

Chapter 4

A Parametric Study of the January 2006 Explosive Eruptions of Augustine Volcano, Using Seismic, Infrasonic, and Lightning Data

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Abstract

A series of 13 explosive eruptions occurred at Augustine Volcano, Alaska, from January 11–28, 2006. Each lasted 2.5 to 19 minutes and produced ash columns 3.8 to 13.5 km above mean sea level. We investigated various parameters to determine systematic trends, including durations, seismic amplitudes, frequency contents, signal characteristics, peak acoustic pressures, ash column heights, lightning occurrence, and lengths of pre-event and post-event quiescence. Individual tephra volumes are not known. There is no clear correlation between acoustic peak pressure and ash column height or between peak seismic amplitude and duration. However, several trends are evident. Two events, January 11 at 0444 AKST (1344 UTC) and January 27 at 2337 AKST (0837 UTC) are short (180 and 140 seconds) and have very impulsive onsets and high acoustic peak pressures of 93 and 105 Pa, as well as high peak seismic amplitudes. We interpret these to be mainly gas releases. Two of the largest events followed quiescent intervals of 3 days or longer: January 17 at 0758 AKST (1658 UTC), and January 27 at 2024 AKST (January 28 at 0524 UTC). These two events had reduced displacements (D_R) of 11.4 and 7.5 cm², respectively. Although these D_R values are typical for eruptions with ash columns to 9 to 14 km, most other D_R values of 1.6 to 3.6 cm² are low for the 7.0 to 10.5 km ash column heights observed. The combination of short durations, small D_R and high ash columns suggests that these events are highly explosive, in agreement with Vulcanian

eruption type. Several events had long durations on individual seismic stations but not on others; we interpret these to represent pyroclastic or other flows passing near the affected stations so that tractions or momentum exchange from the cloud or flow adds energy to the ground only near those stations. The eruption on January 27 at 2024 AKST had more than 300 lightning flashes, whereas the following eruptions on January 28 at 0204 AKST and 0742 AKST had only 28 and 6 lightning flashes. The 2024 AKST eruption had a longer duration (1,180 versus <460 seconds), a higher ash column height (10.5 versus 7.0–7.2 km) and higher acoustic peak pressure (83 versus 66 and 24 Pa). The data suggest that the lightning-rich 2024 AKST eruption produced more tephra than the following eruptions, hence there were more charge carriers injected to the atmosphere. Seismic signals preceded the infrasound signals by 0 to 5 seconds with no obvious pattern in terms of the above groupings. The explosive eruption phase overlapped with the subsequent continuous phase by about 2 days. Parametric data may be useful to estimate eruption conditions in near real time.

Introduction

Following an 8.5-month period of precursory activity, Augustine Volcano began to erupt explosively on January 11, 2006 (Power and others, 2006). A series of 13 strong explosive eruptions occurred over the next 17 days, with most sending ash clouds to elevations of 10 km or more (table 1). New instrumentation added in December 2005 and January 2006 allows for a more comprehensive study of these eruptions than has previously been possible for explosive eruptions in Alaska. In particular, an infrasound pressure sensor located at AUE (fig. 1) recorded all 13 events on scale, temporary broadband seismometers remained on scale and complemented the permanent short-period network, and new lightning detection

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equipment was installed on January 27, 2006, just before the last series of four strong explosive eruptions on January 27–28. This paper presents a systematic study of the 13 explosive eruptions, combining the new data to gain insights into processes contributing to observed variations in the explosivities of the eruptions, including plume heights, amounts of tephra, gas distribution, and electrical properties.

These new data (broadband seismic, infrasound, and lightning) are especially useful because for the 1976 and 1986 eruptions of Augustine Volcano only short-period seismic data were available. The seismic data for 1976 were recorded off island (Power and Lalla, this volume), and for 1986 only short-period data existed (Power, 1988). The short-period stations on the island in 2006 were all saturated (clipped), and several were damaged or destroyed by the eruptions, whereas the broadband stations remained on scale. Distant stations such as OPT (34 km north; fig. 1) remained on scale and provided a basis for comparisons. As will be shown, the new data streams provide many additional constraints on eruptive processes.

The 1976, 1986, and 2006 eruption sequences had remarkably similar precursory stages, which lasted 9, 9, and 8.5 months, respectively (Power and Lalla, this volume). The two previous eruption sequences began with explosive phases lasting 4 and 14 days, followed by effusive phases.

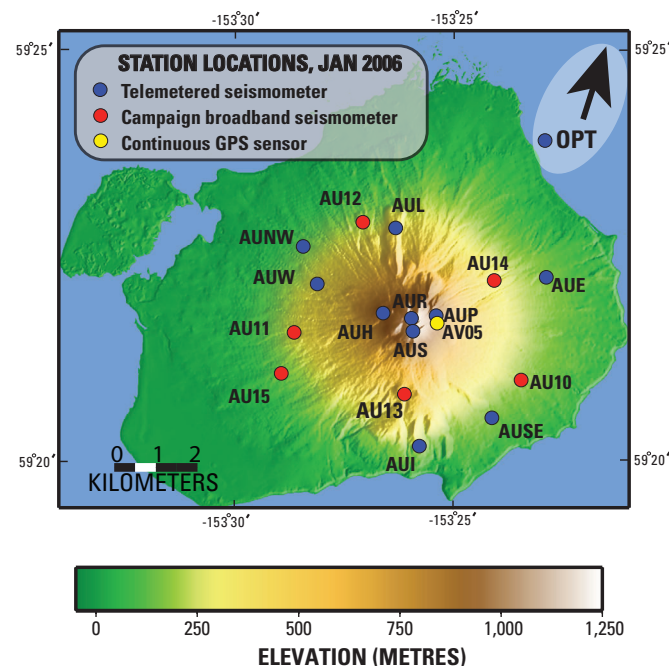


Figure 1. Map of seismic stations on Augustine Island. Stations shown have either short-period or temporary broadband seismometers. AUL has a permanent 3-component broadband station, and AUE has an infrasound sensor. Station OPT is on the Alaska mainland 34 km north of Augustine Volcano. (Image courtesy of H. Buurman.)

This pattern was repeated in 2006; however, the explosive phase lasted 18 days.

Augustine's Vulcanian eruptions are similar to eruptions at other volcanoes including Vulcano, Italy 1888–1890, Ngauruhoe, New Zealand 1975, Galeras, Colombia 1992–1993, Sakurajima, Japan 1985–1990, Asama, Japan 2004, and Montserrat, West Indies 1997 (Morrisey and Mastin, 2000; Ohminato and others, 2006; Druitt and others, 2002). A comparison is given in the discussion section of this paper, following presentation of the Augustine parameters.

Times in this paper are given in local time (Alaska Standard Time or AKST) followed by universal time (UTC) in parentheses where appropriate. At the time of the Augustine eruptions UTC was 9 hours ahead of local time; that is, 1200 (noon) AKST is equivalent to 2100 UTC.

Data and Methods

Seismic Data

The permanent seismic network on Augustine Island consisted of eight short-period stations and one broadband station (AUL; fig. 1). The short-period stations have a natural period of one second and use either Mark Products L4-C or Geotech S-13 vertical seismometers. The permanent broadband station uses a Guralp CMG-40T 3-component seismometer with a natural period of 30 seconds. Analog data from all short-period stations are telemetered to Homer, Alaska, by VHF radio, then by telephone and internet to the University of Alaska Fairbanks Geophysical Institute, where data are digitized at 100 Hz at 12-bit resolution. The broadband station is digitized on site at 100 samples per second and uses digital rather than analog radio telemetry. The permanent network was augmented by the addition of five temporary broadband stations that were recorded on site at 100 samples per second (fig. 1). All the short-period stations on the island were saturated (clipped) for all 13 of the large explosive eruptions. Station OPT, 33 km the north on the Alaskan mainland, is a short-period station that recorded all the events and remained on scale for all but one event (January 27 at 2337 AKST).

Seismic measurements include the duration and reduced displacement (D_R). Duration varies with the individual station used, and the gain, and distance. Because Augustine is a small island, all the local stations are close, within 5 km of the vent. All the short-period stations clipped during each of the 13 explosive eruptions. However, rather than being a problem, this actually afforded a convenient way to measure durations, which were estimated from the length of the continuously clipped (that is, strong) portion of the signal. This was measured from hard copies of seismograms at a standard scale of 600 seconds = 3.4 cm (figs. 2A and 2B; note the printed scale here is different). Several stations gave virtually identical durations, the most reliable being AUH and AUW. The closer station AUH gave preferred values early in the

Table 1. Parameters of the Augustine Volcano January 11–28, 2006, explosive eruptions.[AKST, Alaska Standard Time; UTC, Universal Time; D_R , reduced displacement; OPT, Oil Point seismic station; I, impulsive; E, emergent]

Event Number	Date in 2006	Event Onset AKST (UTC)	Type	Pressure, in Pa	Duration: Acoustic, in seconds	Duration: Seismic, in seconds	D_R , in cm^2 OPT	Preceding Quiescence, in days	Number of lightning flashes	Plume Height, in km ¹
1	January 11	0444 (1344)	I	93	25	180	139	---	---	6.5
2	January 11	0512 (1412)	E	14	100	385	1.8	0.02	---	10.2
3	January 13	0424 (1324)	E	22	130	915	7.7	1.97	---	10.2
4	January 13	0847 (1747)	E	35	100	400	2.4	0.18	---	10.2
5	January 13	1122 (2022)	I	32	150	520	2.6	0.11	---	10.5
6	January 13 (January 14)	1640 (0140)	E	29	150	570	3.3	0.22	---	10.5
7	January 13 (January 14)	1858 (0358)	E	52	170	765	1.6	0.09	---	13.5
8	January 14	0014 (0914)	I	65	100	430	3.6	0.23	---	10.2
9	January 17	0758 (1658)	E + I	93	50	410	11.4	3.32	---	13.5
10	January 27 (January 28)	2024 (0524)	E + I	83	250	1180	7.5	10.52	365	10.5
11	January 27 (January 28)	2337 (0837)	I	105	20	140	178	0.13	1	3.8
12	January 28	0204 (1104)	I	66	150	460	2.9	0.10	28	7.2
13	January 28	0742 (1642)	E	24	160	240	2.1	0.24	6	7.0

¹ Schneider and others, 2006.

eruption sequence but was destroyed on January 27 and had to be replaced by others (for example AUE and AUI) using bootstrapping methods to yield durations. Some adjustments were necessary when pyroclastic or other flows (for example, lahars, rockfalls) passed near stations, because these added extra energy to the ground and prolonged the codas at the stations nearest to the flows (figs. 3A and 3B).

