# Global volcanic earthquake swarm database and preliminary analysis of volcanic earthquake swarm duration

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**Abstract**
Global data from 1979 to 1989 pertaining to volcanic earthquake swarms have been compiled into a custom-designed relational database. The database is composed of three sections: 1) a section containing general information on volcanoes, 2) a section containing earthquake swarm data (such as dates of swarm occurrence and durations), and 3) a section containing eruption information. The most abundant and reliable parameter, duration of volcanic earthquake swarms, was chosen for preliminary analysis. The distribution of all swarm durations was found to have a geometric mean of 5.5 days. Precursory swarms were then separated from those not associated with eruptions. The geometric mean precursory swarm duration was 8 days whereas the geometric mean duration of swarms not associated with eruptive activity was 3.5 days. Two groups of precursory swarms are apparent when duration is compared with the eruption repose time. Swarms with durations shorter than 4 months showed no clear relationship with the eruption repose time. However, the second group, lasting longer than 4 months, showed a significant positive correlation with the $\log_{10}$ of the eruption repose period. The two groups suggest that different suites of physical processes are involved in the generation of volcanic earthquake swarms.

**Key words** *volcanic earthquake swarms – database – swarm duration*

## 1. Introduction

Earthquake swarms are pervasive at volcanoes and are used as one of the main tools for forecasting volcanic eruptions. The creation of the Global Volcanic Earthquake Swarm Database (GVESD), described herein, is a project to systematically compile a global sample of seismic activity in volcanic areas (Benoit and McNutt, 1993, 1994). This relational database is used as a baseline for comparing seismic activity at volcanoes and for extracting general relationships between seismicity and eruptive activity. We chose the *Bulletin of Volcanic Eruptions* (BVE) as our primary data source. The BVE is a yearly supplement of the *Bulletin of Volcanology*, reporting yearly summaries on volcanic eruptions, seismicity, deformation and other forms of volcanic unrest. The database spans an eleven-year period from 1979 to 1989. This time window was chosen to include several well-studied volcanic earthquake swarms which occurred at: Mt. St. Helens, Etna, Kilauea, Augustine, Redoubt, O-Shima, and Izu-Tobu. A strong effort was made to not only focus on these well-studied earthquake swarms, but also to include smaller, less well-known earthquake swarms and swarms not associated with large eruptions.

## 2. Database description

The relational database provides a powerful means to create links between volcanic earthquake swarm parameters, eruption parameters, and general geological features. The relational database structure allows the viewing of these data in many ways. The results presented in this paper were made possible first, by the systematic literature compilation and second, from the database structure itself. Using the database, we easily extracted sub-sets of earthquake swarm data and compared them with eruptive behaviour. The recent volcanic crisis at Popocatepetl provided another example of the utility of the database. During the crisis the question was raised: what is the magnitude of the largest earthquake preceding a large explosive eruption? With the GVESD, we were able to quickly perform a query and produce a table of several large eruptions (VEI ≥ 4) which provided several parameters of the preceding earthquake swarms (table I). Looking to the future, the GVESD can be expanded with the addition of new tables, or it could itself be linked into a larger, more comprehensive volcanological database.

The GVESD consists of three main tables: a volcano table, a volcanic earthquake swarm table, and an eruption table. The volcano table contains general information on 149 volcanoes that were active between 1979 and 1989. This table also serves as the parent table for the rest of the database. A sample record of the volcano and swarm table is shown in fig. 1.

