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Long Swarms and Short Swarms at Volcanoes: Evidence for Different Processes

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Abstract

Many earthquake swarms at volcanoes last several months, then have a sharp uptick in rate in the hours before eruption. Examples include 2006 Augustine, 8.5 months then 10 hours; 1992 Spurr, 10 months then 4 hours; 1994 Rabaul, ~2 years then 27 hours; 2008 Kasatochi, 6 weeks then 31 hours; and 2011 Puyehue Cordon Caulle, 7 weeks then 3.5 days. For the well-studied Augustine case, broadband data showed that very long period (VLP) energy accompanied 221 of 722 located earthquakes in the 10 hours before the first explosive eruption on 11 January 2006. This was revealed by low-pass filtering and the period of the VLP signal was up to 50 sec. The Augustine broadband stations were campaign instruments at distances of 2-3 km from the vent. No similar VLP energy has been found in events during the 8.5-month long swarm. Okmok volcano had a short swarm only, lasting 5 hours prior to its 12 July 2008 eruption. Low-pass filtering of data from broadband station OKSO, 10 km from the vent, showed that 23 of 42 located events had VLP energy with a period of 30-40 sec. Events from Kasatochi volcano were scanned on station ATKA. Here the broadband station is much farther away at 88 km but the earthquakes in the short swarm 6-7 August 2008 were much larger with many $M > 3$ events. The station suffered data gaps so only a few hours of data were scanned but numerous events were observed with VLP energy starting just after the P phase. Low-pass filtering showed VLP energy with a period of 10-12 sec. No VLP energy has been found in events of the preceding 6-week long swarm. These observations at different volcanoes suggest that the short swarms represent a different process than the long swarms. The long swarms likely reflect pressure increases in the surrounding country rock caused by increasing magma pressure. The short swarms in contrast, appear to represent discrete pulses of magma injection at shallow depths. For all the examined volcanoes most of the earthquakes looked like typical volcano-tectonic (VT) earthquakes on short-period stations. The short swarms are very short – 4 hours to 3.5 days – and have important implications for hazards assessments. It is not known how commonly the long swarm-short swarm pairs occur and thus the false alarm rate is also not known.

Keywords: Volcano seismology; Earthquake swarms; Seismicity patterns; b-values; VLP events

1. Introduction

Earthquake swarms are common at volcanoes. Swarms are loosely defined as groups of earthquakes that are clustered in time and space and lack a mainshock. A common definition is “an increase in seismicity rate above

the background rate without a clear triggering mainshock earthquake" (Holtkamp and Brudzinski, 2011); based on Mogi (1963), Sykes (1970) and Hill (1977).

All volcanoes have a background of seismic activity. This is usually on the order of a few events per week. Swarms must be distinguished from the background, usually on the basis of higher rates, new or different locations, or the occurrence of new or different types of events, such as low-frequency events or volcanic tremor.

Earthquakes often precede eruptions, in fact, the identification of swarms and related diagnostics are key to successful eruption forecasting (e.g. McNutt and Roman, 2015; White and McClausland, 2016, Stix, 2018). Many case studies have been published, and these form the backbone of understanding of swarms and their relation to eruptions. A few databases have been compiled, including the Global Volcanic Earthquake Swarm Database (600 swarms, durations and other basic data; Benoit and McNutt, 1996); a Japanese effort (T. Nishimura, writ. comm.); WOVODat (Newhall et al., 2017; Costa et al., 2019), and an ongoing effort by the U. S. Geological Survey/Volcanic Disaster Assistance Program (C. Neal, pers. comm; Ogburn et al., 2024).

Over the years the author noticed that a number of earthquake swarms that preceded eruptions had a particular temporal structure. There was a long-duration swarm (weeks to months), followed by a short-duration swarm (hours to days) of higher activity just before eruption. For semantic convenience, we refer to these as long swarms and short swarms (Fig. 1). This terminology was first used by Jacobs and McNutt (2010) in a study of the 2006 eruption of Augustine Volcano. Systematic observations suggest that there are two different processes linked to the different time scales. The purpose of this paper is to describe the swarms and identify diagnostics for the likely processes. This is a concept paper, so not every test has been completed for the cases described. But the available data are sufficient to identify the likely processes, and the basic idea appears to be viable.

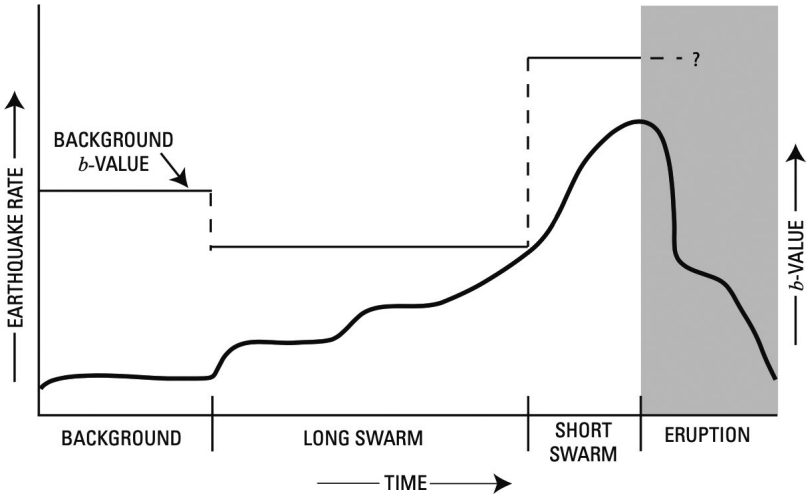

Figure 1. Schematic diagram of the basic structure of long and short swarms. The rate of seismicity increases from background to long swarm and increases again from long swarm to short swarm. The b-values decreases during the long swarm and increases during the short swarm. Adapted from Jacobs and McNutt (2010).