For the 1976 and 1986 eruptions of Augustine Volcano, the stations on the island either were not operational or were mostly clipped (Reeder and Lahr, 1987; Power, 1988). Station OPT, a single-component, 1-second vertical seismometer located 33 km north of the vent, was far enough away that the signals had attenuated and remained on scale. Thus data from OPT are useful for direct comparison between the 1986 and

2006 eruptions. We determined magnitudes for the explosive eruptions using OPT by forcing the origin to be at Augustine's vent and measuring the highest amplitude portion of the signal. The maximum values obtained were $M_L=2.3$ and 2.6, which agree well with the largest events during the 1976 eruption, which were $M_L=2.3$, although these were considered to be earthquakes occurring simultaneously with large tremors and were recorded at station CKK, 82 km to the northwest (Reeder and Lahr, 1987). The 2006 M_L values were then converted to D_R ; both are measures of ground motion that use the same seismic measurements but different normalizations. D_R is peak-to-peak root mean square displacement multiplied by the square root of wavelength times distance (Fehler, 1983). For the 2006 events, we assumed surface wave propagation using

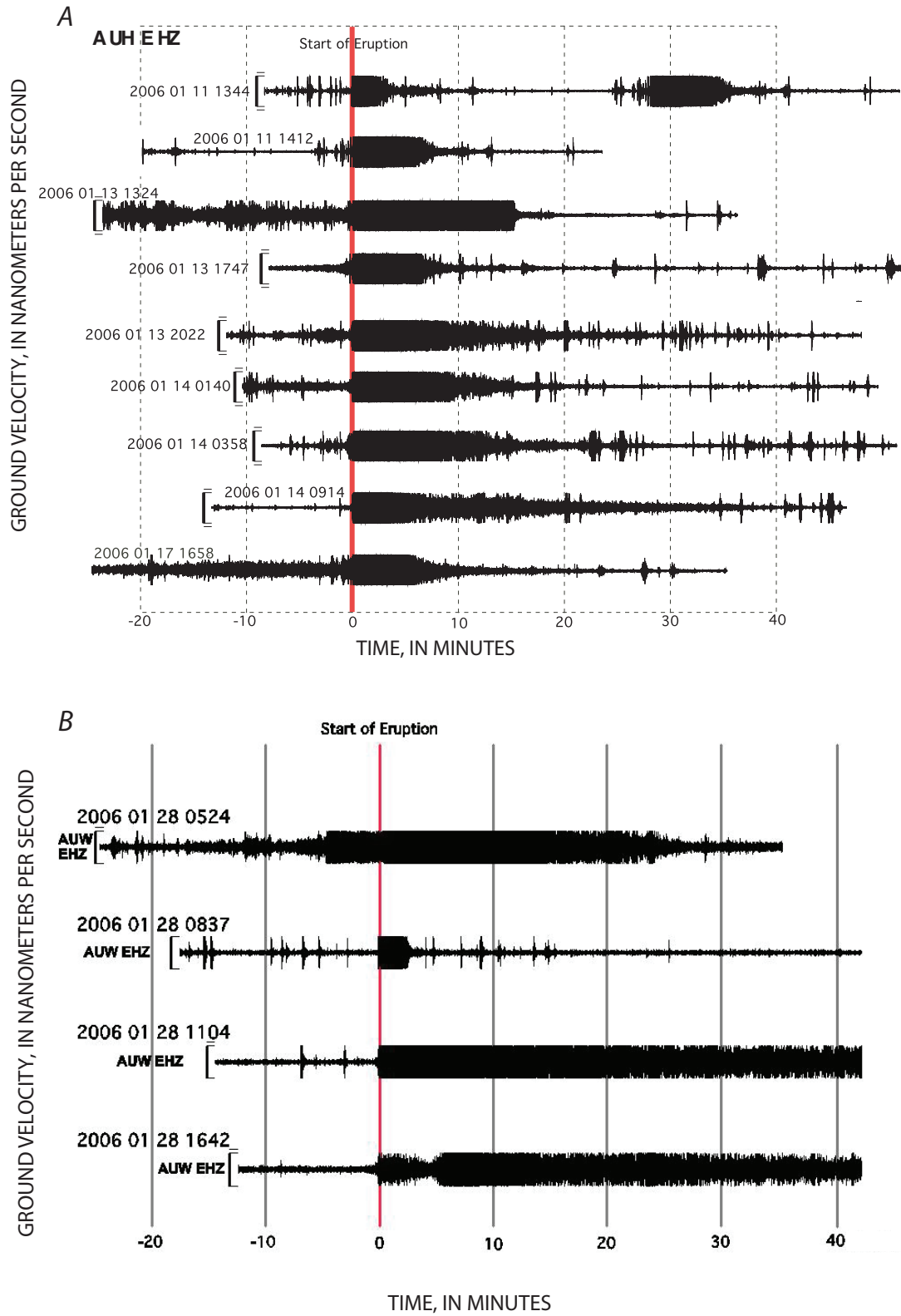


Figure 2. A, Seismograms (unfiltered) for the first 9 of 13 large explosive eruptions at Augustine Volcano in 2006. Data are from station AUH, which was destroyed on January 28, 2006. One hour of data is shown and the seismograms are aligned on the beginning of each explosive eruption. The durations of the clipped portion of the seismograms range from 3 to 15 minutes. B, Seismograms of the last 4 explosive eruptions. Data are from station AUW. Other features are as in part A. Time convention is YYYY MM DD HHMM. Times in UTC.

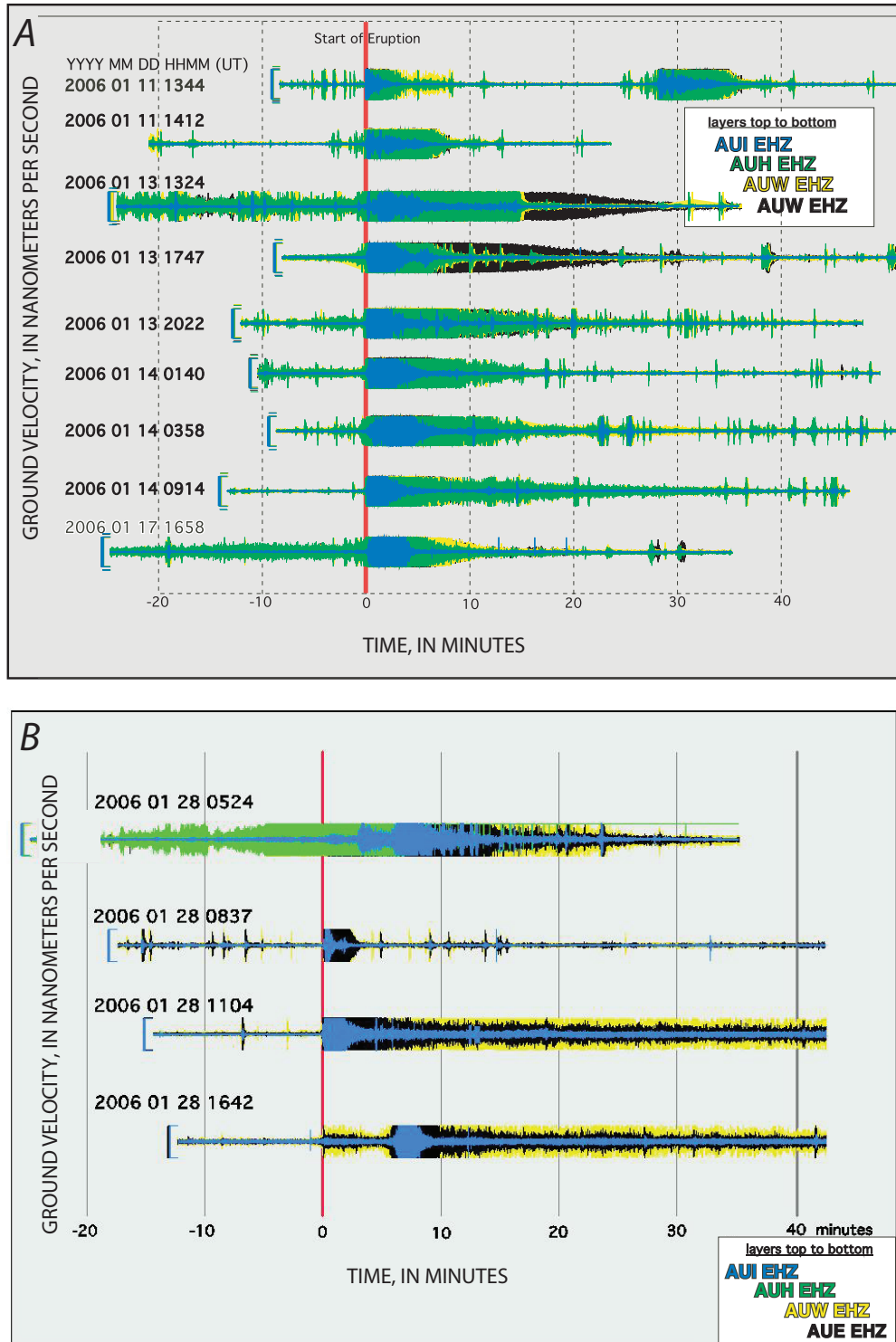


Figure 3. A, Overlaid seismograms for four stations (AUI, AUH, AUW, and AUE) on Augustine Island. Data are aligned on the beginning of each explosive eruption. Note that the codas for events 3 and 4 are much longer on station AUE than for the other stations, suggesting that pyroclastic or other flows passed near that station. B, Seismograms for four stations (AUI, AUH, AUE, and AUW) overlaid. Note that the colors and tiling are different than part A to better show the relative features of the different seismograms. Station AUH was destroyed during event 10 (top trace). EHZ is a code representing short-period seismic stations.

the same formulation, adjusted for differences in frequency content, as was used for the 1976 events to compare them with worldwide data (McNutt, 1994). The D_R values for the 2006 events are shown in table 1.

