The 2006 Eruption of Augustine Volcano, Alaska
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Chapter 1

Seismic Observations of Augustine Volcano, 1970–2007

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Abstract

Seismicity at Augustine Volcano in south-central Alaska was monitored continuously between 1970 and 2007. Seismic instrumentation on the volcano has varied from one to two short-period instruments in the early 1970s to a complex network comprising 8 to 10 short-period, 6 broadband, and 1 strong-motion instrument in 2006. Since seismic monitoring began, the volcano has erupted four times; a relatively minor eruption in 1971 and three major eruptions in 1976, 1986, and 2006. Each of the major eruptions was preceded by 9 to 10 months of escalating volcano-tectonic (VT) earthquake activity that began near sea level. The major eruptions are characterized seismically by explosive eruptions, rock avalanches, lahars, and periods of small repetitive low-frequency seismic events often called drumbeats that are associated with periods of lava effusion, and they all followed a similar pattern, beginning with an explosive onset that was followed by several months of discontinuous effusive activity.

Earthquake hypocenters were observed to move upward from near sea level toward the volcano's summit over a roughly 9-month period before the 1976 and 1986 eruptions. The 1976 eruption was preceded by a small number of earthquakes that ranged in depth from 2 to 5 km below sea level. Earthquakes in this depth range were also observed following the 2006 eruption. The evolution of earthquake hypocenters associated with the three major eruptions, in conjunction with other supporting geophysical and geological observations, suggests that the Augustine magmatic system consists of a deeper magma source area at about 3.5 to 5 km below sea level and a shallower system of cracks near sea level where volatiles and magma may temporally reside as they ascend to the surface. The strong similarity in seismicity and character of the 1976, 1986, and 2006 eruptions suggests that the processes responsible for magma generation, rise, and eruption at Augustine Volcano have been roughly constant since the early 1970s.

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Introduction

Continuous seismic monitoring of Augustine Volcano began in the summer of 1970 and has continued to the present. During this 38-year period Augustine has experienced a minor eruptive event in 1971 and three major eruptions in 1976, 1986, and 2006, as well as long periods of relative seismic quiescence characterized by low-level earthquake activity. The major eruptions were all preceded by roughly 9 months of increased volcano-tectonic (VT) earthquake activity and were characterized by an explosive onset lasting several days to weeks that was followed by several months of episodic effusive activity. The eruptions are characterized by complex sequences of seismic events involving VT and long-period (LP) events, as well as seismic signals from explosions, pyroclastic flows, lahars, rock falls and avalanches, and small shallow repetitive earthquakes (see "Augustine Seismicity" section for definitions). The three major eruptions were remarkably similar in terms of the character of eruptive style, the sequence of eruptive events, and the character of associated seismicity. The similarities in seismic activity and eruptive behavior during these three eruptions suggests that the processes that govern production, ascent, and eruption of magma at Augustine have remained roughly constant or changed only slowly over the 38-year period of instrumental data available for this volcano.

As a result of the volcano's frequent eruptive activity, the associated volcanic hazards, and proximity to communities surrounding Cook Inlet, Augustine has a relatively long history of geologic investigation and seismic monitoring for an Aleutian arc volcano. Augustine's frequent eruptive activity, coupled with magmas recently ranging in composition from high-silica andesite (57 weight percent SiO_2) to dacite (64 weight percent SiO_2), make this volcano an excellent location to study the seismic expression of the processes that govern and accompany the accumulation, ascent, and eruption of higher viscosity magmas that are typical of explosive volcanism in a convergent margin setting.

In this paper we review the long-term seismic observations of Augustine Volcano between 1970 and 2007 and develop a conceptual model of the subsurface magmatic system. We begin with a review of the seismic instrumentation deployed on and around Augustine Island as a function of time. We then discuss the characteristics of seismicity observed during quiescent, precursory, and eruptive periods. This characterization relies principally on seismic measurements, such as the earthquake locations, magnitudes, waveform character, and durations of seismic signals associated with explosion events and lava effusion. We then develop detailed seismic chronologies of the activity surrounding the 1976, 1986, and 2006 eruptions. We offer a volcanological interpretation of the patterns of observed seismicity in combination with associated observations reported by other workers. We conclude with a discussion of the role that seismic observations played in forecasting the 2006 eruptions and make recommendations for evaluating future episodes of unrest through seismic investigations of Augustine Volcano.

Background

Augustine Volcano is a 1,200-m-high stratovolcano located on a small (8 x 11 km) island roughly 280 km southwest of Anchorage, Alaska (fig. 1). Augustine Volcano consists of a central complex of summit lava domes and flows surrounded by an apron of pyroclastic, lahar, avalanche, and ash deposits. The volcano is frequently active, with major eruptions recorded in 1883, 1935, 1963–64, 1976, 1986, and 2006. Minor eruptive events were reported in 1812, 1885, 1908, 1944, and 1971. The large eruptions are characterized by an explosive onset followed by the quieter effusion of lava. The three most recent eruptions in 1976, 1986, and 2006 had explosive onsets lasting from 4 to 18 days and included numerous individual vulcanian explosions that produced large ash plumes reaching altitudes of 10–15 km. Pyroclastic flows generated during these events swept down the flanks of the volcano, often reaching the surrounding waters of Cook Inlet. The quieter effusion of magma that generally followed the explosive onsets formed summit lava domes and/or short blocky flows that moved down the steep upper portions of the volcanic cone. Effusive activity typically occurred episodically over a period of 2 to 6 months and was often accompanied by block and ash flows produced when portions of the growing lava dome and flows became oversteepened and failed. Estimated eruptive volumes for the 1976, 1986, and 2006 eruptions are 0.39 km^3 (Kienle and Swanson, 1985), 0.10 km^3 (Holasek and Rose, 1991), and 0.12 km^3 (Coombs and others, this volume), respectively.

Geologic deposits on Augustine Island suggest that the present volcanic cone began to form more than 40,000 years ago (Waythomas and Waitt, 1998). Deposits from at least 13 major debris avalanches younger than 2,500 years are exposed on the sea cliffs surrounding Augustine Island, and they indicate that the Augustine cone is subject to frequent Bezymianny-style collapses similar to that of Mount St. Helens in 1980 (Gorshkov, 1959; Siebert and others, 1995). The most recent collapse and debris avalanche occurred during the 1883 eruption and generated a small tsunami in southern Cook Inlet (Waythomas and Waitt, 1998). Augustine's eruptive history during the Holocene is described by Waitt and Begét (2009).

Recent Augustine magmas are compositionally heterogeneous, with whole rock compositions ranging from basaltic andesites to dacites (56–64 weight percent SiO_2) (Johnston, 1978; Daley, 1986; Harris, 1994; Roman and others, 2006; Larsen and others, this volume). Roman and others (2006) suggest that the compositional heterogeneity of magmas erupted in 1986 resulted from the mixing of a cooler dacitic magma (residual from the 1976 eruption) and a newly injected more mafic magma. Progressive homogenization was not observed. Roman and others (2006) proposed that the mixing event took place in a network of dikes extending from roughly 2 to 5 km depth that prevented progressive homogenization throughout the 1986 eruption. Larsen and others (this volume) suggest the 2006 eruption was triggered by a similar mixing event that occurred at 3.5 to 5 km below mean sea level (b.m.s.l.)

In 1975, Augustine Volcano was the target of an extensive geophysical investigation that included temperature and heat flow measurements (Kienle and others, 1979), active and passive seismic investigations (Pearson, 1977), and an aeromagnetic survey (Barrett, 1978). The results of these investigations are summarized by Kienle and others (1979). The active seismic experiment involved the firing of 10 chemical shots that were recorded on 14 temporary, as well as the 5 permanent seismic stations. Data from this field experiment combined with data from exploratory wells drilled in southern Cook Inlet and a short seismic refraction line along Augustine's north shore were used to determine a three-dimensional velocity structure of the volcano (Kienle and others, 1979). The elements of this model are described in detail by Lalla and Power (this volume).

Augustine has also been the focus of a long-term program to monitor ground deformation. Between 1986 and 1989 a trilateration network was established that consisted of 19 benchmarks and 30 slope distances measured with an electronic distance measurement (EDM) device and zenith angles measured at six instrumentation stations (Power and Iwatsubo, 1998). This network was partially remeasured using the global positioning system (GPS) in 1992, 1993, 1994, 1995, and 1996. A complete reoccupation of the network with the inclusion of two benchmarks on the western shore of Cook Inlet was completed in 2000 (Pauk and others, 2001). A network of three telemetered single frequency continuous GPS (CGPS) receivers was established on the island in 1992 (Dzurisin and others, 1994), and a dual frequency receiver was added in 2000. These surveys and instruments indicated that the Augustine edifice was stable and not deforming above the precision of the measurements between 1986 and 2000. A portion of the 1986 summit lava dome was found to be subsiding at roughly 8 cm per year, however. This movement was attributed to a landslide block that formed the northern portion of the 1986 lava dome (Pauk and others, 2001). Synthetic aperture radar (InSAR) measurements of the volcano between 1992 and 2005 also indicate that the broader edifice has inflated during this period (Lee and others, this volume). In 2004 a network of five CGPS receivers was installed on the island as part of the National Science Foundation funded EarthScope program (Pauk and others, this volume).

Seismic Instrumentation, Recording and Analysis

Seismometers have been in operation on Augustine Island since 1970 (Harlow, 1971), with only minor gaps in data resulting from station and telemetry failures. A summary of seismic stations operated on Augustine Island between 1970 and 2007 is contained in table 1. The first permanent seismometer, AU1, was installed on the north flank of Augustine Volcano in 1970. By 1972 seismic instrumentation on the island had expanded to a five-station network capable of calculating standard earthquake hypocenters and magnitudes (fig. 2*A*). A number of other seismic stations (OPT, CKK, HOM, CDD, MMN) were installed surrounding southern Cook Inlet in the early 1970s to monitor regional earthquake activity (fig. 1) (Kienle and Swanson, 1983). All of these stations were 1-Hz short-period instruments that used standard analog telemetry. Unfortunately, all stations on Augustine Island failed in late December 1975 as a result of heavy winter storms and did not record the final month of the 1976 eruption's precursory seismicity. Three of these stations were repaired in February 1976, and a network of new stations was established in 1978.

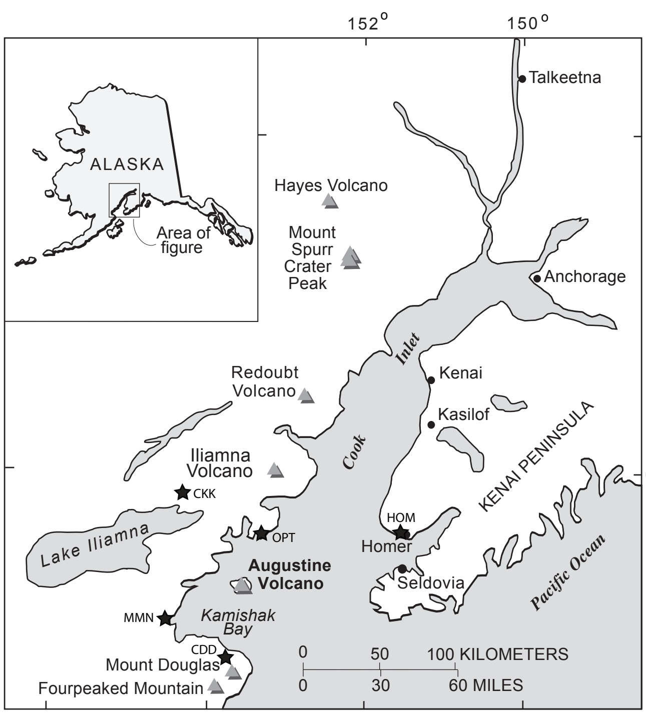


Figure 1. Map showing the location of Augustine Volcano relative to other volcanoes and to population centers in the Cook Inlet region of Alaska. Stars indicate locations of seismic stations CKK, OPT, MMN, CDD, and HOM.

The new four-station network established in 1978 (fig. 2*B*) operated through the 1986 eruption. Station AUT was added to the network on March 22, 1986, just 4 days before the 1986 eruption began (Power, 1988). No seismic stations were destroyed or disabled by volcanic activity in 1986.

Following the 1986 eruption the Augustine seismic network was reconfigured initially with five stations in 1987 and then eventually expanded to nine permanent short-period stations in the early 1990s (table 1). Most of these new stations were placed surrounding the 1986 summit lava dome to track shallow microearthquake activity (fig. 2*C*). A broadband seismometer, AUB, was initially co-located with station AUL in 1995. In 1998 the broadband components were renamed to be part of AUL (table 1).

The 2006 eruption disabled or destroyed stations AUS, AUR, AUP, AUH and AUL (fig. 2*C*). New stations AUSE and AUNW were installed on February 10 and March 30, 2006, respectively, to augment the impaired network, and station AUH was repaired on August 7. AUL and AUP were reestablished on September 4 and 6, 2006, respectively. A strong-motion instrument, AU20, was deployed on the island on January 9, 2006, and replaced by AU22 on September 1, 2006. A six-station temporary network of broadband seismometers, AU10 through AU15, was installed on Augustine Island (fig. 2*C*) in December of 2005 in response to increasing earthquake activity (Power and others, 2006). Three of these instruments operated throughout the 2006 eruption. Station AU12 operated until 0329 Alaska Standard Time (AKST) on January 30, 2006, when it was overrun by a pyroclastic flow, and station AU11 stopped recording data on February 11 as a result of water damage to the seismometer. Station AU10 failed as a result of water damage and did not return any useable data (table 1).

From 1970 through 1985, data from each of the Augustine Island seismic stations was telemetered to Homer, Alaska (fig. 1) and recorded on 16-mm photographic film. Film was read back on a Geotech 6585 film viewer that allows the arrival times from seismograms to be read at a scale of 1 s/cm. The primary limitation of this system is that individual events can be difficult to recognize during intense periods of earthquake or eruptive activity when adjacent traces overlap on the film. Starting in January 1986 the signals were relayed by leased telephone circuits to the Geophysical Institute in Fairbanks and were recorded on photographic film until April 1, 1989. A variety of specialized digital recording systems were used to track the seismic activity during the 1986 Augustine eruption (Power, 1988). Beginning on July 1, 1988, the data were digitally recorded on a number of computerized acquisition systems at the Geophysical Institute. In October 1989, AVO began to record Augustine data on an RSAM system (Endo and Murray, 1991) and intermittently on an event-detected IASPEI system (Lee and others, 1988). On January 1, 1994, the AVO expanded the number of channels on the IASPEI system and began to consistently record event-detected data at 100 samples per second (Jolly and others, 1996). An Earthworm acquisition system replaced the IASPEI system on March 1, 2002, and AVO began to maintain both an event-detected and a continuous archive of seismic data (Dixon and others, 2004).