2. Data

The data for this study come from two main sources. The first is published peer-reviewed papers in the literature. The second is primary data from the University of Alaska Fairbanks and the Alaska Volcano Observatory. Table 1 shows the six case studies that are the basis for this paper. Each is described in detail the following sections.

For each, we describe the onsets of the various components of the swarm, the locations of the events, the rates (compared with background), the long swarm duration, the short swarm duration, the types of events, the b-values (described below) and other parameters. This information is also displayed in Table 2 and Table 3.

Background is important for assessing the conditions prior to injection and eruption of magma. The background gives an idea of the physical conditions prior to activity, and the onset of a swarm needs a prior background to establish the increase in rate of activity that marks the onset of the swarm. For each volcano, we obtained a sample

Volcano	Date	Duration Long	Duration Short	Key Reference
Spurr	1992	10 months	4 hours	Power et al., 1995
Rabaul	1994	~2 years	27 hours	McKee et al., 2018
Augustine	2006	8.5 months	10 hours	Jacobs & McNutt, 2010
Okmok	2008	—	5 hours	Larsen et al., 2009
Kasatochi	2008	6 weeks	31 hours	Ruppert et al., 2011
PCC (Puyehue-Cordon Caulle)	2010	5 months	3.5 days	Basualto et al., 2023

Table 1. The six case studies presented in this paper.

Volcano	Activity	Date Start	Date End	No. Events	Duration Days	Rate. No./day	Rate increase
Spurr	background	13 Oct 1989	28 Jul 1991	78	654	0.12	
	Long swarm	4 Aug 1991	26 Jun 1992	1117	326	3.43	28.73
	Short swarm	27 Jun 1992	27 Jun 1992	84	<1 (4 h)	203.6	59.42
Kasatochi	background	6 Aug 2006	8 Jun 2008	114	665	0.17	
	Long swarm	7 Jul 2008	6 Aug 2008	82	30	2.73	15.94
	Short swarm	6 Aug 2008	7 Aug 2008	1154	2	502.55	183.86
Augustine	background	1 Jan 2004	29 Apr 2005	274	485	.56	
	Long swarm	30 Apr 2005	11 Jan 2006	1245	256	4.86	8.61
	Short swarm	11 Jan 2006	11 Jan 2006	722	.42 (10 h)	1732.8	356.3
PCC	background	no data		—		—	
	Long swarm	23 Mar 2011	31 May 2011	1843	69	26.71	
	Short swarm	1 Jun 2011	4 Jun 2011	1185	4	298.3	11.09
Okmok	background	15 Mar 2006	28 May 2008	73	804	0.09	
	Long swarm	not observed				—	
	Short swarm	12 Jul 2008	12 Jul 2008	17	<1 (5 h)	120.7	1341*

Volcano	Activity	Date Start	Date End	No. Events	Duration Days	Rate. No./day	Rate increase
Rabaul	Background 1	Jan 1992	Nov 1992	2000	320	6.25	
	Background 2	Jun 1991	Jun 1992	2300	365	6.3	
	Long swarm 1	16 Nov 1992	17 Sep 1994	16200	672	24.11	3.86
	Long swarm 2	Jan 1993	Jun 1994	6800	547	12.61	2
	Short swarm	18 Sep 1994	19 Sep 1994	243	1.13 (27h)	216	8.96
Notes: Several short swarms were <1 day; data were normalized to number per day Dates for background correspond to first and last dates of events. The intervals may be slightly longer if the quiet days before and after the interval are included. *Okmok had no long swarm, so the rate change is with respect to the background. References are given in Table 1							

Table 2. Seismicity rates for background, long swarms, and short swarms at six volcanoes.

Volcano	Sample	Date Start	Date End	N	b-value	References
Spurr	background	13 Oct 1989	28 Jul 1991	78	1.55	J. Power, writ. Comm.
	Long swarm	4 Aug 1991	26 Jun 1992	1117	1.34	Power et al., 1995
	Short swarm	27 Jun 1992	27 Jun 1992	84	1.04	this study
Kasatochi	background	6 Aug 2006	8 Jun 2008	114	0.54	Ruppert et al., 2011
	Long swarm	7 Jul 2008	6 Aug 2008	82	1.48	this study
	Short swarm	6 Aug 2008	7 Aug 2008	1154	0.7*	
Augustine	Background 1	1 Jan 2004	29 Apr 2005	—	1.51	Jacobs and McNutt, 2010
	Background 2	1 Jan 2000	29 Apr 2005	274	1.44	"
	Long swarm	30 Apr 2005	11 Jan 2006	1245	1.26	"
	Short swarm	11 Jan 2006	11 Jan 2006	722	0.78	"
PCC	background	no data				
	Long swarm	Dec 2010	25 Apr 2011	—	0.7	Basualto et al., 2023
	Short swarm	26 Apr 2011	4 Jun 2011	—	1.1	"

Volcano	Sample	Date Start	Date End	N	b-value	References
Okmok	background	15 Mar 2006	28 May 2008	73	0.85	this study
	Long swarm	not observed		—	—	
	Short swarm	12 Jul 2008	12 Jul 2008	17	0.98	"
Rabaul	Background 1	Jan 1992	Nov 1992	2000	—	Robertson and Kilburn, 2016
	Background 2	Jun 1991	Jun 1992	2300	—	Kilburn writ. comm.
	Long swarm	Nov 1992	17 Sep 1994	16200	—	"
	Long swarm	Jan 1993	Jun 1994	6900	—	"
	Short swarm	18 Sep 1994	19 Sep 1994	8	0.87	McKee at al., 2018

Table 3. Seismic b-values for background, long swarms, and short swarms at six volcanoes.

of the background. This was previously published for Augustine 2006, and catalogs were available for Spurr 1992, Okmok 2008, and Kasatochi 2008. For PCC we used the data given in Basualto et al. (2023); we searched for but could not find a catalog. For Rabaul 1994, we read the data from Figs. 3 and 6 of Robertson and Kilburn (2016) and Figs. 3 and 7 of McKee et al. (2018). These were monthly values that did not coincide exactly with the dates of onset and termination.

