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GLOBAL VOLCANIC EARTHQUAKE SWARM DATABASE 1979-1989

by

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Development and Description of the Global Volcanic Earthquake Swarm Database

Introduction

Earthquake swarms are pervasive at volcanoes, but have seldom been studied systematically. Most swarms that are described in the literature are those that occurred in association with eruptions; indeed, earthquake swarms are the most reliable method of forecasting eruptions. For the purpose of this report, a swarm is defined as many earthquakes of the same size occurring in a small volume. Swarms are different in these two ways from a mainshock-aftershock sequence or a foreshock-mainshock-aftershock sequence (fig. 1). Swarms are especially common in volcanic areas.

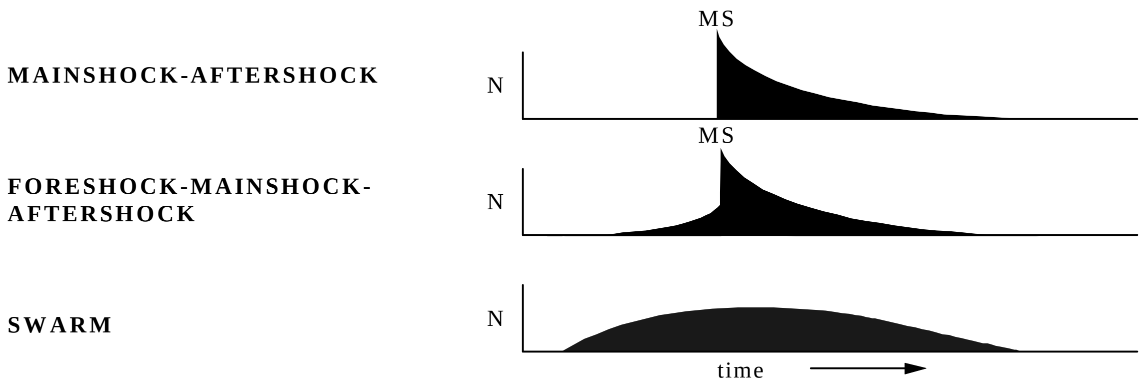

Figure 1. The number of events (N) per unit time versus time is schematically shown for the three types of earthquake sequences. The mainshock (MS) indicates the sharp increase in rate for the upper two distributions.

Because swarms are such a common and important phenomenon, we undertook a systematic and comprehensive study of swarms at volcanoes using modern commercially available database software. We term the result the Global Volcanic Earthquake Swarm Database (GVESD). This report describes the database and how it is structured, and gives preliminary results of a study of swarm durations based on 11 years of data as reported in the *Bulletin of Volcanic Eruptions* (BVE) of the Volcanological Society of Japan.

We chose BVE as our primary data source for several reasons. First, it contains data on many swarms that were never reported in the open literature. This is because most papers report eruptions, and swarms are included only if they were associated with eruptions. In other words, the open literature is biased in favor of eruptions, whereas BVE more fully reports a variety of activity during times of no eruptions. Second, BVE is prepared once per year, which gives investigators the opportunity to summarize data on a broad time scale. Monthly reports, such as the Smithsonian Institution Global Volcanism Network Bulletin, often focus more narrowly on the necessarily short (one month) time scale. Third, BVE is organized by time, so the 1980 issue, for example, contains data on many volcanoes for 1980. This makes it easy to select a sample which includes known large (or small) eruptions, whereas the open literature often has a significant delay between an event and the report. Fourth, BVE data are organized systematically, which greatly aids the preparation of data for entry into the electronic database. Fifth, the BVE includes a section devoted to miscellaneous information. The miscellaneous information section includes many reports of seismic activity at volcanoes that were not in eruption that year. Finally, BVE includes a supplement, which is used to provide additional information on previous years' activity. This systematic updating provides an additional element of quality control which is not found in most standard reports.

In spite of the generally high quality of BVE data, there are a number of limitations in those data as well as in the very nature of the problem we have chosen for study. In many respects this has been an exercise in the study of messy data. We have been faced with the difficult task of converting the judgments and measurements of many other scientists, which are often reported in words, into numerical data. We have thus been faced with a myriad of decisions and have struggled to maintain consistency and high quality control. A most basic decision is the start time of an earthquake swarm. In most cases this has been reported by a remote observer, but the units vary widely from "10:23 on July 24" to "late July." In some cases we have had to read data from a graph or histogram, so we have had to decide whether a factor of 2 or 3 increase above background marks the onset of a swarm. The sections below on the structure of the database provide many examples of such decisions.

It was our initial intention to perform a full multi-parametric study of the database. However, it quickly became apparent that durations of earthquake swarms were the most widely reported parameter whereas many other parameters were poorly reported (e.g., energy, cumulative seismic energy release, detection threshold, b-values). Thus we have focused our initial efforts on understanding the distribution of the swarm duration with respect to eruptive activity.

Database Structure and Description

The GVESD consists of three main tables: a volcano table (VOLCAT), a volcanic earthquake swarm table (SWARMCAT), and an eruption table (ERUPTCAT). The volcano table contains general information on 149 volcanoes active between 1979-1989. 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 figure 2.

KUSATSU-SHIRANE **Honshu-Japan** **36.62 N 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 *Last known eruption after:* 1964

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

Max. Magnitude:
Max. Intensity: MM at
Depth (km): ±
Detection threshold: 1.2
Cum. energy release:

EQ total: 23
Felt total:
b-value:
Repose (yr.): 6
Previous swarms:

Seismograph: permanent
Dist. to vent 1.1 km
Type: electromagnetic
Component: 3
Natural period: 1 s
Magnification: 5 K

OTHER REPORTED OBSERVATIONS
Tremor: Y Migration:
Deformation: Focal mech:
Gravity: Y EQ families:
Magnetic: Y Rumbling: Y
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.

Figure 2. 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 text excerpted from the original reports.

Volcano Table

The volcano name, geographical region, latitude, longitude, and volcano number used within the database are drawn directly from *Volcanoes of the World Data File 1992*, an update of *Volcanoes of the World* (Simkin and others, 1981; Simkin and Siebert, 1994). The *Volcanoes of the World Data File* was expanded to include the volcano elevation, edifice height, morphology, compositional range of erupted products, tectonic framework, and a short geologic summary of each volcano (time is local unless otherwise stated). This supplemental information was taken from the *List of the World Active Volcanoes*, a special issue of the BVE, (Katsui and others, 1971), and *Volcanoes of North America*, (Wood and Kienle, 1990).

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. See figure 2 for an example.

Eruption Table

The eruption table contains summaries of over 160 eruptions associated with well-documented earthquake swarms. It includes information pertaining to eruptive activity, such as dates of activity, eruption intensity (Volcano Explosivity Index), and character of the eruption. This information is drawn from the BVE and the Smithsonian Institution's Global Volcanism Program eruption data file. The eruption table does not include all eruptions that occurred during the time period covered by the database.

The following sections contain detailed descriptions of parameters in each of the above tables.

VOLCAT Organization and Parameter Description

The conventions for the volcano name, geographical region, latitude, longitude, and volcano number used within the GVESD are the same as in the *Volcanoes of the World* (Simkin, and others, 1981). The order of presentation is by geographic region and follows the organization of the *Catalog of Active Volcanoes of the World, IAVCEI, 1951- present*. Table 1 shows the regional organization, the number of swarm records in each region, and the starting page for each region in the GVESD. Table 2 is an alphabetical listing of the volcanoes, the number of swarm records at each volcano, the volcano number, and the page number in the GVESD.

Table 1. Regional Organization

	Region	*Number of swarm records*	*Number of volcanoes*	*Page*
1	Mediterranean	26	4	1
2	Africa and the Red Sea	5	1	14
3	Arabia and the Indian Ocean	28	1	17
4	New Zealand, Kermadec, Tonga, and Samoa	26	5	27
5	Melanesia	81	7	42
6	Indonesia	38	24	80
7	Philippines	26	6	111
8	Japan, Taiwan, and Marianas	138	25	122
9	Kurile Islands	4	4	195
10	Kamchatka	26	4	200
11	Aleutian Islands and Alaska	41	9	213
12	Western North America	40	5	232
13	Hawaiian Islands and Pacific Ocean	104	6	252
14	Central America	23	14	286
15	South America	16	6	307
16	West Indies	7	4	319
17	Iceland and Jan Mayen	8	5	326
18	Atlantic Ocean	2	1	331
19	Antarctica	2	2	332