From 1972 through December 1975, all earthquakes that had identifiable P-arrivals on four or more stations in the Augustine network were located. A total of 678 earthquakes were located during this period. From July 1985 through March 1986, 421 hypocenters were calculated, which is roughly twelve percent of the total number of events that were estimated to have occurred. The selected subset is thought to be representative of the entire population of earthquakes from this interval (Power, 1988). Since 1993 we have relied on the computerized acquisition systems to identify locatable earthquakes. When the detection algorithm identified several shocks closely spaced in time, hypocenters were calculated for all possible earthquakes based on a manual review of the event detected data. From 1993 through 2007, AVO cataloged 3,866 earthquakes at Augustine Island. The details of these locations can be found in a series of annual reports; the most recent is compiled by Dixon and Stihler (2009). From January 1976 to July 1985 and April 1986 to January 1993, hypocenters were not routinely calculated at Augustine Volcano (fig. 3).

From 1989 to the present, events detected by the various AVO seismic acquisition systems were processed using the interactive analysis program XPICK (Robinson, 1990) and the earthquake location program HYPOELLIPSE (Lahr, 1999) in a manner similar to that described by Lahr and others (1994). All detected earthquakes with more than three P and two S phases and with standard hypocentral errors less than 15 km were processed and saved in the AVO earthquake catalog (Dixon and Stihler, 2009). Located events were classified as VT, LP, shore-ice events, or unknown based on the time-domain appearance of the velocity seismogram as viewed on a computer screen. Of the of 3,866 located shocks, AVO classified 3,795 as VT earthquakes, 28 as LP events, and 43 as shore- or sea-ice events between 1993 and the end of 2007. Earthquakes with a P- and S-wave separation of more than 5 seconds on Augustine Island stations were assumed to come from a source other than the volcano and were not located.

We use two location techniques to calculate earthquake hypocenters for this study. The first uses the program HYPOELLIPSE (Lahr, 1999) in a similar fashion to the standard AVO earthquake catalog (Dixon and others, 2008). In both location techniques, hypocentral depths are referenced to sea level, with negative depths reflecting height above mean sea level (a.m.s.l.). For this study we use a one-dimensional

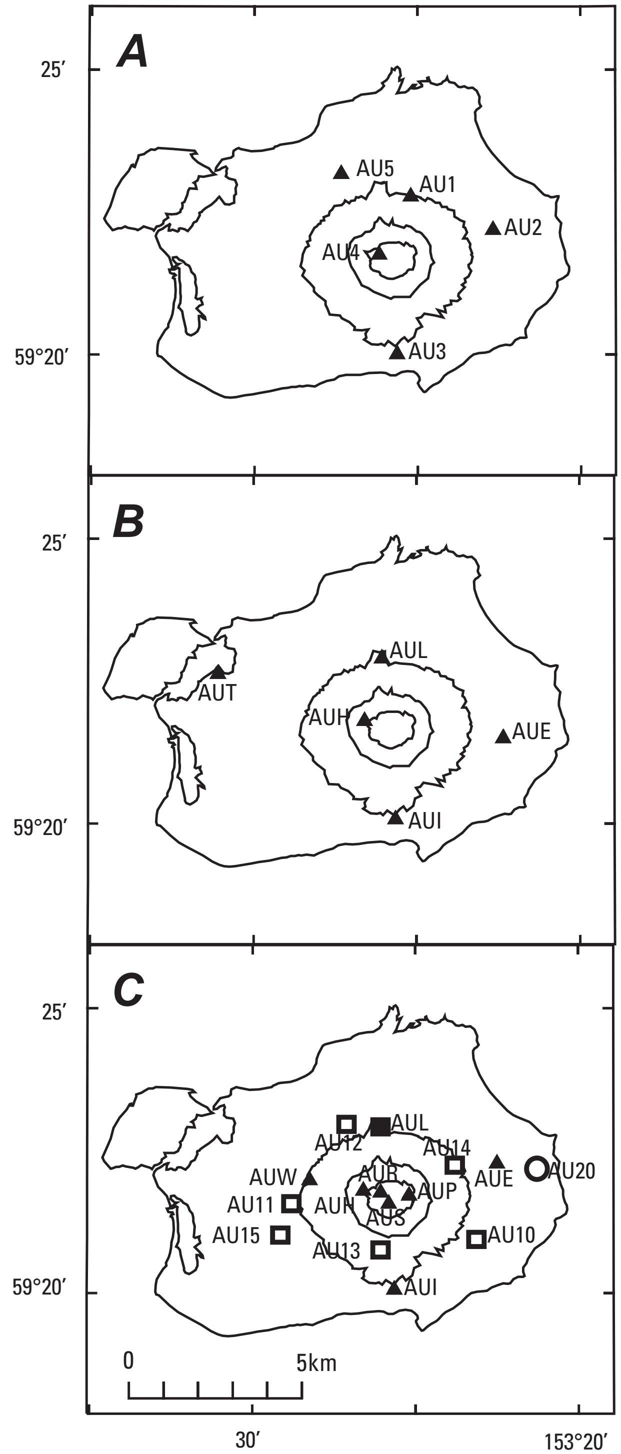


Figure 2. Maps showing the locations of seismic stations on Augustine Volcano before (*A*) the 1976 eruption, (*B*) the 1986 eruption, and (*C*) the 2006 eruption. Solid triangles represent short-period stations, solid squares represent permanent broadband sensors, open squares are temporary broadband stations deployed in late 2005, and the open circle is a strong motion instrument deployed in early 2006. Sea-level, 1,000-ft, 2,000-ft, and 3,000-ft contours are shown in map view.

Table 1. Seismic stations operated on Augustine Island between 1971 and 2007.

Station	North Latitude[1]	West Longitude[1]	Elevation (m)	Installation Date	Termination Date
AU1	59 22.39	153 25.23	508	08/01/1970	01/01/1976
AU2[2]	59 22.22	153 22.68	195	06/15/1971	01/01/1976
AU3	59 20.05	153 25.62	282	1972	04/06/1978
AU4	unknown	unknown	unknown	1972	07/1974
AU4[3]	59 21.79	153 26.19	890	07/1974	01/01/1976
AU5	59 23.19	153 27.35	152	1972	01/01/1976
AUI[4]	59 20.11	153 25.66	293	04/06/1978	current
AUH[5]	59 21.83	153 26.59	890	12/01/1978	current
AUL[6]	59 22.937	153 26.142	360	08/27/1978	current
AUE	59 21.531	153 22.365	172	10/29/1980	10/01/1988
AUE[7]	59 22.309	153 22.50	168	10/01/1988	current
AUP[8]	59 21.805	153 25.210	1033	06/26/1988	current
AUS[9]	59 21.599	153 25.840	1226	09/01/1990	01/11/2006
AUW	59 22.205	153 28.249	276	107/01/986	current
AUC	59 21.596	153 25.469	1175	09/13/1995	12/27/2000
AUR[9]	59 21.766	153 25.876	1204	11/01/1995	01/11/2006
AUB[10]	59 22.937	153 26.142	360	12/21/1995	09/28/1998
AUSE	59 20.481	153 23.850	152	02/10/2006	current
AUNW	59 22.694	153 28.609	160	03/30/2006	current
AU10[11]	59 20.974	153 23.126	219	12/20/2005	12/20/2005
AU11	59 21.576	153 28.818	234	12/20/2005	02/11/2006
AU12[12]	59 23.009	153 27.114	210	12/20/2005	01/30/2006
AU13	59 20.781	153 26.046	518	12/20/2005	05/30/2006
AU14	59 22.268	153 23.811	303	12/21/2005	08/07/2006
AU15	59 21.042	153 29.134	168	12/21/2005	08/10/2006
AU20	59 22.216	153 21.245	102	01/01/2006	08/31/2006
AU22	59 22.247	153 21.301	105	09/01/2006	current

[1] Datum is NAD27; numbers are in degrees and decimal minutes.

[2] Station had a single horizontal component of unknown orientation.

[3] Station relocated in July 1974, but name retained.

[4] Horizontal components added in 1987.

[5] Station destroyed by explosion on January 27, 2006, repaired August 7, 2006.

[6] Station destroyed by explosion on January 27, 2006, reinstalled on September 4, 2006.

[7] Station relocated on October 1, 1988, but name retained.

[8] Station destroyed by explosion on January 13, 2006, reinstalled on September 6, 2006.

[9] Station destroyed by explosion on December 15, 2006.

[10] Broadband station that replaces short-period station AUL on September 28, 1998.

[11] Station did not function properly and returned no useful data.

[12] Station overrun by a pyroclastic flow on January 30, 2007, data recovered from seismometer on August 15, 2006.

velocity model with six horizontal layers with boundaries at depths of −1.2, −0.7, 0.0, 1.0, 9.0, and 44.0 km. The top of the model at –1.2 km depth corresponds roughly with the summit of the volcano. The respective P-wave velocity for each layer is 2.3, 2.6, 3.4, 5.1, 6.3 and 8.0 km/s. These layer boundaries and velocities were determined using the results of the 1975 active source seismic experiment (Kienle and others, 1979) and were found to minimize residuals in a number of test runs of HYPOELLIPSE. For the precursory seismic sequences of the 1976, 1986, and 2006 eruptions we have then relocated the hypocenters using the two-dimensional ray tracing procedure described by Lalla and Power (this volume). This relocation technique uses the three-dimensional velocity model derived by Kienle and others (1979) for Augustine Island and station corrections calculated from the 1975 active source seismic experiment (Lalla and Power, this volume). This technique calculates theoretical traveltimes from grid points with a 0.25-km grid spacing embedded within the Augustine velocity structure and assigns the hypocenter to the grid point that most closely matches the observed arrival times. This technique accounts for the topography of the volcanic edifice when calculating traveltimes and allows hypocenters to be located above sea level. An evaluation of the accuracy of hypocenter determination using this technique indicates that hypocenters can be resolved within 0.25 km for shocks located above sea level and within 0.5 km for shocks located from sea level to 2 km b.m.s.l. (Lalla and Power, this volume). We have chosen this relocation technique for this study as it can be applied in a similar manner to the seismic data collected by both the analog and digital acquisition systems in use during the 1976, 1986, and 2006 eruptions of Augustine. Additionally, this relocation technique provides a means to determine absolute rather than relative locations. Deshon and others (this volume) studied earthquake families using waveform cross correlation techniques between 1993 and 2006. They found multiple earthquake families that occurred between 1993 and 2006

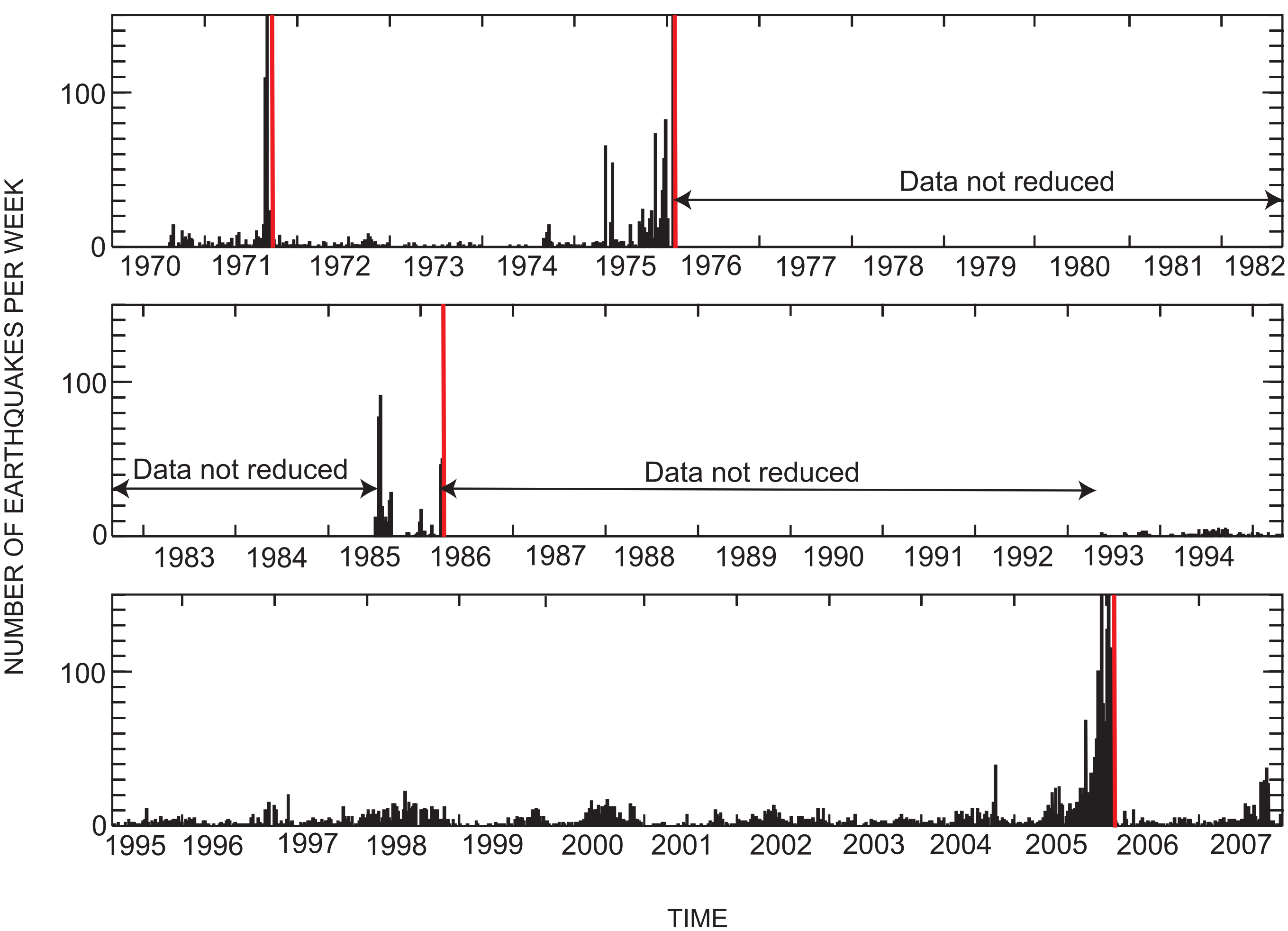


Figure 3. Histograms of the number of earthquakes located at Augustine Volcano per week between 1970 and 2007. Before installation of the full network in 1972 (table 1), data simply reflect number of earthquakes detected. Periods when earthquakes were not routinely located (January 1976 to July 1985 and March 1986 to May 1993) are noted. Red lines correspond to onsets of eruptions in 1971, 1976, 1986, and 2006.

and identified several families that occurred at progressively shallower depths in the weeks prior to the onset of eruptive activity in 2006.

Earthquake magnitudes at Augustine were calculated using several methodologies during the period of this study. From 1970 through 1976 a coda magnitude scale was used for earthquakes located beneath the central volcanic edifice, above 0.25 km a.m.s.l. For earthquakes at greater depth or those with hypocenters located away from the central edifice a local magnitude (M_L) was calculated using frequency-amplitude measurements in the manner described by Lahr (1999). This methodology was adopted to overcome strong attenuation affects observed for earthquakes with deeper hypocenters (Lalla and Kienle, 1978). For larger earthquakes that clipped all local stations on Augustine Island during this period, local magnitudes were determined at station CKK (fig. 1) assuming a hypocentral depth of sea level. Since 1985 we use frequency-amplitude measurements to calculate M_L using HYPOELLIPSE (Lahr, 1999). These methodologies were chosen to provide the most reliable magnitude information possible given the data available during the respective time period. During intereruptive periods, the largest earthquakes at Augustine generally do not exceed magnitude 1.2. The largest earthquakes recorded at Augustine during the period of this study reached magnitude 2.75 and occurred on January 22 and 23, 1976, in a 22-hour sequence that accompanied the onset of explosive activity in 1976 (fig. 4). A study of *b* values for Augustine earthquakes between 1993 and 2007 is given by Jacobs and McNutt (this volume).

