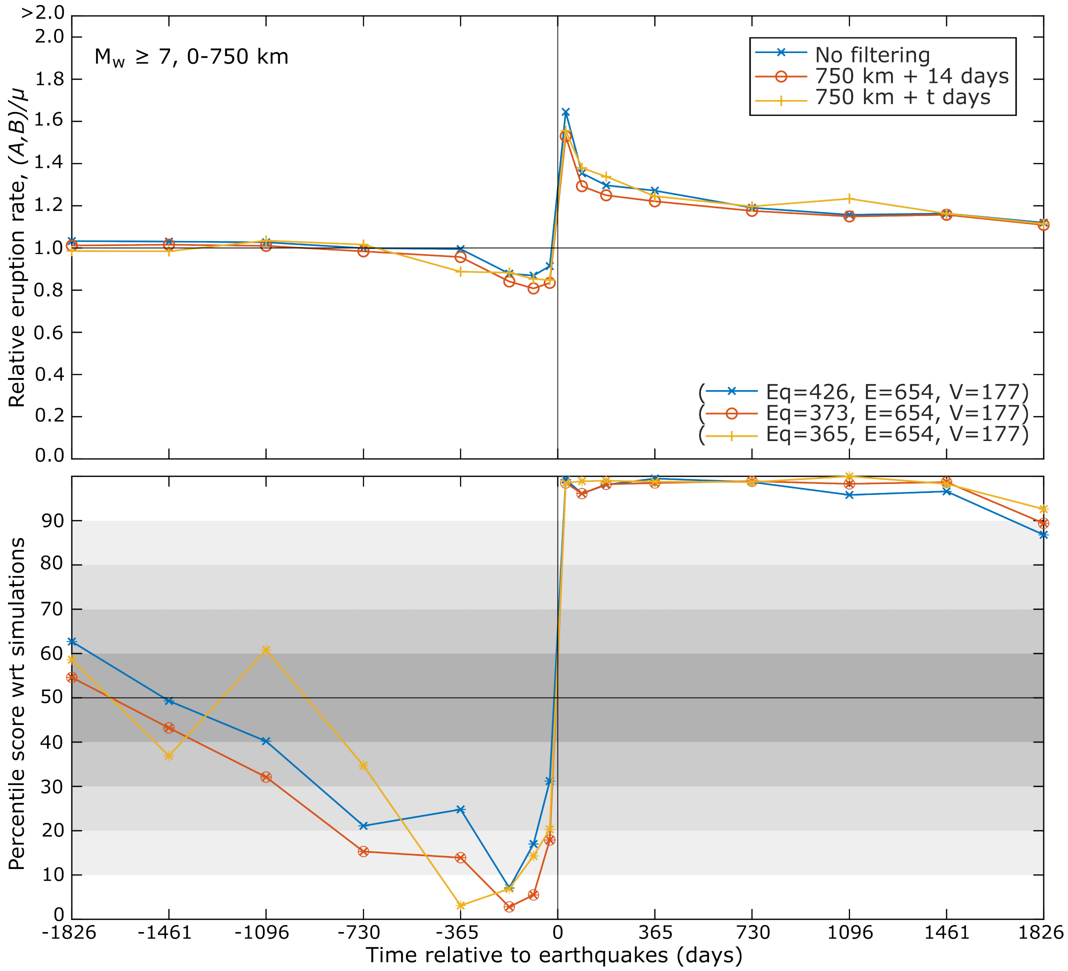

Figure S3: Top panel: Observed combined VEI ≥ 2 eruption rates within 750 km and cumulative timescales of up to 5 years before and after $M_w \geq 7$ earthquakes, relative to average eruption rates. The eruption rates are shown using either the earthquake centroid location (centre of energy release) or the hypocentre location (start of the rupture). This includes repeat eruptions from a single volcano but excludes eruptions with an uncertain start date. 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.

S2.3 Eruption VEI

In the main text, we use a minimum eruption threshold of VEI ≥ 2, as this is the lowest VEI for which we are confident that the eruption record is complete. However, Figure S4 shows that removing the VEI threshold (i.e. VEI ≥ 0) does not greatly alter the principal results, with the exception of a lower percentile score for the above average post-earthquake eruption rates over a timescale of 182 days. By contrast, increasing the threshold to VEI ≥ 3 greatly reduces the percentile scores for the above average post-earthquake eruption rates and also completely removes the below average pre-earthquake eruption rates. This may be due to the lower number of VEI ≥ 3 eruptions in the record, although more data is needed to test this.

