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Triggering of volcanic eruptions

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Although earthquakes and volcanic eruptions are each manifestations of large-scale tectonic plate and mantle motions, it is usually thought that the occurrences of these events are not directly related. There have been some studies, however, in which triggering of volcanic eruptions by earthquakes (remote from the volcano) has been proposed[1,2]. The 1992 Landers (southern California) earthquake caused triggered seismicity at very large distances[3], including the magmatically active[4] Long Valley caldera region which also experienced a significant coincident deformation transient[5]. Motivated by this demonstration of the ability of a distant earthquake to disturb a volcanic system, and the earlier studies of specific cases of eruption triggering, we examine here the historical record of eruptions and earthquakes to see if there are indeed significantly more eruptions immediately following large earthquakes. We find that within a day or two of large earthquakes there are many more eruptions within a range of 750 km than would otherwise be expected. Additionally, it is well known[6] that volcanoes separated by hundreds of kilometres frequently erupt in unison; the characteristics of such eruption pairs are also consistent with the hypothesis that the second eruption is triggered by earthquakes associated with the first.

Small-to-moderate (magnitudes up to ~6) earthquakes usually accompany volcanic eruptions; they may occur before and after the initial eruption as magma movement stresses the surrounding crust. Our concern here is rather with large earthquakes distant from the volcano, and with the activity associated with other eruptions. We are aware of only a few studies in which triggering of volcanic eruptions by earthquakes is considered, even though the possibility had been raised long ago[7]. Yokoyama[1] and Nakamura[2] have collected many reports of volcanic activity (including volcanic earthquakes, explosions, steamings and rumblings) which strongly suggest a connection and Nakamura gives a table of proposed triggered eruptions. They proposed that either the static strains or the seismic waves may have caused the triggering. It has been suggested that eruptions in Java[8] and South America[9] are triggered by earthquakes. Williams[10] commented on activity at Ulawun within a week of the eruption and earthquake at Rabaul (120 km away) in 1994 and suggested that a bubble mechanism[11,12], as proposed by Linde *et al.*[5], could apply. Gudmundsson and Saemundsson[13] reported on a weak relationship between earthquakes and eruptions in Iceland. Caldera unrest[14] often follows large earthquakes. Triggered seismicity, at distances in excess of 1,000 km, was dramatically clear following the Landers earthquake[3]. Also clear from borehole strainmeter and long-baseline tiltmeter records[5] is that the Long Valley caldera experienced a significant deformation transient coherent with the enhanced rate of local seismicity. Although it has been noted[6] that separated volcanoes frequently erupt on the same day, we are unaware of any mechanism proposed to explain this.

Here we take an approach complementary to that of searching for direct evidence[1,2] for the pairing of earthquakes and eruptions. We examine global catalogues for the past several hundred years. We use the Smithsonian Institution, Global Volcanism Program catalogue[6] of volcanic eruptions, and combine the earthquake catalogues from the US Geological Survey National Earthquake Information Center compendium[15] (duplication of events is avoided). The Landers experience indicates that the process being considered is more likely to be activated by large earthquakes—previous smaller earthquakes in California did not generate such clear triggering. Thus we consider great (magnitude ⩾8) earthquakes and also those with magnitudes in the range 7.0–7.9. We also require that the eruption be within a few days of the earthquake in order to be a candidate triggered eruption; earlier investigations have accepted longer time windows. From the eruption catalogue, we consider only those for which the date is given to the day; many eruptions occur in remote areas and the start time of the eruption is often not known. We also limit the search to eruptions with volcanic explosivity index (VEI, a 0–8 scale of explosive magnitude) of 2 or greater; this excludes non-explosive and small eruptions and so adds to the robustness of our