Augustine Seismicity

The dominant seismic activity seen at Augustine Volcano between 1970 and 2007 are small VT earthquakes. These events generally have impulsive to emergent P arrivals and

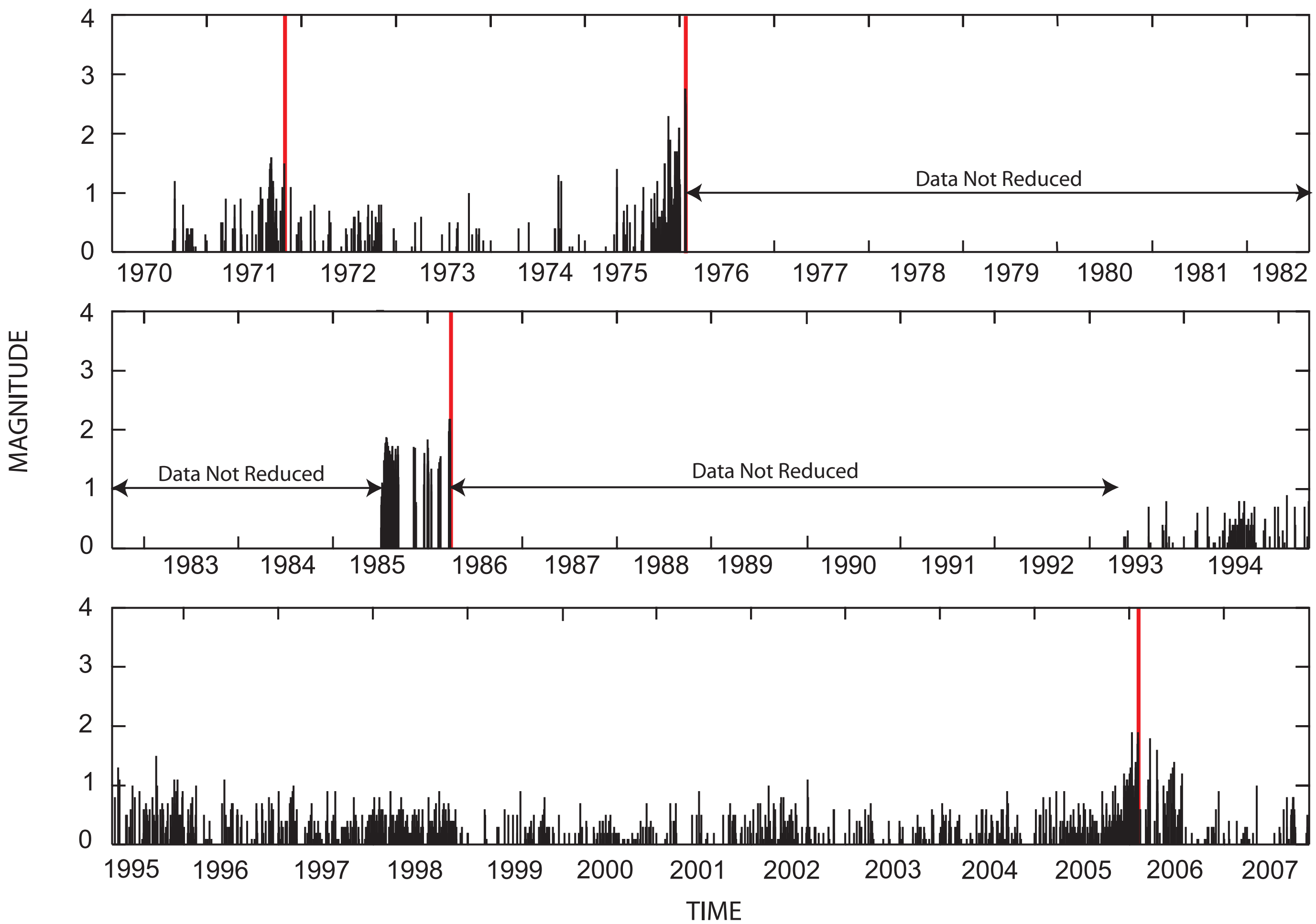


Figure 4. Summary of the magnitudes of detected earthquakes located at Augustine Volcano between 1970 and 2007. Magnitudes that are greater than magnitude (M_L) 0.0 are shown as individual vertical lines. Periods when earthquakes were not routinely located (January 1976 to July 1985 and March 1986 to May 1993) are noted. Red lines correspond to onsets of eruptions in 1971, 1976, 1986, and 2006.

poorly defined S arrivals and a broad spectrum with significant energy between 1 and 15 Hz (fig. 5*A*). At Augustine, waveforms from these earthquakes have well-defined phases on stations located high on the volcanic edifice, and the waveforms degrade rapidly on stations located on the pyroclastic apron (fig. 6). During intereruptive periods epicenters of these earthquakes generally occur within 1 to 2 km of the volcano's summit and range in depth from 1 km b.m.s.l. to 1.2 km a.m.s.l. (the volcano's summit). Infrequently, small VT earthquakes also occur on the south and north flanks of the volcano (fig. 7). Deshon and others (this volume) found that only 30 to 40 percent of located earthquakes occurred in event clusters, or earthquake families, between 1993 and 2006, suggesting that VT earthquake activity is widely distributed throughout the Augustine cone during this period.

At Augustine, LP events are comparatively rare; their occurrence is generally restricted to periods surrounding eruptive episodes. These events usually have emergent to poorly developed phases and have a strong peak frequency near 2 Hz (fig. 5*B*). Well-recorded LP events locate within 1 to 2 km of the volcano's summit at depths of sea level or above. At Augustine we also see a variety of waveforms that have a mix or range of frequencies similar to the hybrid events described by Lahr and others (1994). In this report we do not attempt to classify events as hybrids. Studies of event classifications during the 2006 eruption are given by Buurman and West (this volume) and Jacobs and McNutt (this volume).

Several times during the 1986 and 2006 eruptions, we recorded sequences of small repetitive regularly spaced events that often had similar waveforms. These earthquakes can occur at rates that range from 1 event every few minutes to as high as 8 to 10 events per minute or possibly higher. Similar small repetitive events have been reported at numerous volcanoes, typically during the effusive eruption of magma that ranges from high-silica andesite to dacite in composition. These volcanoes include Mount Usu, Japan (Okada and others, 1981), Mount St. Helens (Fremont and Malone, 1987; Moran and others, 2008; Thelen and others, 2008), Mount Redoubt (Power and others, 1994), Guagua Pichincha, Ecuador (Villagomez, 2000), and Soufriere Hills Volcano, Montserrat (Rowe and others, 2004). As a result of the repetitive character of these earthquakes they have recently been termed "drumbeats" at Mount St. Helens (Moran and others, 2008). At Augustine, drumbeat earthquakes typically have poorly defined phases and fairly narrow spectra, with most energy concentrated between 1 and 6 Hz (fig. 5*C*).

Seismic signals generated by explosive eruptions at Augustine generally have emergent onsets, extended high-amplitude codas, and fairly broad spectrums with peak frequencies near 2 to 3 Hz (fig. 5*D*). Explosive eruptions generally are quite powerful and register well on distant stations such as OPT and CKK (fig. 1). At Augustine, explosive eruptions are often accompanied by seismic signals associated with pyroclastic flows and lahars. These signals generally have a broad spectrum and can be very strong on individual stations on various quadrants of the volcano. A parametric study of explosive eruptions at Augustine in 2006 has been prepared by McNutt and others, (this volume).

Seismic signals from rock avalanches or rockfalls observed at Augustine are generally emergent and have a broad spectrum with energy between 1 and 6 Hz (fig. 5*E*). These signals are most prevalent when the lava dome and associated flows are actively growing and shedding material down the steep upper flanks of the volcano.

A unique type of low-frequency seismic event generated at Augustine results from the interaction of shore–fast sea ice and the ocean tides. During periods of cold winter weather (−15 to −30° C or 5 to −20° F), low frequency seismic events with emergent waveforms, a distinct lack of identifiable phases, and extended codas are often observed. The dominant frequency of these events is generally between 1 and 5 Hz (fig. 5*F*). The largest amplitudes occur on the stations closest to the shoreline and the seismic waves generally do not propagate well enough to be identified on stations high on the volcanic edifice or on the opposite side of the island. Between 1993 and 2007 we have observed these events being generated on all quadrants of the island, although they seem to be most often observed at station AUI (fig. 2*B*), suggesting a frequently active source area along the southern shoreline. We have visited the island when these events were occurring in February 1993 and March 2007 and have noted large accumulations of sea ice along the island's coastline. Mauk and Kienle (1973) found that events with these characteristics were most common during the ocean tide high, although they attributed them to volcanic activity. Because we only observe these events during periods of very cold weather, we believe they most likely reflect the breakage or movement of shore fast sea ice in response to the changing ocean tides in Cook Inlet. A similar explanation was advanced by Lalla and Kienle (1980).

Eruption Chronologies

In this section we describe the sequence of seismic events that accompanied the minor eruption in 1971 and the major eruptions in 1976, 1986, and 2006. For these chronologies we combine seismic information with visual, geological, and geophysical observations of the volcano to provide as much context for the seismic observations as possible. We focus on the periods from the time when seismicity first began to increase to the time when unrest ceased following the eruption. These periods are August 30, 1971, to December 21, 1971; May 2, 1975, to April 24, 1976; July 5, 1985, to September 10, 1986; and April 30, 2005, to March 18, 2006. The number of located earthquakes and the reported periods of eruptive activity for the 1976, 1986, and 2006 eruptions are shown on a comparative time scale in figure 8. In this paper the times of specific events are referenced to either Alaska Standard Time (AKST) or Alaska Daylight Time (AKDT). To convert to UTC before January 1, 1983, subtract 10 hours

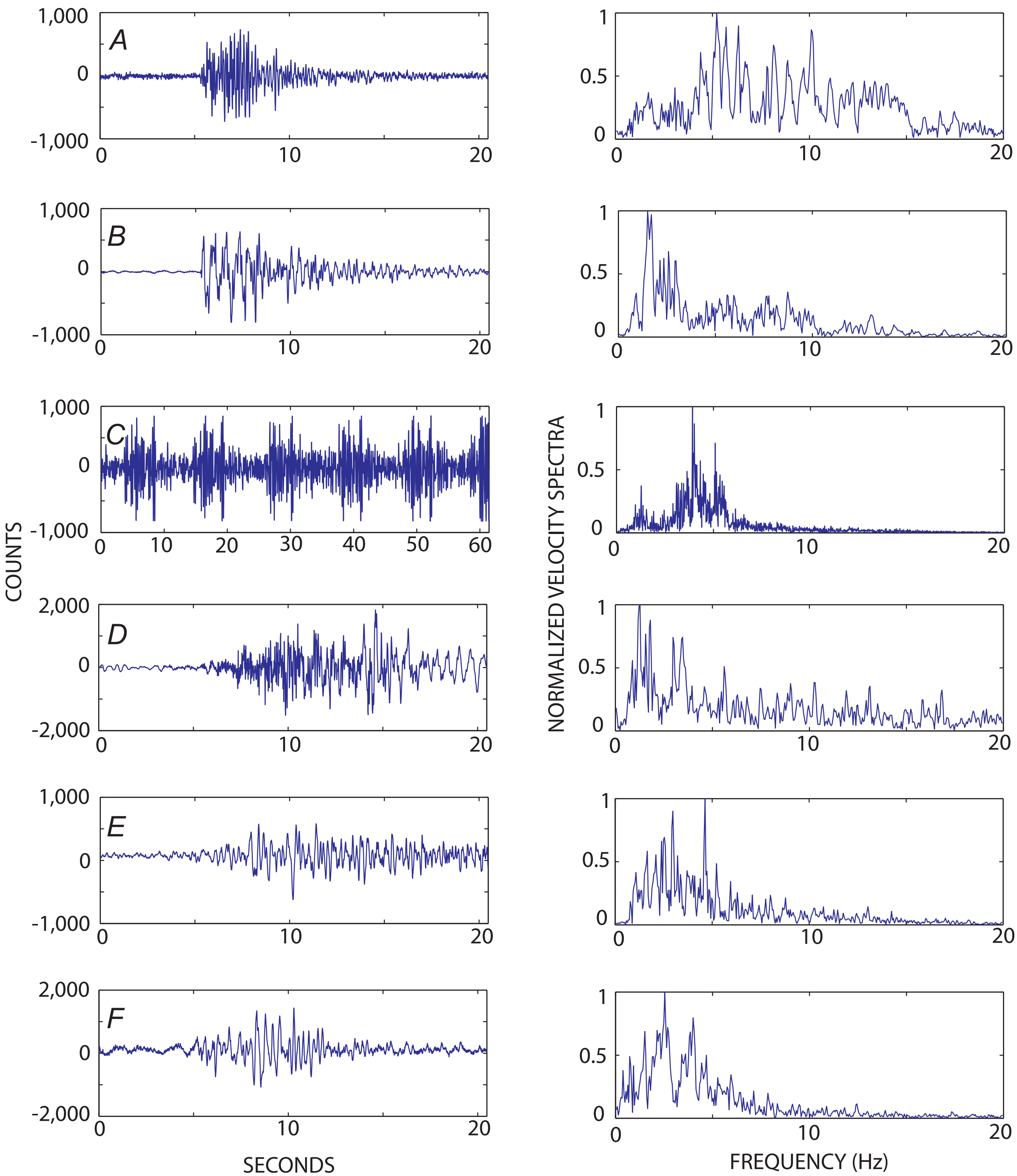


Figure 5. Waveforms and normalized velocity spectra of typical seismic events recorded at Augustine Volcano. Individual events represent, (*A*) volcano-tectonic earthquake at station AUH on May 26, 2005, 1601 AKST, M_L = 0.2, Z = 0.98 km a.m.s.l., station; (*B*) long-period event at station AUH on October 10, 2005, 0410 AKST, ML = 0.2, Z = 0.48 km a.m.s.l.; (*C*) drumbeats at station AUW on March 8, 2006, 1500 AKST; (*D*) explosion recorded at station AU13 on January 11, 2006, at 0514; (*E*) Rockfall on station AUE May 26, 2006, 0006 AKST; (*F*) ice event seen at station AUI on January 10, 2005, 1948 AKST. Spectra were calculated using a 20.48 second sample, except for the drumbeat earthquakes shown in panel *C*, which uses a 61.44-second sample.