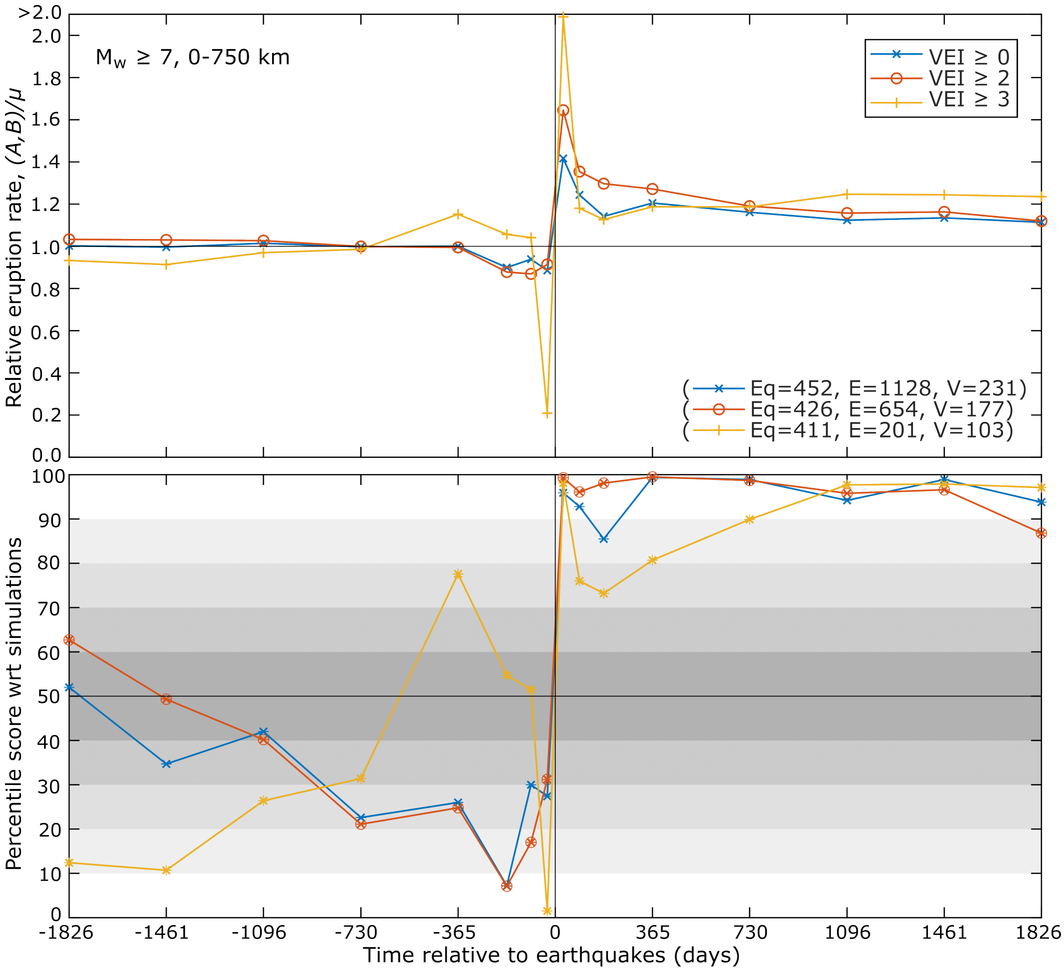

Figure S4: Top panel: Observed combined volcanic eruption rates within 750 km and cumulative timescales of up to 5 years before and after M_w ≥ 7 earthquakes, relative to average eruption rates. The eruption rates are shown for eruptions with a minimum VEI of 0, 1, and 2. This includes repeat eruptions 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.

