Simultaneous Earthquake Swarms and Eruption in Alaska, Fall 1996: Statistical Significance and Inference of a Large Aseismic Slip Event

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Abstract   In the fall of 1996 the Alaska Volcano Observatory recorded an unprecedented level of seismic and volcanic activity. The following were observed: (1) a swarm at Iliamna Volcano (August 1996 to mid-1997); (2) an eruption at Pavlof Volcano (September 1996 to December 1996); (3) a swarm at Martin/Mageik volcanoes (October 1996); (4) a swarm at Strandline Lake, which continued for several years (1996–1999); and (5) deformation of Mt. Peulik (inflation begins after October 1996 and ends in fall 1998), based on interpretation of interferometric synthetic aperture radar data. The number of monitored volcanic areas in 1996 was thirteen. We conducted two formal statistical tests to determine the likelihood of four of these events occurring randomly in the same time interval. The tests are based on different conceptual probabilistic models (classical and Bayesian) that embrace a wide range of realistic tectonic models. The first test considered only the areas in which swarms or eruptions occurred (7 of 13 if Strandline Lake is included; 6 of 12 otherwise), by comparing the real catalog with 10,000 synthetic catalogs under the assumption that the sites are independent. The second method is a hierarchical Bayesian model in which the probability of a swarm at each of the 13 (or 12) areas is different but the parent population is the same. We found that the likelihood of the swarms and eruption occurring nearly simultaneously by chance alone is small for a wide range of probabilistic schemes and, consequently, for different tectonic scenarios. Therefore, we conclude that the events may be related to a single process. We speculate that a widespread deformation pulse or strain transient occurred, mainly in the east half of the arc, and may be the most likely candidate for causing such nearly simultaneous events.

Introduction

In 1996, especially in the late summer and fall, the Alaska Volcano Observatory (AVO) recorded an unprecedented level of seismic and volcanic activity. The following were observed: (1) a swarm at Akutan Volcano (March 1996) including more than 3500 felt events (Lu *et al.*, 2000); (2) the Iliamna Swarm (May 1996; August 1996 to mid-1997); (3) the Pavlof Eruption (11 September 1996 to 29 December 1996); (4) the Martin/Mageik Swarm (16–21 October 1996); (5) a swarm at Strandline Lake (not a volcano), which continued for several years (September 1996–1999); (6) the deformation of Mt. Peulik (inflation begins after October 1996 and ends in fall 1998; Peulik is 140 km northeast of Aniakchak Volcano on Fig. 1), based on interpretation of interferometric synthetic aperture radar (InSAR) data (Lu *et al.*, 2002); and (7) an M_w 7.9 earthquake near Adak in June 1996 (PDE, 1996). The four swarms (or volcanoes) that were active in fall 1996 are located in an 870-km-long section of the Alaska-Aleutian arc (Fig. 1). No comparable swarms or eruptions occurred at these areas or volcanoes in the 6 years from 1997 to 2002.

In this article we briefly describe the eruption or earthquake swarm at each of the four areas and estimate the probability of all the swarms and eruption occurring nearly simultaneously by chance alone. In addition, we examine several possible triggering mechanisms and suggest new data that will be needed to determine physical mechanisms.

Data, Instruments, and Networks

AVO presently operates seismic networks of 6 to 18 short-period ($T = 1$ or 0.5 sec) stations near each of the four active areas (Fig. 2) as well as 21 other volcanoes in Alaska. At the time of the activity under study, networks were operating in 13 areas. Data are telemetered in analog form and digitized at 100 samples/sec in the seismology laboratory at the University of Alaska Fairbanks Geophysical Institute.
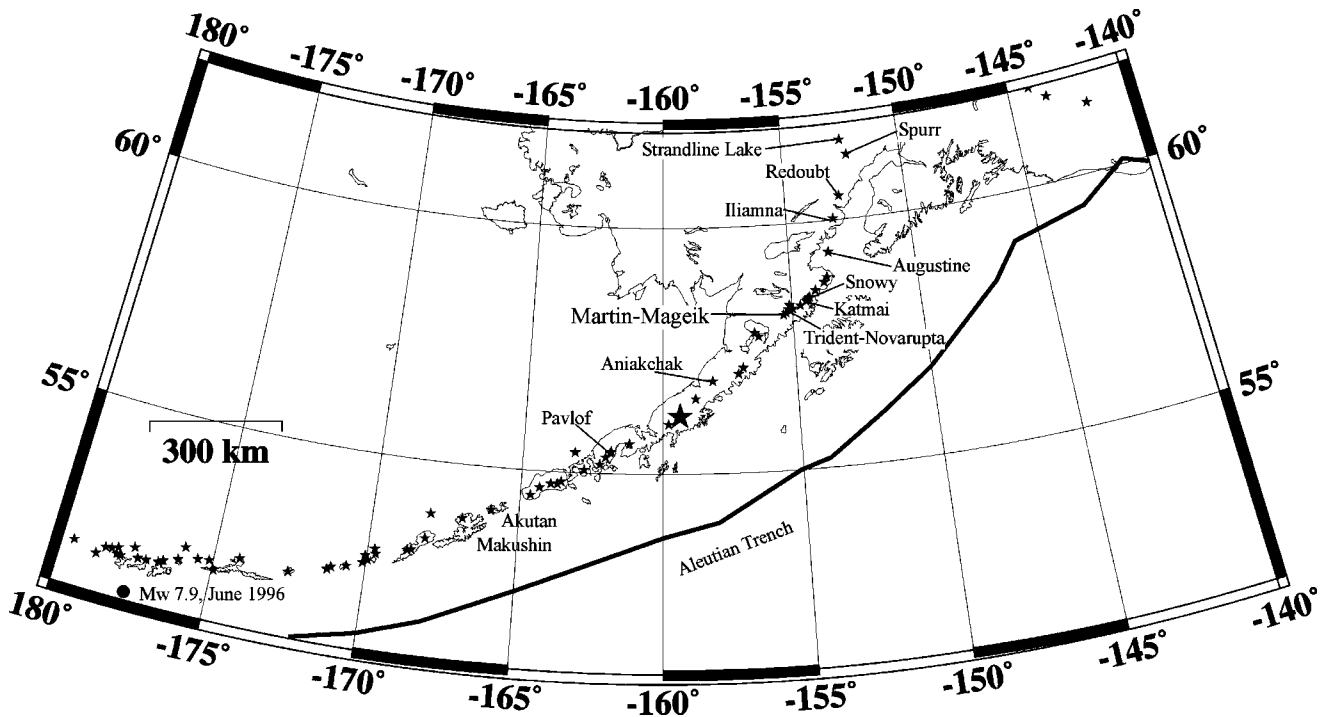
Figure 1.   Index map of the Aleutian arc. Stars are active volcanoes. The monitored volcanoes are labeled. The large dot is the epicenter of the Adak earthquake. The distance from Adak to Strandline Lake is 1970 km.