The D_R values computed here are systematically lower than those determined by van Manen and others (this volume). There are several reasons for this. Van Manen and others (this volume) used broadband stations on the island at close distances. Note that D_R corrects for geometrical spreading but does not correct for attenuation, so stations at distances of a few tens of km such as OPT generally give lower values than close stations. A clear example of this effect was observed for Pavlof Volcano (McNutt and others, 1991). A second effect is the choice of surface waves. Particle motions at many volcanoes show surface waves to be the most common component of tremor, so surface waves were assumed for Augustine Volcano. Further, the velocity of the high-amplitude portion of the signal at OPT is about 2 km/second, a value typical for surface waves. For the nearby broadband stations body waves may be more appropriate. Body waves always return higher values for D_R because of the way the formulations are set up (Fehler, 1983). A third factor is the narrow bandwidth of the short-period seismometer at station OPT; relatively high amplitude but very low frequency waves would not be visible. Finally, near-field terms may exist in the broadband data, which can be large near the source. Such waves would not appear in the OPT data. All these effects can give rise to quite different values for attempts to measure the same quantity using different stations. Because the purpose here is partly comparison with the previous eruptions, we used station OPT data as described above. The choice of other data may be more suitable for other purposes.

Broadband waveforms for all 13 explosive eruptions are shown in fig. 4B for temporary station AU14 (fig. 1). All seismograms are plotted at the same scale and the events are aligned on the start time to facilitate comparison.

Infrasound Data

A Chaparral Model 2.1 microphone was installed at AUE in early January 2006, and data were telemetered in the same manner as seismic data. This site has a direct distance of 3.2 km to Augustine Volcano's active vent (fig. 1). The laboratory calibrated pressure transducer system, consisting of the microphone, a voltage controlled oscillator (VCO) and a discriminator, has a flat response between 0.1 and 50 Hz and a linear response to pressures above 100 Pa. Both high-gain and low-gain channels were operated, with sensitivities of 0.171 and 0.0084 V/Pa, respectively (Petersen and others, 2006). The low gain channel remained on scale for all the explosive eruptions; peak values ranged from 14 to 105 Pa and are shown in table 1. A noise reduction system, consisting of eight microporous hoses spread out over a half circle, is connected to the microphone. Twelve of the large explosive eruptions were also recorded on the I53US infrasound array in

Fairbanks, Alaska, 675 km north of Augustine (Olson and others, 2006). However, because atmospheric conditions varied so widely, it is not possible to use the I53US observations for comparative study of source processes (Olson and others, 2006). Thus, the discussion in this paper is mainly limited to the data from the local sensor, whose close distance of 3.2 km minimizes propagation effects.

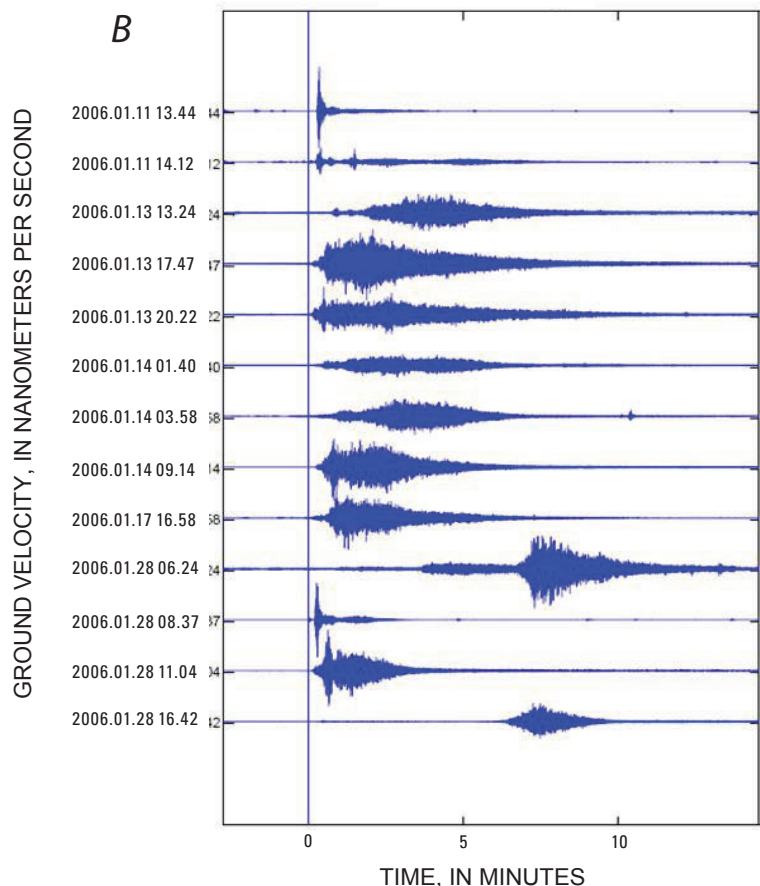
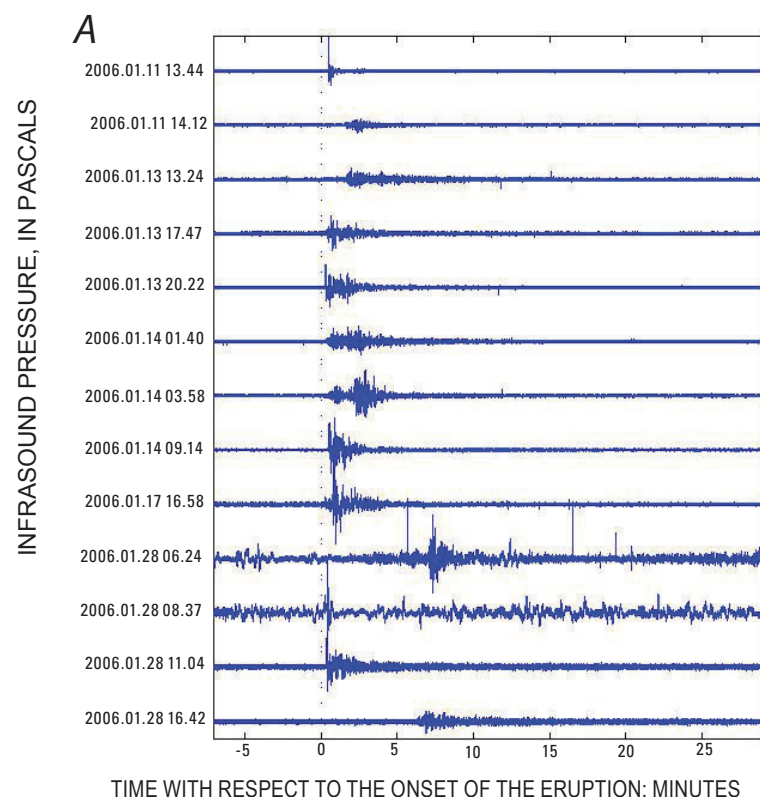
For the infrasound data from station AUE (fig. 4A), durations were measured from the event onset to decay to the background (Petersen and others, 2006). These varied from 25 to 250 seconds (table 1). All the explosive eruptions remained on scale on the low gain channel, so maximum 0-peak (excess) pressures were measured directly from the waveforms. After the first event at 0444 AKST on January 11, with 93 Pa, the next ten events showed gradually increasing pressures from 14 Pa up to the maximum of 105 Pa at 2337 AKST on January 27 (Petersen and others, 2006). The next two events had lower pressures of 66 and 24 Pa and were followed by a continuous phase consisting of explosions with low pressures of 0.5 to 1 Pa occurring every few minutes for several days. These were only visible on the high-gain channel. Reduced pressures (Johnson 2000) may be obtained by multiplying the pressures by the distance to station AUE, which is 3.2 km. Only the 13 large explosions from January 11 to January 28 are considered in detail in this paper.

Infrasound waveforms for all 13 explosive eruptions are shown in fig. 4A for station AUE low-gain channel (fig. 1). All acoustigrams are plotted at the same scale and the events are aligned on the start time to facilitate comparison.

Lightning Data

Two New Mexico Tech Lightning Mapping Array (LMA) lightning detection stations were installed on January 27, 2006, in Homer and Anchor Point, 100 km east of Augustine Volcano (Thomas and others, 2007; Thomas and others, this volume). The stations record time of arrival of electromagnetic radiation in the unused channel 3 TV band (63 MHz) and constitute a minimal network capable of determining the azimuthal direction of impulsive radio emissions from electrical discharges (Thomas and others, 2004). The lightning stations detected both continuous electrical disturbances and lightning flashes in association with the last four explosive eruptions on January 27–28 (table 1) and with four stronger pulses on January 29–30 during the continuous phase. For the earlier eruptions (January 11–17), qualitative lightning reports were obtained from airline pilots, and two eruptions had data recorded by Bureau of Land Management (BLM) stations (Thomas and others, this volume).

The LMA stations recorded two main types of activity: lightning flashes and continuous electrical disturbances at the time of most vigorous eruption. We counted the number of discrete flashes associated with each of the eruptions on January 27–28 (table 1) and also measured the duration and peak radiated power of the continuous signals (Thomas and



others, this volume). Because the lightning data were available only for the last four explosive eruptions, we can make only a few general conclusions about lightning.

Plume Heights and Quiescence Data

Two other parameters of interest are plume heights and the durations of preceding quiescence. Plume heights were determined from ground-based Nexrad Doppler radar measurements (Schneider and others, 2006) using data provided by the National Weather Service (NWS). Errors are discussed by Wallace and others (this volume). Resulting plume heights are shown in table 1. This method may not detect the diluted, uppermost parts of the plumes because the radar is tuned to see millimeter to centimeter sized particles; however, it provides an approximation that is consistent throughout the explosive eruption sequence. We measured the time interval between the start times of the events and show this in table 1 under the column labeled “preceding quiescence.”

Results

This study compiles a set of measured parameters to describe and systematically compare the eruptions of Augustine Volcano in 2006. Once the parameters were measured, it became immediately obvious that the eruptions were not all the same, and that they fell into several clear groups. These are described and interpreted in this section. The infrasound pressure and D_R are shown in time sequence in figure 5. Because some of the explosive eruptions occurred closely spaced in time, the data appear bunched and are difficult to interpret. Thus, the same data are displayed in index order in figure 6. A comparison of the two figures allows for a complementary view of the data trends.

Figure 4. A, Acoustigrams of the 13 large explosive eruptions at Augustine Volcano in 2006. Data are from station AUE BDL (low gain). Thirty minutes of data are shown and the acoustigrams are aligned on the beginning of each explosive eruption (vertical dotted line). The durations of the strong portions of the signals range from 20 to 250 seconds. B, Seismograms of the 13 large explosive eruptions. Data are from broadband seismic station AU14 HHZ (vertical). Other features are as in part A. Times shown at left are UTC.