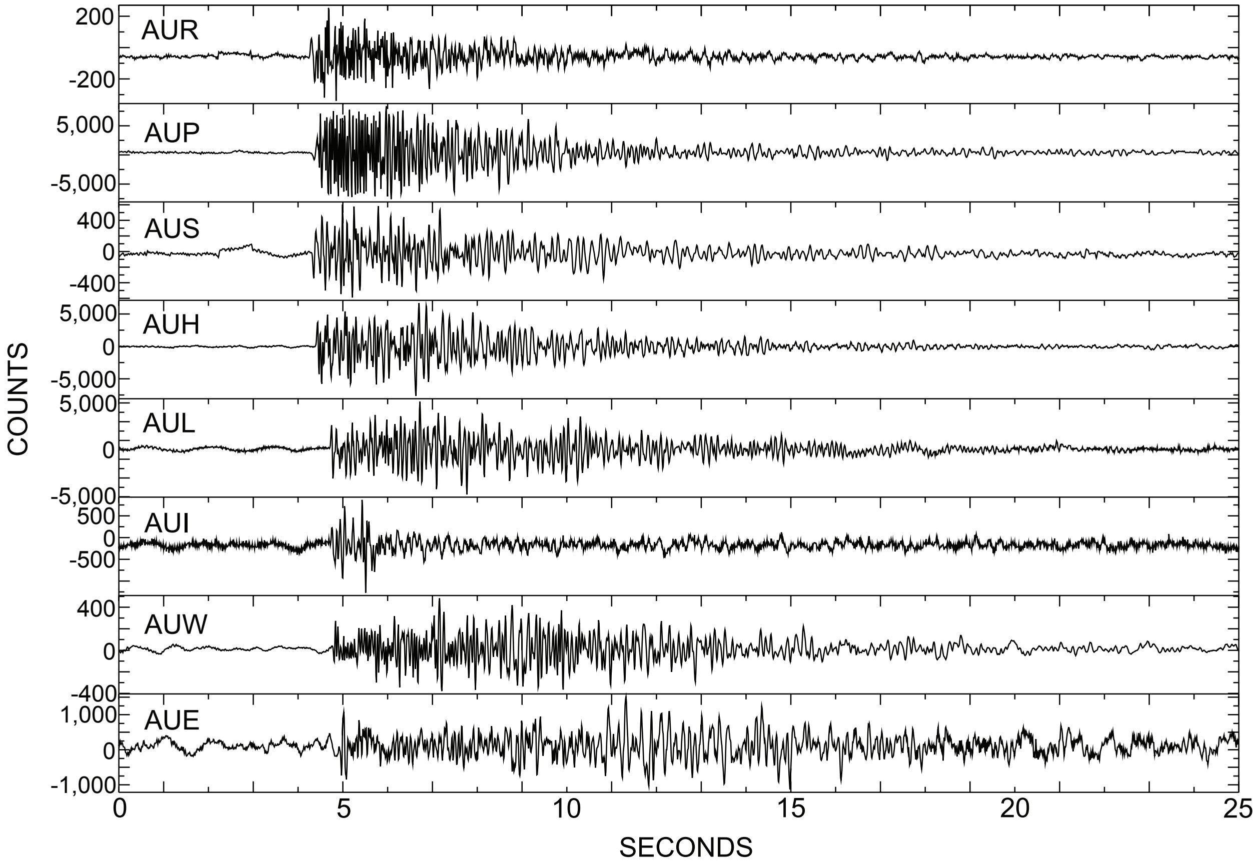


Figure 6. Velocity waveforms of a volcano-tectonic earthquake with magnitude (M_L) 0.1 that occurred on October 10, 2005, at 0037 UTC at a depth of 0.22 km a.m.s.l. beneath the summit of Augustine Volcano as recorded on various seismic stations on Augustine Island.

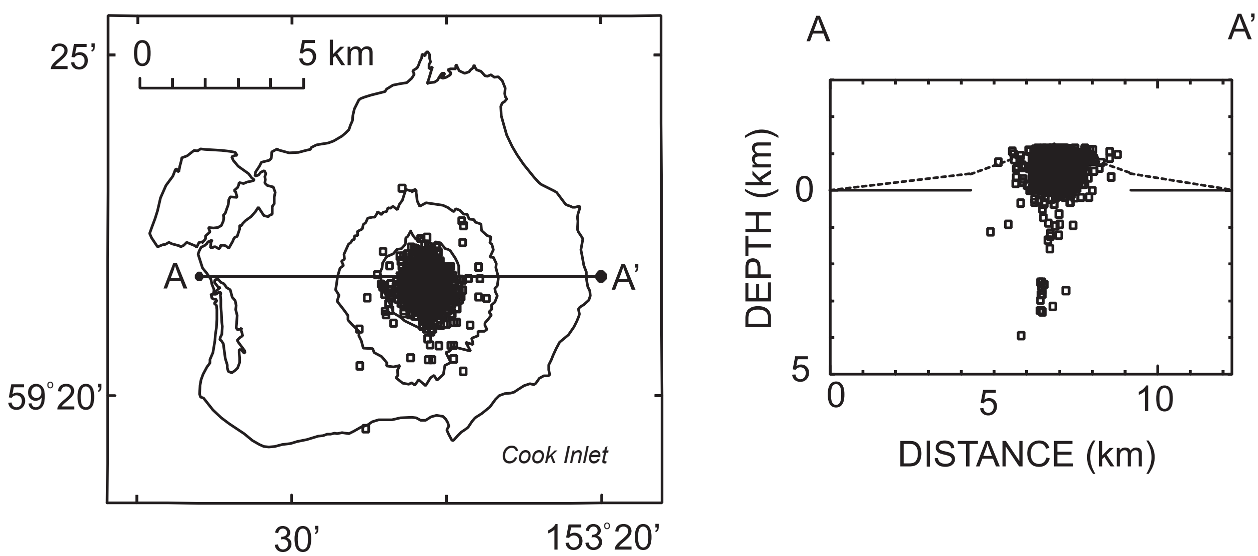


Figure 7. Map and west-east cross section (A to A') showing earthquake hypocenters at Augustine Volcano between 1993 and 2007. Only hypocenters with standard horizontal and vertical errors of less than 5 km are shown. Sea level, 1,000-ft and 2,000-ft contours are shown in map view. Dotted line in cross section represents approximate surface elevation along cross section A–A'. The hypocenters between 2 and 4 km depth all occurred between March 15 and August 16, 2006, following the end of the 2006 eruption.

from AKST and 9 hours from AKDT. After January 1, 1983, subtract 9 hours AKST and 8 hours from AKDT.

To provide a consistent measure of earthquake activity during these precursory seismic sequences we have relocated many earthquakes with the 2-dimensional ray tracing algorithm described by Lalla and Power (this volume). This was not possible for the 1971 eruption, because only two stations were operating on the volcano at that time. Histograms of the number of relocated earthquakes per day during the precursory sequences of the 1976, 1986, and 2006 eruptions are shown in figure 9. Relocated earthquake hypocenters for each precursory period are shown in map and east-west cross section in figure 10, and plots of focal depth versus time are shown in figure 11. Seismic events such as explosive eruptions, rock avalanches, and pyroclastic flows are more difficult to describe because the seismic stations operating on the volcano and the

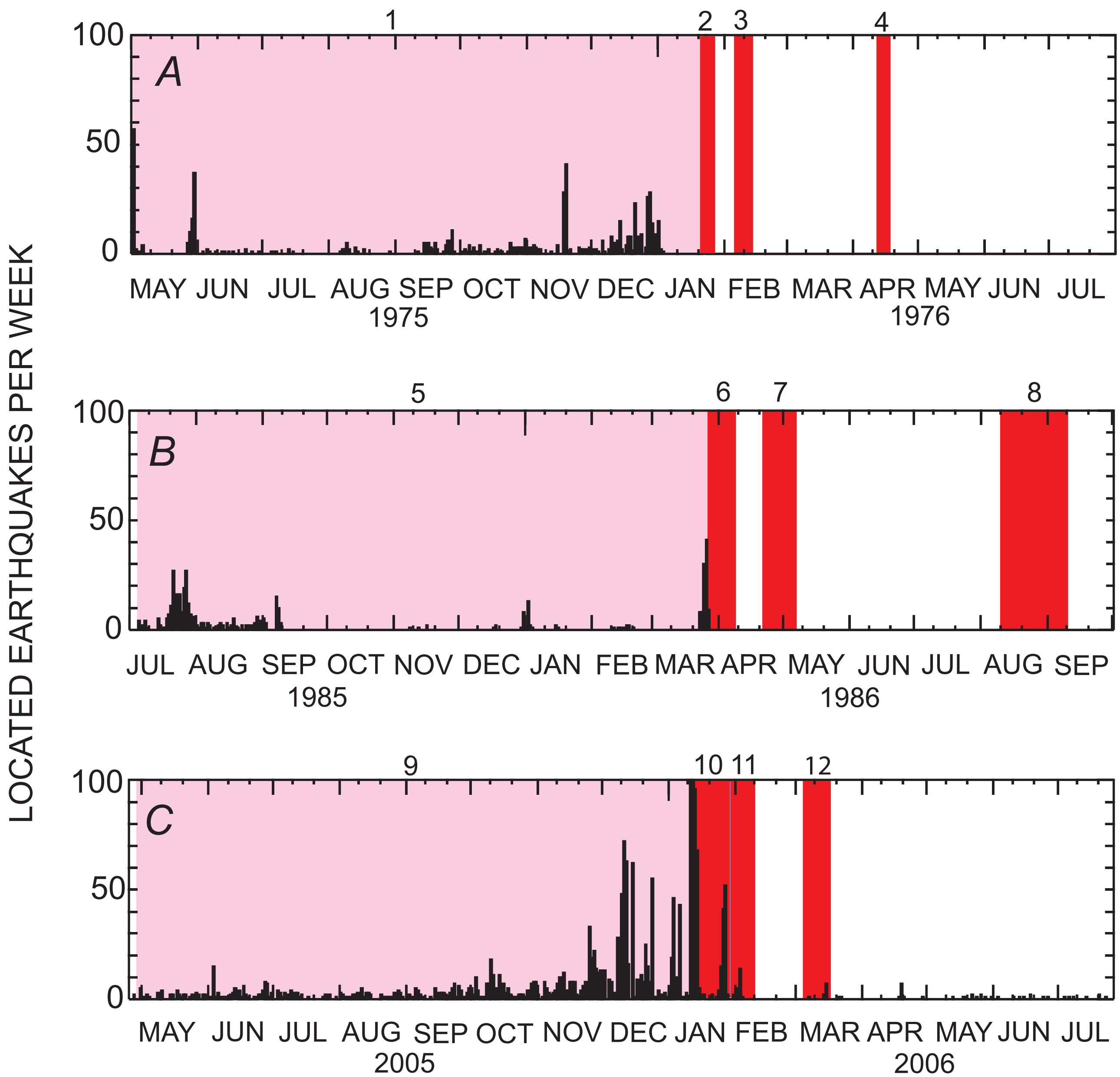


Figure 8. Comparative time lines of the eruptive phases of (*A*) 1976, (*B*) 1986, and (*C*) 2006 eruptions based on histograms of the number of located earthquakes each week. Pink shading corresponds to precursory periods, and red shading corresponds to eruptive periods. Numbers correspond to: 1, 1976 precursory phase; 2, the first 1976 explosive phase; 3, the second 1976 explosive phase; 4, 1976 effusive phase; 5, 1986 precursory phase; 6, 1986 explosive phase; 7, 1986 initial dome building phase; 8, 1986 second dome building phase; 9, 2006 precursory phase; 10, 2006 explosive phase; 11, 2006 continuous phase; and 12, 2006 effusive phase.

resolution of the recording media changed drastically between 1970 and 2007. For earlier time periods we rely on descriptions developed by Reeder and Lahr (1987) for the 1976 eruption and Power (1988) for the 1986 eruption.

The 1971 Eruption

On August 30, 1971, an intense earthquake swarm began that lasted until September 6, 1971 (fig. 3). These earthquakes had broad-spectrum VT waveforms and were of much larger magnitude than those previously recorded at Augustine. During the peak in activity between September 2 and 4, more than 300 identifiable earthquakes per day were recorded on station AU1. Seismic records from AU1 and AU2 on September 6 show the high level of VT earthquake activity recorded during this swarm (fig. 12). A photograph taken by Austin Post of the volcano on September 3, 1971, shows vigorous steaming on the east side of the volcano's summit (Kienle and Swanson, 1985). Smaller earthquake swarms were recorded November 28–30 and December 19–21, 1971 (fig. 3).

On October 7, 1971, a fishing boat 38 km north of the volcano reported a small ash eruption and red glow from the summit. This report coincides with a 2 hour period of volcanic tremor recorded on October 7 and 8 between 2300 and 100 (AKDT) (Kienle and Swanson, 1985). No information exists on the extent or type of eruptive products that may have been produced by this event. The red glow reported by

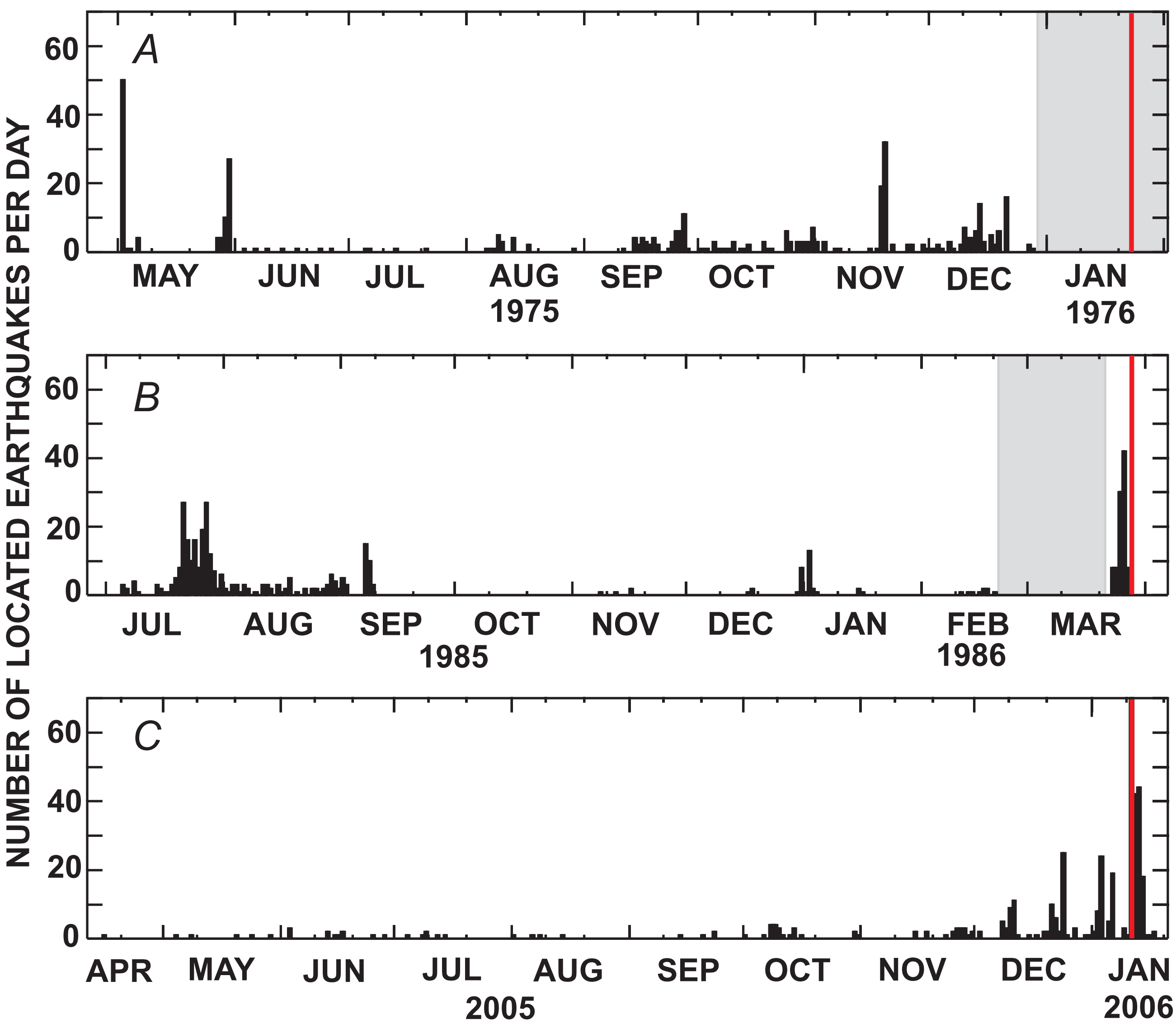


Figure 9. Histograms showing the number of relocated earthquakes that occurred before the *(A)* 1976, (*B*) 1986, and (*C*) 2006 eruptions of Augustine Volcano. The time periods when the Augustine seismic network was not operating sufficiently to relocate earthquakes are shown in gray. Red lines correspond to the onset of explosive events in the 1976, 1986, and 2006 eruptions.