Data are recorded by computers in both continuous and triggered mode, with the latter providing the primary data set for Iliamna, Martin-Mageik, and Strandline Lake, and the former for Pavlof.

Description of Activity

Pavlof

Pavlof Volcano, on the Alaska Peninsula (Fig. 1), is the most active volcano in North America and has had more than 40 documented eruptions since 1760 (Miller *et al.*, 1998). It was monitored from 1973 to 1990 by the Lamont-Doherty Geological Observatory of Columbia University (McNutt, 1986, 1999), then a new network was installed by AVO in July 1996, including six seismic stations within 11 km and three others between 33 and 40 km (Fig. 2) from the active vent. An eruption report was received on the morning of 16 September 1996 from residents of Cold Bay, 37 miles to the southwest (Table 1). Later analyses showed that the small-scale seismicity had actually increased on 11 September (McNutt, 2002). The eruption lasted continuously from 16 September to 4 December, declined, and was followed by two stronger bursts on 10–12 December and 26–29 December (Fig. 3). The seismic activity associated with Pavlof was continuous volcanic tremor with variable amplitude lasting for nearly 3.5 months (McNutt, 2002). Explosion earthquakes were superimposed on the tremor (Garces *et al.*, 2000; Roach *et al.*, 2001). The seismic signal was generally

stronger during more vigorous phases of activity. The tremor amplitude was converted to reduced displacement, a normalized metric that corrects for geometric spreading of waves and instrument magnification (Fehler, 1983). The time series shown in Figure 3 is roughly equivalent to the number of events versus time.

Iliamna

Iliamna Volcano is a 3-km-high stratovolcano located in the eastern Aleutian arc about 225 km southwest of Anchorage, Alaska, on the western side of Cook Inlet (Fig. 1). Glaciers that radiate from a summit ice cap dissect the volcanic cone. Vigorous fumarolic vents exist on the volcano's eastern flank at an approximate elevation of 2740 m. Several Pleistocene vents extend roughly 6 km to the south of the present summit. The volcano has no documented eruptions in historical time; however, activity may have occurred as recently as 300 years ago (Waythomas and Miller, 1999). A four- to six-station seismic network has monitored Iliamna Volcano continuously since 1993 (Fig. 2; Jolly *et al.*, 1996, 2001). Between 1993 and 1996 only a few earthquakes each month were detected at Iliamna. In May of 1996 a small swarm of 90 earthquakes was detected beneath the volcano. A second much larger swarm of earthquakes began in July and peaked in September 1996; elevated rates of seismicity continued until mid-1997 (Jolly *et al.*, 2001). This swarm consisted of more than 1000 located earthquakes. The 1996–1997 hypocenters occurred beneath the summit and ex-
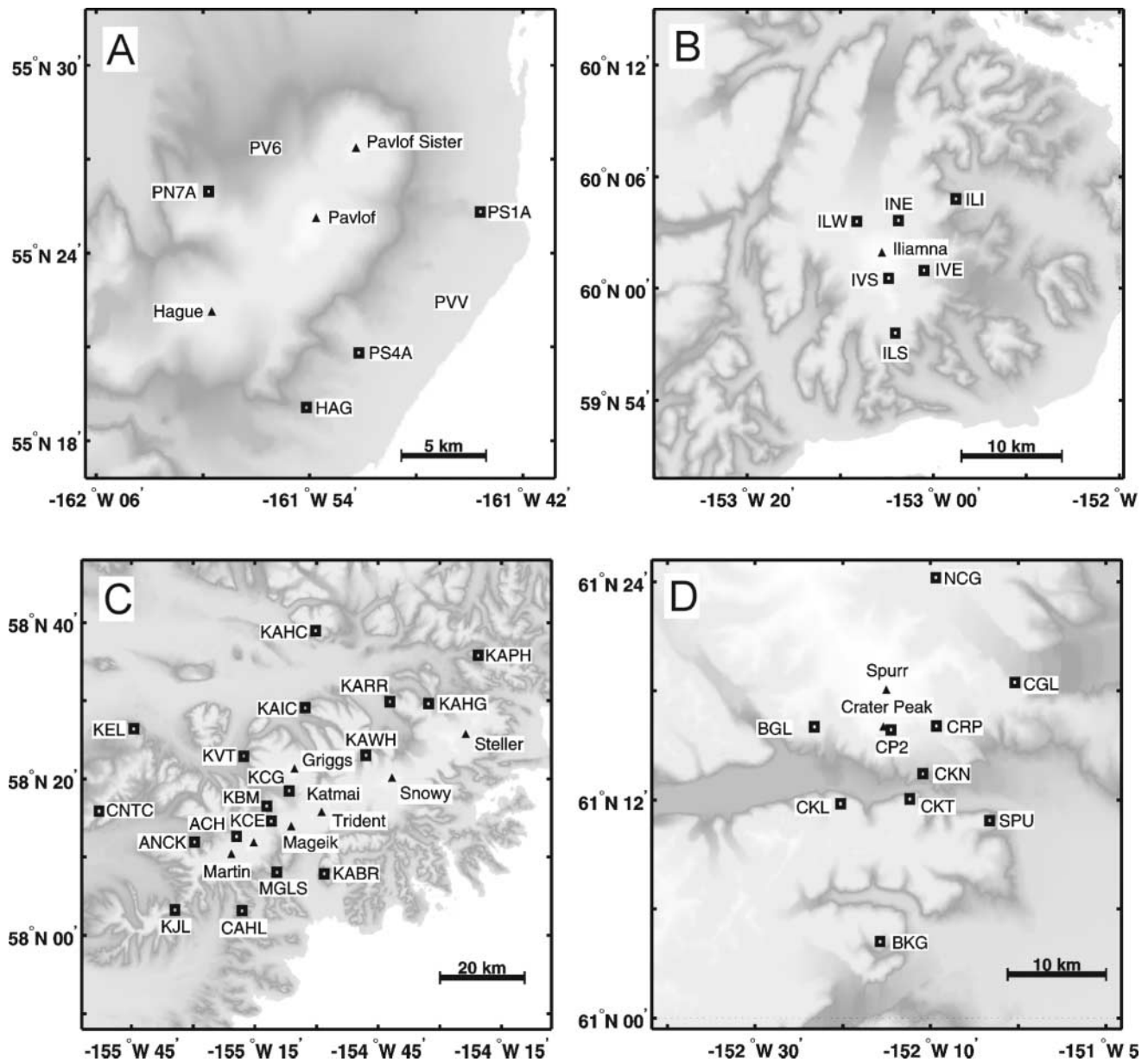
Figure 2. Shaded relief maps showing the seismic networks. Squares are seismic stations, denoted by three- or four-letter station codes. Volcanoes are indicated by solid triangles. (A) Pavlof, (B) Iliamna, (C) Katmai region, and (D) Spurr/Strandline Lake.