S2.4 Repeat and uncertain eruptions

In the main text, we allow repeat eruptions from a single volcano within the specified timescale, but we exclude eruptions with an uncertain start date. Figure S5 shows that over short timescales, excluding repeat eruptions does not greatly affect the percentile scores of the observed below average pre-earthquake eruption rates or the observed above average post-earthquake eruption rates. For timescales ≥1 year, excluding repeat eruptions causes the percentile scores to be higher, but this does not impact our principal findings. By contrast, Figure S6 shows that including eruptions with an uncertain start date causes the percentile scores to be lower, but again this does not affect our principal findings.

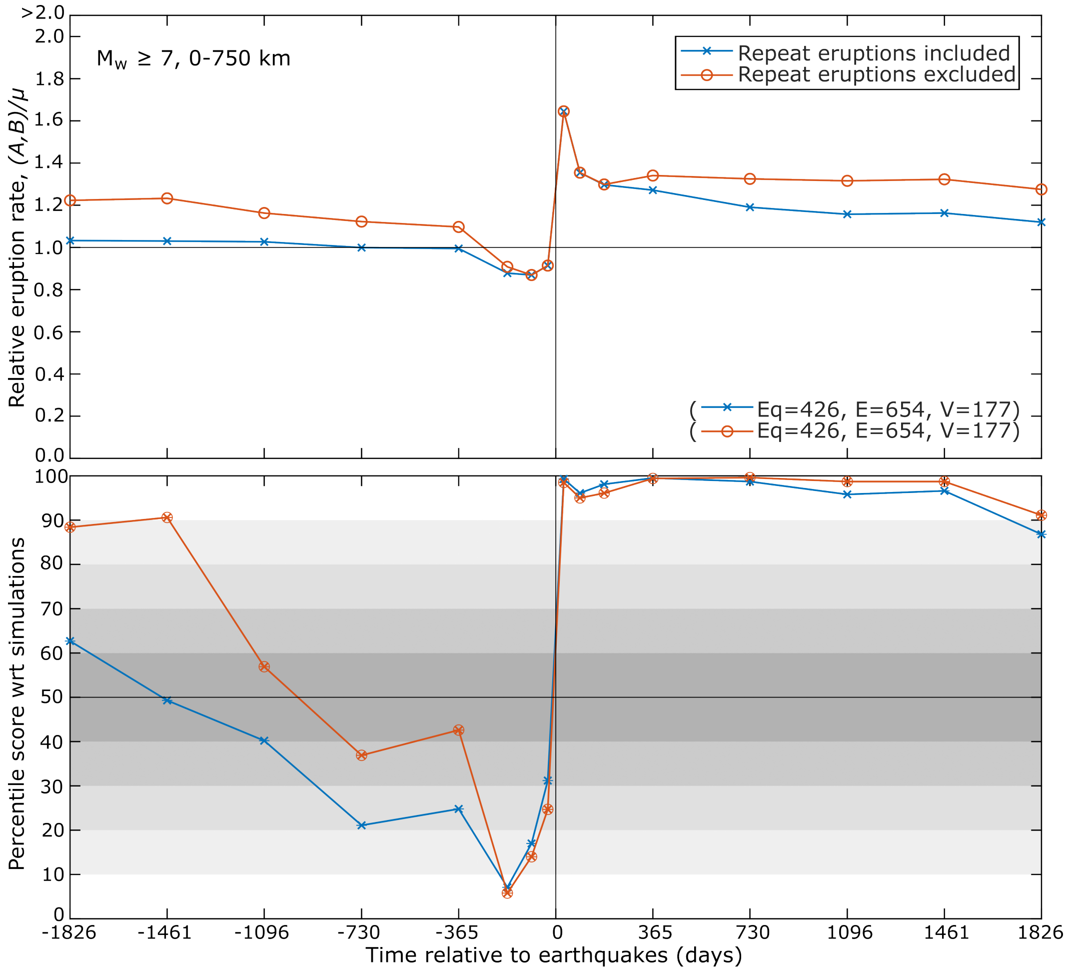

Figure S5: Top panel: Observed combined VEI ≥ 2 eruption rates within 750 km and cumulative timescales of up to 5 years before and after $M_w \geq 7$ earthquakes, relative to average eruption rates. The eruption rates are shown both including and excluding repeat eruptions from a single volcano within the specified timescale. This 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.