Table 2. List of Volcanoes in the GVESD

Volcano Name	*Number*	*Recs.*	*Page*	*Volcano Name*	*Number*	*Recs.*	*Page*
ADAGDAK	1101-112	1	214	ILI BOLENG	0604-22=	4	99
AGUNG	0604-02=	1	96	ILIWERUNG	0604-25=	1	100
AKITA-KOMAGA-TAKE	0803-23=	2	159	IVAN GROZNY	0900-07=	1	195
ALAID	0900-39=	1	199	IWAKI	0803-27=	1	160
AMBRYM	0507-04=	1	78	IWO-JIMA	0804-12=	1	178
ANAK RANAKAH	0604-071	3	98	IZU-TOBU	0803-01=	2	141
ANIAKCHAK	1102-09-	1	225	KARKAR	0501-03=	9	48
API SIAU	0607-02=	4	108	KELUT	0603-28=	1	89
ASAMA	0803-11=	10	146	KICK-'EM-JENNY	1600-16=	1	325
ASO	0802-11=	17	134	KILAUEA	1302-01-	95	253
AUGUSTINE	1103-01-	5	226	KIRISHIMA	0802-09=	9	128
BAGANA	0505-02=	13	74	KLIUCHEVSKOI	1000-26=	15	204
BANDA API	0605-09=	3	102	KOMAGA-TAKE	0805-02=	2	81
BANDAI	0803-16=	3	157	KOZU-SHIMA	0804-03=	1	176
BATUR	0604-01=	1	95	KRAFLA	1703-08=	6	328
BEERENBERG	1706-01=	1	330	KRAKATAU	0602-00=	2	82
BEZYMIANNY	1000-25=	7	201	KUSATSU-SHIRANE	0803-12=	11	150
BROMO	0603-31=	1	91	LAMONGAN	0603-32=	2	92
BULUSAN	0703-01=	11	114	LANGILA	0502-01=	16	53
CAMPI FLEGREI	0101-01=	6	1	LASCAR	1505-10=	1	315
CANLAON	0702-02=	8	111	LASSEN PEAK	1203-08-	1	243
CHICHON, EL	1401-12=	1	290	LIAMUIGA, MT.	1600-03=	1	319
CHIKURACHKI	0900-36=	1	197	LOIHI SEAMOUNT	1302-00-	3	252
COLIMA VOLCANIC COMP.	1401-04=	4	286	LOKON-EMPUNG	0606-10=	3	106
COLO [UNA UNA]	0606-01=	1	104	LONG ISLAND	0501-05=	1	51
CONCEPCION	1404-12=	1	305	LONG VALLEY	1203-14-	17	244
DECEPTION ISLAND	1900-03=	1	333	LONQUIMAY	1507-10=	1	317
DIENG VOLCANIC COMPL.	0603-20=	1	86	MACDONALD	1303-07-	3	284
DON JOAO DE CASTRO BANK	1802-07=	2	331	MAHAWU	0606-11=	1	107
DUTTON, MT.	1102-011	1	216	MAKIAN	0608-07=	1	110
EBEKO	0900-38=	1	198	MALINAO	0703-04=	1	119
EREBUS, MOUNT	1900-02=	3	332	MANAM	0501-02=	17	42
ETNA	0101-06=	18	8	MARAPI	0601-14=	3	81
FOURNAISE, PITON DE LA	0303-02=	28	17	MARU-YAMA	0805-061	3	191
FUEGO	1402-09=	1	296	MASAYA	1404-10=	2	304
FUJI	0803-03=	1	142	MAUNA LOA	1302-02=	6	278
GALUNGGUNG	0603-14=	2	84	MAYON	0703-03=	3	118
GAMALAMA	0608-06=	2	109	ME-AKAN	0805-07=	6	192
GARELOI	1101-07=	1	213	MEDICINE LAKE	1203-02-	1	242
GORELY	1000-07=	2	200	MEHETIA	1303-06-	1	283
GRIMSVOTN	1703-01=	1	327	MERAPI	0603-25=	5	87
GUAGUA PICHINCHA	1502-02=	3	313	MIYAKE-JIMA	0804-04=	1	177
HAKKODA GROUP	0803-28=	1	161	MOMOTOMBO	1404-09=	1	303
HAROHARO COMPLEX	0401-05=	1	30	NASU	0803-15=	5	154
HEKLA	1702-07=	1	326	NEGRA, SIERRA	1503-05=	1	314
HOOD, MOUNT	1202-01-	1	241	NII-JIMA	0804-02=	2	175
IJEN	0603-35=	1	94	NIUAFO'OU	0405-11=	1	41

Table 2 continued. List of Volcanoes in the GVESD

Volcano Name	*Number*	*Recs.*	*Page*	*Volcano Name*	*Number*	*Recs.*	*Page*
NORIKURA	0803-06=	1	145	SOPUTAN	0606-03=	3	105
NYAMURAGIRA	0203-02=	7	14	SORIK MARAPI	0601-12=	3	80
NYOS, LAKE	0204-003	1	16	SOUFRIERE GUADELOUPE	1600-06=	1	320
OKMOK	1101-29-	1	215	SOUFRIERE ST. VINCENT	1600-15=	1	324
ON-TAKE	0803-04=	5	143	SPURR	1103-04-	1	231
OSHIMA	0804-01=	33	162	ST. HELENS, MT.	1201-05-	27	323
PACAYA	1402-11=	5	297	STROMBOLI	0101-04=	5	3
PAGAN, NORTH	0804-17=	1	180	SUWANOSE-JIMA	0802-03=	1	122
PARICUTIN	1401-06=	1	288	TAAL	0703-07=	3	120
PATATES, MORNE	1600-11=	4	321	TACANA	1401-13=	4	291
PAVLOF	1102-03-	21	217	TANGKUBAN PARAHU	0603-09=	3	83
PELEE, MONTAGNE	1600-12=	1	323	TARAWERA	0401-06=	1	31
PINATUBO, MT.	0703-083	1	121	TARUMAI	0805-04=	3	186
POPOCATEPETL	1401-09=	1	289	TEAHITIA	1303-03-	4	281
RABAUL	0502-14=	19	67	TECAPA	1403-08=	1	299
RAUNG	0603-34=	1	93	TELICA	1404-04=	2	302
REDOUBT	1103-03-	9	228	TOKACHI	0805-05=	9	187
RINCON DE LA VIEJA	1405-02=	1	306	TOLIMA	1501-03=	1	316
RUAPEHU	0401-10=	22	32	TUPUNGATITO	1507-01=	2	58
RUIZ	1501-02=	10	307	ULAWUN	0502-12=	25	52
RUMBLE III	0401-13-	1	40	UMBOI	0501-06=	1	179
SAKURA-JIMA	0802-08=	13	123	UNNAMED SUBMARINE	0804-14*	1	131
SAN CRISTOBAL	1404-02=	1	301	UNZEN	0802-10=	6	182
SAN MIGUEL	1403-10=	4	300	USU	0805-03=	8	224
SANGEANG API	0604-05=	2	97	VENIAMINOF	1102-07-	2	318
SANTA MARIA	1402-03=	5	294	VILLARRICA	1507-12=	1	304
SARYCHEV PEAK	0900-24=	1	196	VULCANO	0101-05=	6	5
SEMERU	0603-30=	4	90	WHITE ISLAND	0401-04=	7	26
SHIVELUCH	1000-27=	7	210	YASUR	0507-10=	1	79
SIRUNG	0604-27=	1	101	YELLOWSTONE	1205-01-	1	251
SLAMET	0603-18=	1	85				

Morphology, Tectonic Framework, Elevation, and Edifice Relief

The morphology or volcano type is drawn from the *List of the World Active Volcanoes* (Katsui and others, 1971). Table 3 is a list of the morphologies and the abbreviations used in the VOLCAT table. The majority of swarm records in the GVESD occur at stratovolcanoes and shield volcanoes, with the remainder from calderas, submarine, and compound volcanoes. There are more than twice as many swarm reports from stratovolcanoes as from shield volcanoes.

Table 3. Volcano Morphology

Morphology abbreviation	*Volcano morphology*	*Total number of swarm records*	*Number of swarm records with duration specified*
S	strato or composite	321	267
Sh	shield	137	130
S,Cald	strato with caldera	63	53
S,D	strato with lava dome	57	43
Cald	caldera	49	35
Cald,S	caldera with strato	33	21
S,Sh	strato on a shield	22	21
C	compound or complex	19	12
D	lava dome	17	15
Sub	submarine	17	12
S,CL	strato with crater lake	9	6
	unknown	8	7
Sh,Cald	shield with caldera	3	2
CC	cinder cone	2	2
CC,C	cinder cone in caldera	1	0
LF	lava field (flows)	1	1
S,So	strato with somma	1	1
Sh, D	shield with dome	1	1

The tectonic framework field refers to the regional tectonic setting. We define three general regimes; convergent, divergent, and hot spot. When detailed information is available, we subdivide the tectonic regimes by the type of crust involved. Table 4 shows a summary of the abbreviations used in the GVESD for the tectonic framework. The majority of swarm records occur at volcanoes in convergent margins followed by oceanic hot spots and divergent margins.

Table 4. Tectonic Framework

Tectonic framework abbreviation	*Tectonic framework*	*Total number of swarm records*	*Number of swarm records with duration specified*
C	Convergent (arc)	241	196
CM	Convergent Continental Margin	175	146
HO	Oceanic Hot Spot	133	127
CO	Convergent Intraoceanic	44	41
CM?	Uncert. Convergent Continental Margin	38	28
C?	Uncert. Convergent (arc)	29	28
DRC?	Uncert. Divergent Rift Continental	17	13
DM	Divergent Mid Ocean Ridge	12	11
CO?	Uncert. Convergent Intraoceanic	9	7
DRC	Divergent Rift Continental	8	5
HC	Continental Hot Spot	1	0

The elevation data are drawn from both the *Volcanoes of the World* (Simkin and others, 1981) and the *Catalog of Active Volcanoes of the World IAVCEI, 1951- present*. Elevations are in meters above sea level at the volcano’s highest point. When more than one elevation value is given (e.g., multiple peaks within a massif) the highest value is recorded. The edifice relief or “height over the regional base” is a coarse measurement the volcano’s size. Edifice relief values were extracted from *List of the World Active Volcanoes* (Katsui and others, 1971) for most areas and *The Volcanoes of North America* (Wood and Kienle, 1990) for North America.