Table 1
Alaska Fall 1996 Swarm and Eruption Parameters

Location	Monitoring Start Date	Swarm Start Date (mm/dd/yy)	Swarm Peak Date (mm/dd/yy)	Swarm End Date (mm/dd/yy)	max M
Strandline Lake	October 1989	09/25/96	10/07 & 28/96	12/31/96	3.1
Iliamna	October 1994	08/01/96	08/15/96	02/08/97	3.3
Martin-Mageik	July 1995	10/16/96	10/17/96	10/21/96	1.3
Pavlof	July 1996	09/11/96	Continuous eruption	12/29/96	$D_R = 19$ cm^2

D_R, reduced displacement.

tended roughly 7 km to the south beneath the Pleistocene vents identified by Waythomas and Miller (1999) (Fig. 4). Hypocentral depths range from sea level to approximately 4 km (Roman *et al.*, 2001). The largest event had a local magnitude of 3.3. A large increase in SO$_2$ emissions was also observed coincident with the increased activity beginning in August (Roman *et al.*, 2001).

Martin-Mageik

Mt. Martin and Mt. Mageik are two adjacent stratovolcanoes in the Katmai group on the Alaska Peninsula

(Fig. 1). A monitoring network of five stations was installed by AVO in July 1995, then upgraded to 18 stations over the next four summers (Fig. 2). Seismicity in the Katmai area generally occurs in four clusters along the volcanic axis, one of which is beneath Martin and Mageik volcanoes (Jolly and McNutt, 1999; Moran, 2003). In October 1996 the strongest swarm (in terms of numbers) to date in the entire Katmai region occurred beneath Martin and Mageik (Fig. 5 and Table 1). Although the largest event was only *M* 1.3, more than 500 events with *M* between 0.5 and 1.3 occurred in 5 days. Depths of the events were mostly 2–6 km (Jolly and McNutt,
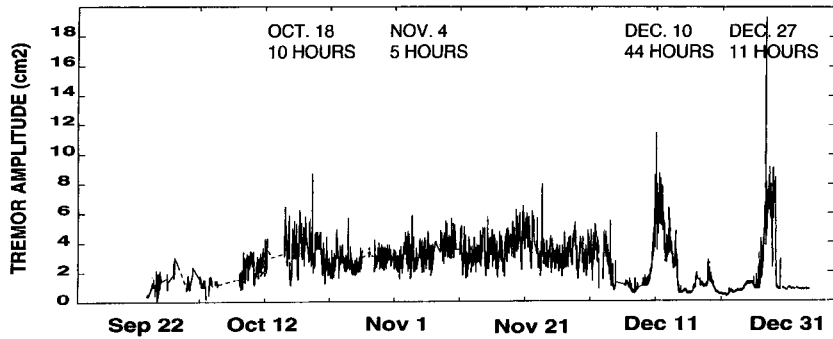

Figure 3.   Reduced displacement of volcanic tremor at Pavlof versus time for the period September to December 1996.
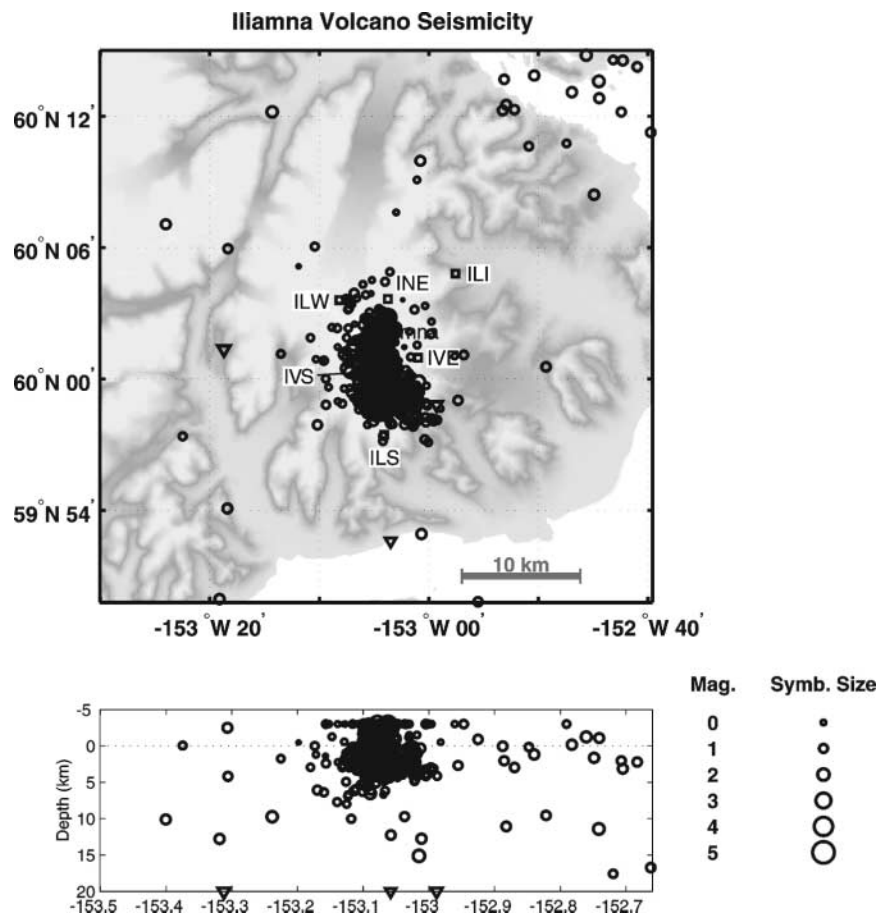