### 2.1. *Volcano table*

The volcano name, geographical region, latitude, longitude, and volcano number used

**Table I.** Swarm parameters for large eruptions 1979-1991.

| | Eruption date | Swarm start date | Swarm duration | Maximum magnitude | Swarm type | Eruption repose (years) |
|---|---|---|---|---|---|---|
| VEI 3 | | | | | | |
| Soufriere St. Vincent | 4/12/79 | 8/12/78 | 240 days | – | 1b? | 8 |
| Ulawun | 10/6/80 | 10/3/80 | 3 days | – | 1b? | 2.4 |
| VEI 4 | | | | | | |
| Alaid | 4/30/81 | 4/26/81 | 22 days | $M$ 3.5 | 1d | 9 |
| Pagan | 5/15/81 | 4/1/81 | > 45 days | $M$ 4.0 | 1b | 58 |
| Galunggung | 5/17/82 | – | – | one felt e.q. 2 h before | | 64 |
| Una Una | 7/23/83 | 7/4/83 | 24 days | $M$ 4.6 | 1c | 85 |
| Augustine | 3/27/86 | 2/10/86 | 45 days | $M_L$ 2.1 | 1b | 10 |
| Chikurachki | 11/18/86 | – | – | «strong» | – | 13 |
| Kelut | 2/10/90 | 11/15/89 | 90 days | < $M_d$ 2.0 | 1a | 24 |
| VEI 5 | | | | | | |
| El Chichon | 4/3/82 | 3/1/82 | 28 days | $M_d$ 4.0 | 1dq | 650 |
| Mount St. Helens | 5/18/80 | 3/20/82 | 59 days | $M$ 5.1 | 1d | 123 |
| VEI 6 | | | | | | |
| Pinatubo | 6/15/91 | 4/5/91 | > 70 days | $M$ 4.3 | 1b? | 600 |
| Hudson, Cerro | 8/12/91 | – | – | «felt» | – | 20? |

**KUSATSU-SHIRANE** Honshu-Japan 36.62N 138.55E *VOTW num.*:0803-12=
*Morphology:* strato or composite *Tectonic framework:* Convergent (arc)
*Elevation above m.s.l. :* 2176 m *Edifice relief :* 500 m
*Range of eruptive products:* andesite

**SWARM DATE:** 82/10/22 ±0.5 Dur. (days): 1.5 ±1 Type: 1aq Event type(s):VE,t Grade : B

| | | | |
|---|---|---|---|
| Max. Magnitude: | # EQ total : 23 | Seismograph: permanent | OTHER REPORTED OBSERVATIONS |
| Max. Intensity: MM at | # Felt total : | Dist. to vent: 1.1 km | Tremor : Y Migration : |
| Depth (km): ± | b-value : | Type: electromagnetic | Deformation : Focal mech: |
| Detection threshold:1.2 | Repose (yr.): 6 | Component : 3 | Gravity : Y EQ families : |
| Cum. energy release: | Previous swarms : | Natural period : 1 s | Magnetic : Y Rumbling : Y |
| | | Magnification : 5 K | Geothermal : Y |

Key phrase: Prior to eruptions, frequency of volcanic earthquakes increased on Oct. 22 (23 events).

The exact time of occurrence of these phreatic explosions was not well known. However, at 08:55 continuous volcanic tremors (amplitude = 0.2 um), possibly due to eruptive activity, commenced and was recorded at 1.1 km NE of Yugama crater and the amplitude became 5 um through about 11:00. Then, the amplitude of continuous volcanic tremors decreased; 1 um after 12:30, 0.3 um after 00:00 on Oct. 27. 0.1 um after 16:15 and stopped at 01:24 on Oct. 30.

Prior to eruptions, the frequency of volcanic earthquakes increased on Oct. 22 (23 events) and one volcanic tremor was recorded. Volcanic earthquakes swarmed from 21:45 (Oct. 26) to 07:38 (Oct. 27) but frequency suddenly decreased after that.

Figs: seismic activity before and after phreatic explosion of Oct. 26.

BVE No. 22, p. 47-50.

**Fig. 1.** An example record from the Global Volcanic Earthquake Swarm Database. The top box shows the information contained in the volcano table. The middle portion shows one swarm record from the swarm table. The bottom portion shows the text excerpted from the original reports.

within the database are drawn directly from *Volcanoes of the World Data File 1992*, an update of *Volcanoes of the World* (Simkin *et al.*, 1981). The *Volcanoes of the World Data File* was expanded to include: the volcano elevation, the edifice height, the morphology, the range of erupted products, the tectonic framework, and a short geologic summary of each volcano. This supplemental information was taken from the *List of the World Active Volcanoes*, a special issue of the BVE (Katsui, 1971), and from *Volcanoes of North America* (Wood and Kienle, 1990).