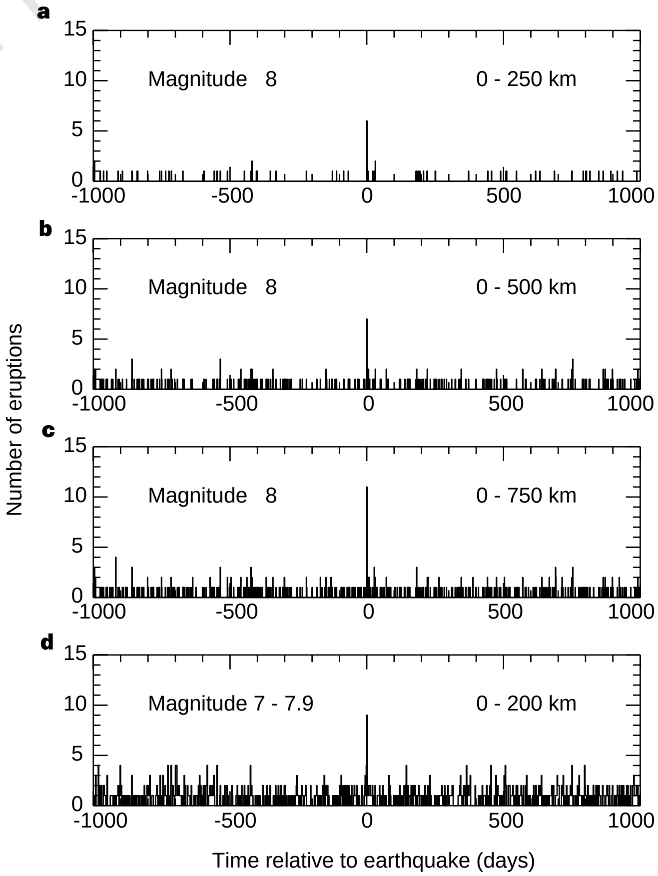

Figure 1 Histograms of number of eruptions occurring within ±1,000 days of large earthquakes. In **a**, **b** and **c**, the eruptions, following earthquakes of magnitude >8, are grouped in 1-day bins; **a**, **b** and **c** are for earthquake–eruption distances of up to 250 km, 500 km and 750 km, respectively. The large peak for the bin following the earthquake is evidence for a triggering effect, although there is no evidence for triggering in the distance range 250–500 km. In **d**, the eruptions following earthquakes of magnitude 7–7.9 are grouped in 2-day bins for the distance range 0–200 km. Most of these eruptions are at distances >100 km. All other time bins display expected random values.

Table 1 List of earthquake-triggered eruption pairs in Fig. 1

Earthquake							Dist. (km)	Eruption							
Year	Local time			Lat. (deg.)	Long (deg.)	Mag.		Type*	Year	Time		VEI†	Lat. (deg.)	Long (deg.)	Volcano‡
	Month	Day	Hour							Month	Day				
1587	09	03	20	–0.22	–78.50	7.7	12	P	1587	09	03	3	–0.17	–78.60	Guargua Pichincha (Ecuador)
1730	07	08	05	–33.05	–71.63	8.7	707	S	1730	07	08	2	–39.42	–71.93	Villarrica (Chile-C)
1737	12	24	00	–39.80	–73.20	7.7	117	S	1737	12	24	2	–39.42	–71.93	Villarrica (Chile-C)
1822	11	19	21	–33.05	–71.63	8.5	180	S	1822	11	19	2	–33.78	–69.90	San Jose (Chile-C)
1822	11	19	21	–33.05	–71.63	8.5	707	S	1822	11	19	2	–39.42	–71.93	Villarrica (Chile-C)
1835	02	20	10	–36.83	–73.03	8.1	663	S	1835	02	20	2	–42.78	–72.43	Minchinmavida (Chile-S)
1835	02	20	10	–36.83	–73.03	8.1	732	S	1835	02	20	2	–43.42	–72.83	Yanteles, Cerro (Chile-S)
1837	11	07	06	–39.80	–73.20	8.0	117	S	1837	11	07	2	–39.42	–71.93	Villarrica (Chile-C)
1837	11	07	06	–39.80	–73.20	8.0	156	S	1837	11	07	2	–41.10	–72.49	Osorno (Chile-S)
1854	06	27	00	50.50	158.00	7.0	178	S	1854	06	27	2	50.86	155.55	Alaid (Kurile Is.)
1868	08	15	15	0.80	–77.70	7.0	183	S	1868	08	15	2	–0.68	–78.44	Cotopaxi (Ecuador)
1899	09	03	20	60.00	–142.00	8.3	249	S	1899	09	03	2	62.00	–144.02	Wrangell (Alaska-E)
1913	03	14	16	4.50	126.50	8.3	144	S	1913	03	14	2	3.67	125.50	Awu (Sangihe Is.–Indonesia)
1913	10	14	19	–19.50	169.00	8.1	371	S	1913	10	14	2	–16.25	168.12	Ambrym (Vanuatu)
1914	01	12	18	31.50	131.00	7.0	153	S	1914	01	13	2	32.88	131.10	Aso (Kyushu–Japan)
1920	12	09	23	–39.00	–73.00	7.4	104	S	1920	12	10	2	–39.42	–71.93	Villarrica (Chile-C)
1934	12	31	10	32.00	–114.75	7.1	121	S	1934	12	31	2	31.77	–113.50	Pinacate Peaks (Mexico)
1939	01	30	12	–6.50	155.50	7.9	52	S	1939	01	30?	2	–6.14	155.20	Bagana (Bougainville Is.)
1939	04	30	12	–10.50	158.50	8.1	174	S	1939	04	30?	2	–9.02	157.95	Kavachi (Solomon Is.)
1974	01	10	19	–14.43	166.86	7.2	71	P	1974	01	11	2	–14.27	167.50	Gaua (Vanuatu)