Range of Erupted Products

The range of eruptive products field is intended to give a rough idea of the silica content of the magmas erupted at each volcano. We divided this field into six categories; basalt (B), basaltic andesite (BA), andesite (A), dacite (D), rhyodacite (RD) and rhyolite (R). For example, for a volcano that has erupted basalt and dacite, the eruptive product range field is coded as B,D or 'basalt and dacite'. The silica ranges, abbreviations, and the number of cases within each field are shown in table 5. Over half of the swarm records are from volcanoes with basaltic to andesitic composition. The majority of these data were extracted from Katsui and others (1971) for areas outside North America, Motyka and others (1993) for Alaska, and Wood and Kienle (1990) for the contiguous U.S. and Canada. For selected individual eruptions we recorded silica content of the erupted products. The eruption table (see below) holds these data for eruptions with well-studied swarms. The silica content data for the individual eruptions are primarily drawn from the BVE.

Table 5. Erupted Products

Erupted products abbreviation	*% Si02*	*Lower bound*	*Upper bound*	*Erupted products*	*Total number of swarm records*	*Number of swarm records with duration specified*
B	46.5	41	52	basalt	256	220
B,BA	50	41	55	basalt to basaltic andesite	61	59
B,A	52.8	41	63	basalt to andesite	88	63
BA	53.5	52	55	basaltic andesite	1	1
B,D	55.3	41	65	basalt to dacite	0	0
BA,A	56.3	52	63	basaltic andesite to andesite	8	7
B,RD	57	41	70	basalt to rhyodacite	0	0
BA,D	58.8	52	65	basaltic andesite to dacite	0	0
A	59	55	63	andesite	199	157
B,R	59.3	41	74	basalt to rhyolite	27	19
BA,RD	61	52	70	basaltic andesite to rhyodacite	0	0
A,D	61.5	55	65	andesite to dacite	58	51
BA,R	63	52	74	basaltic andesite to rhyolite	1	1
A,RD	63.3	55	70	andesite to rhyodacite	0	0
D	64	63	65	dacite	0	0
A,R	65.5	55	74	andesite to rhyolite	2	2
D,RD	65.8	63	70	dacite to rhyodacite	0	0
RD	67.5	65	70	rhyodacite	0	0
D,R	68	63	74	dacite to rhyolite	0	0
RD,R	69.8	65	74	rhyodacite to rhyoloite	0	0
R	72	70	74	rhyolite	3	3

SiO2 values from: Cox et al., (1979), The interpretation of igneous rocks, George Allen and Unwin, London.

SWARMCAT Organization and Parameter Description

For each volcano, one or more earthquake swarm records are linked to the volcano table's records. The swarm records are linked through the *Volcanoes of the World* catalog-number. Each swarm record is composed of: a header of key fields; a body of swarm, instrumental, and other geophysical parameters; a variable length section containing report excerpts; and references. Three fields are used to ensure that every earthquake swarm record is unique. These fields are called the key fields, and are the volcano catalog-number, the swarm start date, and the swarm type. Every swarm record has a unique value of these three combined fields.

Swarm Dates, Durations and Uncertainties

The start date of a swarm in most cases originates directly from the BVE reports. Typically the beginning of a swarm is described as an increase in the number earthquakes reported per day (see swarm duration definition 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 determining the start time and duration of a swarm. Often these difficulties lead to reports that describe the onset of a swarm in imprecise terms. In order to track 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, 1985, 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 6 describes the uncertainty values used in several common situations.

Table 6. Reporting Uncertainties

Dates reported	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

Some reports in the BVE include vague descriptions or occurrences of seismicity that cannot be easily classified. We use one place holding record per year to incorporate this information into the GVESD. Place holder records are delimited using the start date, the uncertainty, and the key phrase fields (see below). The start date is 'year'/7/1 with an uncertainty of ± 183 days for a place holding record. The key phrase field also contains the text; "place holder for 'year'..." to set these records apart. These are examples of our solutions to the problem of coding highly variable reports into quantitative form.

Definition of a Swarm and 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, and others, 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 identify a significant increase over the background rate in a strict statistical sense, but accept 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 report, 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 (QC field explained below).

This working definition was developed through the systematic examination of over 600 swarms. One single fixed definition or algorithm might be preferable, but is 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.

Swarm Type

We grouped volcanic earthquake swarms according to their temporal relationship to eruptive activity. The swarm types are schematically summarized in figure 3. The main categories are: swarms that precede (Type I), or accompany (Type II) eruptive activity, and those not associated with eruptive activity (Type III). There are a few reported cases of eruptions occurring without a detectable increase in seismicity. These eruptions are included in the database and are identified as Type IV. Roman numerals are used throughout the discussion of swarm type, while Arabic numerals are used in the database for compactness.

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 coincident with the start of the eruption (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 ceased (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 a swarms begin and end with the eruption. Type II b swarms begin with the eruption and then continue after the cessation of the eruption. 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 was measured. This quiescent duration is generally less than 10 days with no cases greater than 3 months. Using this observation 100 days is used as a cut-off to separate Type III from Type I a. Post-eruption swarms are also included in Type III category.

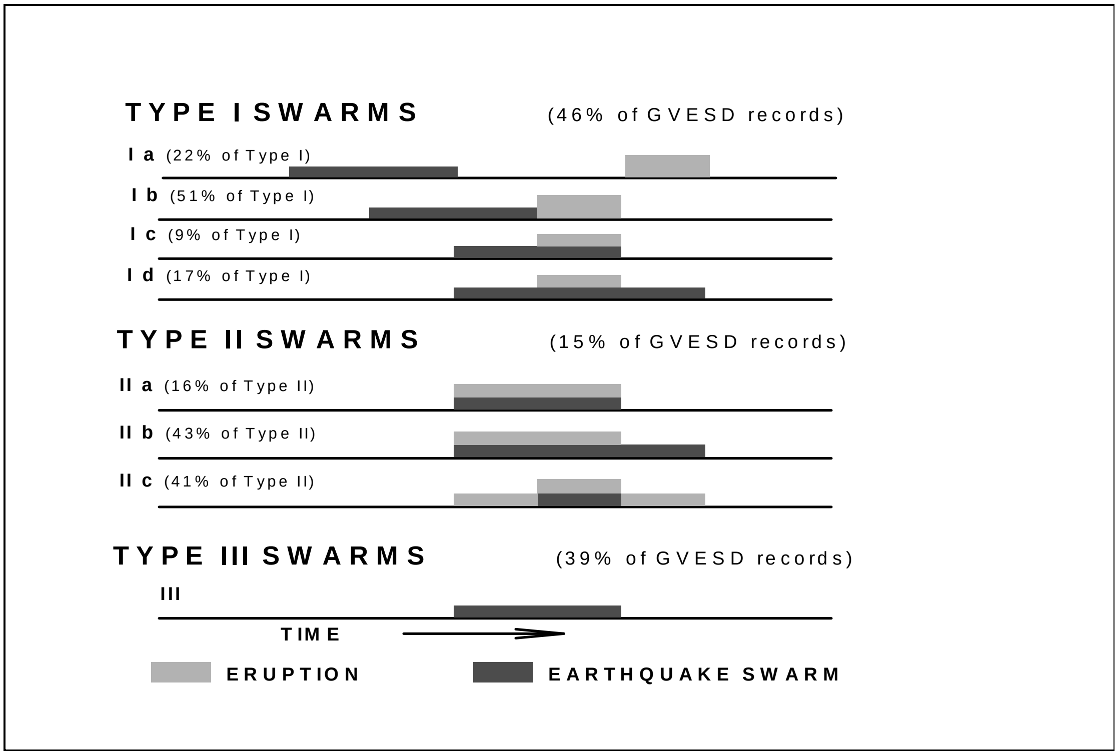

Figure 3. Schematic diagram of the temporal relation between volcanic earthquake swarms and eruptive activity. The stippled boxes represent the earthquake swarms. The vertically striped boxes represent the eruptions.

Event Types

In order to further describe the nature of the seismicity that makes up a swarm we added an event type(s) field. Table 7 shows a list of the events types found in the GVESD. Within any swarm there maybe one or more types of seismic event recorded. The event type field attempts to reflect this complexity by listing (in the order of occurrence, if reported) all the event types that occurred during the swarm. Some swarms are defined and reported by event type. At Kilauea, for example, swarms are reported by location and event type. We separated swarms reported at this level of detail into individual swarm records. Most reports do not provide this level of detail. Therefore, most swarm records contain many different event types. Table 7 lists the event types we have defined, with their abbreviations and the numbers of swarm records in which each was used.

Table 7. Event Types

Event type abbreviation	*Event type*	*Number of cases*
A	A-type	24
B	B-type	82
C	C-type	6
E	explosion	16
Felt	felt earthquake	11
G	gas	2
HF	high frequency	23
LF	low frequency	36
LP	long period	49
M	mixed frequency	1
MF	medium frequecy	1
mseis	micro-seism	1
reg	regional earthquake	1
S	surface	15
SP	short period	39
SV	shallow volcanic	10
Tect	tectonic	7
t	tremor	60
tor	tornillo	2
VE	volcanic earthquake	56
VT	volcano tectonic	37

Quality Grades (QC)

We assign an overall quality grade (QC) to each swarm record. The quality grade is intended to be a qualitative statement of the reliability of the report and the swarm record. We assigned quality grades of A through C to each swarm record. The first two grade levels, A and B primarily reflect the report data source. A QC grade of A is given to swarm records that are taken from the primary reviewed literature or from data to which we have primary access. We assume that swarm records derived from these sources are the most dependable. QC grades of B are assigned to swarm records extracted from reports in the BVE. This QC grade level makes up a majority of the records in the GVESD. The C grade is not a reflection of the data source, but is given to records where there is some question about whether the seismicity constitutes a swarm. Mainshock-aftershock sequences, seismic crises, and vague reports of seismic activity are given a QC grade of C. A parallel grading system is used for tremor episodes. Tremor episodes are delimited from true earthquake swarms by using a lower case QC grade (e.g., a, b, and c).