Short Strong Eruptions

The two shortest events were also two of the three events with the highest infrasound pressures and the two highest seismic amplitudes (table 1; figs. 4*A* and 4*B*). These were the first event on January 11 at 0444 AKST (event 1) and the January 27 event at 2337 AKST (event 11). These were quite short acoustically, only 20 to 25 seconds, whereas seismically they lasted 140 to 180 seconds. The periods of the highest amplitude seismic waveforms at OPT for each event were greater than 1 second each, longer than for any of the other events (the event at 0204 AKST on January 28 also had a long-period pulse near the onset, but this was not the highest amplitude pulse). Both events were very impulsive, with the initial pulse accounting for about 60 percent of the total energy of each event. Cumulative energy plots were used to make this estimate, as shown in figure 3 of Petersen and others (2006). Because they were strong, $D_R=139$ and 179 cm^2 (equivalent to $M_L=2.25$ and 2.55 ; both are measures of amplitude) one might suggest they were in some way the “biggest” of the eruptions. However, these two events appear to have produced the least amount of tephra. Event 11 had a plume only 3.8 km high that quickly dissipated, and event 1 mainly blew out old rock as it reamed out the vent. Its ash plume was the second smallest at 6.5 km high (Schneider and others, 2006). Photographs taken after the January 11 eruptions revealed small deposits near the summit and a few mixed avalanches or lahars. Observations

and samples analyzed by Vallance and others (this volume), Wallace and others (this volume), and Coombs and others (this volume) suggest that little or no juvenile material was present in deposits from the January 11 eruptions. Taken together these observations suggest that these eruptions were gas rich and mainly erupted a large gas pocket or equivalent collection of gas charged magma.

Eruptions Preceded by 3 or More Days of Quiescence

Two of the eruptions followed inter-event quiescent periods of 3 days or more: January 17 at 0758 AKST (event 9) and January 27 at 2024 AKST (event 10). Both eruptions destroyed or partially destroyed new domes that had been emplaced during these quiescent intervals. The domes consisted of magma that had sat on the surface for some time and therefore lost much of its gas, forming a temporary plug. The new eruptions then pushed this material out of the way. Seismic data show that these two eruptions each had emergent onsets followed shortly by impulsive phases (Petersen and others, 2006; figure 4*A*); we suggest that the emergent part of the pressure record represents mostly old dome material being pushed out (gas poor) and that the impulsive phase of the pressure record represents the venting of a gas-rich parcel of magma that was previously

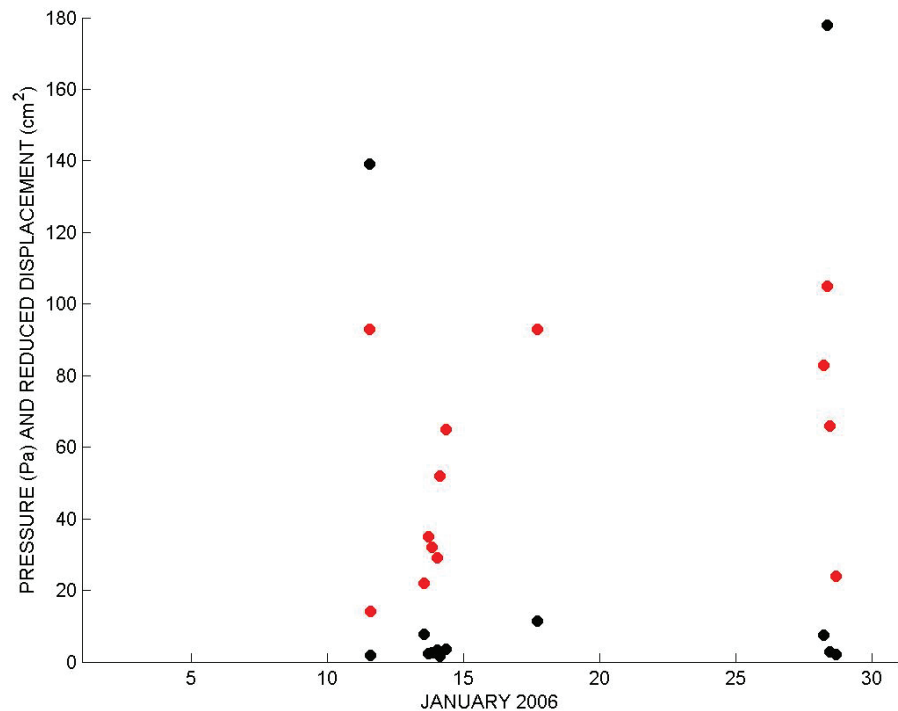


Figure 5. Acoustic peak pressure in Pa (red circles) and seismic reduced displacement in cm² (black circles) as a function of time for the 13 large explosive eruptions at Augustine Volcano in 2006.

beneath the dome. The eruptions produced the 3rd and 5th highest seismic amplitudes, the 2nd and 4th highest infrasound pressures (table 1; figs. 4A and 4B), and appear to be the two largest eruptions in terms of tephra production. The January 17 event was the only individual event to deposit significant tephra on land to the northwest of Cook Inlet, and the January 27 event produced a large pyroclastic flow, the Rocky Point flow (Coombs and others, this volume).

Low D_R but High Ash Column

Many of the eruptions shared the following characteristics: small D_R (1.6 to 3.6 cm²), moderate infrasound pressures (14 to 66 Pa), a short time interval after the previous eruption (0.5 to 5.5 hours) and generally emergent signals on both seismic and infrasound data (table 1). These are the second event on January 11 at 0512 AKST (event 2), most of the events on January 13 and 14 (events 3 through 8) and the last two on January 28 (events 12 and 13). These events all had moderate durations of 100 to 170 seconds acoustically and 240 to 915 seconds seismically. Six of nine were emergent acoustically as determined by Petersen and others (2006), and the other three began with a weak impulsive phase that represented only about 15 percent of the total energy. The emergent character and moderate durations suggest that the gases are rather uniformly distributed in each

batch of magma, so that the eruption is more of an intense “fizz” than a “pop.” The data suggest that these are the most typical explosive eruption events and are most characteristic of the Vulcanian eruption style. The seismic and acoustic waveforms show some variation (figs. 4A and 4B), suggesting that although the events are similar, they are not identical to each other. Volcanic Explosivity Index (VEI; Newhall and Self, 1982) values of 2 to 3 would characterize these events, for which the plume heights were 7.0 to 13.5 km, but the volumes were small ($<2 \times 10^6$ m³, Coombs and others, this volume). Preliminary acoustic modeling by Fernandes and others (2007) suggests exit velocities of 50 to 300 m/second and volume flux rates of 10^3 to 10^4 m³/second.

Lightning and Duration

The four eruptions on January 27–28 differed dramatically in their electrical activity. The first produced 365 lightning flashes, the second 1 flash, and the next two 28 and 6 flashes (table 1). The ash plume heights were similar for events 10, 12, and 13, whereas the plume for event 11 was the smallest of any of the explosive eruptions. This was also the event with the highest infrasound pressure. These observations can be reconciled by inferring that event 11 was mostly gas with very little tephra, an inference confirmed by radar observations (Schneider and others, 2006). Of the other

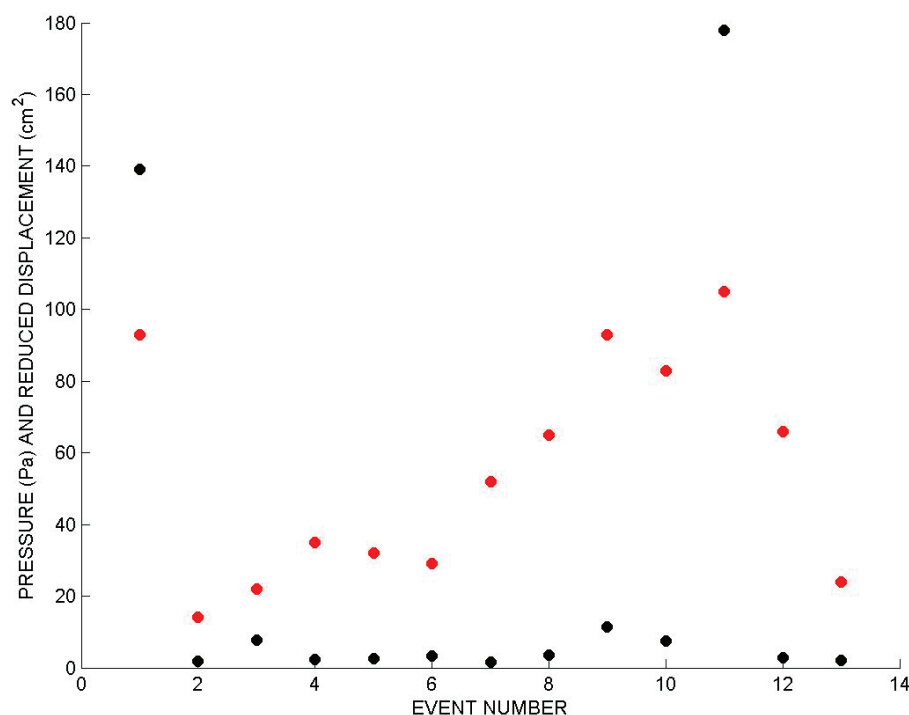


Figure 6. Acoustic peak pressure in Pa (red symbols) and seismic reduced displacement in cm² (black symbols) in index order for the 13 large explosive eruptions at Augustine Volcano in 2006.

parameters listed in table 1, the one that stands out as having the most direct correlation with the amount of lightning is the duration. This suggests that the tephra production is positively correlated with the duration, assuming that eruptions rates are similar. It also implies that the amount of tephra is proportional to the amount of lightning. The basic idea is that each tephra particle is a potential charge carrier, so the more particles, the higher total charge and greater potential to produce lightning. A detailed discussion of the lightning observations is given by Thomas and others (this volume).

End of Explosive Phase

An event that began on January 28 at 1430 AKST appears to be a transition event (fig. 7) between the period of discrete, moderate-large explosive events to nearly continuous, smaller explosions. It had smaller peak pressure (9 Pa) than any of the 13 explosive events and lasted much longer, about 1 hour 45 minutes compared to 15 minutes or less for the explosive events. After the transition event quiescence was observed for 6 hours, then at 1617 AKST on January 29 a series of small explosions (0.5 to 1 Pa) began to occur every few minutes for the next several days (fig. 7). A similar figure showing seismic data from station AU13 is given by Power and Lalla (this volume). Volcanic ash was observed in the air almost continuously starting at 1430 AKST on January 28 (Schneider and others, 2006) and lasting until February 2; this phase of the eruption is termed the continuous phase (Power and Lalla, this volume; Coombs and others, this volume). The continuous phase was punctuated by three larger events at 1119 AKST on January 29 (infrasound 13 Pa), and at 0328 AKST (13 Pa) and 0622 AKST (4.4 Pa) on January 30. These had durations of several minutes each and were accompanied by lightning (Thomas and others, this volume) but were all significantly smaller than all but one of the 13 numbered explosions. One may consider these events to be relatively large bursts of activity within the continuous phase. An alternative explanation is that these events were instead explosive eruptions (similar to the 13 numbered events), hence there was overlap rather than a clear separation between the explosive and continuous phases of the eruption.