Long swarms were identified by the various observatories that study and monitor the volcanoes. The exception was the Rabaul long swarm, which was identified by the author (see Appendix). At Rabaul there were many prior sequences from 1969 to 1985, but the ratio of duration to height (numbers) was different, suggesting different source conditions (Appendix Fig. A9). In particular, the long swarm persisted for almost 2 years with no return to background levels. The previous activity, which consisted of higher numbers of events in bursts, was associated with persistent moderate earthquake activity. The long swarm lasted ~2 years and the peak number of events was smaller than the other bursts from 1968 to 1992.

Short swarms were either identified from figures in papers or from volcano observatories. Note that the terms “long swarm” and “short swarm” were not used by previous papers and observatories (except for Jacobs and McNutt, 2010). Their usage here reflects observations and interpretations by the author for this work.

The following section gives brief summaries of each volcano and its activity, also noting complications and limitations. All the figures are given in the Appendix; a few examples are shown in the main text for clarity.

3. Case studies

3.1 Mount Spurr 1992

The eruption of Mount Spurr started on 27 June 1992. The start date for the long swarms was 4 Aug 1991, 10 months earlier (Fig. 2). Earthquakes occurred near the north rim of the caldera, under the center of the caldera, and near Crater Peak, the eventual eruption site (Appendix Fig. A7; Power et al., 1995). The depths of the events ranged from 3 km above sea level to 7 km below. The closest station was <1 km from the Crater Peak vent.

A background period of 654 days prior to Aug 1991 was chosen based on data availability (J. Power, writ. comm.). The long swarm had a duration of 10 months, and it had a maximum of 28 events per day (VT events) and a mean of 3.4 events per day (Table 2). The onset of tremor bursts (McNutt et al., 1995) began on 5 June 1992; at this time

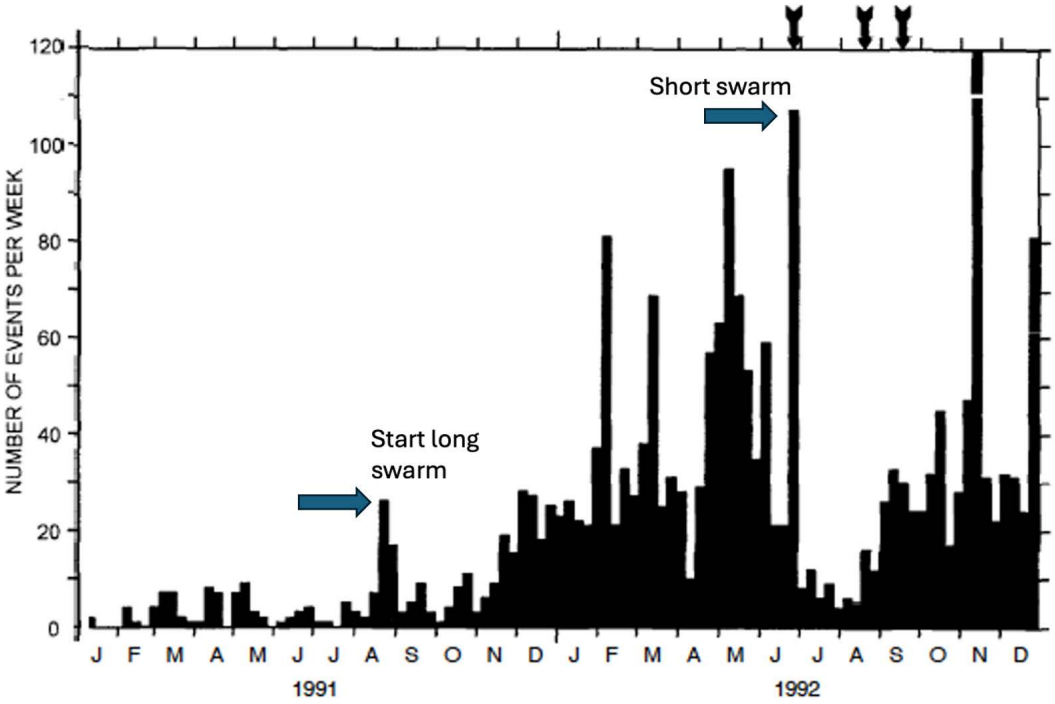

Figure 2. Plot of number of located earthquakes per week at Mount Spurr for 1991-1992. The start of the long swarm and short swarm are labeled. The arrows mark the 3 eruptions in June, August and September 1992. Modified from Power et al. (1995).

the VT rate declined by a factor of ~3; the crater lake later changed color from light blue to gray and became dry; continuous tremor episodes of >2 hr duration began 1 day before the eruption (Eichelberger et al., 1995). The short swarm began on 27 June 1992 and had a duration of 4 hours; about 100 events occurred (not all could be located).

We determined b-values (the slope of the frequency-magnitude relation) for the background, long swarm, and short swarm (Table 3). We intended to examine the events of the short swarm to determine if any very-long period (VLP) events were observed. This was not feasible for the short-period analog data available at the time. However, a few events with lower frequencies were observed during the short swarm (G. Tytgat, pers. comm.).

The information used in this study mainly came from the first generation of studies (published in 1995). Additional analyses of Spurr seismicity have been performed by Roman et al. (2004) and Power et al. (2002). Figures A6 to A8 in the Appendix provide further plots and information.