### 2.2. *Earthquake swarm table*

The volcanic earthquake swarm table holds over 600 records containing summary information related to each swarm and includes the dates of occurrence, durations, and the uncertainties in these measurements. Other parameters related to swarms such as the swarm type (see definitions below), the event type, the magnitude and intensity of the largest shock, the number of felt and unfelt events, and a short summary of the seismic instrumentation are included with each swarm record. This summary information is supplemented with an extended field that contains text excerpted from the original reports. A reference list is included with each record.

### 2.3. *Eruption table*

The eruption table contains summaries of over 160 eruptions associated with well-documented earthquake swarms and includes information pertaining to eruptive activity, such as dates of activity, eruption intensity, eruption repose time, and character of the eruption. This table is not complete for the entire study period at this time.

## 3. Swarm dates, durations and uncertainties

In most cases the starting date of a swarm originates directly from the BVE reports. Typi-

**Table II.** Reporting uncertainties.

| Dates reported to | Uncertainty assigned |
|---|---|
| Minute | 0 |
| Hour | ± 0.02 day |
| Day | ± 0.5 day |
| Week | ± 3.5 days |
| Month | ± 15 days |

| Date modifiers | Within a month (*e.g.* «mid» Jan.) | Within a year (*e.g.* «mid» 1980) |
|---|---|---|
| «Early» | 5 Jan. ± 5 days | 1 Mar. 1980 ± 60 days |
| «Mid» | 15 Jan. ± 5 days | 1 Jul. 1980 ± 60 days |
| «Late» | 25 Jan. ± 5 days | 1 Nov. 1980 ± 60 days |

cally the beginning of a swarm is described as an increase in the number of earthquakes reported per day (see definition of swarm duration below). Gradual increases in seismicity, problems in network coverage, a high detection threshold, and the lack of a clear definition of when a swarm begins (or ends) are all problems with the determination of the onset and duration of a swarm. These difficulties often lead to reports that describe the onset of a swarm in imprecise terms. In order to assess these problems a field was added to capture the uncertainties in these measurements. A typical swarm report may read: «Seismicity increased in the middle of November to about 60 events per day. However, there was a decline to 5-20 per day in late December» (Bagana volcano, BVE No. 25, p. 20). This swarm was entered into the GVESD as beginning on 85/11/15 ± 5 days, with a duration of 40 ± 10 days. Table II describes the uncertainty values assigned in several common situations.

## 4. Definition of swarm duration

Earthquake swarms are generally defined as a sequence of events closely clustered in time and space without a single outstanding shock (Mogi, 1963). Our working definition follows Mogi's outline and also requires a significant increase in the rate of local volcanic earthquakes above the background rate. We take volcanic earthquakes to be of any type, for example A, B (Minakami, 1960), high frequency, low frequency, short period, long period (Koyanagi *et al.*, 1987), volcano-tectonic (Latter, 1981), explosion events, etc., but they must occur within an arbitrary near distance to the volcano (typically < 15 km). We do not take a significant increase with respect to the background rate in a strict statistical sense, but rather the experience and point of view of each reporter. In other words, if the reporter feels that an increase in seismicity is significant enough to be reported, then we include that report as a swarm record along with a quality modifier. We also do not consider seismic crises (peak seismicity rates within a swarm), obvious mainshock-aftershock sequences, and tremor episodes as swarms. These «non-swarm» seismic sequences are recorded in the GVESD and are delimited in a separate field.

This working definition was developed through the examination of over 600 swarms. One single fixed definition or algorithm is preferable, but not feasible due to the widely varying qualities and formats of the data. Future studies would greatly benefit from standardized reporting and the strict application of an algorithm to distinguish the starts, ends, and durations of swarms.