Figure 4.   Shaded relief map of Iliamna Volcano. Squares are seismic stations. Circles are earthquake epicenters from October 1994 to December 2001, with symbol size proportional to magnitude. Events deeper than 20 km are indicated by triangles.
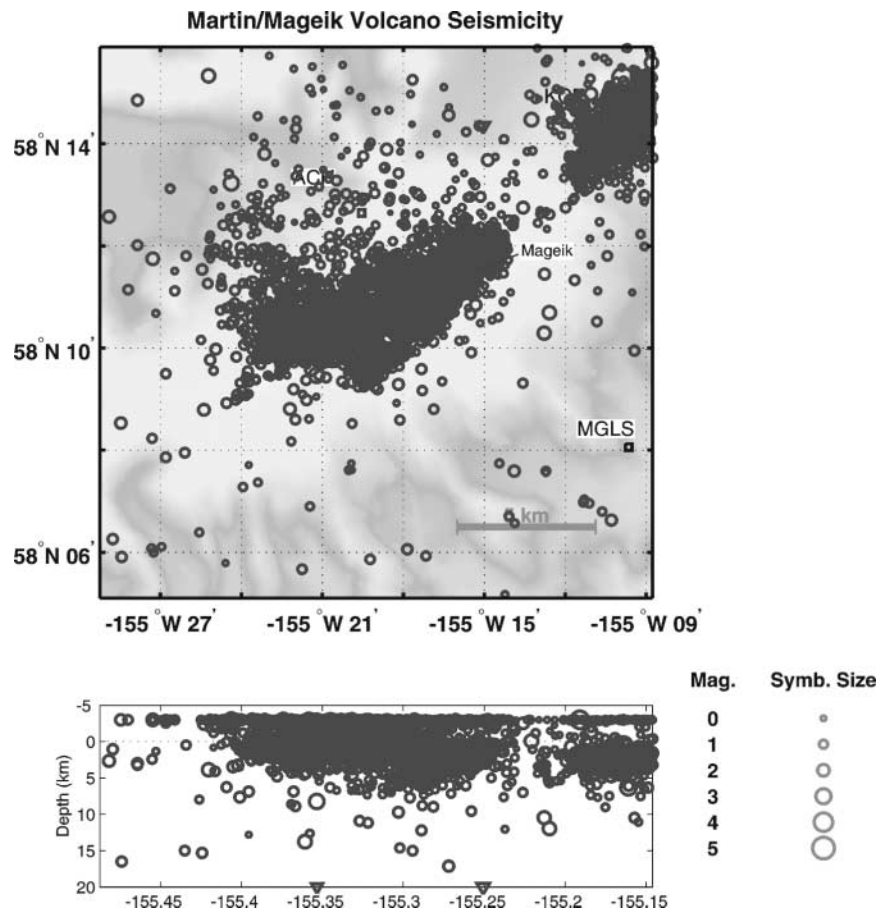
Figure 5.   Shaded relief map of Martin-Mageik volcanoes. Squares are seismic stations. Circles are earthquake epicenters from July 1995 to December 2001, with symbol size proportional to magnitude. Events deeper than 20 km are indicated by triangles.

1999). The *b*-value of the frequency–magnitude relation was higher ($b = 1.54$) during the swarm and for several months afterward compared with prior values ($b = 0.92$), suggesting that pore pressures were relatively higher and that an intrusion occurred (Jolly and McNutt, 1999).

Strandline Lake

Strandline Lake is a small lake 30 km northeast of Mt. Spurr (Fig. 1) and southeast of Mt. Hayes Volcano. It is located near the strike of the volcanic axis. Earthquakes in the area (Fig. 6) are recorded on the Mt. Spurr network (Fig. 2), and an additional station was added at Strandline Lake itself in the summer of 1997, which improved the quality of locations. The site of the 1996 swarm is a long-standing feature in the Alaska earthquake catalog; see, for example, figure 4 of Jolly *et al.* (1994), which shows a cluster of events surrounding Strandline Lake recorded between 1981 and 1991. Three larger events occurred in this area in 1989 (magnitudes 2.1, 3.2, and 3.0 on 30 March, 9 April, and 9 April 1989, respectively). Figure 7 of Jolly *et al.* (1994), shows that the best-constrained focal mechanism in this cluster is dominantly strike-slip. The less well constrained focal

mechanisms have some thrust component. The 1996 swarm began on 25 September, peaked in October, and ended approximately 31 December, at which time the rate dropped by a factor of 4 (Table 1). The background rate, however, remained higher than the preswarm level until April 1999. The maximum magnitude earthquake was *M* 3.1, which occurred on 1 July 1997. This swarm was deeper than the others, with most events occurring from 3 to 12 km (Fig. 6).

Probability Calculations

In late summer and fall 1996, four almost simultaneous seismic swarms occurred in different sites in the eastern Aleutian arc. Here we want to calculate the probability that these simultaneous swarms could occur by chance alone. Initially we examined the period ending 31 December 2000; the calculations were repeated when an additional year of data became available. We present both results to demonstrate the minor effect of extending the length of time.