3.2 Augustine 2006

The eruption of Augustine started on 11 January 2006. The start date of the long swarm was 29 April 2005. Two samples of background were determined, from 1 Jan 2000 to 29 Apr 2005, and 1 Jan 2004 to 29 Apr 2005. These gave similar rates and b-values (Tables 2 and 3).

The long swarm began 29 Apr 2005 (Jacobs and McNutt, 2010) and the duration was 8.5 months (similar to the 1976 and 1986 Augustine eruptions; Power and Lalla, 2010). The maximum rate was 70 events per day. All the events of the swarm occurred at shallow depths in a small volume 2 km in diameter centered on the summit (Fig. A18 in Appendix). The closest stations were <1 km from the vent.

Increased steaming and a sulfur smell were noted in December 2005, and GPS data indicated both inflation of the summit area and uplift of the entire island (Cervelli et al., 2010). The short swarm began on 11 January 2006 (UTC) and its duration was 10 hours. It was comprised of 722 events (Jacobs and McNutt, 2010) and ended when the first explosive eruptions occurred (Fig. A22 in Appendix). The M distribution was complicated by the mixing of different types of events.

The b-value for the background was 1.51, for the long swarm1.26, and for the short swarm 0.78 for all data, but with values as high as 2.2 using a moving-window analysis (Appendix Fig. A19).

VLP energy was observed in some events of the short swarm. This was identified by low-pass filtering (Fig. 3). Thirty percent of the events had VLP energy, with periods as long as 50 sec (Jacobs and McNutt, 2010). The broadband stations were added on December 20, 2005, so it was not possible to determine if VLP energy was present in events prior to that date.

While the information used in this study mainly came from the first generation of studies (2010), several follow-up studies have been performed to further elucidate processes (Zhan et al., 2022a; 2022b). Figures A17 to A22 in the Appendix provide further plots and information.

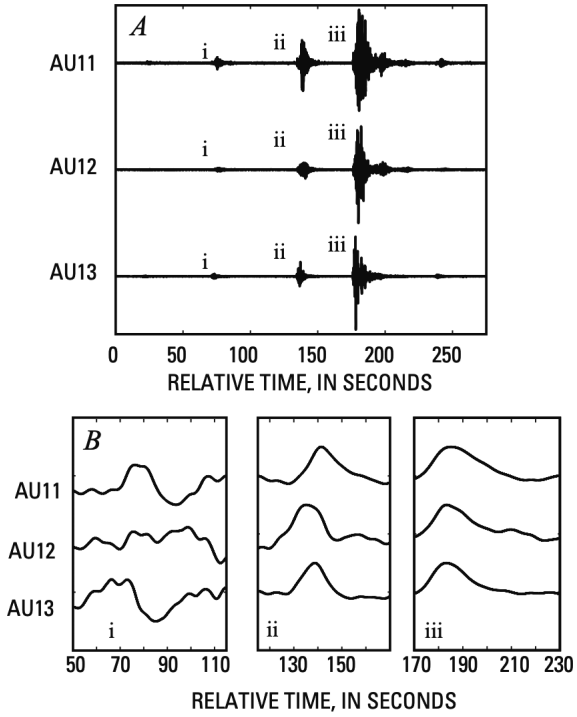

Figure 3. Three small events from the short swarm at Augustine Volcano. Top: the three events i, ii, and iii at three broadband stations, unfiltered. Bottom: the three events low-pass filtered to show VLP energy with periods up to 50 sec. After Jacobs and McNutt (2010).

3.3 Kasatochi 2008

The long swarm start date was 7 July 2008, although a manual search by the author showed events as early as 1 July and a later effort by S. Holtkamp (writ. comm.) using match filters showed activity a few days earlier. The long swarm had a duration of ~6 weeks; the rates showed a maximum of 23 events per day. The short swarm began 6 August 2008 and had a duration of 31 hours; the rate was a max of 36 located events per hour. The short swarm also showed increasing M with time (Fig. 4). The depths for the events ranged from 5 to 15 km, although these are not well constrained because the closest stations were 30 km away to the west and 88 km to the east (Fig. A2).

The largest event of M5.8 occurred 3 hours before the onset of the eruption (see Fig. A5 in the Appendix). The b-value for the background was 0.54, for the long swarm 1.48, and for the short swarm 0.75 (the relative values differ from the other cases). There were no known previous earthquakes at the volcano. Ruppert et al. (2011) determined an intermediate b-value of 0.9 for the full sequence. For the background, we used a circle with a radius of 50 km centered on the volcano to select events. This represents an average of the adjacent area rather than a value for only the volcano itself.

VLP energy was observed for some earthquakes in the short swarm; there were clear VLP signals associated with the P wave; these are obvious in raw (unfiltered) broadband seismograms for station ATKA, 88 km to the west (Fig. 5). Data were later filtered to better elucidate periods. We examined a sample of the events of $M > 3$ and found ~30 percent of the events had such VLP energy. Ruppert et al. (2011) determined focal mechanisms for the

largest 12 events and found that all had significant non-double couple mechanisms. Waythomas et al. (2010) gives a detailed chronology of the eruption. Figures A1 to A5 in the Appendix provide further plots and information.