Approximately 15% (93 records) of the swarm records in the GVESD are derived from the reviewed literature or locally available data (A-QC). Over half (327 records) of the records were drawn from the BVE (B-QC). A quarter (148 records) of the records are questionable swarms and therefore given a C-QC grade. Tremor episodes comprise about 8% (50 records) of the GVESD.

Maximum Magnitude, Intensity, and Depth

The maximum magnitude field contains the magnitude of the largest shock within each swarm. Over one fourth (168 cases) of the swarm records contain the magnitude of the largest shock in the swarm. We added a magnitude scale field to qualify the type of magnitude reported (e.g., M

m_b, M_{JMA}, etc.). A specific magnitude scale is reported with the maximum magnitude in only 6% of the swarm records.

The maximum intensity field records the felt intensity of the largest shock of the swarm. Another field holds the distance between the observer and the active vent. Intensity is reported in about 10% (67 records) of the swarm records, while the distance to the active vent is reported in only one half of these cases. We have recorded all the intensities in the GVESD using the Modified Mercalli (MM) scale. When an intensity is given in a different scale (e.g., JMA or Rossi-Forel) we assign a MM intensity to the value. Where differing intensity scales overlap, the greater MM value is used. For example, the JMA grade 1 spans MM1 to MM3, so a JMA grade 1 is given a MM3. A table of the intensity scales, from Newhall and Dzurizin (1988), is shown in Appendix A.

The depth field is a measure of the mean depth of the swarm. The depth field is supplemented with another field to express the range of depths where the earthquakes are located. The mean depth is recorded in 16% (103 records) of the swarm records. Figure 4 shows the distribution of the mean depth of volcanic earthquake swarms recorded in the GVESD. Volcanic earthquakes are generally shallower than their tectonic counterparts.

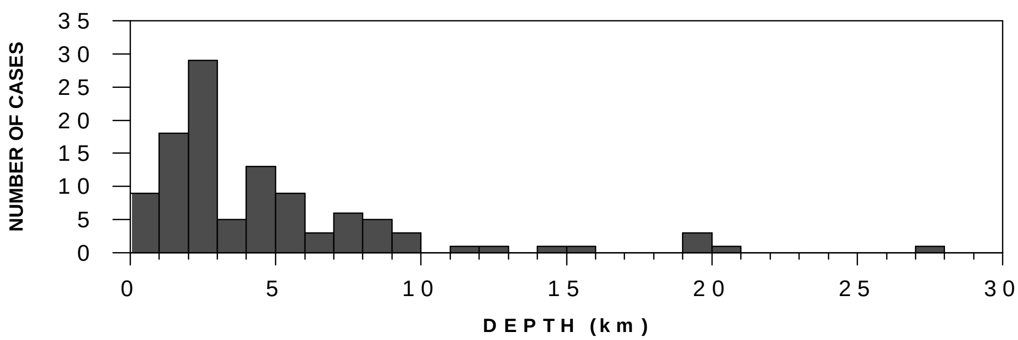

Figure 4. The mean depth of volcanic earthquake swarms.

Cumulative Energy, Energy Release Rate, and Repose

The cumulative energy and the energy release rate fields were included to use a standard measure for comparison with eruption parameters. In practice, the energy parameters are rarely reported (only 2% of the swarm records). This is most disappointing; with a homogenous data set the energy field could prove to be an interesting parameter to compare with eruptive activity. Energy has obvious physical relevance. The energy values and rates are reported in Joules and Joules per day, respectively.

The repose field refers to the eruption repose period. The eruption repose period is here defined as the period of time between the end of the last eruption to the beginning of the next eruption. This field is reported in 20% of the swarm records (127 cases).

Earthquake Counts and Magnitude Detection Threshold

The total number of earthquakes and the number of felt earthquakes are reported in nearly one half of the GVESD records (268 records). The total number and number of felt earthquakes are recorded in the "# EQ total" and "# felt total " fields respectively. The number of reported earthquakes in a swarm is sensitive to the magnitude detection threshold of the local network. The magnitude detection threshold is recorded in a separate field. The detection threshold is reported in about a fourth of the swarm records. Where sufficient information about the network is available the detection threshold was estimated. When reported, the distance from the felt observations to the active vent is included in the comments field.

Seismograph Information

The seismograph section of SWARMCAT is devoted to a summary of the seismic instrumentation at each volcano. The summary includes the type of seismometer, the distance between the nearest station and the active vent, the number of components, the natural period, and the magnification. The seismograph field indicates if the instruments are permanent or temporary stations. The distance (in kilometers) between the nearest station and the active vent is recorded in the distance to vent field. The seismograph and distance fields are commonly reported and are recorded in 84% (530 cases) of the swarm records. The type and component fields describe the type and the number of components in the instrument. We also record the natural period (in seconds) and the magnification at the natural period when available. The natural period and the magnification fields are reported in about 60% (369 cases) of the swarm records.

Previous Swarms and Other Reported Information

The previous swarms field is intended to determine whether or not there is a basis for comparison of a database swarm with other, earlier swarms. The OTHER REPORTED INFORMATION section of the SWARMCAT table provides a quick reference to other reported phenomenon. It was created to be a starting point to build or link other databases. The fields are either filled with 'Y' (yes), 'N' (no), or blank (no information reported). A 'Y' or 'N' in any of the field means some information regarding that parameter was reported. If the parameter was observed and either changed or no information on change was given, then a 'Y' is indicated. For example, a report may state "tilt measurements were conducted," this information is recorded as a 'Y' in the deformation field even though it is not clear if any tilt occurred. A 'N' or no in any field represents a negative result was reported. If, for example, a report explicitly states "no migration of earthquake hypocenters was observed" the migration field will be filled with a 'N.' The details of seismological observations are included in the comment field. For non-seismological observations details can be found in the references section of the record.

Volcanic tremor is the most commonly reported observation followed by reports on ground deformation or tilt. Table 8 shows the number of positive and negative cases reported for each field. The fields are mostly self-explanatory, but a few need some further explanation. The Geothermal field refers to any temperature measurement conducted near the volcano. This includes fumaroles, crater lakes, or hot springs. As stated above, Migration refers to the migration of earthquake hypocenters. The EQ (earthquake) families field refers to earthquakes with nearly identical waveforms, also known as multiplets. The Rumbling field describes audible observations made at the volcano.

Table 8. Other Reported Observations

Parameter	*number of observations*	
	yes	*no*
Tremor	340	10
Deformation	255	1
Magnetic	108	0
Geothermal	89	0
Gravity	60	0
Rumbling	47	0
Migration	42	0
EQ families	36	0
Focal mechanism	8	0

References, Comment and Key Phrase fields

The references used to compile the swarm records are listed at the bottom of each record. The first reference in the list is the primary data source, unless otherwise noted. The other references of seismological interest are included with the BVE reports. The comment field is above the reference field within the swarm record. This variable length field contains text excerpted from the original reports. If the report includes pertinent figures a short note is added in the comment field. The Key phrase field is a one or two line summary of the comment field and gives the essence of the report from which the numerical data were derived.

ERUPTCAT Organization and Parameter Description

The eruption table (ERUPTCAT) contains basic descriptive parameters for 170 eruptions. The task of systematically compiling a complete database of eruption parameters for all eruptions (occurring during the time period covered by the GVESD) is beyond the scope of this study. We selected a set of eruptions that were preceded by well-reported swarms. From these eruptions, data were collected and entered into the eruption table. The eruption parameters chosen are, the start date, the volume of erupted material, the height of the eruption plume, an estimate of the silica content of the erupted products, and the Volcanic Explosivity Index (VEI).The ERUPTCAT table is shown below as table 9. The eruptions are listed in chronological order (grouped by year), beginning and ending with a few eruptions outside the time period systematically covered by the GVESD.