The problem is complicated by the fact that three swarms occurred at volcanoes, but the fourth (Strandline Lake) did not. Further, we do not know how many other
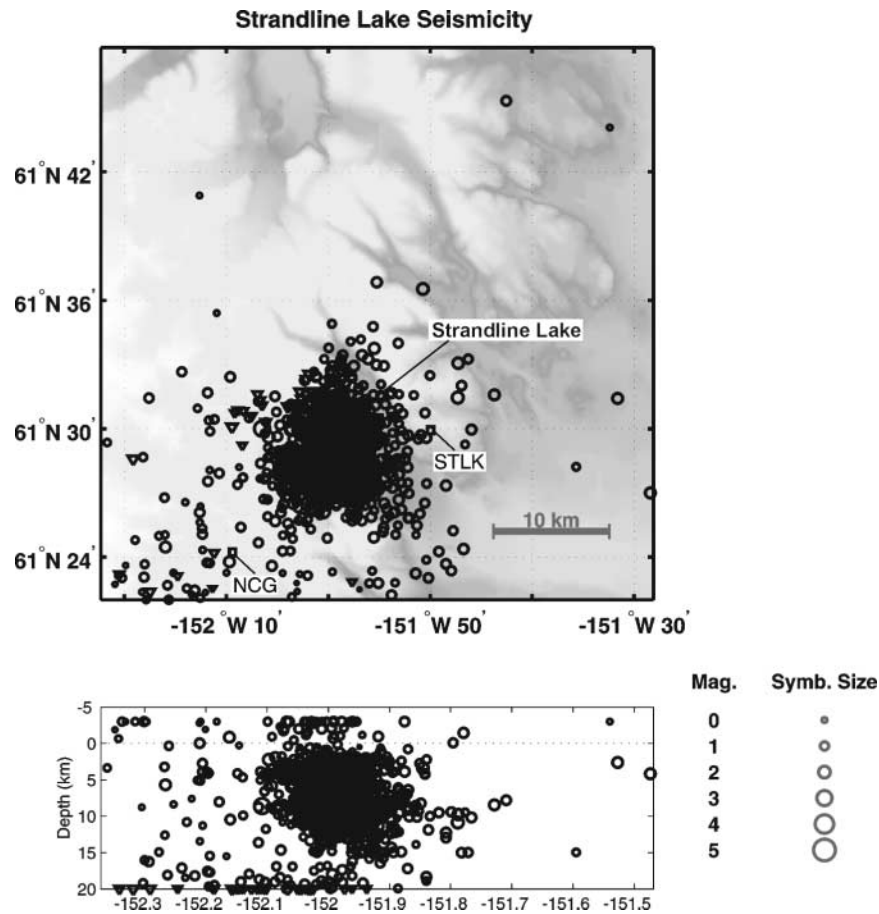
Strandline Lake Seismicity

Figure 6.   Shaded relief map of Strandline Lake. Squares are seismic stations. Circles are earthquake epicenters from October 1989 to December 2001, with symbol size proportional to magnitude. Events deeper than 20 km are indicated by triangles.

"tectonic" sites exist along the Alaska Peninsula and the Aleutian Islands. We include Strandline Lake because within a volcanic arc it may be reasonable to assume that most seismicity is ultimately related to the same stresses that result in the formation of volcanic centers. Inclusion of Strandline Lake creates some restrictions in the probability framework, which are explained as needed below.

The general method we use can be subdivided into three parts: (1) Definition of the probability framework. (2) Generation of synthetic catalogs built under the null hypothesis that the sites are independent. We use two different techniques (TEST) based on different assumptions. (3) Calculation of the significance level, that is, the probability to make a mistake in rejecting the null hypothesis. In other words, we seek the probability of observing the "coincidences" in the real catalog by chance.

Setting Up the Probabilistic Scheme

The first step in establishing the probability scheme is to define the concepts of "site" and "event." In general, we define a site as a place where seismic swarms can occur (or occurred) and that have been monitored since 1996 or be-

fore. An event is the occurrence of a seismic swarm, and we do not consider as events clear single mainshock-aftershock sequences. It is important to remark that these definitions contain a certain degree of subjectivity that we cannot overcome. For instance, we define two volcanoes of the Katmai group, Martin/Mageik, as a single site, mainly because seismic swarms occur half way between these volcanoes, as opposed to distinct spots beneath each. This appears to be a stable long-term feature of the seismicity in the vicinity of Katmai (Jolly and McNutt, 1999; Moran, 2003). The choice of one site is certainly questionable. For this reason, we also check the stability of our results by adopting different definitions of site and event that will be discussed in depth in the following sections.

By using our definition of sites and events we have 13 sites, 12 of which are volcanoes, and the thirteenth is the area near Strandline Lake. Each site experienced one or zero seismic swarm in the monitoring period (variable start dates, but all ending 31 December 2001). The monitoring period for each site is discretized by n_i ($i = 1, \ldots, 13$) adjacent and nonoverlapping time windows of length τ. Intervals of 30 to 360 days were tested. Obviously, n_i depends on the
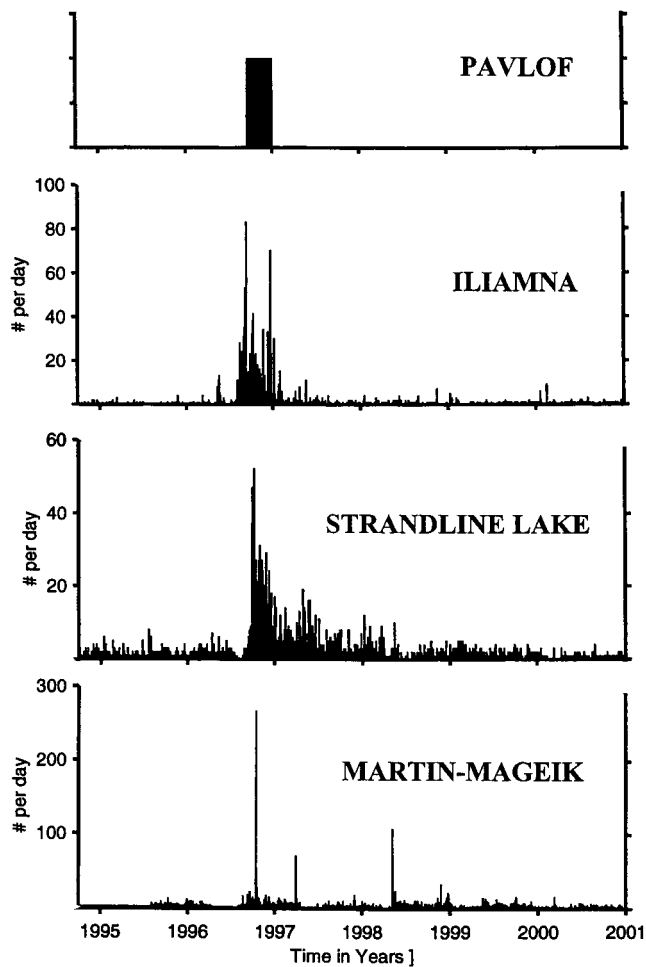
Figure 7. Time series of seismicity for Pavlof, Iliamna, Strandline Lake, and Martin-Mageik areas from mid-1995 to 31 December 2001. The Pavlof data are schematic (see Fig. 3 for details). The others show the number of located events per day. Note that the vertical scales are different. All areas showed increased seismicity in late summer and fall 1996 and at no other time.