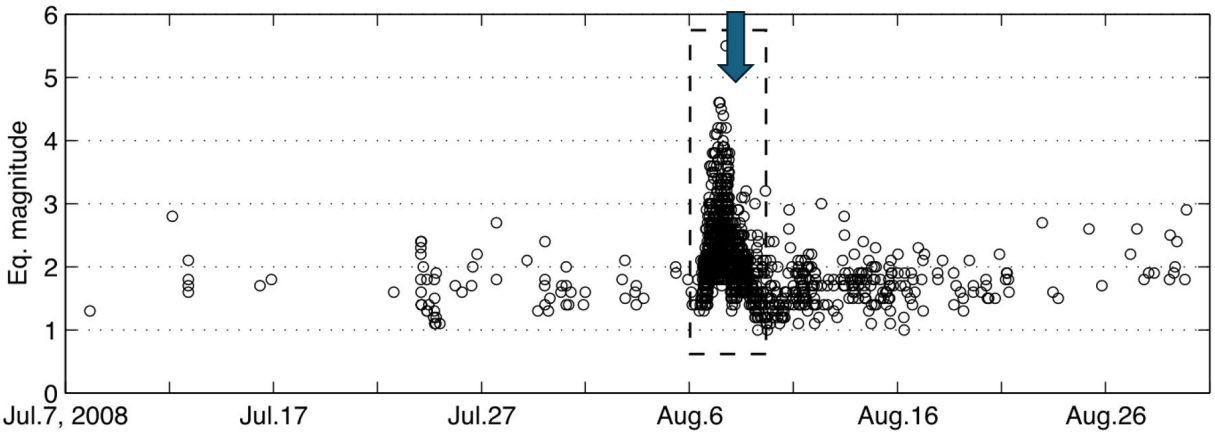

Figure 4. Time series of earthquake magnitudes versus time for Kasatochi Volcano, July-August 2008. Note the increase in magnitudes during the short swarm on August 6. Arrow marks the onset of the eruption. Also see Fig. A1 in the Appendix. After Ruppert et al. (2011).

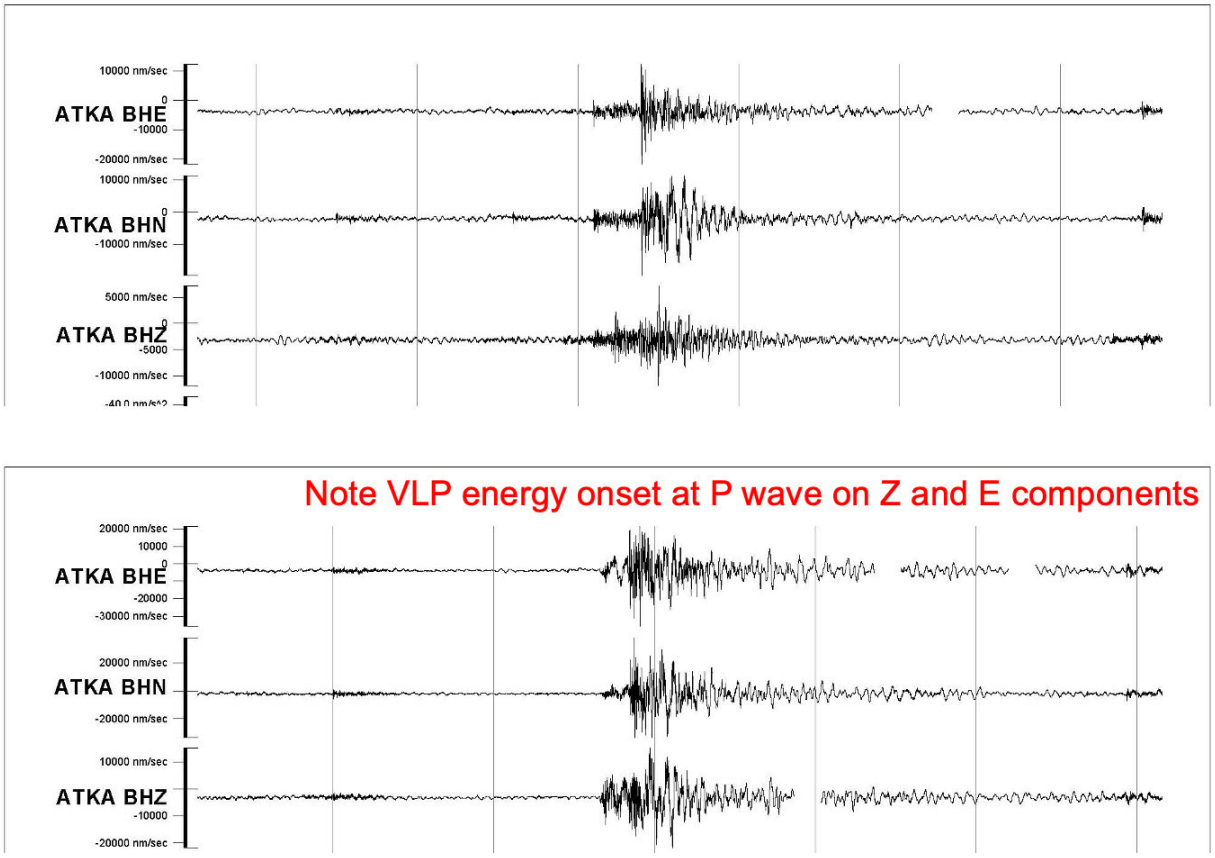

Figure 5. Seismograms from 3-component broadband station ATKA, 88 km to the east of Kasatochi Volcano. The top panel shows a typical regional earthquake; note the large S waves and the small P waves. The bottom panel shows an event from the Kasatochi short swarm; strong VLP energy is obvious in the Z and E components. The VLP signal is larger on E than N because of the geometry of the station with respect to the volcano and the source orientation. See also Appendix Fig. A4.

3.4 Okmok 2008

The eruption of Okmok occurred on 12 July 2008. The long swarm onset and duration are problematic – none were observed. Instead, there was a persistent background; long term inflation also occurred as measured by GPS and InSAR (Freymueller and Kaufman, 2010; Fournier et al., 2009). The short swarm had a duration of 5 hr 4 min; approximately 40 events were located. The depths of the events were 0-12 km and the closest station was about 2 km from the new vent. The seismicity was later studied by Johnson et al. (2010) and Garza-Giron et al. (2023). Geologic features were studied by Larsen et al. (2015). Figures A12 to A16 in the Appendix provide further plots and information.