Events Producing Pyroclastic Flows

Several of the 13 large explosive eruptions showed seismic evidence for the occurrence of pyroclastic or other flows, such as lahars or debris avalanches. These deposits have been described and mapped by Coombs and others (this volume) and Vallance and others (this volume). As shown in figure 3A, the events at 0424 AKST and 0847 AKST on January 13 had unusually long codas at station AUE (fig. 1). This suggests a primary part of the signal from the vent that appears on all stations, as well as a secondary part caused by pyroclastic material falling out of the cloud and transferring momentum to the

ground near specific stations along the pyroclastic flow path, AUE in this case. Alternatively the extended codas may represent lahars, mixed avalanches, or other flow events that passed near the affected station, with tractions at their bases transferring seismic energy into the ground. Thus, the data suggest that the 0424 AKST and 0847 AKST eruptions (events 3 and 4) were accompanied by pyroclastic flows traveling to the east. Events 1, 9, and 10 showed slightly extended codas for station AUW (fig. 1) to the west, suggesting weak pyroclastic flows traveling to the west (figs. 3A and 3B). The last two events, numbers 12 and 13, had very long extended codas on station AUW (fig. 3B), suggesting sustained pyroclastic flows traveling to the west. The parameters concerning pyroclastic flows are summarized in table 2.

We also checked broadband data and radar data to confirm and to further elucidate these findings. The broadband data did not clip, so instead we see the primary signal from the eruption, followed by relative quiescence, and then an increase in signal level a few minutes later as the pyroclastic flow material applies tractions or transfers momentum near a particular station. The overall principle is the same, but the signals look different on the broadband stations as compared with the short-period stations. The broadband station parameters are also given in table 2. An example of the broadband data is shown in figure 8 for event 8. Here station AU12 (second from the top) shows a second signal pulse between 700 and 900 seconds that does not appear on other stations. This suggests that a pyroclastic or other flow travelled to the north-northwest (see fig. 1 for station locations). Coombs and others (this volume) and Vallance and others (this volume) used similar criteria, as well as spectrograms, to determine which eruptions produced various flow units. Some spectrograms showed higher frequencies for nearby flow events, in contrast to the lower frequencies of the more distant primary explosions. Similar observations were made by Zobin and others (2009) for Colima Volcano, Mexico.

Seismic and Infrasound Origin Times

The event times for the 13 explosive eruptions were assigned to the nearest minute based only on seismic data during the eruption response, mainly as a way to identify and keep track of the separate eruptions. Here we perform retrospective analyses of the origin times using both seismic and infrasound data. The measurements were made for the onset of seismic clipping to the nearest second on station AUH, AUE, or AUW (fig. 1). These are systematically late by about 1 second (the typical time from the onset to clipping), but the signal preceding the explosive eruptions was often contaminated by small earthquakes so the absolute onsets could not be uniformly determined. The acoustic onsets to the nearest second were determined by Petersen and others (2006) for station AUE BDL. Acoustic times for some subevents were determined by the authors. The seismic travel time is a few tenths of a second to station AUH because of the close distance of about 700 m, and assumed

to be 1 second for AUE and AUW. The acoustic travel time is determined to be 10 seconds from detailed analysis of the 2337 AKST event on January 27, which had a very impulsive acoustic onset and also continuous electrical activity which began abruptly at the same time as the acoustic origin time (Thomas and others, this volume). Thus, we determined both seismic and acoustic origin times. These were generally not the same; a comparison (table 3) shows that they differ by 0 to 5 seconds, with the seismic origin time always earlier than

the acoustic one. The time difference may be interpreted as a proxy for depth or as the time interval over which the final preeruptive processes occur. The measured time differences do not agree well with the groupings of events as given above (for example, short strong eruptions), although events 1 and 11 both share a seismic versus acoustic time difference of 4 seconds. Of the two events that followed quiescence (events 9 and 10), event 9 had a time difference of 0 seconds, which we interpret to represent an explosive source

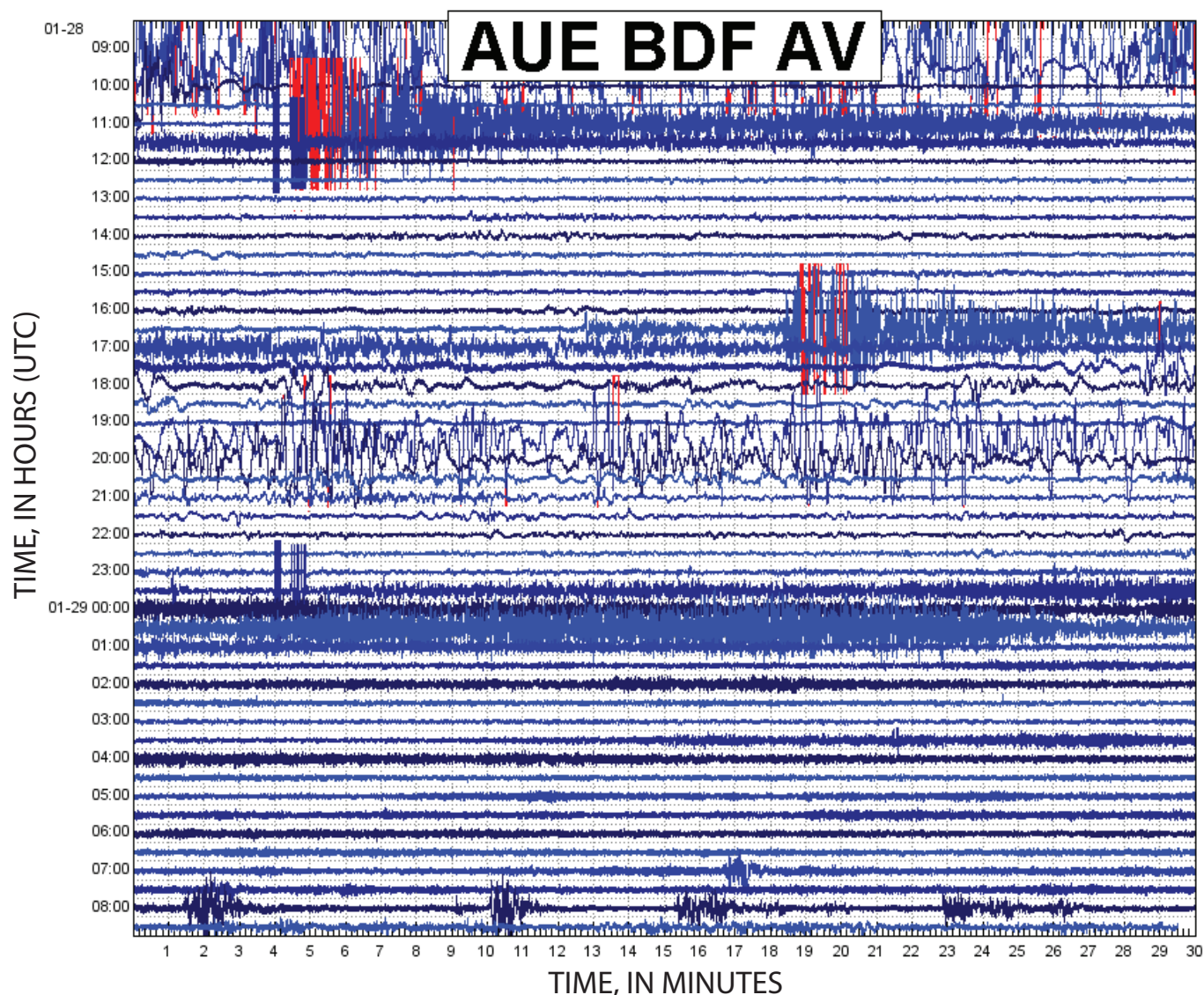


Figure 7. Acoustigram for eruptions at Augustine Volcano on January 28–29, 2006. Twenty-four hours of data are shown for acoustic station AUE BDF (high gain). Each line is 30 minutes. Events 12 (1104 UTC) and 13 (1642 and 1648 UTC) show partially clipped data in red and have codas about 45 minutes long. The event at 2330 UTC is a transitional event that lasts about 2 hours. Starting at 0717 UTC on January 29 are small discrete events occurring every few minutes that were characteristic of the continuous phase of the eruption (Coombs and others, this volume). Strong wind noise occurs from 0900 to 1000 UTC and from 1930 to 2030 UTC. AV is a code for stations maintained by the Alaska Volcano Observatory.

Table 2. Parameters of Augustine Volcano January 11–28, 2006, explosive eruptions showing evidence for pyroclastic flows.

[AKST, Alaska Standard Time; PF, pyroclastic flow; AUW, AU14, and others are seismic stations codes]

Event Number	Date in 2006	Event Onset AKST	Long Coda	Broadband Delayed Pulse	Seismic Station Destroyed	Interpretation
1	January 11	0444	AUW	---		Possible mixed avalanches
2	January 11	0512	---	---		---
3	January 13	0424	AUE	AU14	AUP	PF East
4	January 13	0847	AUE	AU12, AU13		PF East, North, South
5	January 13	1122	---	AU12		PF North
6	January 13	1640	---	AU14		PF East
7	January 13	1858	---	AU12		PF North
8	January 14	0014	---	AU12		PF North
9	January 17	0758	AUE, AUW	AU12, AU15		PF North, East, West, Southwest
10	January 27	2024	AUW	AU15	AUL, AUH	PF West, Southwest, North
11	January 27	2337	---	---		---
12	January 28	0204	AUW	---		PF West
13	January 28	0742	AUW	---		PF West

right at the surface, where the time difference for event 10 could not be determined because the seismic traces were already clipped when the largest phase occurred (table 3). The time differences for the largest group of events, characterized by low D_R and high ash columns (events 2, 3, 4, 5, 6, 7, 8, 12, and 13), spanned the range from 0 to 5 seconds. We note that all the events with a 5 second time difference fell in this group. The large time difference suggests a systematically deeper source or a prolonged initiation process for that group of explosive eruptions.