length of τ. For each site we choose the time axis directed from the present toward the past, and the origin is at 31 December 2001. Each time window can contain zero or one seismic crisis (we use only the starting time of the swarm). Therefore, we can determine the probabilistic scheme conceptually to be composed of 13 urns. For the ith urn, n_i balls are extracted. Although urns containing black and white balls give a convenient representation of the procedure, in practice the algorithm is performed by a computer simulation. The sequences we observe in the real catalog are composed only of white balls and zero black balls (the sites that do not experience any seismic swarm), or $n_i - 1$ white balls and 1 black ball (the sites where one [m] time window contains a seismic swarm). In our case, $m = 1$ for all sites, but we also verify the calculation by using $m = 3$ for Martin/ Mageik (see in the following section). Therefore, the coin-

cidences consist of simultaneous extraction of black balls at different urns (sites).

Generation of the Synthetic Catalogs

We generate 10,000 synthetic catalogs under the assumption that the sites are independent. The main difficulty in building realistic catalogs is that we do not know the probability of occurrence of the seismic swarms at each site. To overcome this problem and to check the stability of the results we adopt two stochastic models based on quite different (nearly antithetical) assumptions (Larsen and Marx, 1986). Such models reflect two limiting cases that encompass a wide range of possible models and that probably include the most realistic models. Under this perspective, stable results would indicate the low sensitivity of our calculations to a wide range of possible models.

Method 1. We consider only the urns where different balls exist, that is, only TEST 1, the seven sites where at least one seismic swarm occurred. We shuffle these urns 10,000 times, and each time we extract randomly (without replacement) the balls from the urns. In this way we generate 10,000 synthetic sequences by assuming that the sampling from the urns is independent. (This is equivalent to saying that the seismic swarms at the sites occurred independently of one another.) The method used has one important physical assumption: the random shuffling of the urns implies that the white and black balls inside the urns are representative of the statistical distributions. In practice, this means that if we take independent time periods comparable in length with the real case, the sites where one seismic swarm occurred are largely dominated by the probability of having exactly one event. Instead, in the sites where no seismic swarms occurred the probability of having zero events is largely predominant. From a geophysical point of view this also implies that the sites have different levels of tectonic activity.

Method 2. In this case we consider a hierarchical Bayesian model, in which (TEST 2) the probability to have one black ball inside any urn is different, but each derives from a unique parent distribution. We consider as a parent distribution a *beta* distribution with hyperparameters α and β (Gelman *et al.*, 1995). The values of α and β are related to the average and standard deviation calculated from the empirical probabilities for each urn (Gelman *et al.*, 1995). Therefore, each synthetic series is composed by randomly generating 13 probability (P_i) values from the parent *beta* distribution. Each value represents the probability of having one black ball in the urn (i.e., a seismic swarm at each site). Then, for each ith urn we generate an ordered extraction of n_i balls. The white balls have a probability $(1 - P_i)$ of being extracted, and the black balls have a probability P_i of being extracted. The use of a single parent distribution implies that the tectonic activity of the Alaska arc is the same everywhere. The different probabilities at the sites are then due only to random fluctuations. This underscores the problem

with respect to Strandline Lake. We know that an earthquake swarm occurred there, so this draws attention (and inclusion as a site in this study). But there are hundreds of other candidate sites of similar size along the Alaska Peninsula and in the Aleutian Islands. We do not know, however, how many of these to include in the analyses. The lowest number is 13, but we lack a basis for estimating the highest number. Thus our estimates that include Strandline Lake are underestimates of the probabilities. Next we calculate the probabilities both including and excluding Strandline Lake to demonstrate the small difference in the estimates.

Calculating the Significance Level

The final step consists of evaluating the significance level. Generally speaking, we count how many times the feature observed in the real catalog can be seen also in the synthetic catalogs. To avoid the dependence on the value of τ, we perform a stacking of the results. That is, we sum, for different values of τ, the maximum number of "coincidences" observed in the sequences. We repeat the same calculation on the 10,000 synthetic catalogs and count how many times the sum of the maximum number of coincidences for different τ is equal to or larger than the number observed for the real catalog. Let us call this number R. The probability of observing the coincidences by chance is therefore $R/10,000$.

Results

The parameters for tests ending in 31 December 2000 and 31 December 2001 are shown in Tables 2 and 3, re-

spectively. The results are clear. For the two methods we obtain a probability less than 3% for both tests (Tables 4 and 5). Probabilities are lower (less than 1%) when Strandline Lake is included (Table 5, bottom). The stabilities of the results reported in the tables are checked by considering the two volcanoes Martin and Mageik to be two different sites only one of which experienced a seismic swarm in

Table 3
Parameters Used for Probability Calculations Using 31 December 2001 End Date

Site	Length of Monitoring Interval, T (days)	Time of Last Event Since 31/12/01, T1 (days)	P1*	P2[†]
Mt. Spurr	4444	3791	$1/T \cdot \tau$	$\xi_1 \cdot \tau$
Strandline Lake	4444	1923	$1/T \cdot \tau$	$\xi_2 \cdot \tau$
Redoubt	4444	4400	$1/T \cdot \tau$	$\xi_3 \cdot \tau$
Iliamna	2618	1964	$1/T \cdot \tau$	$\xi_4 \cdot \tau$
Augustine	4444	—	0	$\xi_5 \cdot \tau$
Martin-Mageik	2361	1902	$1/T \cdot \tau$	$\xi_6 \cdot \tau$
Trident-Novarupta	2361	—	0	$\xi_7 \cdot \tau$
Katmai	2361	—	0	$\xi_8 \cdot \tau$
Snowy	2361	—	0	$\xi_9 \cdot \tau$
Pavlof	1995	1937	$1/T \cdot \tau$	$\xi_{10} \cdot \tau$
Akutan	2114	2105	$1/T \cdot \tau$	$\xi_{11} \cdot \tau$
Makushin	1990	—	0	$\xi_{12} \cdot \tau$
Aniakchak	1995	—	0	$\xi_{13} \cdot \tau$

*P1 represents the probabilities of a single event for each site, used to generate the 10,000 synthetic catalogs with the METHOD1. τ is the length (in days) of the time window considered.