* Type of eruption is either S for start or P for paroxysmal event.
† VEI is a measure of the explosive magnitude of the eruption.
‡ In volcano region, C denotes central; S denotes south; E denotes east.

results. (Similar, but more pronounced, results obtain if we include all eruptions.) Our procedure is simple: for each earthquake we search the eruption catalogue for events within various distance and time separations. We stack the results for all earthquakes, so the final result of the search process is a matrix of values of number of eruptions as a function of time and distance relative to the earthquakes.

The results of this processing are shown in Fig. 1; Fig. 1a–c is for eruptions occurring within 250 km, 500 km and 750 km, respectively, of great earthquakes. For all of these ranges, there is a peak in the number of eruptions on the same day as the earthquake, although there is no incremental increase in the 250–500 km range. The ratio of this peak amplitude to the average in the other bins (the background rate) is very high. There is no enhanced eruption rate at distances greater than 750 km. Division of the distance intervals into smaller increments shows that these peaks are derived dominantly from the 100–250 km and the 600–750 km ranges, with no contribution from distances less than 117 km.

The relatively large number of eruptions that occur soon after a great earthquake appear to be a clear indication that some of these earthquakes have triggered eruptions. Our catalogue contained 204 great earthquakes, eight of which have triggered eruptions.

We have repeated this search process for earthquakes with magnitude 7–7.9 (Fig. 1d). In this case, the peak eruption count for the 2 days following the earthquakes is evident for distances as large as 200 km (9 eruptions). This observation of a larger number of eruptions within 2 days of the earthquakes is consistent with the fact that at Long Valley the deformation excursion took several days to reach its maximum. Table 1 is a list of all earthquake–eruption pairs in the peak groups in Fig. 1.

One difficulty in grouping these eruptions in time bins arises because eruption times are reported only to the day, and thus there can be some ambiguity as to which event was first. Figure 1 shows the counts assuming that all same-day eruptions follow the earthquake. In some cases (March 1913, T. Simkin, personal communication; both 1835, Darwin[16]) it is known that the eruption followed the earthquake; we know of no cases to the contrary in our list. Even if we were to assume that those same-day events for which we have no definite discriminating information are divided equally between before and after the earthquake, then the peaks in the histograms would be many times the background rate on the day following and would still be significant. We would also have a smaller, but significant, peak for the day preceding the earthquake. As there is other work supporting the triggering of eruptions, but we are unaware of evidence for the converse, we assign the same-day eruptions as following, but our conclusions do not hinge on this assignment. Additionally, there may be concern that a following eruption is noted only because of heightened awareness after the earthquake shaking. From the database it is impossible to determine whether this is significant, but where we do have information it is clear that the eruptive activity began after the earthquake. Also arguing against a spurious effect is that most triggered eruptions are more than 100 km from trigger earthquakes with magnitude <8 and many are more than 500 km from events of magnitude $\geqslant 8$.

The most direct, assumption-free method for determining whether such a high bin count could occur by chance is to use a variation of the bootstrap method of computer intensive analysis[17]. We use the actual eruption catalogue and a randomized earthquake catalogue. Because the catalogue does not have a uniform temporal distribution of events (many more big earthquakes listed for this century because of the dramatic change in detection and location capabilities), we change the origin time of each earthquake by a time

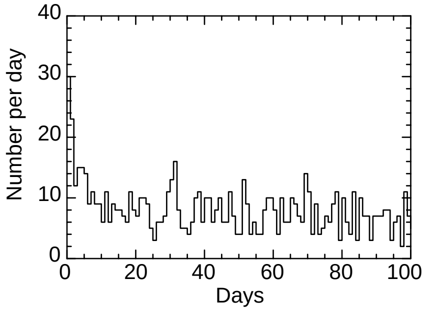

Figure 2 Histogram showing number of eruptions per day following a previous eruption and within 200 km of the first eruption. This distribution has a mean of 8.15 eruptions per day, with a standard deviation of 4.0. Paired eruptions, within two days, are more common than the average rate; the number of eruptions on the same day and following days are 5.4σ and 3.7σ above average. No such enhancement is observed for separations >200 km, and the effect decreases with separation up to 200 km.