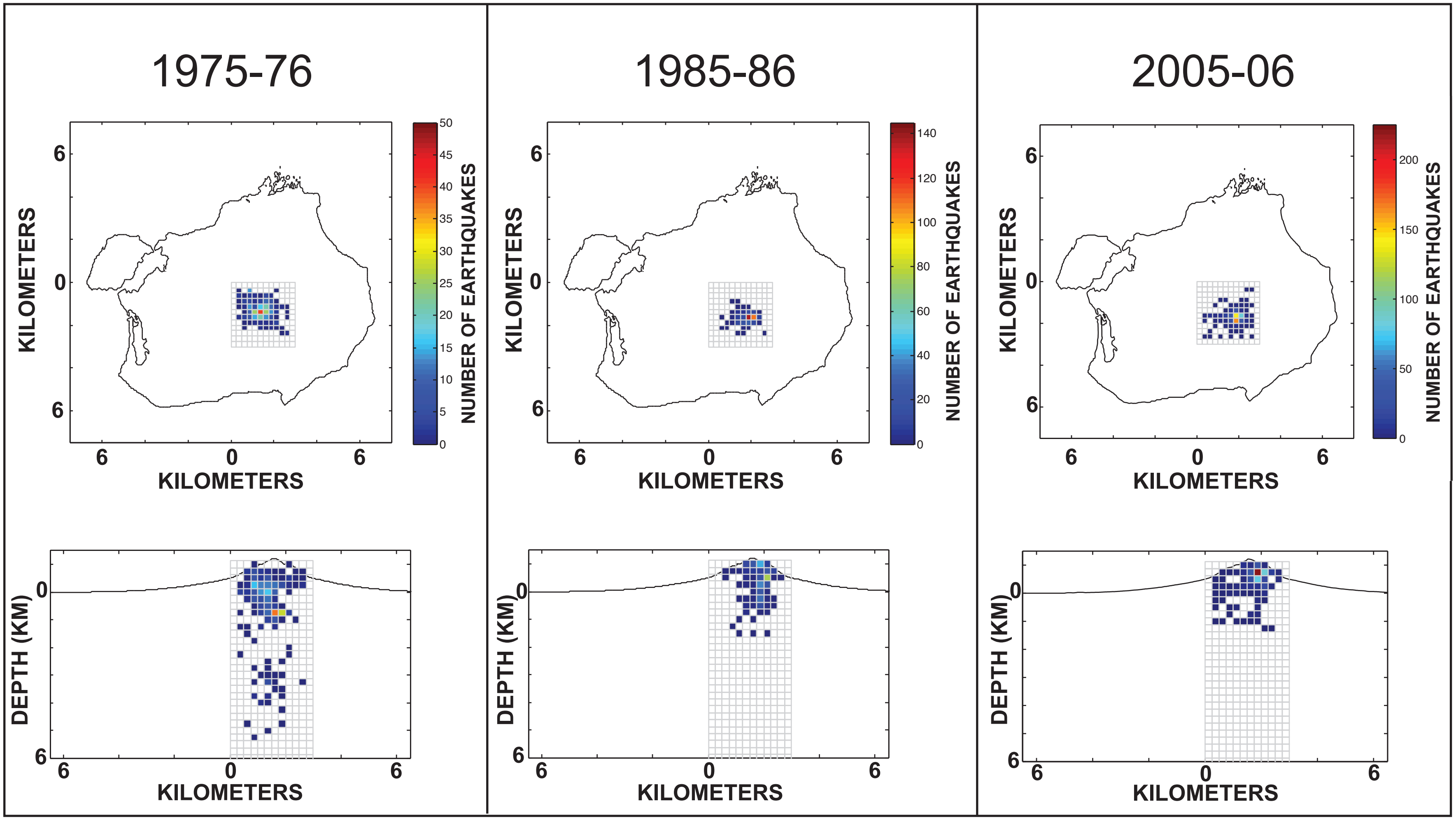


Figure 10. Map and east-west cross sections of relocated earthquakes at Augustine Volcano during precursory phases of the 1976, 1986, and 2006 eruptions. Color scales indicate the number of earthquakes located in each grid square.

the fishing boat suggests that it represents more than a simple phreatic explosion, perhaps mild explosive activity and a small lava extrusion near the volcano's summit.

The 1976 Eruption

Seismic activity associated with the 1976 eruption of Augustine Volcano was closely observed by the five stations on the island (fig. 2*A*) and the additional stations surrounding southern Cook Inlet (fig. 1). Unfortunately, all the stations on the island failed in early December 1975 as a result of severe winter weather (Johnston, 1978). However, station CKK on the Alaska Peninsula (fig. 1) operated at an unusually high gain and provided a means of tracking earthquakes at Augustine Volcano as small as magnitude (M_L) 0.25. The 1976 eruption consisted of four distinct phases based on the character of seismic activity and eruptive behavior. For this discussion we define the phases as follows:

1. Precursory phase (May 2, 1975, to January 23, 1976).
2. Explosive phase (January 22 to 25, 1976).
3. Second explosive phase (February 6 to 14, 1976).
4. Effusive phase (April 13 to 18, 1976).

These time periods were selected on the basis of descriptions of seismicity and eruptive activity provided by Reeder and Lahr (1987), Kienle and Shaw (1977), and Kienle and Swanson (1985).

Precursory Phase—May 2, 1975, to January 22, 1976

The precursory phase began with a pronounced swarm of VT earthquakes on May 2, 1975 (fig. 8). These shocks had impulsive arrivals and well-defined phases compared to most Augustine earthquakes. Relocated hypocenters clustered near sea level, and the largest magnitude was 1.4. This swarm quickly died off, with the last locatable event occurring on May 6, 1975. The volcano was then seismically quiet until May 27, when a second pronounced swarm of earthquakes began. This swarm consisted of 67 earthquakes large enough to be relocated (fig. 9), and the largest event had a magnitude of 0.7 (fig. 4). Seismicity following this swarm continued at a new higher rate of 5 to 10 relocated events per month. On September 14 the rate of seismicity climbed to a higher rate of tens of earthquakes located each month. This rate climbed again in late November to 100 to 200 events per month

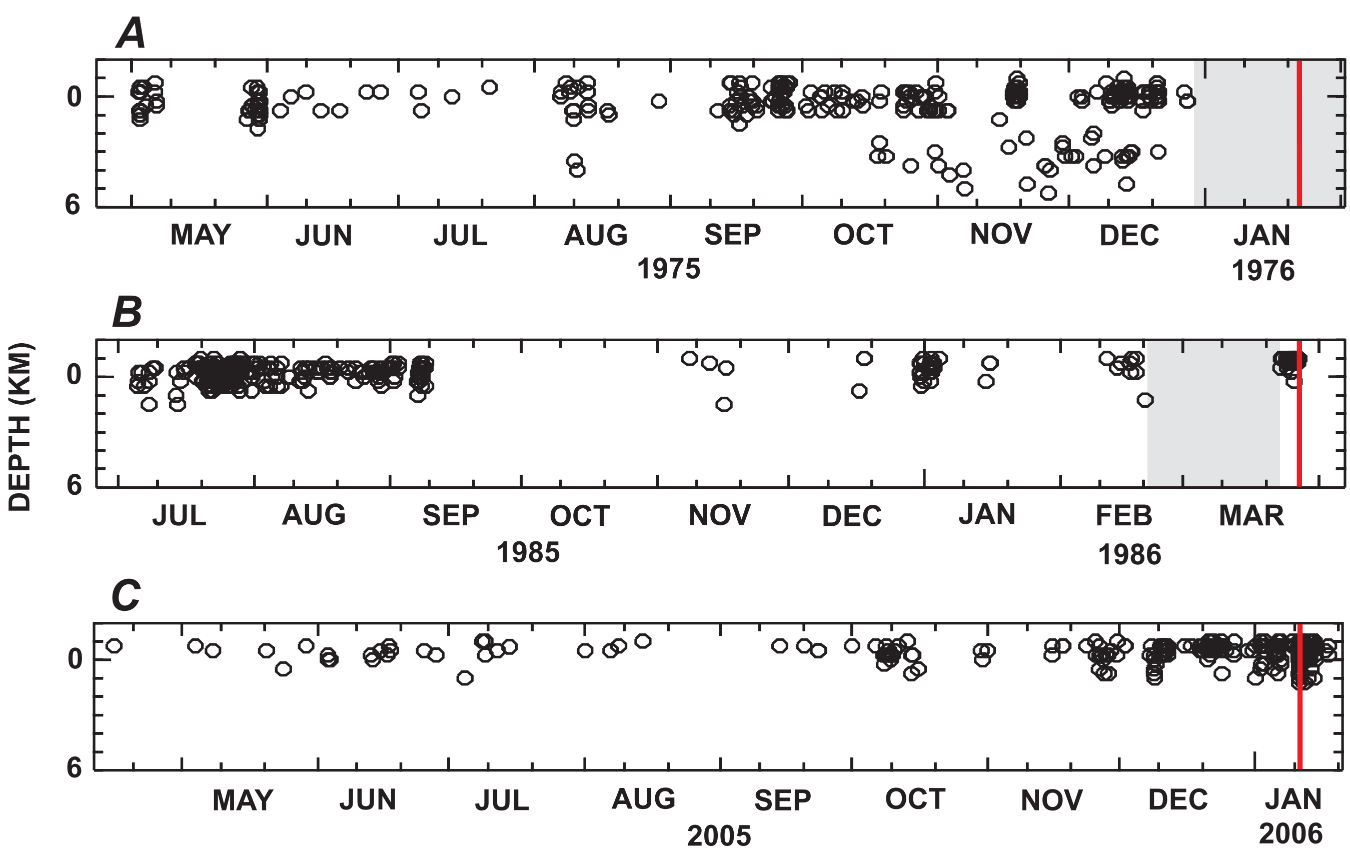


Figure 11. Plots of focal depth versus time for earthquakes relocated during the precursory phases of the (*A*) 1976, (*B*) 1986, and (*C*) 2006 eruptions of Augustine Volcano. The time periods when the Augustine seismic network was not operating sufficiently to relocate earthquakes are shown in gray. Red lines correspond to the onset of major explosive events in 1976, 1986, and 2006.

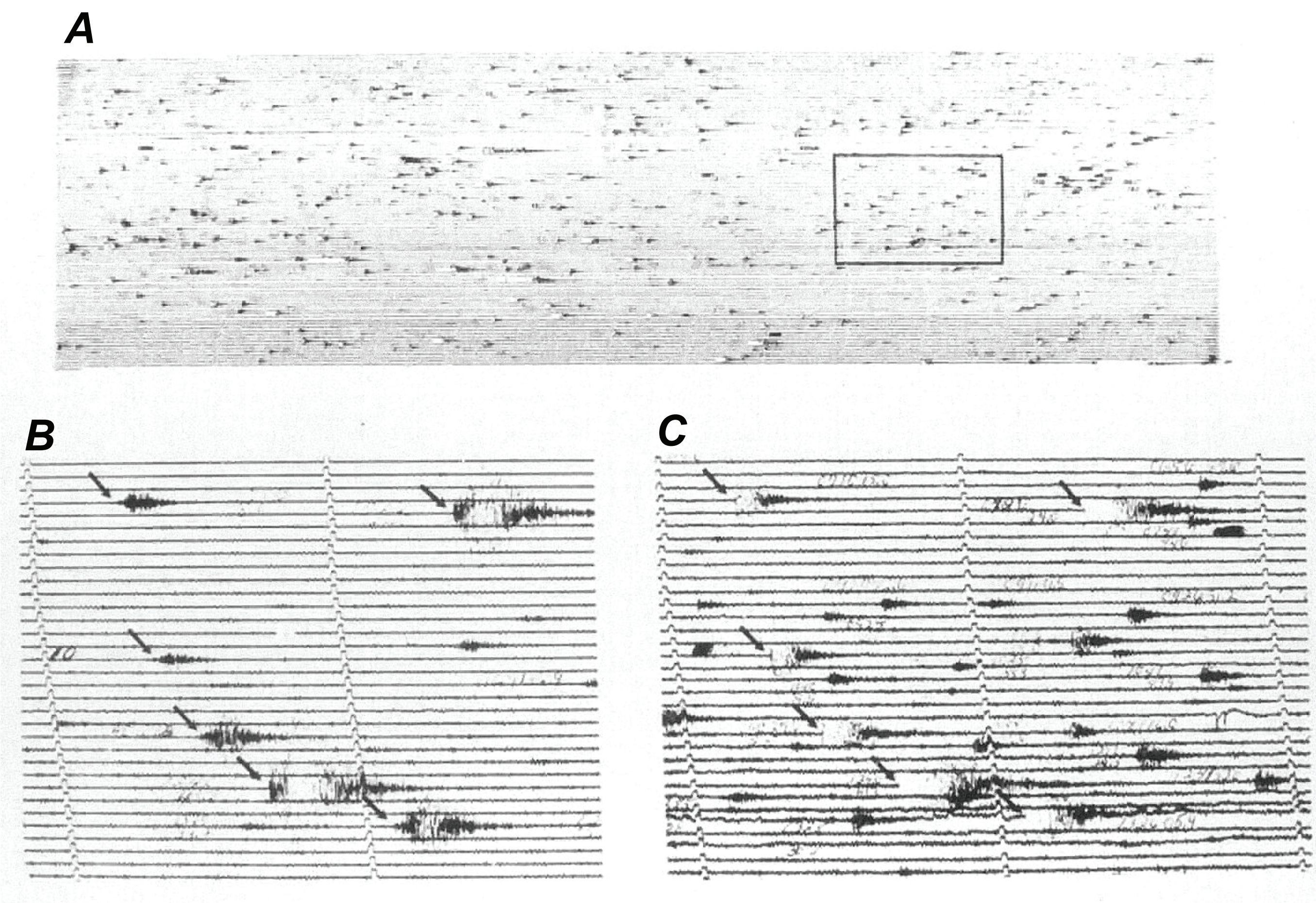


Figure 12. Drum records showing the character of earthquake activity prior to the 1971 eruption of Augustine Volcano. *A*, 24-hour drum record from seismic station AU1 on September 6, 1971. Small box in *A* denotes time periods shown in *B* and *C* on stations AU2 and AU1, respectively. Time marks represent 1 minute intervals.