[†]P2 represents the probabilities of a single event for each site, used to generate the 10,000 synthetic catalogs with the METHOD2. For each synthetic catalog, the vector ξ_i is randomly selected from a BETA distribution (see text for details). τ is the length (in days) of the time window considered.

Table 2
Parameters Used for Probability Calculations Using 31 December 2000 End Date

Site	Length of Monitoring Interval, T (days)	Time of Last Event Since 31/12/00, T1 (days)	P1*	P2[†]
Mt. Spurr	4079	3426	$1/T \cdot \tau$	$\xi_1 \cdot \tau$
Strandline Lake	4079	1558	$1/T \cdot \tau$	$\xi_2 \cdot \tau$
Redoubt	4079	4035	$1/T \cdot \tau$	$\xi_3 \cdot \tau$
Iliamna	2253	1599	$1/T \cdot \tau$	$\xi_4 \cdot \tau$
Augustine	4079	—	0	$\xi_5 \cdot \tau$
Martin-Mageik	1996	1537	$1/T \cdot \tau$	$\xi_6 \cdot \tau$
Trident-Novarupta	1996	—	0	$\xi_7 \cdot \tau$
Katmai	1996	—	0	$\xi_8 \cdot \tau$
Snowy	1996	—	0	$\xi_9 \cdot \tau$
Pavlof	1630	1572	$1/T \cdot \tau$	$\xi_{10} \cdot \tau$
Akutan	1749	1740	$1/T \cdot \tau$	$\xi_{11} \cdot \tau$
Makushin	1625	—	0	$\xi_{12} \cdot \tau$
Aniakchak	1630	—	0	$\xi_{13} \cdot \tau$

*P1 represents the probabilities of a single event for each site, used to generate the 10,000 synthetic catalogs with the METHOD1. τ is the length (in days) of the time window considered.

[†]P2 represents the probabilities of a single event for each site, used to generate the 10,000 synthetic catalogs with the METHOD2. For each synthetic catalog, the vector ξ_i is randomly selected from a BETA distribution (see text for details). τ is the length (in days) of the time window considered.

Table 4
Results of Probability Calculations for Different Intervals Using Two Probability Methods, for Period Ending 31 December 2000

T (days)	Number of Coincidences Observed	P1*	P2[†]
30	2	0.17	0.18
60	2	0.33	0.32
90	4	<0.01	<0.01
120	2	0.58	0.49
150	4	<0.01	<0.01
180	4	<0.01	0.01
210	4	0.01	<0.01
240	4	0.02	0.01
270	4	0.02	0.02
300	5	0.03	0.02
330	4	0.04	0.02
360	5	<0.01	<0.01
Stacked	44	<0.01	0.01

*P1 is the probability to obtain by chance a number of "coincidences" equal to or larger than the number observed in the real catalog, by using the scheme described in METHOD1.

[†]P2 is the probability to obtain by chance a number of "coincidences" equal to or larger than the number observed in the real catalog, by using the scheme described in METHOD2.

Table 5

Results of Probability Calculations for Different Intervals Using
Two Probability Methods, for Period Ending 31 December 2001

T (days)	Number of Coincidences Observed	P1*	P2[†]
30	2	0.17	0.17
60	3	0.01	0.02
90	4	<0.01	<0.01
120	3	0.04	0.05
150	3	0.06	0.07
180	4	<0.01	<0.01
210	4	<0.01	0.01
240	4	0.01	0.02
270	5	<0.01	<0.01
300	4	0.02	0.04
330	4	0.03	0.05
360	5	<0.01	<0.01
Stacked	45	<0.01	<0.01
Without Strandline Lake			
Stacked	33	0.02	0.03

*P1 is the probability to obtain by chance a number of "coincidences" equal to or larger than the number observed in the real catalog, by using the scheme described in METHOD1.

[†]P2 is the probability to obtain by chance a number of "coincidences" equal to or larger than the number observed in the real catalog, by using the scheme described in METHOD2.

1996. Moreover, we have also considered that Martin/Mageik could have experienced more than one seismic swarm in the past. This last case is very conservative. In Figure 7 we can see that the network at these two volcanoes recorded two other peaks of seismicity. These were caused by mainshock-aftershock sequences in the vicinity (not under Martin/Mageik). In any case, we decided to include these two further "events" just to verify the sensitivity of our results to the definitions of event and site adopted. In all the cases the significance level is always less than 10%, ranging from less than 1% to 9% for the most conservative choices. All the results mean that there is a very small probability that the coincidences are due to chance. Note that we used 12 different values of τ, from 30 to 360 days ($\tau = i*30$, $i = 1, \ldots, 12$) to rule out the possibility of producing significant results only because of the particular choice of a time window. Indirectly, this choice also helps to account for the fact that we could use the start dates of the swarms, the dates of peak rates, the dates of the middles of the durations, etc. In other words, the results are robust regardless of the details of the parameterization of the swarms. Results of specific calculations using these different values are displayed in Tables 4 and 5.

Discussion

The year 1996 in the Aleutian Arc was one of high seismic and volcanic activity by any standard. The following were observed: (1) a swarm at Akutan Volcano (March 1996) including more than 3500 felt events; (2) the Iliamna

Swarm (May 1996, August 1996 to mid-1997); (3) the Pavlof Eruption (September 1996 to December 1996); (4) the Martin/Mageik Swarm (October 1996); (5) the swarm at Strandline Lake, which continued for several years (1996–1999); (6) deformation of Mt. Peulik (inflation begins after October 1996 and ends in fall 1998; earthquakes near Becharof Lake occurred in May 1998); (7) and $M_w = 7.9$ earthquake near Adak in June 1996. The majority of these swarms could only be identified from instrumental data. The areas where they occurred are remote and mostly uninhabited, so none of the earthquakes were felt except at Akutan and Adak.

An interpretation of these events is complicated by the fact that we have very few empirical and physical constraints. We do not know the starting conditions or threshold of the physical system at each locality, so we do not know the magnitude of any effect needed to serve as a trigger (see Ziv and Rubin, 2000). Further, we cannot be certain that the swarms represent the same processes. Pavlof erupted, so obviously there was intrusion and eventual eruption of magma. Indirect evidence favors intrusion of magma or other fluids at Iliamna (Roman *et al.*, 2001) and Martin-Mageik (Jolly and McNutt, 1999). The mechanism is likely different at Strandline Lake, where the swarm was deeper and lasted longer, and there is no volcano at the surface. For these reasons, at this stage of knowledge we can only provide speculations about possible causative physical models for such nearly simultaneous events.