increment that varies randomly in the range ±100 days. This ensures that our random samples have the same overall distribution of events with time. Actual locations are retained. Using exactly the same procedure as for the real data, we ran 100,000 trials, with a ±1,000-day time span, and determined the largest count in the 2,000 bins for each run. The largest count generated in any time bin was 8 (once), so that the probability of getting, by chance, a bin count of 8 with the real data is 10^{-5}; the data set has a bin count of 11 for the day following the earthquakes. If we consider the event distributions to be poissonian, we reach comparable conclusions.

We have also examined the eruption catalogue for paired eruptions. Figure 2 shows that volcanoes separated by less than 200 km have paired (within two days) eruptions with frequencies much higher than for the background rate. As volcanic earthquakes are usually not large (infrequently as big as magnitude 6), these time–distance characteristics for the enhanced paired eruptions are consistent with our hypothesis that the second eruption is triggered by the passage of seismic waves. (For the time period examined, the earthquake catalogue is not complete, especially for smaller magnitudes, so we cannot identify the triggering earthquakes.)

The interval between eruptions for many volcanoes is usually decades or longer. If the recharge rate of the shallow reservoir is essentially constant with time, then the volcano can be at a near critical level for years. As the Landers earthquake produced an increase in pressure in the magma reservoir under Long Valley at a distance of about 400 km, then the same should be true generally: seismic waves from earthquakes have the potential to increase the pressure in magma chambers even at large distances from large earthquakes. For a volcano already close to the critical pressure state, this could result in a premature eruption. This conclusion is based on secure observations and does not depend on which (if any) of the various models[5,18–23] proposed is correct, although we note that our suggestion[5] is the only one that leads naturally to the timescale and character of the observed deformation.

The work emphasizes the need for a programme of continuous deformation monitoring of active volcanoes on a global scale, with sufficient sensitivity to be able to detect deformation transients on these short timescales. We note that a two-colour laser ranging system, with resolution of about 1 mm, was not able to detect changes during the period of triggered seismicity at Long Valley; seismic monitoring is important but gives only indirect information about the deformational changes. Very few active volcanoes are currently monitored well enough to allow detection of potentially important transient deformations. ☐

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Electric fish measure distance in the dark

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Distance determination in animals can be achieved by visual or non-visual cues[1]. Weakly electric fish use active electrolocation for orientation in the dark[2]. By perceiving self-produced electric signals with epidermal electroreceptors, fish can detect, locate and analyse nearby objects. Distance discrimination, however, was thought to be hardly possible because it was assumed that confusing ambiguity could arise with objects of unknown sizes and materials[3–5]. Here we show that during electrolocation electric fish can measure the distance of most objects accurately, independently of size, shape and material. Measurements of the 'electric image' projected onto the skin surface during electrolocation[6–8] revealed only one parameter combination that was unambiguously related to object distance: the ratio between maximal image slope and maximal image amplitude. However, slope-to-amplitude ratios for spheres were always smaller than those for other objects. As predicted, these objects were erroneously judged by the fish to be further away than all other objects at an identical distance. Our results suggest a novel mechanism for depth perception that can be achieved with a single, stationary two-dimensional array of detectors.

For orientation in their environment, animals use sensory information to judge the distance of an object. Disparities in the two retinal images of an object can give stereoscopic depth perception in animals whose eyes have overlapping fields of vision[9,10]. Other mechanisms for distance discrimination rely on the movement of detectors and successive comparison of images[11], on binocular convergence, or on measuring the speed at which objects' images move across the retina[12]. Nocturnally active animals, however, must supplement vision with other senses such as hearing, mechanoreception or olfaction[13–15].

Weakly electric fish orient themselves at night by using active electrolocation[2,16]. By emitting an electric signal (Fig. 1b) with a specialized electric organ, they generate an electric field and perceive the resulting current that flows through epidermal electroreceptors. Nearby objects distort the electric field and alter the current flowing through the electroreceptors[6]. Analysis of the 'electric image', that is, the spatial pattern of voltage change, that objects project onto the