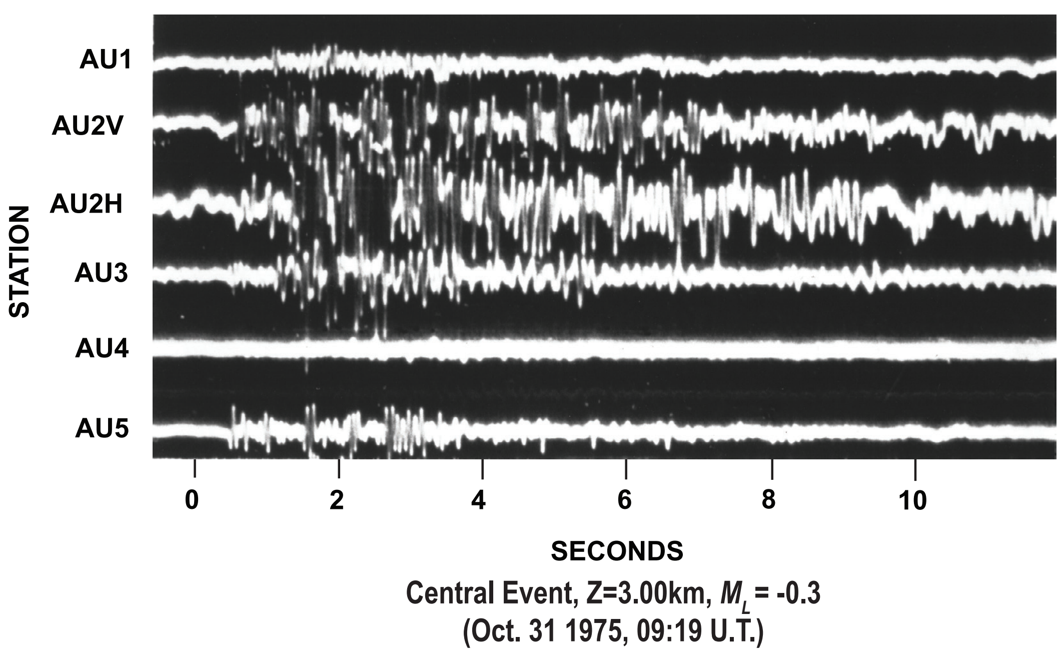


Figure 13. Seismograms from various seismic stations on Augustine Island of a magnitude (M_L) –0.3 earthquake located at a depth of 3 km below sea level on October 30, 1975 at 2319 AKST. Note small amplitudes observed at station AU4 (fig. 2*A*), which is near the summit, compared with other stations that are located on the flanks of the volcanic edifice. Stations AU2H and AU2V represent the horizontal and vertical components of station AU2, respectively.

(fig. 3). This high rate of earthquake activity continued until the network failed on December 22, 1975.

On August 10, earthquakes with hypocentral depths ranging from 2.75 to 5.25 km b.m.s.l. began to occur. Two of these deeper events were located on August 10 and 29, and additional events were located between October 18 and December 21, 1975 (fig. 11). The waveforms of these earthquakes have well-defined P and S phases and broader frequency content typical of VT earthquakes (fig. 13). Earthquakes in this depth range were found to have characteristically higher amplitudes on the flank stations such as AU2 and AU3 and lower amplitudes on the higher station AU4 (fig. 2*A*). This is the opposite of relative amplitudes observed for earthquakes with hypocentral depths of 1 km b.m.s.l. and above. Magnitudes of the deeper events ranged from −2.0 to 1.3. Increased steaming and fumorolic activity was reported by Johnston (1978) beginning in October of 1975.

Initial Explosive Phase—January 22 to 25, 1976

The 1976 eruption of Augustine began with a large explosion at 1759 AKST on January 22 which produced an ash plume that rose to 14 km a.m.s.l. (Kienle and Shaw, 1977; Reeder and Lahr, 1987). This explosion initiated a 22-hour-long sequence of more than 668 earthquakes that ranged in magnitude from 1.6 to 2.75 as determined by amplitude measurements on station CKK (fig. 1) located on the Alaska Peninsula. The rate and magnitudes of earthquakes recorded at station CKK and the times of explosive eruptions reported by Kienle and Shaw (1977) are shown in figure 14. This energetic swarm is the most vigorous recorded at Augustine Volcano between 1970 and 2007. The swarm was most intense between 0300 and 0600 AKST and was declining in intensity when the larger explosive events occurred (fig. 14). The explosive eruptions on January 23, 1976, as described by Kienle and Shaw (1977) were clearly the most powerful observed at Augustine during the 38 years of this study.

Kienle and Shaw (1977) report 12 additional Augustine explosions between 0353 on January 23 and 0457 AKST on January 27 that produced detectible infrasonic signals in Fairbanks. Reported plume heights for these explosions ranged from 6 to 12 km a.m.s.l. Reeder and Lahr (1987) report the occurrence of “large tremors” at station CKK associated with all 12 of these explosions. They report the occurrence of 22 additional “small tremors” recorded at station CKK between January 22 and 25 that may represent smaller explosions. Ashfall from these eruptions covered many areas surrounding Cook Inlet including Anchorage, Kenai, Homer, Seldovia, and Iliamna (Johnston, 1978).

The strong explosions in January 1976 removed a significant portion of the summit lava dome emplaced at the end of the 1964 eruption, leaving a crater that was estimated to be 200 m deep (Johnston, 1978). On the basis of coordinates of benchmarks located on the remnant crater rim (Power and Iwatsubo, 1998), we estimate the size of this crater to be roughly 550 by 350 m.

Second Explosive Phase—February 6 to 14, 1976

Eruptive activity resumed at 1444 AKST on February 6 with a powerful seismic signal recorded on station CKK. Activity continued at a sustained rate through February 14. Larger seismic signals were recorded late February 8 (Reeder and Lahr, 1987, figure 22). This phase of the eruption again produced large plumes that deposited ash on communities on the Kenai Peninsula, as well as numerous block-and-ash flows that moved down the north side of the volcano (Johnston,

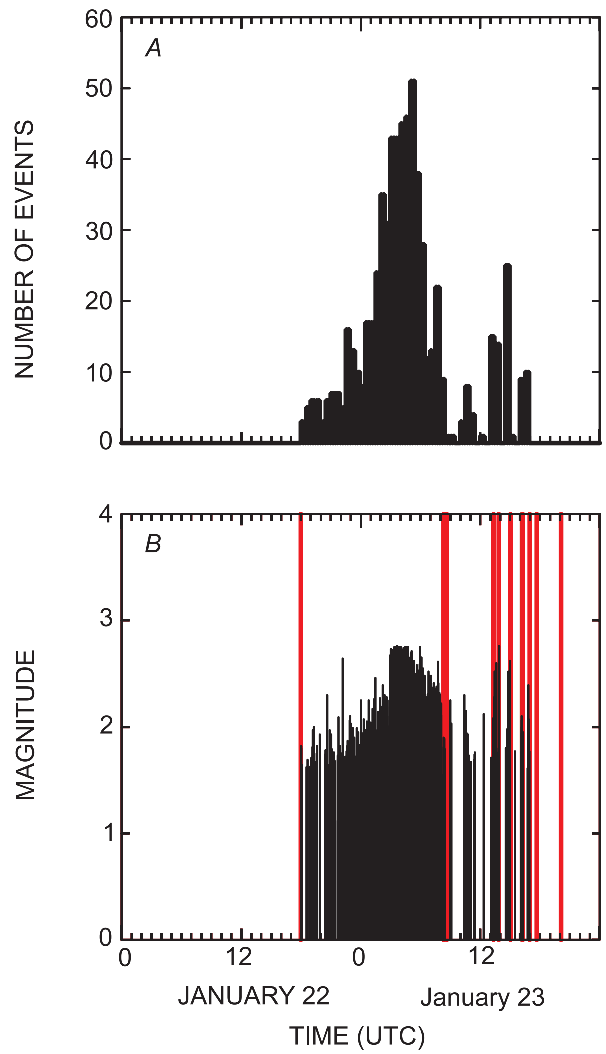


Figure 14. Time history of earthquake occurrence, magnitude, and explosive eruptions at Augustine Volcano on January 22 and 23, 1976. *A*, Number of earthquakes detected at station CKK during each 30-minute period. *B*, Each vertical line represents the magnitude of one earthquake as determined at station CKK. Red lines indicate times of explosive eruptions reported by Kienle and Shaw (1977). Time is referenced to UTC; to convert to AKST subtract 10 hours.

1978). Kienle and Swanson (1985) report that a new lava dome within the summit crater was first observed on February 12, 1976.

Effusive Phase—April 13 to 18, 1976

Seismic activity consisting of small tremors and shallow earthquakes resumed on April 13 and continued through April 18 (Reeder and Lahr, 1987, figure 24). Kienle and Swanson (1985) report that three seismic stations were reestablished on the island in February and these recorded numerous signals associated with block and ash flows that continued until April 24.

The 1986 Eruption

The 1986 eruption was well observed seismically by the network of four to five stations that was operating on the volcano throughout this eruption (fig. 2*B*). Descriptions of the 1986 eruption based on observations from individuals in the vicinity of the volcano, radar, observational overflights, satellite photographs, and a qualitative analysis of the seismic record were prepared by Yount and others (1987) and Swanson and Kienle (1988). A more detailed discussion of the seismic activity associated with the 1986 eruption was prepared by Power (1988).

Power (1988) divided the eruption into four phases based on the character of seismic activity and eruptive activity as follows:

1. Precursory phase (July 5, 1985 to March 26, 1986).
2. Explosive phase (March 26 to April 8, 1986).
3. Initial dome-building phase (April 21 to May 7, 1986).
4. Second dome-building phase (August 10 to September 10, 1986).

The character of seismicity changes dramatically from the precursory to the eruptive phase, and there are also significant differences among the remaining eruptive phases.

Precursory Phase—July 5, 1985 to March 26, 1986

The precursory phase to the 1986 consisted of several distinct swarms separated by long periods of seismic quiescence (Power, 1988). This phase began with a very energetic swarm of VT earthquakes that started on July 5, 1985, and continued until September 9, 1985. Relocated hypocenters in this swarm appear to have begun at depths of 0.2 to 0.4 km b.m.s.l. and quickly migrated to depths of 0.1 to 0.5 km a.m.s.l. The largest earthquake had a magnitude of 1.5. The swarm reached maximum intensity in late July 1985 (fig. 8).

Following this swarm the volcano went through a period of seismic quiescence from roughly September 10 to December 18. No other unusual behavior of the volcano was noted (Yount and others, 1987; Power, 1988). A small increase in the number of earthquakes began on December 18. This increase culminated in a short but intense swarm from December 31, 1985 to January 2, 1986. A magnitude 1.3 (M_L) earthquake on January 1 was the largest event of this period. Except for a small increase in mid-January, the volcano then remained relatively quiet until February 10 (fig. 8).

On February 10, 1986, the number of earthquakes increased an order of magnitude to tens of events per day. Unfortunately, on February 20 station AUI (fig. 2*B*) failed and earthquakes could not be located until it was repaired on March 22. To track seismicity during this period Power, (1988, figure 21) counted earthquakes from helicorder records of station AUH that were larger than M_L 0.25. Although, the number of events fluctuated greatly from day to day, the overall level of seismicity did not drop from this level until after the eruption. Earthquake activity during this period consisted of highly clustered bursts with 20 to 100 earthquakes occurring in a period of one to four hours. Earthquake activity of this character has been referred to as spasmodic bursts by Hill and others (1990). Figure 15 shows a helicorder record from station AUH illustrating a typical spasmodic burst on March 17, 1986. Individual spasmodic bursts can be separated by as much as 24 to 48 hours of relative quiescence. This increase in seismicity, coupled with reports of increased steaming, prompted the U.S. Geological Survey in Anchorage to make a series of observational overflights on February 22 and 28, and March 14 and 21. Increased fumarolic activity and snow melt were observed on successive flights (Yount and others, 1987).

A second order-of-magnitude increase in the seismicity rate to over 100 earthquakes per day greater than M_L 0.25 occurred on March 22. A ground party visited the volcano on this day to repair station AUI and to install station AUT. Vigorous steaming in the summit area and a strong sulfur smell downwind from the volcano were observed. The repair of station AUI allowed us to locate earthquakes again (fig. 9). Hypocentral depths of relocated earthquakes between March 22 and March 26 all cluster at 0.75 and 1.0 km a.m.s.l. (fig. 11). Late on March 24, a number of spasmodic bursts occurred that raised the rate of earthquake occurrence even higher (fig. 16). The largest events recorded during the 1986 eruption of Augustine Volcano occurred on March 26 and 27 and ranged in magnitude from 1.3 to 2.1 (fig. 4). Seismic signals with waveforms that resemble explosion events began to appear at 0957 AKST on March 26 (Power, 1988) (fig. 16). Power (1988) reported an upward migration of average hypocentral depth from 0.21 to 0.82 km a.m.s.l. during the precursory phase.

Explosive Phase—March 26 to April 8, 1986

The start of the eruption on March 26 marked a dramatic change in the character of the seismicity. However, analysis of this period is difficult because the film and helicorder records are saturated by the high levels of seismic activity. Before the

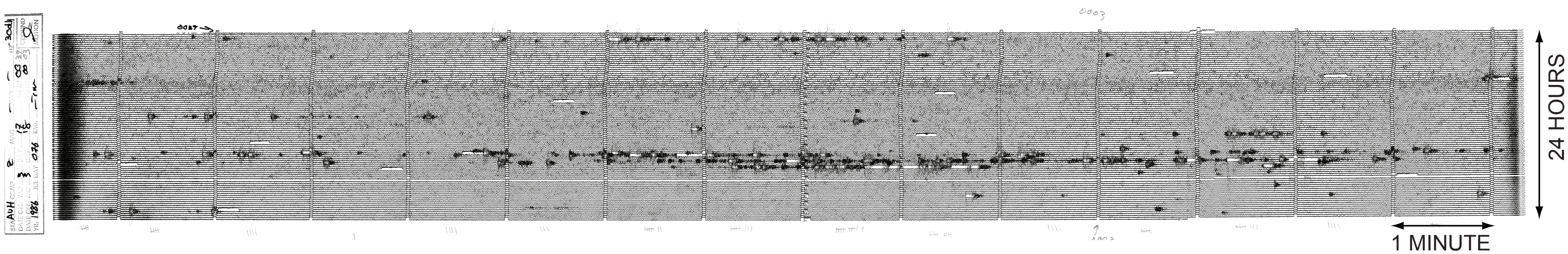


Figure 15. Drum record from seismic station AUH for March 17, 1986, showing a prominent spasmodic burst of earthquake activity composed of more than 75 earthquakes between 0630 and 0845 AKST. Note relative quiescence before and after spasmodic burst.