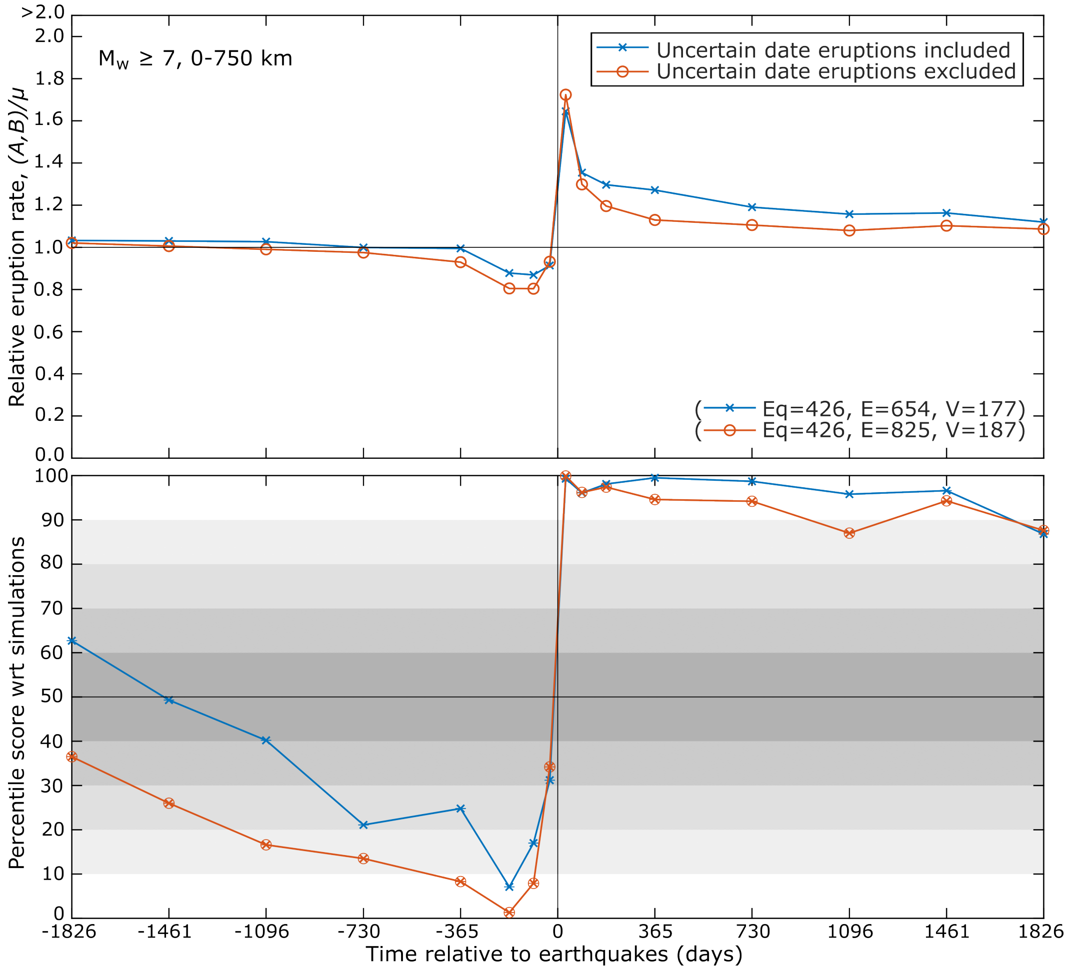

Figure S6: Top panel: Observed combined VEI ≥ 2 eruption rates within 750 km and cumulative timescales of up to 5 years before and after $M_w \geq 7$ earthquakes, relative to average eruption rates. The eruption rates are shown both including and excluding eruptions with an uncertain start date. This includes repeat eruptions from a single volcano. 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.

S2.5 Earthquake location method

In the main text, we use earthquake locations from the centroid location (centre of energy release) given in the CMT catalogue. However, when comparing our results to those of Nishimura [2017], who used hypocentre locations (start of the rupture), we find significant differences. Therefore, we investigate the sensitivity of our principal results to which earthquake location method is used. Figure S7 shows that using hypocentre locations from the CMT instead of centroid locations does not greatly alter the principal results. The differences when comparing directly with Nishimura [2017] therefore likely arise due to the smaller distance (250 km) being more susceptible to changes in which eruptions are counted. Additionally, the higher earthquake magnitude threshold ($M_w \geq 7.5$) of Nishimura [2017] means there are fewer earthquakes and eruptions being counted, so the results are more sensitive to changes of a few individual eruptions either being counted or not.