Okmok did not have a long swarm. It was included here for several reasons. The rate of seismicity during the short swarm was similar to that of the other cases. The duration was also similar. The data were readily available. The broadband station 10 km away allowed determination of VLP energy.

A sample of the background was used to estimate the b-values of 0.85. This was done by using a circle of radius 20 km centered on the center of the caldera. The short swarm had a b-value of 0.98. VLP energy was observed in some of the events of the short swarm; about one third of events showed VLP energy, identified via low-pass filtering (see Fig. A15 in the Appendix). This was performed manually by the author. Periods ranged from 15 to 20 sec.

3.5 Rabaul 1994

The start date of the eruption was 19 September 1994. The long swarm had a duration of ~2 years, determined by reading data from Fig. 7 of McKee et al., 2018 (see Fig. A9 in the Appendix). The short swarm had a duration of 27 hours (McKee et al., 2018; GVN 1994). It began with a M4 event and aftershocks, followed by a M5.1 event and an increase in activity instead of typical (expected) aftershock decay. All events had depths of <4 km and the closest stations were 0-4 km away (the events occurred in an annulus similar in dimension to that of the caldera; Fig. A10). When observed in the early morning of 19 Sept, the coast near Matupit Island had uplifted ~2 m, and near Vulcan, ~6 m. Tavurvur began erupting at 0606 local time and Vulcan began 1 hour and 9 minutes later (McKee et al., 2018).

A sample of background data was obtained using data from Fig. 6 of Robertson and Kilburn (2016). Similarly, the duration and rates of the inferred long swarm were estimated from the same paper. The long swarm had rates of 12-24 events per day, the short swarm had a rate of >216 events per day (J. Mori, writ. comm.). McKee et al. (2018) noted that as many as 2 events per minute were recorded; this would be 2880 events per day if the rate persisted for an entire day. The threshold for magnitudes was 1.0 in the Vulcan area, 1.3 in the southern Blanche Bay area and 0.5 in the Greet Harbour area (J. Mori, writ. comm.).

VLP energy in short swarms could not be identified (only analog data existed at the time). However, several LP events occurred in the 12 hours preceding the M5.1 earthquake (McKee at al., 2018). The short swarm had a b-value of 0.87 as estimated from data in Table 2 of McKee et al. (2018). The number of events is too small to be reliable, but the estimate is included for completeness.

Rabaul caldera is a larger structure than the other volcanoes in this study; a further complication is that two volcanoes erupted (Tavurur and Vulcan). Overall, Rabaul had a higher rate of seismicity than the other volcanoes. However, relative rate increases agree reasonably well with other cases. Figures A9 to A11 in the Appendix provide further plots and information.

3.6 Puyehue-Cordon Caulle 2011

The eruption of Puyehue-Cordon Caulle (PCC) occurred on 4 June 2011. The long swarm had a duration of 2.3 months. It consisted of two parts: 1) initial unrest starting December 2010; 2) enhanced unrest starting 23 March, 2011 (Basualto et al., 2023). The enhanced unrest most closely resembles the long swarms as determined at the other volcanoes in this study, so we used this for comparison. The duration was 69 days and the rate was 26.7 events per day. The depths of events ranged from 1 to 15 km and the closest station was about 10 km away.

The short swarm duration was 3.5 days and it included 1185 events (counted from Fig. 4 of Basualto et al., 2023). The mean rate was 296.3 events per day, so the rate increased by a factor of 11.09. Earthquake locations are shown in Fig. A24 of the Appendix. The b-value for the background was 0.8; for the long swarm 0.7; and for the short swarm 1.1

(Basualto et al., 2023). Additional details of the eruption and chronology are provided by Elissondo et al. (2015) and Swanson et al. (2016). Figures A23 to A26 in the Appendix provide further plots and information.

4. Synthesis and Discussion

We remind the reader that this is essentially a concept paper. The "results," then, are relative, and are a measure of the extent to which the swarms have features in common, and whether the accumulated diagnostics support the ideas of different main mechanisms for the long and short swarms.

We looked for and measured systematic features of the seismicity including the following:

- Rates of background seismicity (5 of 6 cases; Kasatochi estimated, see above).
- Locations of background seismicity (all cases).
- b-value of the background (4 of 6 cases).
- Onset of the long swarm (5 of 6 cases; no long swarm for Okmok).
- Rates of the long swarm (5 of 6 cases; does not apply to Okmok).
- Rate increases relative to background (5 of 6 cases; background not known for PCC).
- Locations of long swarm seismicity (5 of 6 cases; no long swarm for Okmok).
- b-value for the long swarm (4 of 6 cases; insufficient data for Rabaul and Okmok).
- Onset of the short swarm (all cases).
- Rates for the short swarm (all cases).
- Rate increases relative to long swarm (5 of 6 cases; Okmok determined relative to background).
- Locations of short swarm seismicity (all cases).
- VLP parts of short swarm (3 of 6 cases; the others had some LP events).
- b-value of the short swarm (all cases).

To what extent do these swarms resemble each other? Of the 14 parameters listed above, all six cases had data for 5 of the parameters, and 5 of 6 cases had data for 5 additional parameters. At least half the cases had data for 3 or more parameters. While not perfect, the data allow some generalizations.

4.1 Durations and Rates

The absolute rates and durations of the various cases of long swarms are variable (as are the network geometries and magnifications), however, the relative rates are similar. The durations of the long swarms range from 6 weeks to 2 years; the durations of the short swarms range from 4 hours to 3.5 days. Five volcanoes had rate increases from background to long swarm of a factor of 3.8 to 28.7 (Table 2) averaging one order of magnitude. This is expected because a rate increase is part of the basis for determining whether a swarm is occurring. All cases had additional rate increases from the long to short swarms of a factor of 59 to 356, or between one and two orders of magnitude (Okmok was omitted as an outlier because the rate was relative to background; however, the Okmok rate relative to background is similar if the others are compared to background instead of long swarms). These rate increases alone would have been cause for concern.