Discussion

The results, which divide the explosive eruptions into several groups based on common parameters, require a conceptual model of gas storage and release to explain the observations. An example of such a conceptual model is the schematic diagram shown in figure 9. The basic idea is that initially gases are uniformly distributed in the magma at depth. If the magma ascends relatively quickly, the gases remain uniformly distributed at the time of eruption (fig. 9A). The resulting eruption would then be expected to have an emergent onset and rather steady gas release throughout. This corresponds to the cases above with low D_R but high ash columns. A second scenario would be slow ascent of magma

into a “leaky” system, so that most of the gases escape to the surroundings (fig. 9B). This is the scenario corresponding to the eruptions that follow three or more days of quiescence, and the domes that formed represent the accumulation of degassed magma. The third situation is the coalescence of gas into a large irregular pocket or a zone of gas charged magma (fig. 9C). This requires slow ascent of magma under sealed conditions so that the gas collects rather than escaping to the surroundings. The resulting eruption would be gas rich (or ash poor) and likely impulsive if the gas pocket ruptures quickly. The short strong eruptions correspond to this case.

This conceptual scheme allows us to use the eruption styles to “map” the pattern of gas distribution or storage underground for the times just before eruptions. Obviously this is a gross simplification; however, the basic elements are straightforward. The conceptual scheme also has testable elements: the deposits resulting from the eruptions may contain textural or other evidence to support the gas distribution hypotheses (Larsen and others, this volume; Coombs and others, this volume; Vallance and others, this volume). A diagram of the pre-eruption gas distribution based on the above scheme is shown in figure 10.

One major data gap is that we do not have high-quality measurements of the volumes of tephra for the various individual eruptions. Augustine is an island, so much of the fall deposits fell in the sea. Only the eruption on January 17

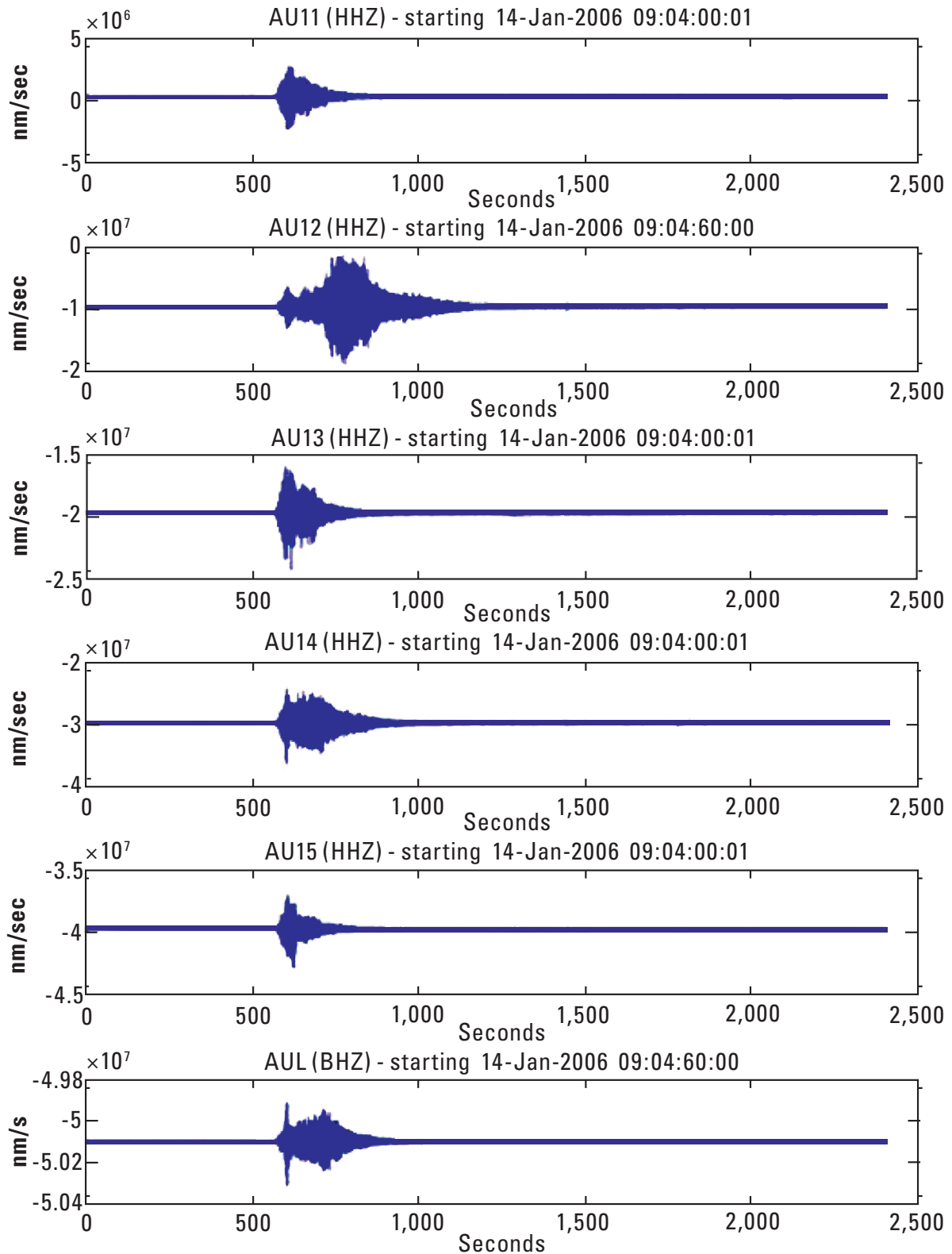


Figure 8. Broadband seismograms from all available stations for Augustine Volcano's January 14, 2006, explosive eruption at 0914 UTC (event 8). Data from the vertical component are shown. Note that the initial part of each trace is similar but that station AU12 (second from the top) shows a strong pulse from 700 to 900 seconds. This is interpreted to represent a pyroclastic flow or other flow event passing near that station only.

Table 3. Timing of seismic and infrasound onsets of Augustine Volcano January 11–28, 2006, explosive eruptions.

[AKST, Alaska Standard Time]

Event Number	Date in 2006	Event Onset AKST	Seismic Onset ¹ AKST	Acoustic Onset ² AKST	Seismic Origin Time ³ AKST	Acoustic Origin Time ⁴ AKST	Time Difference Seconds	Seismic Station Used
1	January 11	04:44	04:44:40	04:44:55	04:44:40	04:44:45	4	AUH
2	January 11	05:12	05:14:13	05:14:24	05:14:13	05:14:14	2	AUE
3	January 13	04:24	04:24:15	04:24:30	04:24:15	04:24:20	5	AUH
4	January 13	08:47	08:48:14	08:48:25	08:48:14	08:48:15	2	AUE
5	January 13	11:22	11:22:07	11:22:15	11:22:07	11:22:05	1	AUE
6	January 13	16:40	16:40:28	16:40:38	16:40:28	16:40:28	0	AUH
7	January 13	18:58	18:58:02	18:58:17	18:58:02	18:58:07	5	AUH ⁵
8	January 14	00:14	00:13:22	00:13:37	00:13:22	00:13:27	5	AUH
9	January 17	07:58	07:58:19	07:58:28	07:58:18	07:58:18	0	AUE
10	January 27	[20:19] ⁶	20:19:45	---	---	---	---	AUH
		20:24	20:24:49	---	---	---	---	AUH
		[20:27]	20:27:42	---	---	---	---	AUE
		[20:31]	--- ⁷	20:31:05	---	20:30:55	---	---
11	January 27	23:37	23:37:34	23:37:47	23:37:33	23:37:37	4	AUE
12	January 28	02:04	02:04:15	02:04:26	02:04:14	02:04:16	2	AUE
13	January 28	07:42	07:42:29	07:42:43	07:42:28	07:42:33	5	AUE
		[07:48]	07:48:12	07:48:24	07:48:11	07:48:14	3	AUW

¹ Time of seismic trace clipping continuously.² Acoustic onset time from Petersen and others, 2006.³ Seismic origin time assuming $v = 3$ km/sec (1 sec difference at AUE).⁴ Acoustic origin time assuming $v = 320$ m/sec (10 sec difference at AUE).⁵ Not clipped but significant pulse.⁶ Brackets [] indicate onset times of subevents.⁷ Seismic traces were already clipped so onsets could not be determined.

(event 9) produced a significant deposit on land (West side of Cook Inlet; Wallace and others, this volume) that could be measured sufficiently well to make volume estimates. The volume for this event, about 2×10^6 m³, was then extrapolated from geologic data to make estimates of the total volume of tephra for all the eruptions. However, caution should be used in using extrapolated values because the variance is unknown. Another factor that is poorly known is the vent size and shape. Coombs and others (this volume) estimated the vent dimensions to be 30 by 45 m; assuming these as conduit dimensions yields drawdown depths of about 1.9 km for the eruptions of about 6×10^5 m³ of tephra. Better estimates of these dimensions would help to infer the depths of each batch of magma

that formed an eruption and would allow a depth scale to be added to figure 10. More data are needed here, and it is difficult to infer precise mechanisms without the individual volume estimates.

The approach used in this paper may be useful in terms of providing rapid feedback to improve future monitoring efforts at Augustine Volcano and elsewhere. The parameters are easy to measure, so they can be done in a few minutes during crises. They provide additional insight into factors such as likely ash production that are important for aviation safety. An additional benefit of the systematic study of parameters is that they may be combined to provide insight into other related questions. As an example, in figure 11 we plot durations as measured at

AUW (seismic), AUE BDL (infrasound), and on the I53US infrasound array in Fairbanks. The different symbols show which eruptions were accompanied by lightning (Thomas and others, this volume). It is clear that the eruptions that were of long duration both locally (AUE and AUW) and at distance (I53US) produced lightning, whereas the short ones at both did not (lower left of plots). The implication of this is that the longer the eruption, the more tephra is produced; each tephra particle is a potential charge carrier, so the more particles the higher the total charge available for lightning and other electrical phenomena (see also Thomas and others, this volume for additional discussion). From a monitoring perspective, these simple measurements may provide a rapid means of verifying the amount of tephra.

The four eruptions that occurred on January 27–28 were also the four for which we had instrumental data on lightning from the New Mexico Tech LMA stations (Thomas and others, this volume). Otherwise we would not have known the lightning occurred because no lightning was observed due to poor local weather, and further, the signals were not strong enough to show on the Bureau of Land Management (BLM) array in central Alaska. One factor that may have contributed to lightning production was a composition change that occurred approximately January 27 (Larsen and others, this volume; Coombs and others, this volume). The initial explosive eruptions produced mostly low-silica andesite, but for the January 27–28 eruptions the magma composition was dominantly high-silica andesite. The higher silica content may have contributed to greater lightning efficacy, but we cannot address this in detail with the limited data in hand. Another factor was that the January 27 eruption at 2031 AKST produced the largest pyroclastic flow unit, a $10.1 \times 10^6 \text{ m}^3$ unit known as the Rocky Point flow (Coombs and others, this volume) that entered a pond on the north flank of Augustine Volcano (Begét, this volume). We speculate that interaction of the pyroclastic flow with the water

in the pond may have created additional charged particles, but we cannot quantify this effect.