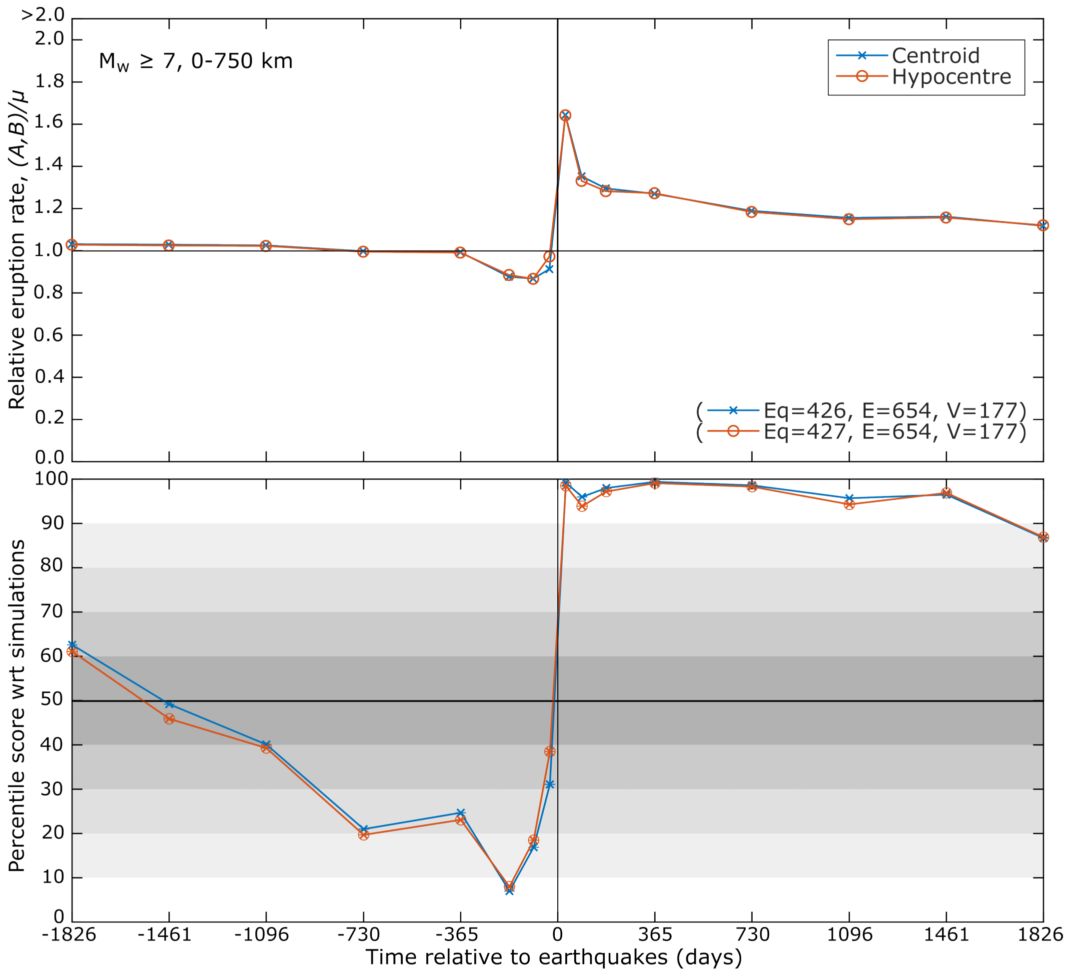

Figure S7: Top panel: Observed combined VEI ≥ 2 eruption rates within 750 km and cumulative timescales of up to 5 years before and after $M_w \geq 7$ earthquakes, relative to average eruption rates. The eruption rates are shown for earthquakes using both centroid locations and hypocentre locations. This 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.