4.2 Frequency-Magnitude Distribution or b-values

Many studies of the Frequency-Magnitude Distribution (FMD) as a function of time, space, and depth have been conducted since Ishimoto and Iida (1939) and Gutenberg and Richter (1944) introduced the relation between the frequency of occurrence and magnitude of earthquakes ($\log 10N = a - bM$), where N is the cumulative number of earthquakes having magnitudes larger than M, and a and b are constants The slope, or b-value, has been shown in laboratory studies, mines, and numerical simulations to depend on environmental conditions. Several authors explained variations in the FMD as being caused primarily by material properties (e.g. heterogeneity, Mogi, 1962), magnitude of applied shear stress or effective stress (Scholz, 1968; Urbancic et al., 1992), pore pressure (Wyss, 1973), and temperature gradient (Warren and Latham, 1970). Volcanic areas are commonly reported to have high b-values,

presumably because of the higher activation of small faults with respect to larger ones (e.g. Warren and Latham, 1970), and some authors have investigated b-value changes in volcanic areas as a function of time (e.g. Zobin, 1979). In the vicinity of magma chambers three of the aforementioned mechanisms favor a high b-value. In general, volcanoes have high heterogeneity because of layering of lava flows and ash, the presence of cooling cracks, dikes and sills, and high thermal gradients in the vicinity of magma. Of course, in magma itself no earthquakes should be produced due to the limited shear strength of molten material. The b-value plots are also useful to determine M threshold (e.g. Wiemer and Wyss, 2000).

In terms of this study, the key observation is that increasing pore pressure, thermal gradient, and material heterogeneity all lead to higher b-values. Increasing stress leads to lower b. Thus, an increase in stress (pressure) would show up in the data as a lower b-value, which is observed in several of the cases (Augustine and PCC) for the long swarms. This suggests that pressurization of a magma chamber is driving the long swarms. Half of the cases had the expected b-value polarities as suggested in Fig. 1.

Augustine and PCC used maximum likelihood estimates for b and did moving window analyses (previously published in Jacobs and McNutt, 2010 and Basualto et al., 2023). The observed variations are within errors, but the polarity agrees (i.e. a decrease in b during the long swarms). This is the evidence for increased pressure because all the other known factors would cause b to increase.

Some samples were too small for reliability (Table 3) and the maximum likelihood method is not appropriate. Estimates were instead made using linear regression. This is sufficient for comparison between portions of swarms (e.g. background to long to short) but absolute values may not be meaningful.

Locations of earthquakes were variable (compare, for example, Augustine versus Rabaul; Appendix) but most were centered on volcano of interest.

Identifying changes in b should be part of a monitoring strategy. It is recommended to perform b-value calculations on background seismicity using 100 earthquakes per sample with a 10-event moving-window average. This would allow determination of background values and their stability, and changes that may be related to seasons or other periodicity or changes in instrumentation. The baseline obtained would be useful for identifying if a lowering of b occurred during long swarms.

4.3 Short swarms

For the short swarms, the key diagnostics are a dramatic rate increase, higher b-value, and the appearance of new types of events including LP, hybrid, and VLP events. In particular, VLP (periods >10 sec) energy was observed for small events at three of the cases (Augustine, Okmok, and Kasatochi). At Rabaul, some LP events were noted (McKee et al., 2017) and at PCC both hybrid and LP events were tabulated (Basualto et al., 2023).

Most of the long-swarm events have not been checked for VLP energy. This is not part of standard data reduction for most volcano observatories. However, this is a potentially interesting part of the story. The available data suggest that the long swarms represent adjustment in the surrounding country rock due to magma injection, which may be itself aseismic. Thus, most of the earthquakes are volcano-tectonic (VT) or high-frequency events.

These conditions address whether the process of magma injection is a gradual build-up, which then reaches some threshold and transitions to a different suite of processes. This is expressed as the onset of the short swarms. A key point is when do VLP events start? Immediately at the start of the short swarm? This has not been determined precisely, but the number of VLP events is about 30 percent of the short swarms, so a mixture of ordinary and VLP events is present. I infer that the VLP events represent pulses of magma injection and represent cracks opening. This may occur at a fixed location (e.g. conduit enlarging), or in association with dike propagation. The data cited in this paper do not allow detailed mapping of systematic changes in earthquake locations.

4.4 Impact on hazards forecasts

Long swarms have uncertainty about whether or not there will be an eruption and when it will occur; the time frame is months. In contrast, short swarms present a higher likelihood of eruption but a very short time for preparation (hours to days).

It is likely not possible to do all the geophysical work needed to fully analyze swarms for the noted features (most of this study is long term and retrospective) during a crisis. Hence, simple measurements (or automated methods) are needed. We also note that there is a high demand for information by emergency responders and the public at the same time as there is a high demand computationally. Hence a robust team required; there is a need to identify relevant issues in advance so teams can work semi-autonomously.

4.5 Implications for petrology

The results, particularly the durations of short swarms, are likely to be of interest to petrologists. If the starting depth is known, then the ascent rates can be easily calculated. There are uncertainties associated with the starting depths. For example, the depth of the Mogi source at Okmok is determined from geodetic data to be <2.8 km (Fournier et al., 2009). Using this depth and the time of 5:04 yields an ascent rate of 552 m/hr.

For the other cases, a depth of 7 km is often assumed, based on the presence of stable mineral assemblages and reaction rims (C. Nye, pers. comm.) which may indicate shallow residence times. Using 7 km yields ascent rates of 83 m/hr (PCC) to 1750 m/hr (Spurr). Most were 226-700 m/hr. Using shallower depths would decrease all these values.