The parameters reported here do not permit us to comment on the terminations of the eruptions. Why were there six eruptions on January 13–14 a few hours apart instead of one larger one? Were these separate batches of magma? Did the eruptions stop when the gas-rich part had erupted? Did the vent partially close up or pinch off when the top-most

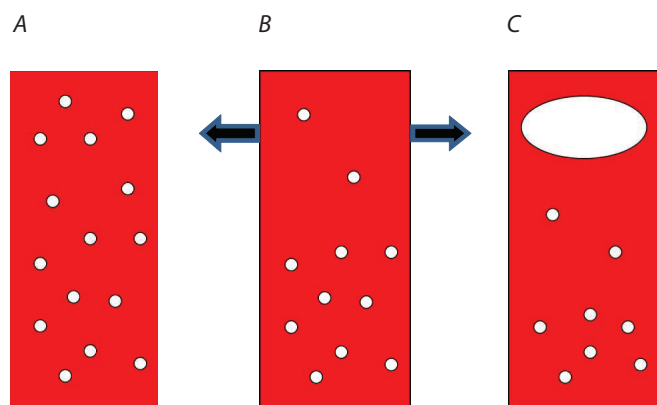


Figure 9. Schematic diagram of gas distribution in magma for three scenarios. *A*, Uniform gas distribution and rapid ascent. *B*, Slow ascent under leaky conditions; upper portion of column is gas poor. *C*, Slow ascent during sealed conditions; gas accumulates in a large bubble or irregular pocket or a gas-rich foam.

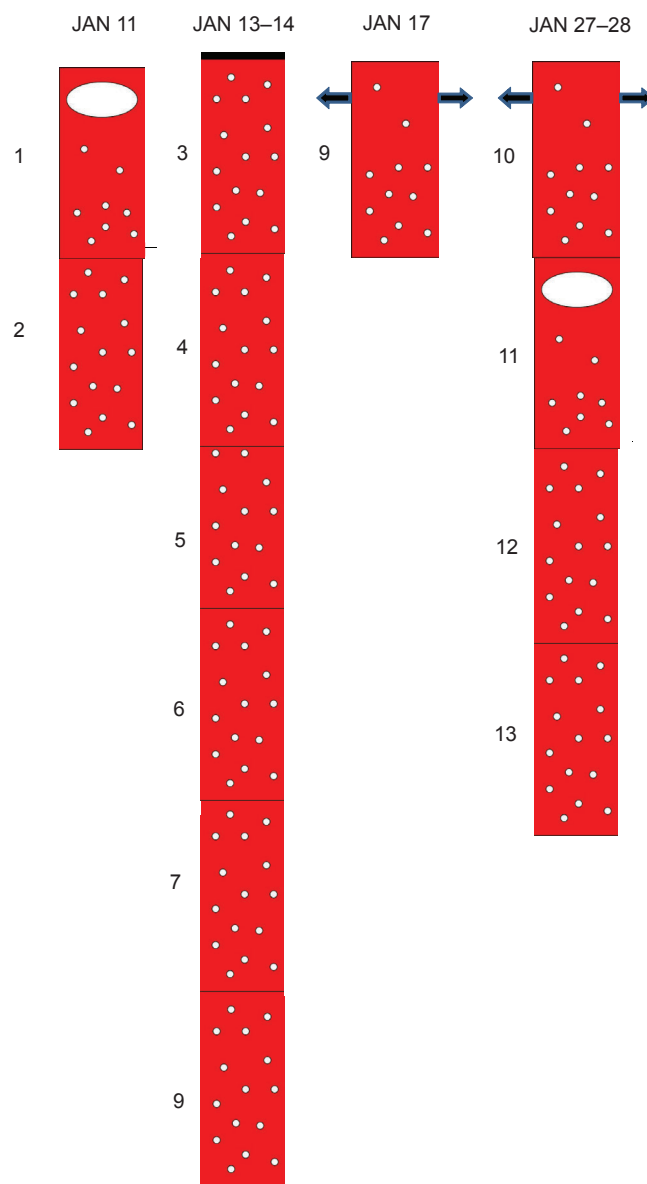


Figure 10. Schematic diagrams of gas distribution in the upper part of the conduit prior to Augustine Volcano's eruptions on January 11, 13–14, 17, and 27–28, 2006. These are “mapped” using the parameters and groupings of this paper to infer underground preeruptive conditions. Numbers to the left correspond to the event index number. The arrows represent gas loss to the surroundings.

material was removed? Some of the data reexamined may help to answer these questions, although they provide only indirect clues. For example the rates of decay of the seismic codas are variable. The coda decayed very abruptly for event 3 (see fig. 2*A*), suggesting possible pinching off of the conduit. The rates of decay were more gradual for most other events, some of which included complications such as small earthquakes in the coda. The codas for events 8, 12, and 13 were very long, suggesting a gradual loss of energy through an open conduit. The rates of decay as seen on broadband data (fig. 4*B*), however, were rather similar.

We briefly compare the Augustine explosive eruptions from 1976, 1986, and 2006. The durations of the largest events were remarkably similar: 11.83 minutes for 1976 (station CKK), 13.6 minutes for 1986, and 11 minutes for 2006 (both

at OPT). The 1976 eruption had 13 large tremor events (the terminology used by Reeder and Lahr, 1987) versus 16 events with durations >2 minutes for 1986 (Power, 1988) and 13 large explosive events in 2006 (this paper). An infrasound array in Fairbanks (I53US and its predecessor) recorded 13 events in 1976 (Reeder and Lahr, 1987) and 12 in 2006 (Wilson and others, 2006); the array was not in operation in 1986. The first large explosion in 1976 was noted as being impulsive (Reeder and Lahr, 1987), similar to 2006 (event 1, this paper), whereas 1986 built up more gradually (fig. 22 of Power, 1988). The range of durations of the individual events also appears to be similar for all three eruptions. If one includes smaller events, such as the 35 small tremors in 1976 (Reeder and Lahr, 1987) and the 22+ events with durations between 1 and 2 minutes in 1986 (fig. 22 of Power, 1988)

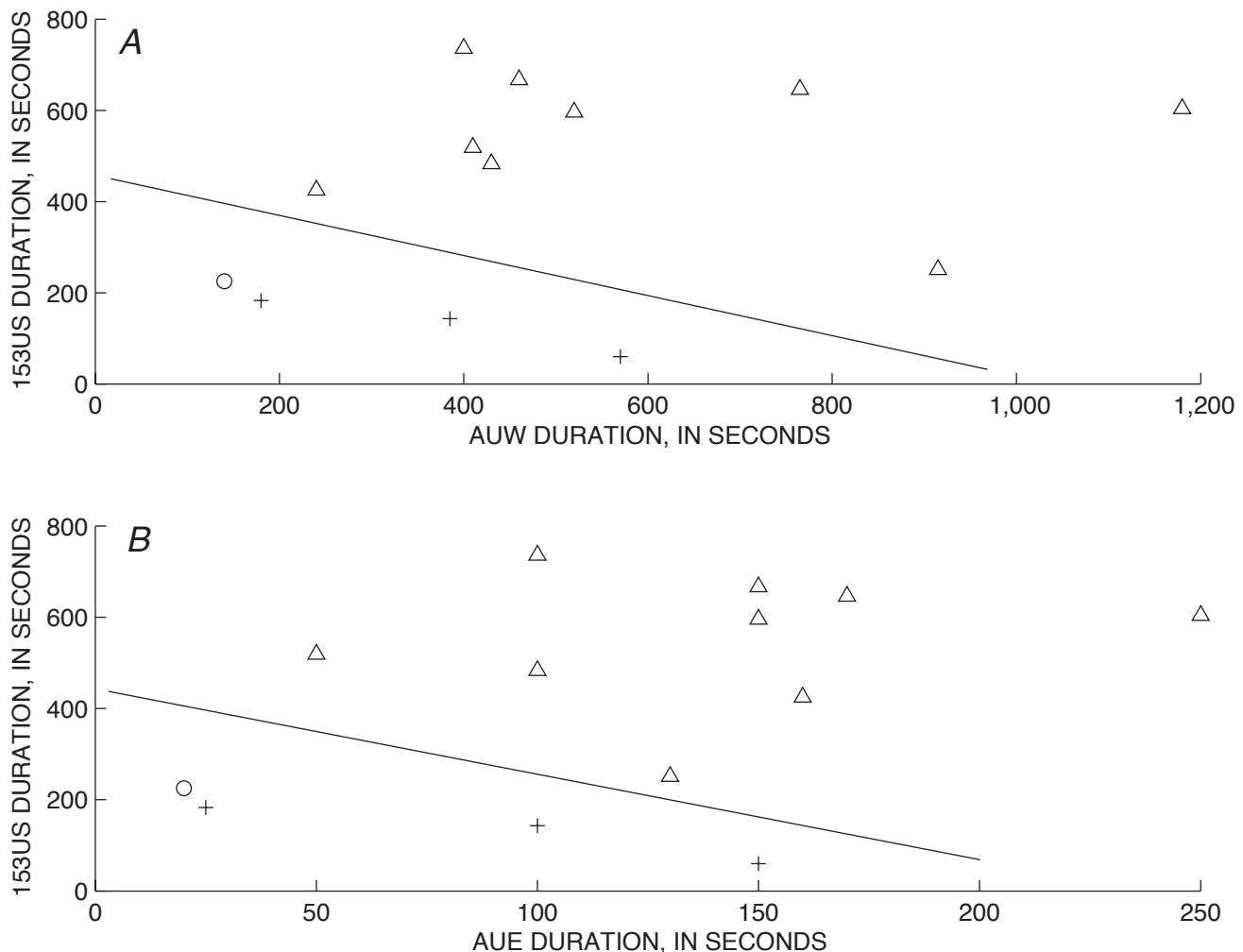


Figure 11. A, plot of I53US acoustic array duration (Wilson and others, 2006) versus AUW seismic duration for the 13 large explosive eruptions at Augustine Volcano in 2006. The triangles represent eruptions that were accompanied by lightning, and "+" symbols represent those with no reported lightning. B, I53US acoustic array duration versus AUE acoustic duration for the 13 large explosive eruptions. Symbols are as in part A. In both A and B a line is drawn from upper left to lower right to separate the eruptions that had lightning from those that did not. In both cases the eruptions with longer durations produced lightning. The point labeled "o" is event 11 which had only a single weak lightning flash.

then the two earlier eruptions have more events during the explosive phase. The 1976 explosive phase lasted just 4 days, the 1986 explosive phase lasted 14 days, and 2006 explosive phase lasted 18 days, suggesting that the rate of explosions was lowest in 2006. Otherwise the common parameters of the larger events of the three eruptions are quite similar, suggesting that the volcano has characteristic explosive behavior.