## 5. Swarm type

We grouped volcanic earthquake swarms according to their temporal relationship to eruptive activity. The swarm types are schematically summarized in fig. 2. The main categories are: swarms that precede (Type I), or accompany (Type II) eruptive activity, and those which are not associated with eruptive activity (Type III).

Type I, or precursory swarms (46% of the GVESD records), were further divided into 4 sub-types (I a, I b, I c, and I d) according to when the swarm ends in relation to the eruptive activity. Type I a are swarms that begin and end before the eruption commences (for example, 1989 precursory swarm at Izu-Tobu). Type I b are swarms that begin before the eruption and end when the eruption starts (for example Asama, 1983). Type I c are swarms that begin before the eruption, continue through the duration of the eruption, and end as the eruption ends (for example Oshima, 1987). Type I d swarms begin before the eruption and end after the eruption has stopped (for example Soufriere de Guadeloupe, 1976).

Type II swarms, those accompanying eruptions (15% of the GVESD records), are separated into three sub-types (II a, II b, II c). Type II swarms begin and end with the eruption. Type II b swarms begin with the eruption and then continue after the eruption has stopped. Type II c is reserved for swarms that occur during an extended eruption (*e.g.*, the continuing eruption of Kilauea).

Type III swarms are not associated with eruptions (39% of the GVESD records). To separate this category from swarms of Type I a, the time period between the end of the swarm and the next eruption must be greater than 100 days. Post-eruption swarms are also included in the Type III category.

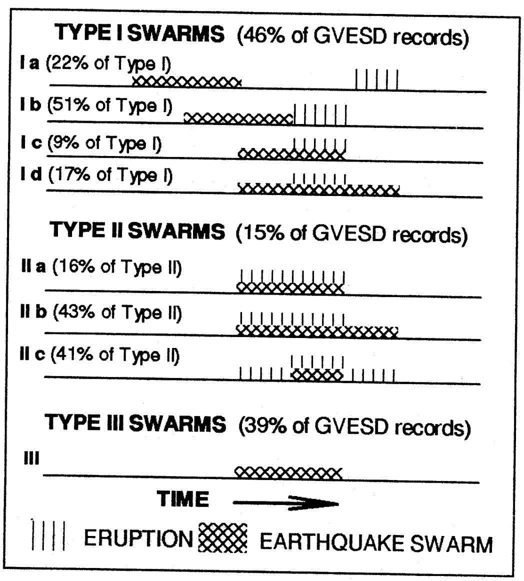


**Fig. 2.** Schematic diagram of the temporal relation between volcanic earthquake swarms and eruptive activity. The stippled boxes represent the earthquake swarms. The vertically striped boxes represent the eruptions.

## 6. Preliminary analyses and results

The duration of a volcanic earthquake swarm was found to be the most commonly reported parameter. The database contains 385 swarm duration records of high quality. The distribution of swarm durations is shown in fig. 3. The durations vary from very short, intense swarms lasting less than an hour, such as those reported at Piton de la Fournaise and Kilauea, to swarms lasting a few years, such as the activity recorded at Long Valley Caldera and Usu (Usu at 1682 days is the longest swarm in the database). The geometric mean of the duration distribution is 5.5 days, with a median of 7 days. The $\log_{10}$ transformed duration distribution was tested for normality using the Kolmogorov-Smirnov (KS) test (Rock, 1988). The test showed that the distribution was not log-normal at the 95% confidence level. The duration distribution is skewed to the left. In other words, there is an excess of shorter swarms.