Regardless of the specific nature of the unrest at each site, we can generally assume that all the sites represent systems very close to a critical state, where small perturbations are able to induce unrest. This is typical for some volcanic areas that appear to be very sensitive to the passage of seismic waves (e.g., Hill *et al.*, 1993), to earth tides (McNutt and Beavan, 1981, 1984), to slow perturbations induced by postseismic effects of remote earthquakes (Hill *et al.*, 2002; Marzocchi, 2002; Marzocchi *et al.*, 2002), and to other similar effects. For instance, previous studies on Pavlof and its seasonal eruptions have suggested that ocean loads are partly responsible for triggering eruptions (McNutt, 1999). The pattern of ocean loading occurs annually with minor variations and produces volume strains of about 10^{-9} (McNutt and Beavan, 1987). However, the 1996 eruption was larger and longer lasting than most others, suggesting that there could be additional causes. Another reasonable assumption is that a single origin is responsible for the nearly simultaneous perturbations found at different sites in 1996.

Because of its magnitude (M_w 7.9) and the infrequent occurrence of such events (about once per decade) the Adak earthquake might be an appealing candidate for a source of deformation. However, the distance from Adak to the four areas is large: Adak–Pavlof, 1100 km; Adak–Martin, 1600 km; Adak–Iliamna, 1830 km; Adak–Strandline, 1970 km. Based on comparison with measured deformation from other large earthquakes, static effects from the Adak earthquake at those distances do not appear to be large enough to have

been the trigger. Other mechanisms, such as a time-dependent stress transfer due to seismic waves (Hill *et al.*, 2002) or to viscoelastic relaxation of the lower crust and/or asthenosphere (e.g., Wahr and Wyss, 1980) act on different timescales compared with the few months of time lag between the Adak earthquake and the unrest observed in fall 1996. On the contrary it appears plausible that the Adak earthquake may have been a response to the same widespread event that also triggered the other activity. Hill *et al.* (2002) discuss several cases of possible interaction between large earthquakes and volcanoes at comparable distances (1000–2000 km) and with similar time offsets.

Another interesting empirical feature is the lack of a spatial-temporal trend for the unrest. If, for example, stress diffusion had occurred propagating from the west (if caused by the Adak earthquake), then we would expect the order of the swarms/eruption to be Pavlof, Martin-Mageik, Iliamna, and then Strandline Lake. (This assumes that the levels of criticality or thresholds at each place are the same.) The observed order was Iliamna, Pavlof, Strandline Lake, and Martin-Mageik (Fig. 7; see Fig. 1 for locations). Similar reasoning rules out stress diffusion propagating from the east. While stress diffusion may act over long timescales (e.g., Pollitz and Sacks, 1997), the combination of time, distance, and relative order of the swarms/eruption tends to rule it out unless we know more about the mechanisms.

Most of the increased earthquake activity (Iliamna, Martin-Mageik, and Strandline Lake [also Peulik, but it has no known earthquakes, and there is no local monitoring]) occurred in the eastern part of the arc. Pavlof and Akutan occurred in the central arc, whereas the Adak earthquake was much farther west. Thus it may or may not have been related. Given these facts it seems that the most likely causal mechanism was some type of strain transient in the eastern or central portion of the arc. Iliamna, Martin-Mageik, Strandline, and Peulik all fall within or close to the boundaries of the 1964 (M_w 9.2) rupture zone (Fig. 1; south of the coastline from longitude 145° to 156° W). We infer that a possible explanation for these nearly simultaneous events might be a deeper aseismic slip event that occurred along this zone. This would perhaps be similar to the "silent slip" event reported by Dragert *et al.* (2001) in the Cascadia subduction zone in 1999 under Vancouver Island. Dragert *et al.* (2001) suggest that such aseismic slip events may play a role in stress loading of the shallow seismogenic zone. We have no evidence of an aseismic slip event in 1996; however, aseismic slip was inferred to have occurred in the Shumagin Islands regions (near Pavlof) in 1978–1980 (Beavan *et al.*, 1984) and in southern Alaska near Cook Inlet in 1998–2002 (Freymueller *et al.*, 2002).

We also note that the three swarms highlighted in the present study were several orders of magnitude larger and lasted much longer than previous swarms observed in the same areas triggered by dynamic strains from *S* waves. For example, a M_s 7.0 earthquake near Kodiak, Alaska, in December 1999 triggered a small earthquake swarm 160 km

away at Martin-Mageik, one of the four areas of the present study (Power *et al.*, 2001). The December 1999 swarm was tiny, having only about a dozen events and lasting only a few hours. This evidence suggests that in the present case the trigger, or the physical mechanism underlying it, could have been larger and longer lasting.

Unfortunately, at this stage the identification of any specific mechanism is pure speculation. Under this perspective, we suggest that the trigger might be due to some transient in deformation such as a silent earthquake. Hopefully, in the future it will be possible, through an expanded Global Positioning System network and more frequent InSAR passes over the regions of Alaska, to integrate ground deformation and seismicity data to better identify regional stress triggers. Without continuous deformation measurements it is probably not possible to confirm any mechanism. Our purpose here has been to take the first important steps to document the activity that occurred in 1996 and to establish statistical significance.

Conclusions

The likelihood of three swarms and an eruption occurring simultaneously by chance alone ranges from 9% to less than 1%, depending on the different choices made to estimate such probabilities. We thus conclude that the events may have been triggered by a single process. We speculate that a widespread deformation pulse or strain transient occurred, affecting the eastern portion of the Aleutian arc. This transient may also be responsible for other relevant geophysical events that occurred in 1996, such as the M_w 7.9 earthquake that took place in the central portion of the arc in June 1996. However, no arc-wide continuous deformation data exist for 1996, so we cannot determine physical mechanisms. The high level of earthquake and volcanic activity in the Aleutian arc suggests that such triggering or interaction may occur again. If so, then in the future, with continuous Global Positioning System and InSAR data, we will be better able to confirm the effects of widespread deformation pulses or strain transients in the Aleutian arc.

Acknowledgments

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