The Augustine explosive eruptions were similar to those at Asama (Ohminato and others, 2006), Montserrat (Druitt and other 2002), and Vulcano, Galeras, Ngauruhoe, and Sakurajima (Morrissey and Mastin, 2000) in terms of the strengths of the seismic and acoustic signals. However, there is significant variation in plume heights and volumes of ejecta. For the 2004 eruptions of Asama the infrasound signals ranged from 19 to 205 Pa as measured at a site 8 km away (these would be equivalent to 48 and 513 Pa at the 3.2 km distance of AUE). For Asama the seismic single force intensity was measured and eruption deposits were known for all five eruptions. The air shock intensity showed a positive correlation with the eruptions deposits, whereas the seismic force showed more variability. The differences in the parameters showed a similar spread to those for Augustine.

Vulcanian eruptions at Ngauruhoe, Galeras, and Sakurajima generally had ash plumes up to 4 to 5 km (Morrissey and Mastin, 2000). These most closely resemble the short strong eruptions (events 1 and 11) at Augustine, which had the lowest plume heights and inferred least amounts of ash. The other Augustine events most closely resemble those at Montserrat in terms of ash plume heights (3 to 15 km) and intervals between events (2.5 to 63 hours; Druitt and others, 2002). A full comparative study of these eruptions may be warranted.

Conclusions

Study of the major geophysical parameters of the 13 Augustine Volcano explosive eruptions from January 11–28, 2006, suggests that they fall into four main groups: (1) short strong eruptions (VEI=2), (2) events following quiescent intervals of 3 days or longer, (3) events with small D_R and high ash columns (low VEI=3), and (4) events with long durations and large amounts of tephra leading to high lightning production (high VEI=3). Systematic variations in gas storage and release are used to provide a conceptual basis for the differences in activity. New estimates of event origin times were based on seismic and acoustic data, and seismic evidence for pyroclastic or other flow events is presented. The various parameters are generally easy to measure, hence they could be used to make rapid measurements to aid crisis response. The diverse measurements made at Augustine are potentially useful for comparison with previous eruptions at other volcanoes; however, lack of data on tephra volumes for individual events leaves certain questions beyond reach. The Augustine eruptions are among the larger Vulcanian eruptions known to us and resemble some recent eruptions at Montserrat, 1995–99.

References Cited

- Begét, J.E., 2010, Characterizing pyroclastic-flow interactions with snow and water using environmental magnetism at Augustine Volcano, *in* Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., The 2006 eruption of Augustine Volcano, Alaska: U.S. Geological Survey Professional Paper 1769 (this volume).
- Coombs, M.L., Bull, K.F., Vallance, J.W., Schneider, D.J., Thoms, E.E., Wessels, R.L., and McGimsey, R.G., 2010, Timing, distribution, and volume of proximal products of the 2006 eruption of Augustine Volcano, *in* Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., The 2006 eruption of Augustine Volcano, Alaska: U.S. Geological Survey Professional Paper 1769 (this volume).
- Druitt, T.H., Young, S.R., Baptie, B., Bonadonna, C., Calder, E.S., Clarke, A.B., Cole, P.D., Harford, C.L., Herd, R.A., Luckett, R., Ryan, G., and Voight, B., 2002, Episodes of cyclic Vulcanian explosive activity and fountain collapse at Soufriere Hills Volcano, Montserrat, *in* Druitt, T.H., and Kokelaar, P., eds., The eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999: Geological Society London, Memoirs, p. 281–306.
- Fehler, M., 1983, Observations of volcanic tremor at Mount St. Helens volcano: Journal of Geophysical Research, v. 88, p. 3476–3484.
- Fernandes, J.J., Bellesiles, A.K., and Caplan-Auerbach, J., 2007, Estimates of gas flux from infrasonic signals at Augustine Volcano during the January 2006 eruption—Implications for eruption plume types [abs.]: Geological Society of America Cordilleran Section, 103rd annual mtg., paper no. 32-6.
- Johnson, J.B., 2000, Interpretation of infrasound generated by erupting volcanoes and seismo-acoustic energy partitioning during Strombolian explosions: University of Washington, Seattle, Ph.D. dissertation.
- Larsen, J.F., Nye, C.J., Coombs, M.L., Tilman, M., Izbekov, P., and Cameron, C., 2010, Petrology and geochemistry of the 2006 eruption of Augustine Volcano, *in* Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., The 2006 eruption of Augustine Volcano, Alaska: U.S. Geological Survey Professional Paper 1769 (this volume).
- McNutt, S.R., 1994, Volcanic tremor amplitude correlated with eruption explosivity and its potential use in determining ash hazards to aviation: U.S. Geological Survey Professional Paper 2047, p. 377–385.
- McNutt, S.R., Miller, T., and Taber, J.J., 1991, Pavlof Volcano—seismological and geological evidence of increased explosivity during the 1986 eruptions: Bulletin of Volcanology, v. 53, p. 86–98.

- Morrissey, M. and Mastin, L., 2000, Vulcanian Eruptions in Sigurdsson, H., B. Houghton, S.R. McNutt, H. Rymer, and J. Stix, eds. *Encyclopedia of Volcanoes*: San Diego, Calif., Academic Press, p. 463–475.
- Newhall, C.G., and Self, S., 1982, Volcanic Explosivity Index (VEI)—An estimate of explosive magnitude for historical volcanism: *Journal of Geophysical Research*, v. 87, p. 1231–1238.
- Ohminato, T., Takeo, M., Kumagai, H., Yamashina, T., Oikawa, J., Koyama, E., Tsuji, H., and Urabe, T., 2006, Vulcanian eruptions with dominant single force components observed during the Asama 2004 volcanic activity in Japan: *Earth Planets Space*, v. 58, p. 583–593.
- Olson, J.V., Wilson, C.R., McNutt, S.R., and Tytgat G., 2006, Infrasonic wave observations of the January 2006 Augustine Volcano eruptions: *Eos (American Geophysical Union Transactions)*, v. 87, abs. V51C-1685.
- Petersen, T., De Angelis, S., Tytgat, G., and McNutt, S.R., 2006, Local infrasound observations of large ash explosions at Augustine Volcano, Alaska, during January 11–28, 2006: *Geophysical Research Letters*, v.33, L12303, doi:10.1029/2006GL026491.
- Power, J.A., 1988, Seismicity associated with the 1986 eruption of Augustine Volcano Alaska: University of Alaska Fairbanks, M.S. Thesis, 142 p.
- Power, J.A., and Lalla, D.J., 2010, Seismic observations of Augustine Volcano, 1970–2007, in Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., *The 2006 eruption of Augustine Volcano, Alaska*: U.S. Geological Survey Professional Paper 1769 (this volume).
- Power, J.A., Nye, C.J., Coombs, M.L., Wessels, R.L., Cervelli, P.F., Dehn, J., Wallace K.L., Freymueller, J.T., and Doukas, M.P., 2006, The reawakening of Alaska's Augustine Volcano: *Eos (American Geophysical Union Transactions)*, v. 87, no. 37, p. 373, 377.
- Reeder, J.W. and J.C. Lahr, 1987, Seismological aspects of the 1976 eruptions of Augustine Volcano, Alaska: *U.S. Geological Survey Bulletin* 1768, 32 p.
- Schneider, D.J., Scott, C., Wood, J., and Hall T., 2006, NEXRAD weather radar observations of the 2006 Augustine volcanic clouds: *Eos (American Geophysical Union Transactions)*, v. 87, abs. V51C-1686.
- Thomas, R.J., Krehbiel, P.R., Rison, W., Hunyady, S.J., Winn, W.P., Hamlin, T., and Harlin, J., 2004, Accuracy of the lightning mapping array: *Journal of Geophysical Research*, v. 109, no. D14, D14207, doi: 10.1029/2004JD004549
- Thomas, R.J., Krehbiel, P.R., Rison, W., Aulich, G., Edens, H., McNutt, S.R., Tytgat, G., and Clark, E., 2007, Electrical activity during the 2006 Mount St. Augustine volcanic eruptions: *Science*, v. 315, p. 1097.
- Thomas, R.J., McNutt, S.R., Krehbiel, P.R., Rison, W., Aulich, G., Edens, H.E., Tytgat, G., and Clark, E., 2010, Lightning and electrical activity during the 2006 eruption of Augustine Volcano, in Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., *The 2006 eruption of Augustine Volcano, Alaska*: U.S. Geological Survey Professional Paper 1769 (this volume).
- Vallance, J.W., Bull, K.F., and Coombs, M.L., 2010, Pyroclastic flows, lahars, and mixed avalanches generated during the 2006 eruption of Augustine Volcano, in Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., *The 2006 eruption of Augustine Volcano, Alaska*: U.S. Geological Survey Professional Paper 1769 (this volume).
- van Manen, S.M., Dehn, J., West, M.E., Blake, S., and Rothery, D.A., 2010, The 2006 eruption of Augustine Volcano—Combined analyses of thermal satellite data and reduced displacement, in Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., *The 2006 eruption of Augustine Volcano, Alaska*: U.S. Geological Survey Professional Paper 1769 (this volume).
- Wallace, K.L., Neal, C.A., and McGimsey, R.G., 2010, Timing, distribution, and character of tephra fall from the 2005–2006 eruption of Augustine Volcano, in Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., *The 2006 eruption of Augustine Volcano, Alaska*: U.S. Geological Survey Professional Paper 1769 (this volume).
- Wilson, C.R., Olson, J.V., Szuberla, C.A.L., McNutt, S.R., Tytgat, G., and Drob, D.P., 2006, Infrasonic array observations at I53US of the 2006 Augustine Volcano eruptions: *Inframatics*, March 15, 2006, 18 p.
- Zobin, V.M., Plascencia, I., Reyes, G., and Navarro, C., 2009, The characteristics of seismic signals produced by lahars and pyroclastic flows—Volcan de Colima, Mexico: *Journal of Volcanology and Geothermal Research*, v. 179, p. 157–167.