Swarm durations were then separated according to their relationship with the eruptive activity: those which preceded eruptions (Type I) and those not associated with eruptions (Type III). The durations of Type I swarms tended to be longer than Type III swarms

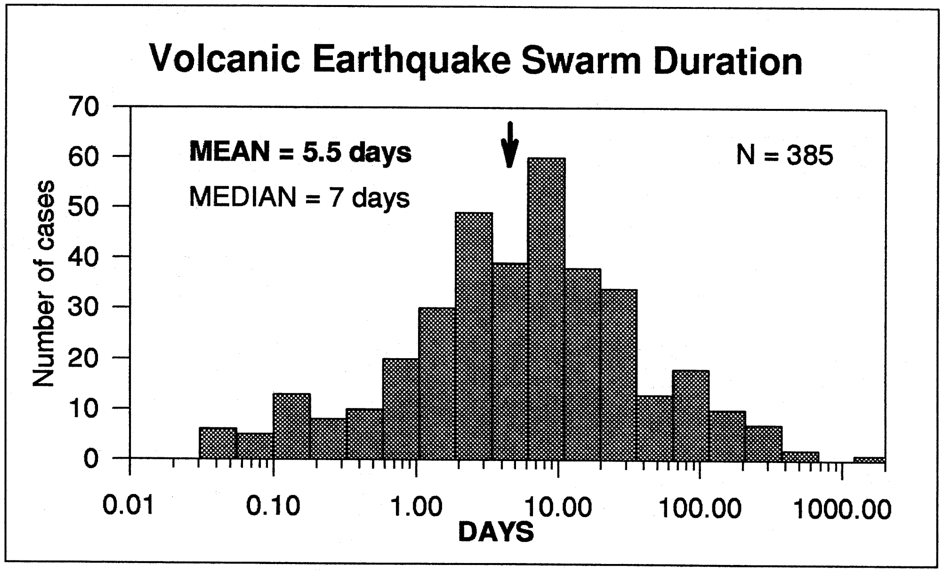


**Fig. 3.** Histogram of the durations of 385 volcanic earthquake swarms. The horizontal axis is logarithmic. The data form a nearly log-normal distribution (the distribution is skewed toward shorter swarms) with a geometric mean of 5.5 days (marked with a bold arrow) and a median of 7 days.

(fig. 4). The geometric mean durations were 8 and 3.5 days, respectively. The means of the duration distributions were found to be significantly different (at the 95% confidence level) using a t-test. In other words, the durations of each swarm type are drawn from different parent populations. The $\log_{10}$ transformed duration distributions for the two swarm types were again tested for normality. We found that the Type I and III swarm duration distributions are again not log-normal (at the 95% confidence level) using the KS test. Using a second test (Martinez and Iglewicz, 1981) we were unable to reject normality for the Type III distribution. As with the combined distributions, the Type I duration distribution is skewed to the left.

The precursory swarm durations of Type I b were then compared to the eruption repose time. The eruption repose time was defined as the time from the end of the last eruption to the beginning of the next eruption. The durations of 65 swarms were plotted against the $\log_{10}$ of the eruption repose time (fig. 5). The points appear to fall into two groups, swarms with durations greater than about 4 months and those lasting less than 4 months. For the longer swarms there is a strong positive correlation ($r$ = 0.94, significant at the 99% confidence level) with the eruption repose time. However, shorter swarms appear to have no correlation with the eruption repose time.

## 7. Discussion

Previous studies on volcanic earthquake swarms have dealt mostly with a small number of cases at a few volcanoes, with the notable exception of Newhall and Dzurisin's (1988) compilation on calderas. The GVESD provides a large systematic global sample of seismicity at more than 140 active volcanoes. Using the GVESD, for the first time we can give a quantitative statement of the mean duration as well as the distribution of the durations of volcanic earthquake swarms. Our result of a mean duration of 5.5 days is within previous rough estimates of days to weeks at mafic calderas, but shorter than the weeks to months estimates at silicic calderas (Newhall and Dzurisin, 1988). Tokarev (1985) studied earthquake swarms preceding three large eruptions at andesitic strato-volcanoes. Tokarev stated that the durations of precursory swarms are on the order of weeks to months. Our determination of the mean duration is shorter, but the value of 5.5 days is drawn from a combination of precursory and non-precursory swarms. When precursory and non-precursory swarms are separated, the mean duration of precursory swarms is 8 days, which is within Tokarev's estimate.