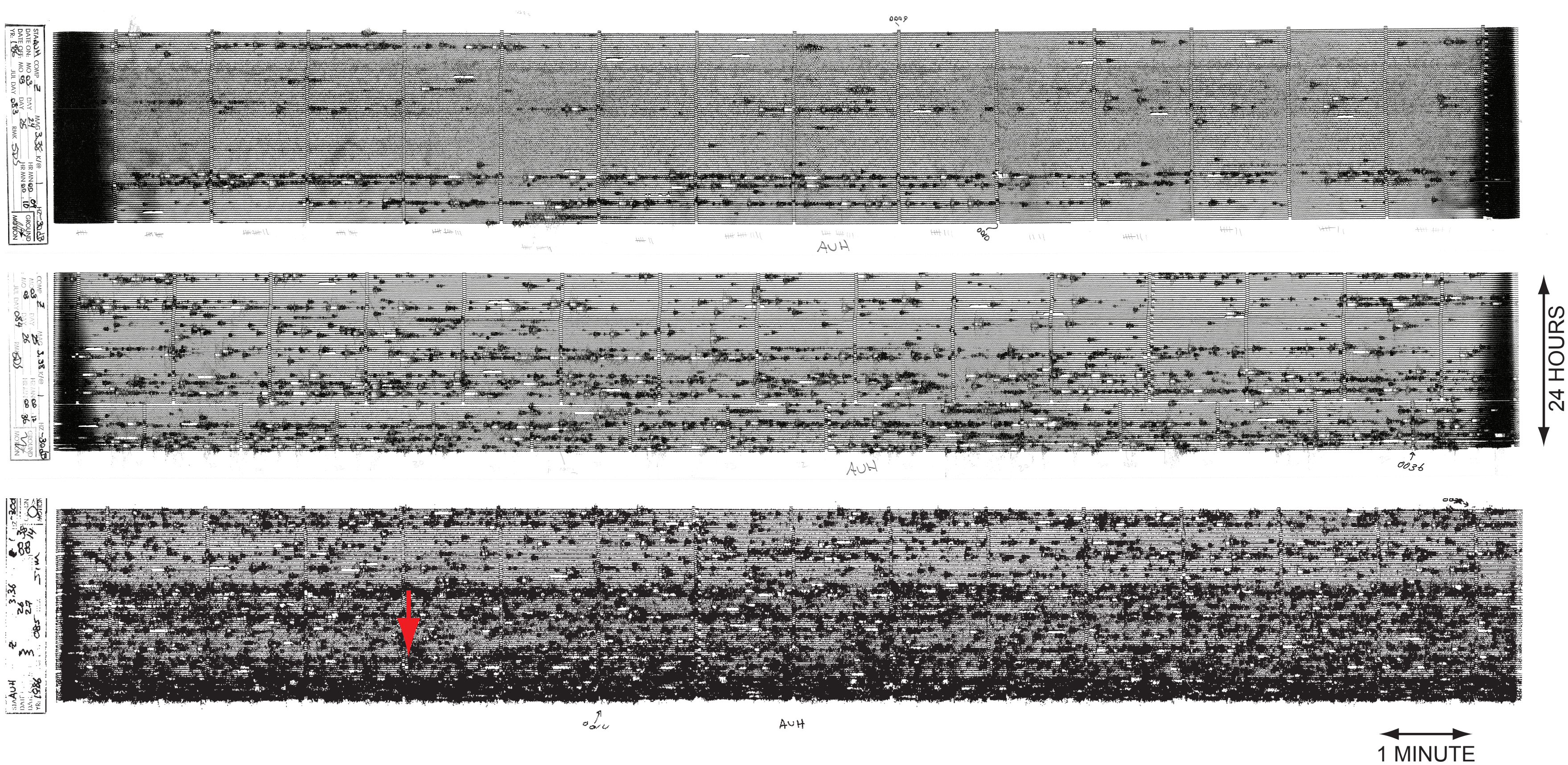


Figure 16. Drum records from seismic station AUH (fig. 2*B*) for March 24 through March 26, 1986, showing the strong buildup in earthquake activity before the onset of explosive activity in 1986. The red arrow notes the approximate onset of explosive activity at 0957 AKST on March 26, 1986.

explosive phase of the eruption, the seismic record is dominated by small VT earthquakes, generally of magnitude less than 1.3. Beginning at 0957 AKST on March 26 small explosions began to be interspersed with the earthquake signals. By 1711 AKST these explosions became strong enough to be recorded at station OPT, 25 km to the north of Augustine Volcano (fig. 1). As these explosion events began to increase in both amplitude and duration, the number of earthquakes began to diminish. By 0335 AKST on March 27 VT earthquakes were only occurring 5 to 10 minutes before the explosion events. Finally, by 1023 AKST on March 27 explosion events were taking place with no preceding earthquake activity. This sequence of intermixed earthquakes and explosions suggests that the Augustine vent opened rather slowly in 1986. This phase of the eruption produced widespread tephra throughout south-central Alaska and pyroclastic flows and lahars on Augustine Island (Yount and others, 1987).

To determine the relative size and rate of occurrence of explosions, Power (1988, figure 22) measured the onset and duration of the seismic signal at station OPT (fig. 1). These data show the relative intensity of explosive activity during this phase. The duration of individual events and the intensity of explosive activity increased slowly to a maximum on March 28 and then slowly decreased until March 31. At 0955 AKST on March 31 the largest single explosion occurred; the duration of this event was greater than 13 minutes at station OPT (Power, 1988). This explosion produced an eruption column that rose to more than 12 km above sea level, and spread ash over a wide area to the east of the volcano. Small explosions were also observed at OPT through April 4, and explosion events continued to be recorded on the island stations through April 8. Observations of these explosions, plume heights, and trajectories are discussed by Yount and others (1987). In addition to explosions, many events which could be related to pyroclastic flows and rock avalanches were also recorded during this phase.

Initial Dome Building Phase—April 21 to May 7, 1986

During this phase of the eruption a new lava dome was emplaced on the volcano's summit and a small lava flow moved down the upper northeast face of the volcano. Seismic activity was dominated by the occurrence of small repetitive earthquakes or drumbeats (Power, 1988, figure 29). A detailed description of observations of the volcano during this phase of the eruption is given by Yount and others (1987).

Drumbeat earthquakes first became apparent as a small increase above background noise at station AUH (fig. 2*B*) on April 21. By roughly 2000 AKST on April 21 the earthquakes were visible on helicorder records on all stations on the volcano and the signals from individual earthquakes began to run together, forming a continuous disturbance. To quantify this activity, Power (1988; figure 28) made hourly measurements of the signal amplitude on develocorder film on station AUH and identified periods when the signal was continuous or composed of identifiable discrete events. These measurements indicate that the drumbeat earthquakes increased in amplitude from April 22 to 27, then rapidly declined and disappeared completely by April 30. A second but less energetic period of drumbeats occurred from May 2 to 6 (Power, 1988). During this second period of drumbeats, individual events could be identified within the signal. On April 25 the approximate frequency of the signal was determined to be between 3 and 4 Hz.

Second Dome-Building Phase—August 10 to September 10, 1986

During this phase, dome building activity resumed and a peleean spine developed on the volcano's summit (Swanson and Kienle, 1988). This eruptive phase began about August 10, when Power (1988) reports that the number of avalanche signals began to increase gradually. Most of these signals were generated as small portions of the actively growing lava dome sloughed off the north side of the volcano's summit, forming pyroclastic flows (Kienle and Swanson, 1985). The seismic record became saturated with these signals on August 20. A count of surface events remained high until roughly September 10 (Power, 1988; figure 25). No associated increase in earthquake activity was noted (Power, 1988).

The 2006 Eruption

The 2006 eruption of Augustine Volcano received a much higher degree of monitoring and observation than earlier eruptions in 1971, 1976, and 1986. In addition to the increased seismic instrumentation (fig. 2*C*), a network of six continuous GPS receivers (CGPS) had been installed on the volcano by the Alaska Volcano Observatory (AVO) and EarthScope's Plate Boundary Observatory (PBO) (Pauk and others, this volume). Once unrest began, AVO deployed six temporary broadband seismometers, a strong-motion seismometer (AU20) (table 1), and five additional temporary CGPS (Cervelli and others, this volume) on the volcano. AVO also began a series of overflights to make visual observations, measure volcanic gas (McGee and others, this volume), and obtain thermal imagery (Wessels and others, this volume). AVO also deployed time-lapse and Web cameras (Paskievitch and others, this volume), and took high-resolution aerial photographs (Coombs and others, this volume). Researchers from the University of Alaska Fairbanks deployed a low-light camera in Homer, Alaska (Sentmen and others, this volume), and researchers from the New Mexico Institute of Mining and Technology deployed a lightning detection system (Thomas and others, this volume). Subsequent investigations of the deposits from the 2006 eruption are described by Coombs and others, (this volume), Vallance and others, (this volume), Larsen and others, (this volume), and Wallace and others (this volume).

The 2006 eruption of Augustine, like the 1976 and 1986 eruptions, consisted of four distinct phases defined by the character of seismicity, geophysical unrest, and eruptive activity, which are described below. The time periods for these phases are:

1. Precursory phase (April 30, 2005 to January 11, 2006).
2. Explosive phase (January 11 to 28, 2006).
3. Continuous phase (January 28 to February 10, 2006).
4. Effusive phase (March 3 to 16, 2006).

The number of located earthquakes per week, approximate times of phreatic and magmatic explosions, RSAM values from station AU13, ground deformation, measured SO_2 output, erupted volume, and the time periods of the four eruptive phases are summarized in figure 17.

Precursory Phase—April 30, 2005 to January 11, 2006

The precursory phase began as a slow, steady increase in microearthquake activity beneath the volcano on April 30, 2005. These earthquakes were all classified as VT earthquakes during standard AVO processing (Dixon and others, 2008). An earlier swarm in October of 2004 (fig. 3) developed seismicity rates that exceeded any observed since the 1986 eruption; however, the six-month-long period of quiescence between this swarm and April 30, 2005, makes any connection to the 2006 eruption uncertain. The number of located VT earthquakes slowly increased from an average of one to two per day in May 2005 to five to six per day in October 2005 to 15 per day in mid-December 2005 (fig. 3). Relocated hypocenters had average depths generally between 0.1 and 0.6 km a.m.s.l. between April and December of 2005. These hypocentral depths are shallower than those observed during the initial precursory stages of both the 1976 and 1986 eruptions (fig. 11). In July 2005, geodetic baselines measured by the CGPS receivers began to lengthen, showing a clear radial pattern indicative of a pressurization source beneath the volcano's summit near sea level (Cervelli and others, 2006).

On November 17 there was a clear offset in the GPS data (fig. 17) that Cervelli and others (2006) attribute to the onset of the upward propagation of magma or associated volatiles in a dikelike structure. This was followed on December 2 by the onset of a series of small phreatic explosions that were clearly recorded on the Augustine seismic network. The largest of these explosions occurred on December 10, 12, and 15. An observational overflight on December 12 revealed vigorous steaming from the summit area, a new vigorous fumarole on the summit's southern side at roughly 3,600 feet elevation, and a light dusting of ash on the volcano's southern flanks. A strong plume of steam and

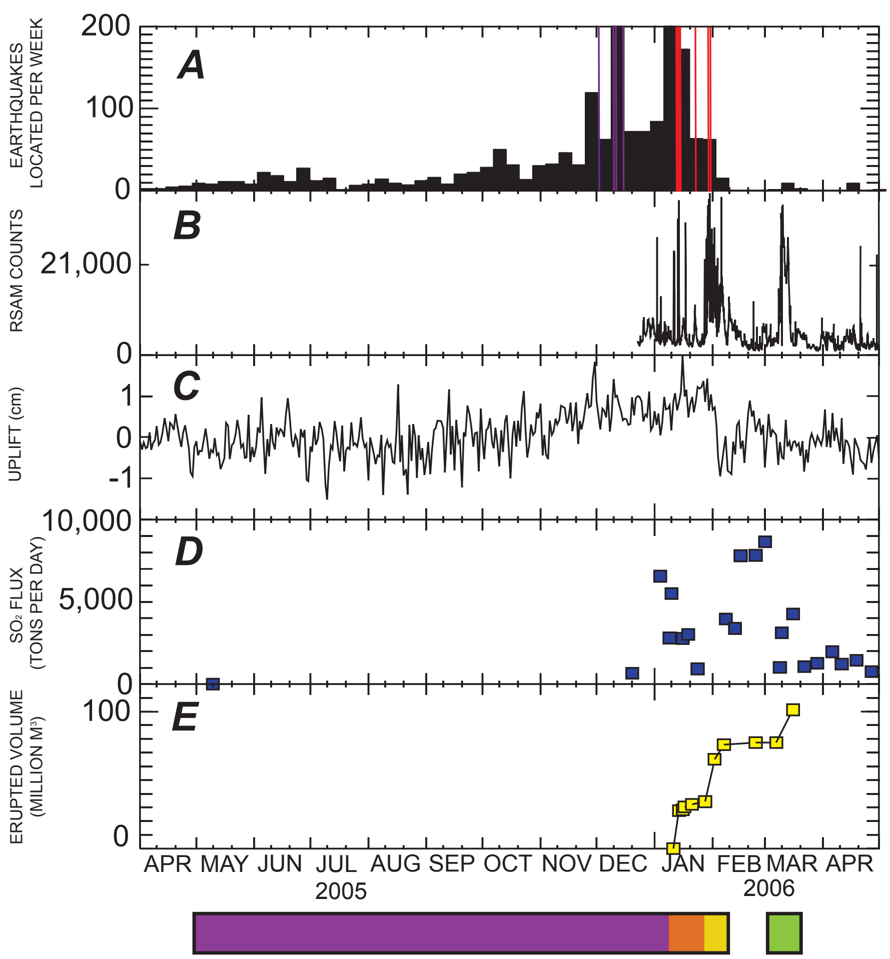


Figure 17. Summary of the 2006 eruption that shows (*A*) the number of earthquakes located each day, (*B*) the hourly RSAM record from station AU13, (*C*) the displacement measured between GPS stations A59 and AV02 (Cervelli and others, this volume), (*D*) the measured SO_2 flux (McGee and others, this volume), and (*E*) the erupted volume determined by Coombs and others (this volume). Purple and red lines in *A* correspond to approximate times of phreatic and magmatic explosions, respectively. Colors in bar at base of figure (purple, orange, yellow, and green) correspond to the precursory, explosive, continuous and effusive phases, respectively. Gap in bar represents hiatus in eruptive activity.

gas extended to the southeast. The explosion on December 15 disabled seismic stations AUS and AUR, the two highest seismic stations (fig. 2*C*). The ash was sampled on December 20 and was found to be a mix of weathered and glassy particles; the latter appear to be remobilized 1986 tephra (Wallace and others, this volume). Measurements of SO_2 flux on December 20, 2005, and January 4 and 9, 2006, returned values of 660, 6,700, and 2,800 tons per day, respectively (McGee and others, this volume).