Table 9. ERUPTCAT

Volcano		Bulletin of Volcanic Eruptions Eruption data							VOTW Eruption data				SWARMCAT Swarm data			
Number	Name	start			volume		plume	SiO2	start	T	L	VEI	start	type	dur.	Mmax
0805-03=	Usu								10/7/25	6		2	10/7/22	1bq	4	Ms 5.1
0802-08=	Sakura-Jima								14/1/12	8	9	4	14/1/10	1b	2	Ms 5.2
1401-06=	Paricutin								43/2/20	9	8	4	43/1/7	1b	45	M 4.5
0802-08=	Sakura-Jima								55/10/13			3 *	55/4/20	1aq	175	
1000-25=	Bezymianny								55/10/22	9		5 *	55/10/11	1b	172	M 4.4
1000-27=	Sheveluch								64/11/12	8		4 +	64/11/2	1b	10	M 4.9
1503-05=	Negra, Sierra	79/11/13		g			14		79/11/13			3	79/11/13	1c?	2	M 4.8
1302-01-	Kilauea	80/3/11							80/3/11			0	80/3/10	1c?	1.25	M 4.2
1201-05-	St. Helens, Mount	80/5/18		g	4.0E+8		22	64	80/3/27	9	5	5 *	80/3/20	1d	59	ML 5.1
0502-12=	Ulawun	80/10/6		g				64	80/10/6	7		3	80/10/3	1b?	3	
1201-05-	St. Helens, Mount	80/7/22		g	5.0E+7		20	52	80/3/27			3 #	80/7/22	1b	0.5	M 2.0
1201-05-	St. Helens, Mount	80/10/19	*1*	m		1.2E+6		64	80/3/27			3 #	80/10/4	1b	11	M 2.8
1102-03-	Pavlof	80/11/8		m?			8	50	80/11/8	6		3 ^	80/11/6	1d	80	M 2.3
1201-05-	St. Helens, Mount	80/12/27	*1*	m		1.6E+6		63	80/3/27			1 #	80/12/24	1b	2	
0303-02=	Piton de la Fournaise	81/2/3		m		1.6E+7		48	81/2/3		7	2	81/1/21	1b	13	
1201-05-	St. Helens, Mount	81/2/5	*1*	m		3.6E+6		62	80/3/27			1 #	81/2/2	1b	3	
0805-04=	Tarumai	81/2/27		l	4.0E+2				81/2/27	2		0	80/11/15	1cq	240	
0101-06=	Etna	81/3/17		g		3.0E+7	0.3	48	81/3/17	5	6	1	81/3/12	1aq	6	
1201-05-	St. Helens, Mount	81/4/10	*1*	m		4.1E+6		62	80/3/27			1 #	81/4/5	1b	5	
0703-01=	Bulusan	81/4/27							81/4/9			3 #	81/4/20	1b	8	
0900-39=	Alaid	81/4/27					12		81/4/27	8		4 *	81/4/26	1b	6	M 3.5
0804-17=	Pagan, North	81/5/15		g	3.6E+7	4.3E+7	20	52	81/5/15	8	7	4 *	81/4/1	1b	45	M 4.0
1201-05-	St. Helens, Mount	81/6/18	*1*	m		4.1E+6		62	80/3/27			1 #	81/6/13	1b	5	
1502-02=	Guagua Pichincha	81/8/31		l	5.0E+3		1	64	81/8/31	4		1 ^	81/8/15	1b	15	
1201-05-	St. Helens, Mount	81/9/6		m		3.9E+6		62	80/3/27			1 #	81/8/30	1b	8	
1102-03-	Pavlof	81/9/25		m	7.5E+6		10.5		81/9/25	7	6	3	81/9/25	1d	96	M 2.3
1201-05-	St. Helens, Mount	81/10/30	*1*	m		3.6E+6		62	80/3/27			1 #	81/10/24	1b	7	
0203-02=	Nyamuragira	81/12/25		g			5	56	81/12/25	7	7	3	81/12/25	1b	0.13	M 1.3
1404-04=	Telica	82/2/12		m			4.3		81/11/25			2 ^	82/1/15	1cq	27	M 3.0
1201-05-	St. Helens, Mount	82/3/18		m		3.4E+6		62	80/3/27		6	3 #	82/2/24	1b	22	
1303-03-	Teahitia	82/3/25							82/3/16			0	82/3/14	1c	39	M 4.0
1401-12=	Chichon, El	82/3/28		g	5.0E+8		25	59	82/3/28	9		5 *	82/3/1	1bq	28	Md 4.0
0803-11=	Asama	82/4/26		m			0.5	59	82/4/26			2	82/1/15	1aq	15	
1302-01-	Kilauea	82/4/30		m		5.0E+5	0.05	49	82/4/30		5	0	82/4/30	1c?	0.16	
1201-05-	St. Helens, Mount	82/5/14	*1*	m		2.7E+6		63	80/3/27				82/5/6	1b	8	
1201-05-	St. Helens, Mount	82/8/18	*1*	m		4.6E+6		63	80/3/27				82/7/27	1b	21	
1302-01-	Kilauea	82/9/25		m		3.0E+6	0.07	49	82/9/25		6	1 ^	82/9/25	1aq	1.6	
1404-10=	Masaya	82/10/7		ml					65/10/10			1 ^	82/10/7	1d	1.5	M 2.3
0803-12=	Kusatsu-Shirane	82/10/26		l			0.1	59	82/10/26			1	82/10/22	1aq	1.5	
0804-12=	Iwo-Jima	82/11/28		l					82/11/28			1	82/11/25	1aq	5	
1302-01-	Kilauea	83/1/3		g		1.4E+7		49	83/1/3		7	1 ^	83/1/1	1aq	6	
1201-05-	St. Helens, Mount	83/2/2		g		1.4E+7	6	63	80/3/27		7	2 #	83/1/20	1b	13	
0101-06=	Etna	83/3/28		g	1.5E+6	1.0E+8	0.1	48	83/3/28	5	8	1	83/1/22	1b?	53	
0803-11=	Asama	83/4/8		m	1.3E+4		0.6	59	83/4/8			2	83/3/17	1aq	7	
1703-01=	Grimsvotn	83/5/28		m			3.5	49	83/5/28			2	83/5/28	1aq	0.39	M 4.0
0606-01=	Una Una	83/7/23		g			14		83/7/18			4 *	83/7/4	1c	24	M 4.6
1302-01-	Kilauea	83/7/25		m		9.0E+6		49	83/1/3			1 #	83/7/5	1b	16	
0803-12=	Kusatsu-Shirane	83/7/26		l			0.2	59	83/7/26			1	83/7/19	1aq	5	
0603-09=	Tangkuban Parahu	83/9/14							83/9/14			1	83/9/5	1bq	10	
0804-04=	Miyake-Jima	83/10/4			4.7E+6	6.0E+6			83/10/3	6	6	3	83/10/3	1b	0.06	
0502-12=	Ulawun	83/11/6		l			2	47	83/11/6			1	83/1/25	1aq	285	
1102-03-	Palvof	83/11/14		l					83/11/14	7		3	83/11/5	1d	29	M 2.3
1302-01-	Kilauea	83/11/30		m		8.0E+6		49	83/1/3			1 #	83/11/24	1aq	1	
0303-02=	Piton de la Fournaise	83/12/4		m		8.0E+6		48	83/12/4		7	2	83/11/20	1b	14	
0803-12=	Kusatsu-Shirane	83/12/21		l			0.3	59	83/7/26			1	83/12/18	1c	2	