The observation that the mean duration of swarms that precede eruptions is about twice as long as swarms that are not associated with

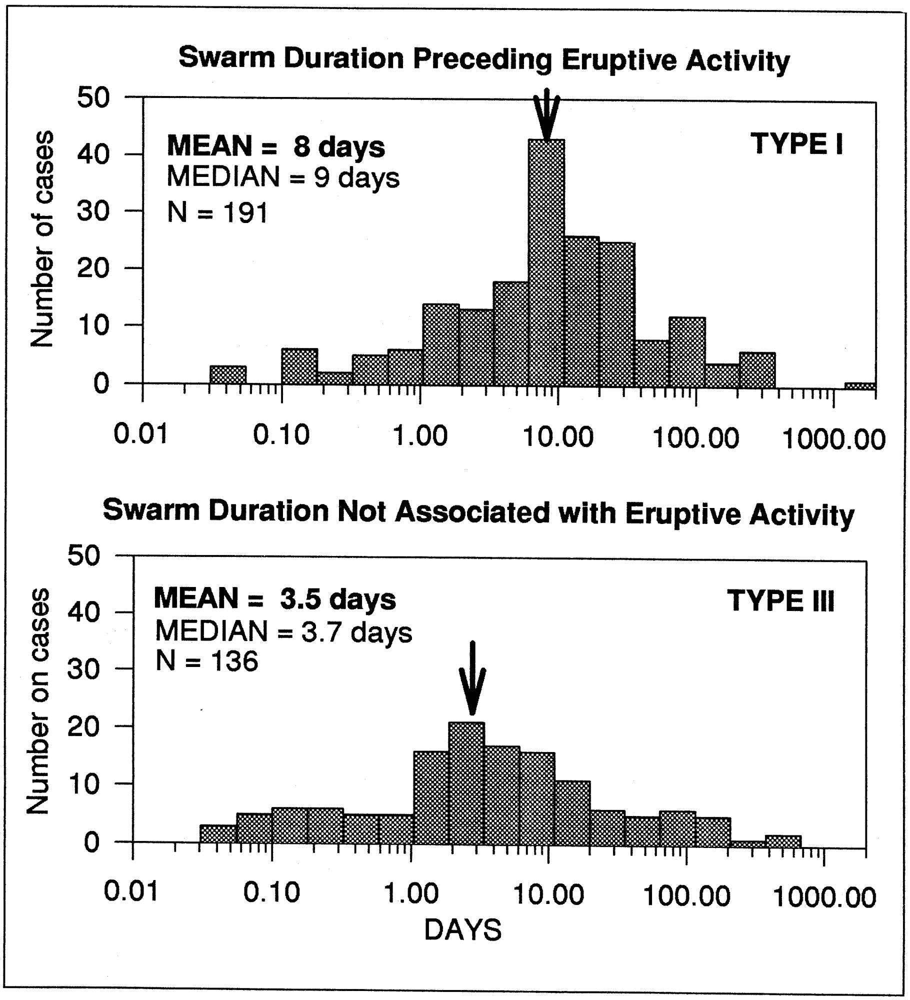


**Fig. 4.** Comparison of the distribution of 191 earthquake swarm durations that precede eruptive activity (Type I) and 136 durations that are not associated with eruptive activity (Type III). As with the combined distributions, the Type I duration distribution is skewed toward shorter swarms. The geometric means are 8 and 3.5 days (marked with bold arrows) and the medians 9 and 3.7 days for Type I and III swarms respectively.