4.6 Other cases

The number of cases in this study is small: six. There are several other examples known, but these have not been studied in detail:

- Augustine 1976 (Power and Lalla, 2010)
- Augustine 1986 (Power and Lalla, 2010)
- Great Sitkin 2021 (Power and Roman, 2024)
- Soufriere Hills 1995-1997 (Aspinal et al., 1998)
- Unzen 1991 (Umakoshi et al., 2001) is also a possibility

A fuller compilation and study appear to be warranted. Such cases would be especially welcome if sufficient broadband seismometers exist to confirm source mechanisms for VLP portions of signals.

A related question is what volcanoes would be expected to have the observed patterns? For example, the volcanoes presented here are all located on convergent plate boundaries and have relatively long repose times. These are decades for Augustine, Spurr, PCC, and Rabaul, and centuries for Kasatochi. The long-swarm short-swarm behavior is typically not observed at more frequently active volcanoes such as Pavlof. There may be generalizations that can be developed for this behavior that involve such factors as repose interval, magmatic chemistry, and tectonic setting that favor long- and short-swarms. These are difficult to characterize with only 6 case studies. The long-swarm short-swarm pattern has apparently not been observed at extensional plate boundaries such as Iceland, or hot spots like Hawaii or Piton de la Fournaise. Such swarms may exist, but they have not yet been identified. A broader data set would make this concept more useful in forecasting future eruptions.

Recent papers by Rosi et al. (2022) and Accocella et al. (2024) explored the subsurface conditions associated with eruption precursors. In terms of their categories, the long swarms in this paper would correspond to closed-conduit eruptions (or conditions). The short swarms in this paper would correspond to semi-open conduit eruptions (or conditions). Related ideas are that the long swarms represent the late stages of magma accumulation, and the short swarms represent magma propagation (Acocella et al., 2024), although direct evidence for propagation is lacking here. These ideas are complementary with the main points of the present work, that different processes, time scales, and diagnostics are associated with long swarms and short swarms.

4.7 Probabilities of eruption

The work presented here is essentially a conceptual model. As a complementary exercise, we consider the probabilities of eruption if various scenarios occur. If only a long swarm occurs, we estimate the likelihood of

eruption to be about 20 percent. This is based on polling experts (a half dozen colleagues in volcano seismology). Estimates ranged from 1/10 (10 percent) to 1/3 (33 percent) with unknown error bounds. These are small values but are well above long-term probabilities. For example, Augustine erupts approximately every 20 years, so the probability of eruption in any one year is only 0.05 or 5 percent.

If a short swarm occurs, and events are observed with VLP energy, then the likelihood of eruption is much higher, probably >50 percent. The sample in this paper (6 cases) is small and does not warrant strict probability estimates. A larger sample might provide such estimates.

As an example of applying this model, we consider Campi Flegrei in 2024. At the time of this writing, there is an ongoing earthquake swarm near the town of Pozzuoli (Saccorotti et al., 2024). The duration to date is about 4 years (stronger for the last 1.5 years; Saccorotti et al., 2024) and the rates have been as high as 180 events/day. The b-value has been estimated as 0.85 (Saccorotti et al., 2024). Based on the activity described, this would be characterized as a long swarm alone. The duration and rates are similar to those of the other cases described here. No VLP energy has been observed or reported. Based on these diagnostics, I believe that Campi Flegrei is unlikely to erupt without additional precursors, such as a short swarm. These would be events at a much higher rate than that observed so far, and events would likely include VLP energy. The b-value would likely be greater than 1.0. The good news is that there are distinct diagnostics to be measured. The bad news is that there would be very little time (as short as 4 hours) to make measurements, reach consensus, and issue warnings or public statements. This is unfortunate but is an accurate reflection of the state of the art.

4.8 Future Work

Future work would include adding more cases; several candidates are mentioned above. This would allow better understanding of the range of values for rates and durations. Data should be checked for whether there are any known cases where all the steps occurred but with no eruption. A longer time frame study would be to check all events (background and long swarms) for VLP components. When there are sufficient broadband 3-component stations, both in numbers and geographic distributions, individual VLP events should be modeled for mechanisms. This would help validate the idea and determine the geometry and locations of pulses of magma injection.

5. Summary and conclusions

Study of 6 cases of earthquake swarms at volcanoes shows that the swarms consist of a long (weeks to months) component followed by a short (hours to days) component preceding eruptions. The long swarms represent an order of magnitude rate increase above background. The likely mechanism is an increase in magma pressure as revealed by lowering of b-values. The short swarms represent an additional rate increase of one to two orders of magnitude above the rate for the long swarms. The likely mechanism is pulses of magma injection as indicated by the presence of VLP (10-50 sec) energy in the seismograms. Observations of elevated b-values are additional evidence of fluid involvement. The probabilities of eruption are relatively low with long swarms alone. The probabilities are likely much higher when short swarms occur. The short time frame of the short swarms (hours to days) suggests that monitoring and mitigation strategies need to be determined in advance to allow for meaningful response.

Data Availability Statement. Much of the earthquake catalog data is available from the USGS catalog search web site: https://earthquake.usgs.gov/earthquakes/search/
An updated version of the AVO earthquake catalog from 1989 through 2018 using updated velocity models and station response information that is consistent with the data is available here: https://earthquake.usgs.gov/earthquakes/search/ The reference is: Power et al. (2019).
AVO catalog data are available from various Open-File Reports.
Dixon et al. (2019) provide additional information on the AVO catalog data.

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Appendix. Figures from all the case studies are given in the Appendix. These 26 figures are a mix of published figures and several new ones prepared by the author.

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