Table 9 continued. ERUPTCAT

Volcano		Bulletin of Volcanic Eruptions Eruption data							VOTW Eruption data					SWARMCAT Swarm data			
Number	Name	start		volume			plume	SiO2	start	T	L	VEI		start	type	dur.	Mmax
1302-01-	Kilauea	84/1/20		g		1.0E+7		49	83/1/3			1	#	83/12/30	1aq	2	
1000-25=	Bezymianny	84/2/5		m			5		84/2/5	7		3	^	84/1/15	1d	20	K 6.5
1302-01-	Kilauea	84/2/14		m		8.0E+6		49	83/1/3			1	#	84/2/5	1a	4	
1302-01-	Kilauea	84/3/3		g		1.2E+7		49	83/1/3			1	#	84/2/24	1a	7	
1302-01-	Kilauea	84/3/16		g		1.0E+7		49	83/1/3			1	#	84/3/16	1a	8	
1302-02=	Mauna Loa	84/3/25		g		2.2E+8	0.05	51	84/3/25		8	0		84/3/24	1d	120	M 4.0
1302-01-	Kilauea	84/4/18		g		2.4E+7		49	83/1/3			1	#	84/4/10	1b	10	
1302-01-	Kilauea	84/5/16		m		2.0E+6		49	83/1/3			1	#	84/5/7	1b	8	
1302-01-	Kilauea	84/6/7		m		6.0E+6		49	83/1/3			1	#	84/6/1	1a	5	
0603-25=	Merapi	84/6/15		g	8.8E+6		6	54	72/10/6			3	*	84/6/7	1b	8	
1302-01-	Kilauea	84/6/30		m		5.7E+6		49	83/1/3			1	#	84/6/17	1b	12	
1302-01-	Kilauea	84/7/28		m		9.5E+6		49	83/1/3			1	#	84/7/17	1b	11	
1302-01-	Kilauea	84/8/19		g		1.2E+7		49	83/1/3			1	#	84/8/7	1b	12	
0606-03=	Soputan	84/8/31		m			6	59	84/5/24		7	3	^	84/8/6	1aq	19	
1302-01-	Kilauea	84/9/19		g		1.1E+7		49	83/1/3			1	#	84/9/1	1b	20	
1000-25=	Bezymianny	84/10/12		g			3.5		84/2/5	7		3	^	84/10/12	1d	23	K 6.0
1302-01-	Kilauea	84/11/2		m		6.6E+6		49	83/1/3			1	#	84/10/2	1b	29	
1302-01-	Kilauea	84/11/20		m		8.4E+6		49	83/1/3			1	#	84/11/11	1b	9	
1302-01-	Kilauea	84/12/3		g		1.3E+7		49	83/1/3			1	#	84/11/23	1b	9	
0502-12=	Ulawun	84/12/30		l			2	47	84/12/30		5	1		84/12/24	1c	29	
1302-01-	Kilauea	85/1/3		g		1.3E+7		49	83/1/3			1	#	84/12/24	1b	11	
1706-01=	Beerenberg	85/1/6	*2*	m	8.0E+5	6.2E+6	1		85/1/6			2		85/1/4	1b	2	
1302-01-	Kilauea	85/2/4		g		1.4E+7		49	83/1/3			1	#	85/1/16	1b	20	
0702-02=	Canlaon	85/3/13		l			0.7		85/3/13			1		85/3/13	1bq	0.19	
1302-01-	Kilauea	85/3/13		g		1.9E+7		49	83/1/3			1	#	85/2/28	1b	14	
1302-01-	Kilauea	85/3/13		g		1.9E+7		49	83/1/3			1	#	85/3/14	1b	2	
0403-11=	Niuafo'ou	85/3/21		l	1.0E+2			54	85/3/21	2		0		85/3/21	1?	0.13	ML 2.4
1302-01-	Kilauea	85/4/21		g		1.6E+7		49	83/1/3			1	^	85/3/27	1b	27	
0606-03=	Soputan	85/5/19		m	5.0E+6		5		85/5/19	6		2		85/3/15	1bq	65	M 5.6
0401-10=	Ruapehu	85/5/25		l					85/5/21			1		85/5/20	1d	12	ML 2.4
1302-01-	Kilauea	85/6/12		m		7.9E+6		49	83/1/3			1	#	85/5/10	1b	35	
0303-02=	Piton de la Fournaise	85/6/14		m		1.0E+6		49	85/6/14		8	1		85/5/15	1b	29	M 1.0
0805-05=	Tokachi-Dake	85/6/19		l			0.1		85/6/19			1		85/6/12	1bq	7	M 4.4
1302-01-	Kilauea	85/7/6		g		1.1E+7		49	83/1/3			1	#	85/6/21	1b	19	
1302-01-	Kilauea	85/7/26		m		7.2E+6		49	83/1/3			1	#	85/7/4	1b	13	
0604-05=	Sangeang Api	85/7/30		m	5.0E+6		6.5	47	85/7/30		7	3	*	85/4/29	1b	90	
0303-02=	Piton de la Fournaise	85/8/5		m		4.0E+6		48	85/6/14			1		85/8/5	1c	0.13	
1302-01-	Kilauea	85/9/2		g		1.2E+7		49	83/1/3			1	#	85/8/14	1b	18	
0303-02=	Piton de la Fournaise	85/9/6		g		1.7E+7		49	85/6/14			1		85/9/6	1b	0.05	
1302-01-	Kilauea	85/9/24		g		1.5E+7		49	83/1/3			1	#	85/9/10	1b	15	
1302-01-	Kilauea	85/10/21		g		1.5E+7		49	83/1/3			1	#	85/10/5	1b	16	
1302-01-	Kilauea	85/11/13		g		1.4E+7		49	83/1/3			1	#	85/10/30	1b	14	
1501-02=	Ruiz, Nevado del	85/11/13		g	4.3E+7				85/9/11	7		3	^	84/11/13	1a	360	M 4.0
0603-09=	Tangkuban Parahu	85/11/15		l			0.2		85/11/15			1		85/4/15	1bq	210	
0502-12=	Ulawun	85/11/20		m	7.5E+6	2.0E+6	8	49	85/11/17	6	6	3	*	85/11/12	1cq	10	
0303-02=	Piton de la Fournaise	85/12/2		m		1.0E+6		49	85/6/14			1	#	85/12/2	1b	0.01	
0303-02=	Piton de la Fournaise	85/12/29		m		7.0E+6	0.15	49	85/6/14			1	#	85/12/25	1c	4	
1302-01-	Kilauea	86/1/1		g		1.2E+7		49	83/1/3			1	#	85/11/26	1a	32	
1302-01-	Kilauea	86/1/27		g		1.4E+7		49	83/1/3			1	#	86/1/19	1b	10	
1302-01-	Kilauea	86/2/22		g		1.2E+7		49	83/1/3			1	#	86/2/8	1b	16	
0303-02=	Piton de la Fournaise	86/3/19		g		2.0E+6			85/6/14			1	#	86/2/11	1a?	1.5	M 2.0
1302-01-	Kilauea	86/3/22		g		1.0E+7		49	83/1/3			1	#	86/3/7	1a	9	
1103-01-	Augustine	86/3/27		m			12	61	86/3/27	8		4	?	86/2/10	1b	45	ML 2.1
0702-02=	Canlaon	86/3/30		l			0.7		87/3/30			1		87/3/1	1b	64	
1302-01-	Kilauea	86/4/13		g		1.2E+7		49	83/1/3			1	#	86/4/6	1b	8	

Table 9 continued. ERUPTCAT

Volcano		Bulletin of Volcanic Eruptions Eruption data							VOTW Eruption data					SWARMCAT Swarm data			
Number	Name	start		volume			plume	SiO2	start	T	L	VEI		start	type	dur.	Mmax
1302-01-	Kilauea	86/5/7		m		9.4E+6		49	83/1/3			1	#	86/4/27	1b	11	
1401-13=	Tacana	86/5/8		l			1		86/5/8			1		86/5/7	1b	2.5	ML 5.0
1401-13=	Tacana	86/5/8		l			1		86/5/8			1	?	85/12/15	1a?	72	
1302-01-	Kilauea	86/6/2		m		9.8E+6		49	83/1/3			1	#	86/5/21	1b	12	
0702-02=	Canlaon	86/6/22		m	1.4E+5		4		86/6/3	5		2		86/6/14	1b	8	
1302-01-	Kilauea	86/6/26		m		8.8E+6		49	83/1/3			1	#	86/6/18	1b	8	
0601-12=	Sorik Marapi	86/7/5		l	6.7E+2		0.7		86/7/5	2		1		86/7/4	1c	8	
0203-02=	Nyamuragira	86/7/16		g	5.0E+6	6.0E+7	0.25	45	86/7/16	7	7	2		86/7/16	1b	0.54	
1302-01-	Kilauea	86/7/18		m		6.0E+6		49	83/1/3			1	#	86/7/9	1b	10	
1501-02=	Ruiz, Nevado del	86/7/20					4		85/9/11			2		86/7/20	1b	0.29	
1501-02=	Ruiz, Nevado del	86/7/20		l			4		85/9/11			2		86/7/5	1a?	5	
0603-20=	Dieng	86/8/6		l			0.3		86/8/6			1		86/4/15	1aq	45	
0303-02=	Piton de la Fournaise	86/11/12		m		3.0E+5		49	85/6/14			1	#	86/11/12	1b	0.04	
1102-03-	Pavlof	86/11/16							86/4/16		6	3	^	86/4/7	1d	16	M 2
0804-01=	O-Shima	86/11/21		g	2.5E+7	2.2E+7	16	55	86/11/15	7	7	3	^	86/11/21	1c	9	M 6
0604-22=	Ili Boleng	86/11/24		m			1		86/5/28			1		86/11/14	1b	10	
0303-02=	Piton de la Fournaise	86/11/26		m		3.0E+5		48	85/6/14			1	#	86/11/17	1aq	9	M 3
1000-26=	Klyuchevskoy	86/11/27							86/11/27		7	3	^	87/12/27	1d?	10	Ks 9
0303-02=	Piton de la Fournaise	86/12/18			2.0E+6	m		48.9	85/6/14			1	#	86/12/2	1b	6	
0303-02=	Piton de la Fournaise	86/12/30						48.9	85/6/14			1	#	86/12/29	1b	1.5	M 2.0
0303-02=	Piton de la Fournaise	87/1/6		m		1.1E+6		49	85/6/14			1	#	87/1/6	1b	1.3	Md 1.0
1000-26=	Klyuchevskoy	87/2/23		l				53	86/11/27		7	3	^	87/2/20	1c	14	
1501-02=	Ruiz, Nevado del	87/6/9		l					85/9/11			2	?	87/5/21	1a	1.5	M 2.0
0303-02=	Piton de la Fournaise	87/6/13							85/6/14		8	1		87/6/8	1a	4	M 2.7
0303-02=	Piton de la Fournaise	87/7/19		m		1.0E+6		49	85/6/14			1	#	87/7/11	1b	8	
1501-02=	Ruiz, Nevado del	87/8/10		l					85/9/11	7		3	^	87/7/31	1a	1.5	
0401-10=	Ruapehu	87/8/24		l					87/8/24			1		87/8/18	1b	6	ML 2.0
0604-22=	Ili Boleng	87/10/2		l			0.3		87/10/2			1		87/6/20	1a	5	
0303-02=	Piton de la Fournaise	87/11/6		m		1.6E+6		49	85/6/14			1		87/11/3	1b	3	
0804-01=	O-Shima	87/11/16					4.3		87/11/16	4		3	^	87/9/15	1c	64	
0303-02=	Piton de la Fournaise	87/11/30		g		1.0E+7		49	85/6/14			1	#	87/11/29	1b	1.5	
0203-02=	Nyamuragira	87/12/30		m		3.0E+6		45	87/12/30	6	6	1		87/11/1	1b	30	
0604-071	Anak Ranakah	88/1/3		l			1.5		87/12/28	7	6	3	*	87/12/30	1b	5	
0805-07=	Me-Akan	88/1/5							88/1/5			1		87/9/9	1a	105	
1000-26=	Klyuchevskoy	88/1/20		g		3.4E+7		47	86/11/27			2		88/1/19	1b	12	
0303-02=	Piton de la Fournaise	88/2/7		m		8.0E+6		49	85/6/14			1	#	88/2/4	1b	3	
0608-06=	Gamalama	88/2/12		l			2		88/2/12			2		88/1/5	1bq	28	
0703-01=	Bulusan	88/2/20		m	3.2E+4		1.5		88/2/20	4		2		88/1/20	1b	30	
0605-09=	Banda Api	88/5/9		m	3.2E+4	6.0E+6	3.5		88/5/9		6	3	?	88/4/20	1b	18	M 3.7
0702-02=	Canlaon	88/6/21		l			1		88/6/21			1		88/5/6	1b	45	
0608-07=	Kie Besi	88/7/29		g			10		88/7/29			3		88/7/20	1b	9	
0303-02=	Piton de la Fournaise	88/12/14		m		8.0E+6		48	85/6/14			1		88/12/14	1b	0.16	
1507-10=	Lonquimay	88/12/27		m			5.5	58	88/12/25	8	8	3	^	88/12/7	1b	18	M 4.6
0502-12=	Ulawun	89/1/1					2	47	89/1/1			2		88/10/5	1c	66	
1000-26=	Klyuchevskoy	89/1/1					0.2	47	86/11/27			2		89/1/1	1c	16	
0900-24=	Sarychev Peak	89/1/13							89/1/13			1	?	89/1/5	1b	7	
1402-11=	Pacaya, Volcan de	89/3/7					3		65/7/4			3	^	89/2/25	1b	10	
0803-01=	Izu-Tobu	89/7/13						71	89/7/13	5		1		89/6/30	1aq	11	M 5.5
1000-26=	Klyuchevskoy	89/7/30					3	47	86/11/27			2	?	89/7/22	1bq	8	
0101-06=	Etna	89/9/11						47	89/9/11		7	2		89/8/17	1aq	9	
1103-03-	Redoubt	89/12/14	*3*	m	4.4E+5		10	61	89/12/14			2	#	89/12/13	1b	0.95	ML 2.0
1103-03-	Redoubt	90/1/2	*3*	g	2.5E+7		12	61	89/12/14		7	3	#	89/12/26	1b	7	
0603-28=	Kelut	90/2/10		m			12		90/2/10	8		4		89/11/15	1a	90	Md 2.0
1103-03-	Redoubt	90/2/15	*3*	m	5.6E+6		10	61	89/12/14		7	2	#	90/2/12	1b	3.42	
1103-03-	Redoubt	90/3/14	*3*	m	1.2E+6		12	61	89/12/14		7	2	#	90/3/13	1b	1.42	