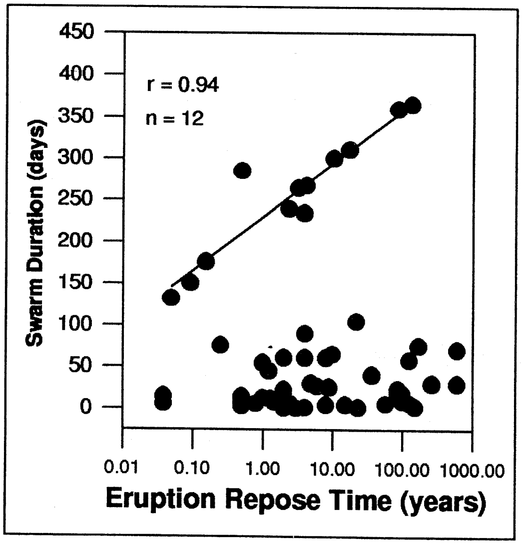


**Fig. 5.** Graph of the durations of 65 precursory swarms (Type I b) versus the $\log_{10}$ of the eruption repose times. Note the strong positive correlation for swarms lasting greater than about 4 months. The regression line shown is for 12 durations of 100 days or greater. The correlation coefficient is 0.94, which is significant at the 99% confidence level.

eruptions may be due to: 1) reporting bias, 2) mis-identification of small tectonic mainshock-aftershock sequences as swarms, or 3) different time scales for the processes involved with transport of magma to the surface, when compared with time scales of intrusion or various transient forcing phenomena (tidal, barometric pressure fluctuations, seasonal ocean-loading, etc.).

Reporting bias is a possible source of error which must be considered when interpreting these results. The database was compiled primarily from the BVE where the emphasis is on the reporting of eruptions. Therefore, there may be a tendency to more frequently report seismic activity associated closely with eruptions as opposed to swarms that occur at volcanoes with little or no historic activity. Furthermore, if an eruption occurs, the reporter may examine the preceding seismicity more rigorously, and perhaps include a longer period of time as the precursory seismicity.

The mean magnitude for the largest shocks in volcanic areas is about *M 3*, based on data from 116 swarms at 61 volcanoes in the GVESD. Using aftershock decay parameters given by Reasenberg and Jones (1989) for tectonic earthquakes in Southern California, the duration of an aftershock sequence following an *M 3* earthquake is about half a day and for an *M 4*, 3.5 days. Thus, the durations of a small mainshock-aftershock sequence are similar to the mean duration of Type III (non-eruptive) swarms. In areas where the magnitudes are not available or not reliable, small tectonic earthquakes and their aftershocks may be reported as swarms.

The above problems of reporting bias and mis-identification are certainly factors in some of the reports. However, we believe that given our large sample size, these effects will not bias the general result. With these limitations in mind, we can speculate that differing earthquake swarm durations are due to several suites of physical processes operating at different time scales. For example, the ascent of magma to the surface may express itself in longer lasting swarms, while intrusions or failed eruptions are manifested by shorter swarms. Other factors not directly associated with the movement of magma may also lead to shorter duration sequences of earthquakes. Volcanic and geothermal areas have been shown to be sensitive to small strains. Such strains can be generated by earth and ocean tidal stresses (Rydelek *et al.*, 1988; McNutt and Beavan, 1981; Klein, 1976), surface waves from regional or teleseimic earthquakes (Hill *et al.*, 1993), seasonal ocean-loading (McNutt and Beavan, 1987), or changes in barometric pressure (Rinehart, 1980).

The separation (fig. 5) of the precursory swarm durations as a function of repose time into two groups suggests that there are two dominant processes, or suites of processes, involved. The first, affecting shorter swarms, again may reflect shallow intrusion modulated by factors such as variations in tidal stresses, barometric pressure, or ocean loading, as well as the vesiculation of magma. The second group permits a simpler explanation. Longer repose times suggest a cooler and mechanically stronger crustal environment of the volcanic conduit. Thus, longer lasting earthquake swarms may be the result of ascending magma encountering a cooler and stronger crustal environment. Other factors or attributes that are shared between the two groups have yet to be discovered.

## 8. Future work

Future work with the GVESD will explore more fully the relationship between swarm parameters (such as the duration, the magnitude of the largest shock, and the event types) and specific eruption parameters such as the Volcanic Explosivity Index. The GVESD will also be used to define a common suite of processes that are observed in different types of seismicity leading into an eruption. The GVESD is available as USGS open-file report 96-69.

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