S3 Global distribution of eruption rates

The eruption rates for each individual earthquake can also be used to investigate whether there are any spatial patterns in the eruption rates associated with earthquakes. Figure S8a shows the global distribution of eruption rates within 750 km and 1 year following $M_w \geq 7$ earthquakes, while Figure S8b shows the global distribution of eruption rates within 750 km and 182 days before $M_w \geq 7$ earthquakes. It is noticeable that earthquakes which occur near eruptions are restricted to subduction zones. Although it is difficult to identify any spatial patterns in the eruption rates, the similarity between Figure S8a and Figure S8b further highlights how post-earthquake and pre-earthquake eruption rates are correlated.

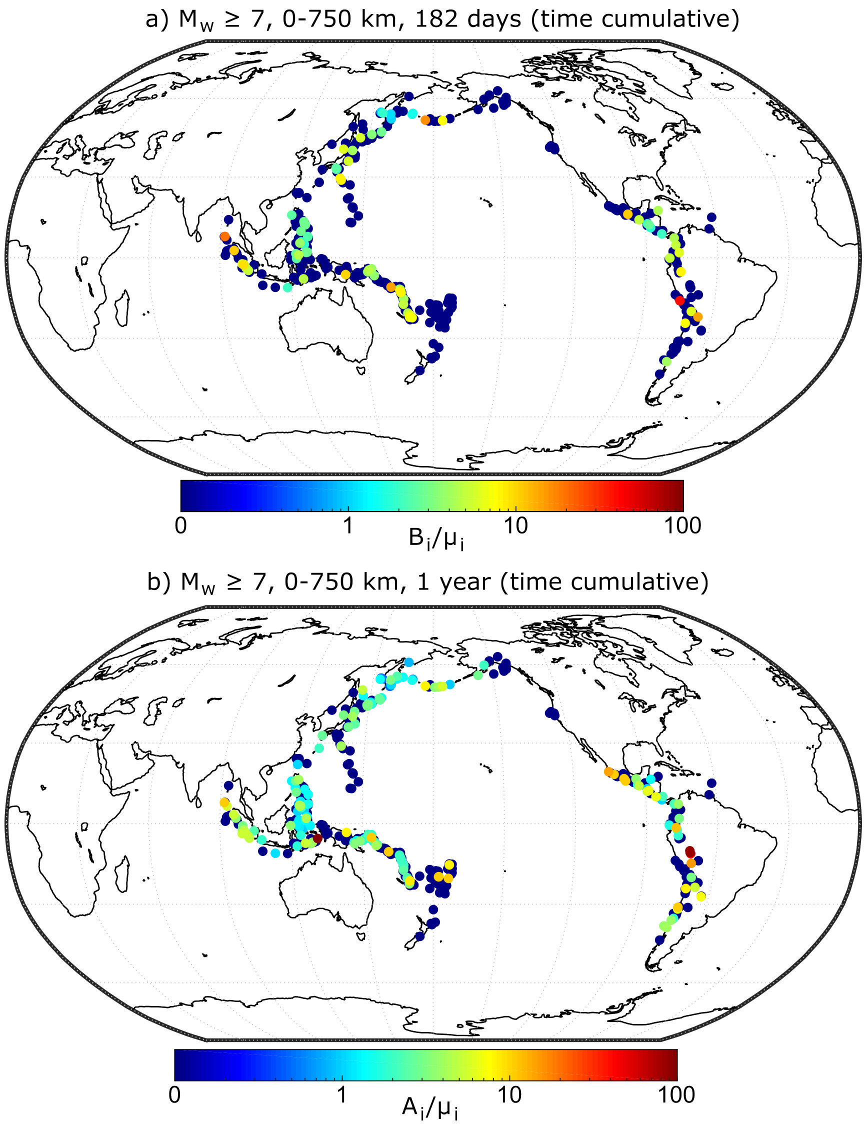

Figure S8: Spatial distribution of observed VEI ≥ 2 eruption rates within 750 km of $M_w \geq 7$ earthquakes for each individual earthquake. a) Pre-earthquake relative eruption rates within 182 days and b) Post-eruption relative eruption rates within 1 year. This includes repeat eruptions from a single volcano but excludes eruptions with an uncertain start date. No foreshock or aftershock filtering is applied. Only earthquakes which occur within 750 km of an active volcano (i.e. μ_i and/or B_i and/or A_i > 0) are shown. Note that the earthquakes are plotted in order from lowest to greatest relative eruption rate.

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