Table 9 continued. ERUPTCAT

Volcano		Bulletin of Volcanic Eruptions Eruption data							VOTW Eruption data				SWARMCAT Swarm data			
Number	Name	start		volume			plume	SiO2	start	T	L	VEI	start	type	dur.	Mmax
1103-03-	Redoubt	90/3/23	*3*	m	3.8E+5		10	61	89/12/14		7	2 #	90/3/22	1b	1.42	
1103-03-	Redoubt	90/3/29	*3*	m	1.1E+6			61	89/12/14		7	1 #	90/3/28	1b	1.17	
1103-03-	Redoubt	90/4/6	*3*	m	5.2E+5		9	61	89/12/14		7	2 #	90/4/6	1b	0.54	
1103-03-	Redoubt	90/4/14	*3*	m	8.5E+5		10	61	89/12/14		7	2 #	90/4/15	1b	0.13	ML 1.7
0802-10=	Unzen	90/11/17		l			0.3		90/11/17	6	8	1	89/11/21	1a?	3	M 3.7
0703-083	Pinatubo	91/6/12		g	3.0E+9		40		91/4/2	10		6 *	91/4/2	1b	70	ML 4.3
1103-05-	Spurr		*4*		5.0E+7		14.5	57	92/6/27	7		4 ^	91/8/15	1bq	180	ML 1.7
1401-09=	Popocatepetl			m		1.4E+6	1		94/12/21			2	94/10/15	1b	60	M 2.9

1 Swanson, D. A. and R. T. Holcomb (1989)
2 BVE No. 26 (1986)
3 Scott and McGimsey (1994)
4 Alaska Volcano Observatory staff (1993)
Symbols are explained in the text.

Data Sources

The ERUPTCAT table is composed of three sections. The first section is eruption data drawn from the *Bulletin of Volcanic Eruptions* (BVE). The second section is eruption data drawn from *Volcanoes of the World second edition* (VOTW). The third section is the associated swarm data preceding each eruption drawn from the SWARMCAT table. The BVE section of the table includes the eruption start date, erupted volume, plume height, and silica content. The VOTW section also includes the start date, tephra and lava volumes, and adds the VEI for each eruption. The third section shows the precursory swarm parameters including the swarm start date, type, duration, and the magnitude of the largest earthquake preceding the eruption.

Both the BVE and VOTW data are listed because the two data sources differ in some respects. The BVE section describes all of the eruptions that were preceded by the well-reported swarms. In the VOTW directory, in many cases, these eruptions have been grouped as an eruptive phase of a longer eruptive sequence. For example, all the eruptions at Mount St. Helens between 1980 and 1986 are considered as one eruptive sequence in the VOTW directory. The BVE describes these as individual phases. All of the data listed in the BVE section are drawn from the BVE covering that year, unless an italic numeral (e.g. *1*) is listed following the start date. The italic numeral points to a reference used to complete or supplement data for that eruption or eruptive phase.

Erupted Volume, Plume Height, Silica Content, and the VEI

The BVE classifies the size or intensity of an eruption into three categories: Little (l), medium (m), and great (g) according to the bulk volume of erupted material. The BVE uses the following correlation between them:

$$(l) <1x10^4 m^3, (m)\ 1x10^4 \text{ to } 1x10^7 m^3, (g) >1x10^7 m^3 .$$

This field gives an estimate of the size of the eruption when no estimate of the erupted volume is available. This one letter size code is recorded in the first column of the volume field. The next two columns of volume field are the bulk tephra and lava volumes in cubic meters. If a range of values are reported the average is recorded.

The plume field records the maximum height in kilometers of the eruption cloud above the crater. The SiO2 field records the silica content of the main erupted product. The silica content values are taken directly from the BVE reports. In many cases, silica values are explicitly stated while others are derived from reported rock names.

The VOTW section of the ERUPTCAT table is directly extracted from the Smithsonian Institution's Global Volcanism Program eruption data file. The start date, tephra and lava volume, and the VEI are listed. The following field descriptions are from the Global Volcanism Program eruption data file.

The eruptive volume is broken into two fields, tephra (*T*) and lava (*L*). The volume is an order of magnitude value in cubic meters (e.g., 8 = >10 to the 8th power cubic meters = >100,000,000 m^3 = >0.1 km^3, 9 = >1 km^3, etc.). The tephra volume is a bulk volume, not dense rock equivalent.

The VEI is a 0-8 scale of explosive magnitude. An asterisk (*) follows the maximum VEI of an eruption for which additional VEI values have been assigned for specific phases. We have added a "pound sign" (#) to these specific phases where we have estimated the VEI. A "plus" (+) following VEIs greater than 4 identifies eruptions in the upper third of that VEI range. A "^" accompanies those eruptions early in a region's historical record that have been upgraded by 1 VEI unit, as explained in *Volcanoes of the World* and Newhall & Self (1982).

The parameters of the third section of the ERUPTCAT table are described in the SWARMCAT organization and parameter description section of this report.

Preliminary Results

Swarm Duration

The duration of a volcanic earthquake swarm was found to be the most commonly reported parameter. The database contains 385 swarm duration records with high quality grades. The distribution of swarm durations is shown in Figure 5. The durations vary from very short, intense swarms lasting only a few hours, 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 distribution of durations is nearly log-normal with a geometric mean of 5.5 days, a median of 7 days and a mode of 2 days. The $\log_{10}$ transformed duration distribution was tested for normality using the Kolmogorov-Smirnov test (Rock, 1988). The test showed that the distribution was not normal. The duration distribution is skewed to the left. In other words, there is an excess of shorter swarms.

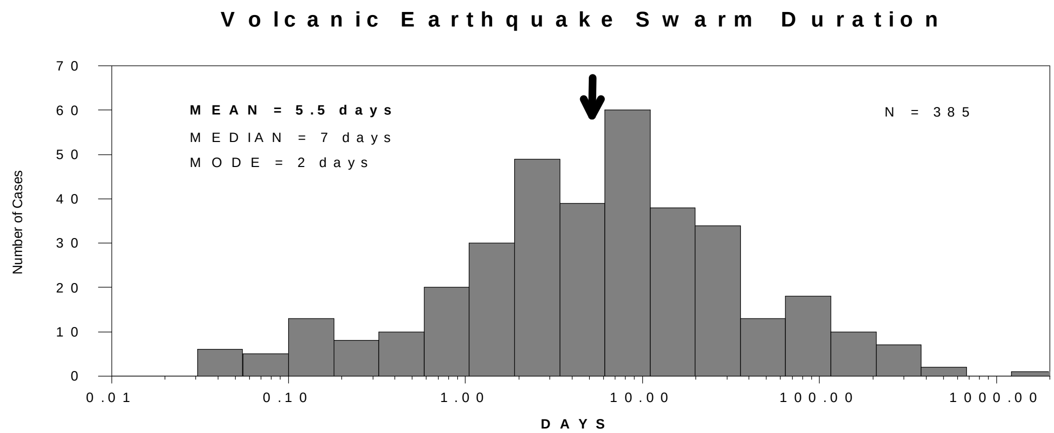

Figure 5. Histogram of the durations of 385 volcanic earthquake swarms. The horizontal axis is logarithmic. The data indicate a log-normal distribution (with a slight skew toward shorter durations) with a geometric mean of 5.5 days (marked with a bold arrow), a median of 7 days, and a mode of 2 days.

Swarm durations were then separated based on their relationship to 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. 6). The geometric mean durations were 8 and 3.5 days, respectively. The means of the duration distributions were found to be significantly different from one another, 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 swarm duration distribution is again not log-normal, while the Type III distribution is log-normal. As with the combined distributions, the Type I duration distribution is skewed towards shorter durations.

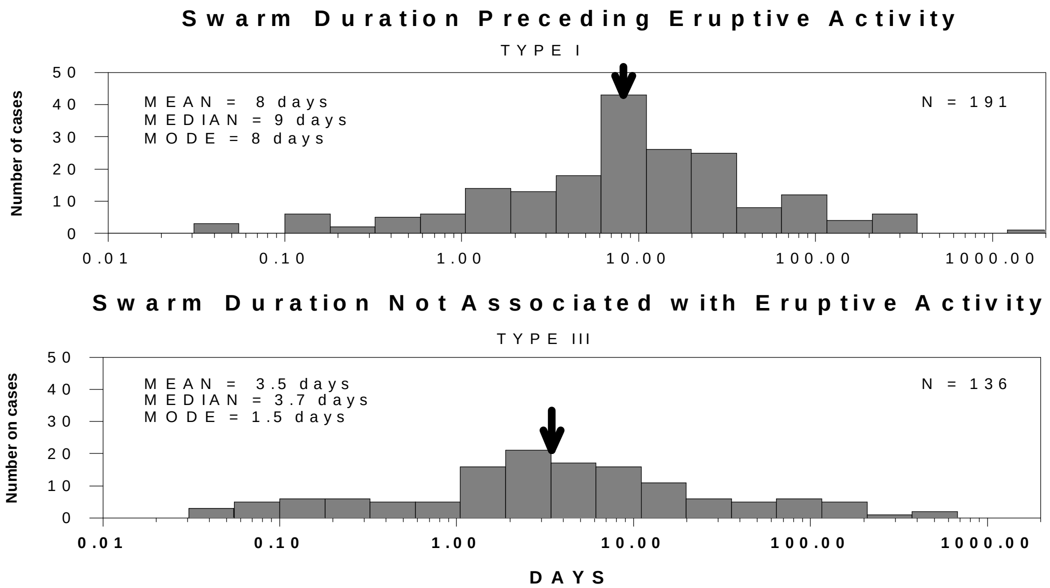

Figure 6. Comparison of the distribution of 191 earthquake swarm durations that precede eruptive activity (Type I) and 136 durations that are not associated with eruptive activity (Type III). The Type I swarm duration distribution is nearly log-normal, while the Type III distribution is log-normal. As with the combined distributions, the Type I duration distribution is skewed to the left. The geometric means are 8 and 3.5 days (marked with bold arrows), the medians 9 and 3.7 days, and the modes 8 and 1.5 days for Type I and III swarms respectively.

Earthquake Magnitude

Apart from swarm duration the next most commonly and reliably reported parameter is the magnitude of the largest shock (M_{max}). The database contains 113 magnitude records with high quality grades. The M_{max} values range from 0.5 to 6.2. The largest events in the database, M_s 6.2 at Miyake-jima in 1983 and M6.0 at Oshima in 1986, occurred during large fissure eruptions. A M5.6 event at Soputan in 1985 is the largest event preceding an eruption in the database. The largest events occurring without a following eruption are a M_{JMA} 5.7 at Unzen in 1984 and a M6.2 in Long Valley Caldera in 1980.

Although many magnitude scales are used in reporting these events, only the Russian energy class measurements were converted for comparison. The Russian energy scale K_s was converted to M_s using: $M_s = (K_s - 4.6)/1.5$; where M_s is the magnitude determined from surface waves; K_s is the mean energy class determined as the arithmetical mean from short-period S-waves of several stations (Gorelchik, 1989).

The mean of the M_{max} distribution for precursory swarms (Type I) is not significantly different from the mean for swarms not associated with eruptions (Type III) (fig. 7). The mean M_{max} is 3.2 for both precursory or Type I swarms and for non-precursory or Type III swarms. The Type I distribution is slightly more spread out than the Type III. The standard deviations of the distributions are 1.3 and 1.0 for Type I and Type III swarm respectively.

The eruptive character is used to divide Type I swarms into two groups. The shaded bars of the top histogram of figure 7 show events that preceded central vent eruptions, while the open bars are from swarms that preceded eccentric (flank) or radial fissure eruptions. With two exceptions, the eccentric and radial fissure eruptions are preceded by larger shocks than central vent eruptions.

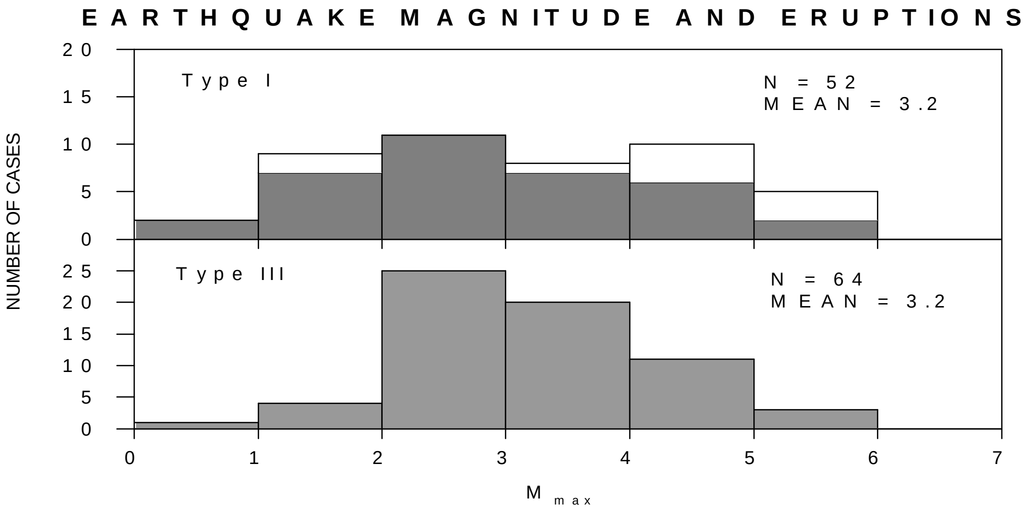

Figure 7. Comparison of the distribution of magnitude of the largest shock (M_{max}) within 53 swarms that precede eruptive activity (Type I) and 64 swarms that are not associated with eruptive activity (Type III). The striped bars are events that preceded central vent eruptions, while the open bars are from swarms that preceded eccentric (flank) or radial fissure eruptions. The M_{max} values plotted on the abscissa are the upper bound (inclusive) of each interval.

Data Limitations and Discussion

The observation that the mean duration of swarms that precede eruptions is about twice as long as swarms that are not associated with eruptions may be due to: 1) reporting bias, 2) mis-indentification 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 intrusion or other 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 the reporting of eruptions. Therefore, there may be a tendency more frequently to 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 M3, based on data from 113 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 a M3 is about half a day and for a M4, 3.5 days. Thus, the durations of a small mainshock-aftershock sequences are similar to the mean duration of Type III 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 a large sample size, these effects will not unduly 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 and others, 1988; McNutt and Beavan, 1981; Klein, 1976), body and 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).

Volcanic earthquake swarms, unlike tectonic mainshock-aftershock sequences, do not release the majority of seismic energy in the largest earthquake of sequence. Swarms, by definition, have one or more shocks of similar magnitude. Therefore, the seismic energy released during a swarm is spread over a longer period of time than tectonic mainshock-aftershock sequences. The difference in swarm duration distributions suggests that duration is more likely to reflect future eruptive activity than the magnitude of the largest event within a given swarm.

Improvements and Future Work

In designing this project we hoped to cast a wide net over seismological phenomena occurring at volcanoes. We found that the net had many holes; only very few parameters are frequently reported in the literature. Filling in the blanks of this current version of the database would be highly desirable. We believe that much of this data exists, but was never published. The next step is to contact the individual reporters and begin collecting this primary data.

The database would be improved by the addition of new high quality records. The number and quality of case studies on volcanic earthquake swarms have been steadily improving as more volcanoes are becoming monitored. The addition of the most recent swarms (occurring after 1989) will be given priority over the cases studied before 1979.

Along with the addition of more records, each record could be expanded to included summary figures such as; seismicity rate, time-depth, time-magnitude, earthquake location, and example seismograms. The database software that we are currently using does support fields that contain digital images. Future versions of the GVESD will incorporate these figures.

Future work with the GVESD will explore more fully the relationship between swarm parameters (such as the duration, M_{max}, and event types) and specific eruption parameters such as the Volcanic Explosivity Index, chemistry of the erupted products, eruption repose, volcano edifice height, etc. We are developing a generic volcanic earthquake swarm model which will provide a conceptual framework to interpret sequences or swarms of volcanic earthquakes which involve several different types of events. The GVESD will provide the data to explore the succession of particular event types within swarms and their durations.

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Appendix A

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<tr><th>ROSS-FOREL</th><th>MODIFIED MERCALLI</th><th>MSK (GEOFIAN)</th><th>JMA</th></tr>
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from Newhall and Dzurisin (1988)