Between December 12, 2005, and January 10, 2006, seismicity rates were strongly elevated, with more than 420 earthquakes located by the AVO (Dixon and others, 2008). Much of this activity occurred in spasmodic bursts similar to those observed before the 1986 eruption (fig. 15). Jacobs and McNutt (this volume) determined a *b* value of 1.85 for earthquakes during this period. Relocated hypocenters continued to cluster between 0.4 and 0.8 km a.m.s.l. On the basis of geodetic data, Cervelli and others (2006) suggest that magma and/or volatiles continued to move to progressively shallower depths within the Augustine edifice during this period.

On January 10 at roughly 1535 AKST, a 13-hour long swarm of VT earthquakes began that would culminate in two large explosions at 0444 and 0512 AKST on January 11, marking the onset of the explosive phase of the eruption (fig. 18). AVO would eventually locate more than 300 earthquakes during this swarm. Relocated hypocenters cluster beneath the volcano's summit at depths of 0.5 to 1.0 km a.m.s.l. The swarm began slowly, with locatable earthquakes occurring roughly every 2 minutes and magnitudes smaller than 1.0 (fig. 9). The seismicity rate peaked twice during the swarm at roughly 1800 January 10 and 0200 AKST January 11, and the magnitudes of located events also followed a similar progression (fig. 19).

Explosive Phase—January 11 to January 28, 2006

The two explosions on January 11 produced ash plumes, reported by the U.S. National Weather Service (NWS) to have reached heights greater than 9 km a.m.s.l. that moved slowly to the north and northeast (Bailey and others, this volume). Ash sampled on January 12 was primarily dense or weathered fragments, suggesting the involvement of little or no juvenile magma (Wallace and others, this volume). Over the next 36 hours, several sequences of drumbeat earthquakes occurred at rates as high as three to four per minute. Each of these sequences of drumbeats lasted 2 to 3 hours (fig. 18). These earthquakes suggest that magma may have begun to move within the shallow portions of the Augustine edifice, possibly forming a new lava dome if material reached the surface.

Explosive activity resumed on January 13 with a series of six powerful explosions that occurred at 0424, 0847, 1122, 1640, 1858 on January 13 and 0014 AKST on January 14 (fig. 18). The first explosion destroyed the seismometer at AUP (fig. 2*C*). Plumes reached altitudes of 14 km a.m.s.l. and deposited traces of ash on southern Kenai Peninsula communities. Ash from these eruptions was more heterogeneous than that from the January 11 explosions and contained dense particles as well as fresh glass shards, indicating the eruption of new magma (Wallace and others, this volume). Satellite imagery tracked these plumes as they moved eastward and disrupted commercial airline traffic to and from Alaska (Bailey and others, this volume). These explosions opened a new vent in the top of the 1986 lava dome that was estimated to be roughly 100 by 200 m in diameter (Coombs and others, this volume).

A January 16 overflight revealed a small new lava dome at the summit partially filling the new crater. An explosive eruption at 0758 AKST on January 17 sent ash to 13 km a.m.s.l. in a plume that moved westward. This explosion left a 20- to 30-meter-diameter crater in the new dome and produced ballistic fields on the volcano's western flanks (Coombs and others, this volume; Wallace and others, this volume; Schneider and others, 2006).

The eruptions of January 13–17 generated pyroclastic flows, snow avalanches, and lahars that moved down most flanks of the volcano. The January 17 explosion was followed by roughly 9 days of relative seismic quiescence. Brief periods of drumbeat earthquakes occurred throughout this period, and lava again filled the new crater and formed a small lava flow that moved to the east (Coombs and others, this volume; Vallance and others, this volume).

Explosive activity resumed on January 27 with two explosions at 2024 and 2337 and two on January 28 at 0204 and 0742 AKST (fig. 20) that generated ash plumes to heights of 9 km a.m.s.l. Ash moved southward and fell in trace amounts on Kodiak Island (Bailey and others, this volume; Wallace and others, this volume). The explosion at 2024 AKST on January 27 generated the largest single pyroclastic flow of the eruption, which moved down the north flank of the volcano (Coombs and others, this volume; Vallance and others, this volume). This explosion destroyed seismic stations AUH and AUL on the west and north flanks of the volcano. Destruction of these two final stations on the upper flanks of the volcano compromised AVO's ability to assign reliable hypocentral depths to earthquakes in near real-time.

Continuous Phase—January 28 to February 10, 2006

The volcano entered a period of more continuous eruptive activity starting at about 1430 AKST on January 28, 2006, with a roughly 2-hour period of volcanic tremor (fig. 20) that was accompanied by a significant ash plume that reached 9 km a.m.s.l. (Wallace and others, this volume). This phase of the eruption was characterized by continuous lower level ash production that gradually transitioned to the effusion of lava. Early in this phase the volcano erupted a more silicic magma (62.5 weight percent SiO_2) that formed a rubbly dome atop the remnants of the 1986 dome. By early February the composition of erupted magma had shifted back to a more andestic composition that formed a short lava flow that moved a short distance down the volcano's north side (Coombs and others, this volume).

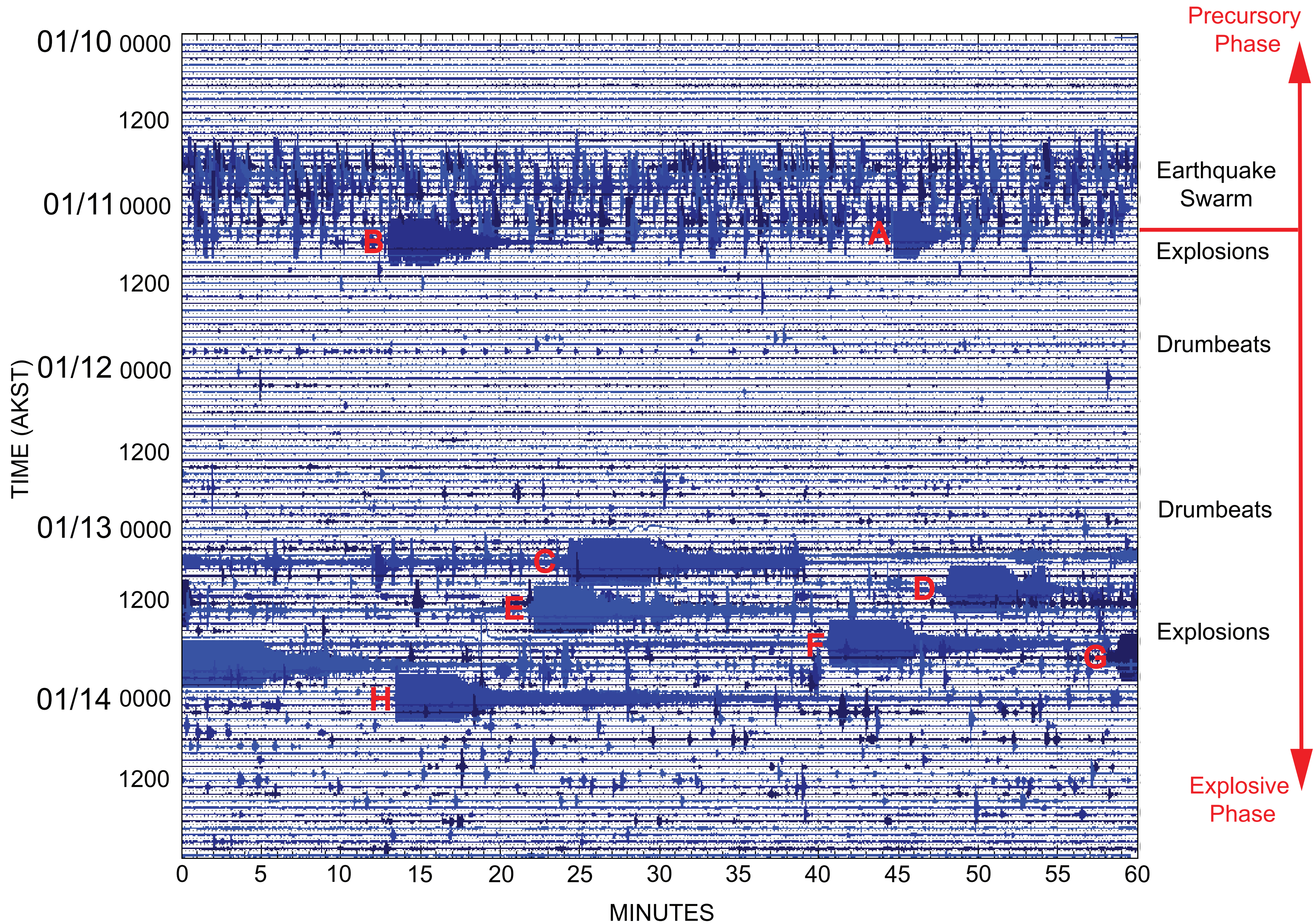


Figure 18. A 5-day velocity seismic record from station AU13 that shows the precursory earthquake swarm on January 11, 2006, the first eight explosions on January 11, 13, and 14, and the intervening periods of drumbeat earthquakes. Labeled events are A, explosion at 0444 AKST on January 11; B, explosion at 0512 AKST on January 11; C, explosion at 0424 AKST on January 13; D, explosion at 0847 AKST on January 13; E, Explosion at 1122 AKST on January 13; F, explosion at 1640 AKST on January 13; G, explosion at 1858 AKST on January 13; H, explosion at 0014 AKST on January 14.

At approximately 2200 AKST on January 28, the seismic network began to detect numerous signals associated with rock falls and block-and-ash flows generated by small failures of the growing lava dome and flows, cascading down the volcano's northern flanks (fig. 20). These signals generally have emergent onsets, extended codas, and a broad spectrum between 1 and 10 to 15 Hz. Numerous LP events are also observed during this time. Automatic event classification by Buurman and West (this volume) indicates that most seismic events had a lower frequency content or LP character during this phase of the eruption. One of these flows swept over seismic station AU12 at 0329 AKST on January 30, 2006, destroying the station's batteries. Fortunately, the seismometer and internally recorded data were recovered on August 11, 2006. Signals from rockfalls and small pyroclastic flows, as well as individual shallow LP events, declined markedly on February 3 at about 1500 AKST and then gradually decreased through the remainder of this phase.

Data from the remaining CGPS stations indicated that the volcano reversed its long inflationary trend on January 28 and began a sharp deflation that continued until 10 February. Modeling suggests the locus of deflation was at about 3.5 km b.m.s.l. (Cervelli and others, this volume).

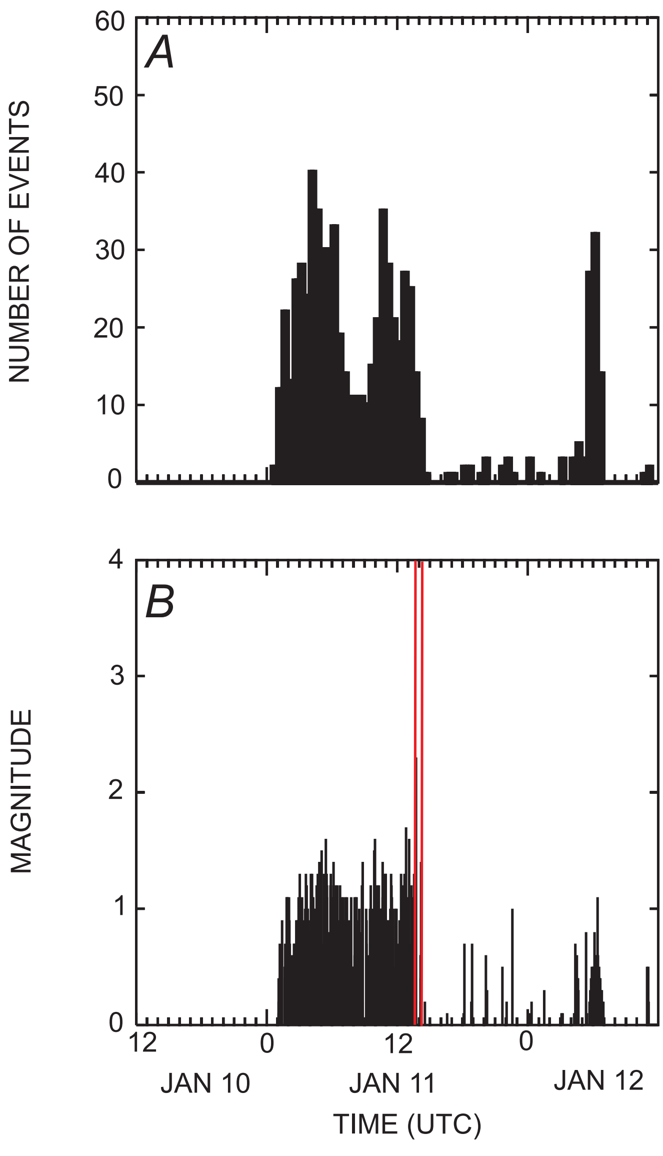


Figure 19. Time history of earthquake occurrence, magnitude, and explosive eruptions on January 10 through 12, 2006. *A*, Number of earthquakes located in each 30-minute period. *B*, Each vertical line represents the magnitude of one located earthquake. Red lines indicate times of explosive eruptions. Time is referenced to UTC; to convert to AKST subtract 9 hours.

Effusive Phase—March 8 to16, 2006

Following the end of the continuous phase, the volcano then entered a period of relative seismic quiescence that continued until March 3, 2006. This period is characterized by only an occasional rockfall signal. Visual observations of the volcano indicate that the period from February 10 to March 3 represents a cessation in eruptive activity. Geodetic data indicate that the volcano slowly inflated between February 10 and March 1 and then entered an 11-day period of deflation between March 1 and 12, 2006. The strength of this signal on the remaining CGPS instruments was not sufficient to accurately model a source depth for this episode of deflation (Cervelli and others, this volume).

On March 3 the number of rockfalls seen on the remaining seismic stations began to slowly increase. This activity peaked on March 6 and early on March 7. Starting on March 8, small repetitive drumbeat-style seismic events began to slowly emerge from the seismic background. The rate and size of the drumbeat events waxed and waned several times before forming a nearly continuous signal late on March 8 (fig. 21). Between 0500 and 2000 AKST on March 8 the rate of individual drumbeat events varied from two to as many as six per minute. After 2000 AKST on March 8, the events were occurring so rapidly (eight or more per minute) that they formed a continuous signal and it is no longer possible to distinguish individual events. RSAM records from station AU13 indicate that the amplitude of the continuous signal reached a maximum late on March 10 (fig. 17). This continuous signal lasted until about 1200 AKST on March 13 when the amplitude began a slow decline and individual events could again be distinguished occurring at a rate of about 5 per minute. The rate of events slowly declined, and by roughly 1200 AKST on March 16 they could no longer be identified.

Lava extrusion at the summit increased markedly in association with these drumbeat events, and two blocky lava flows moved down the north and northeastern flanks. Observations indicate that the effusion of lava had stopped by mid-March. The estimated volume of erupted material during this phase is 23 million cubic meters (Coombs and others, this volume).

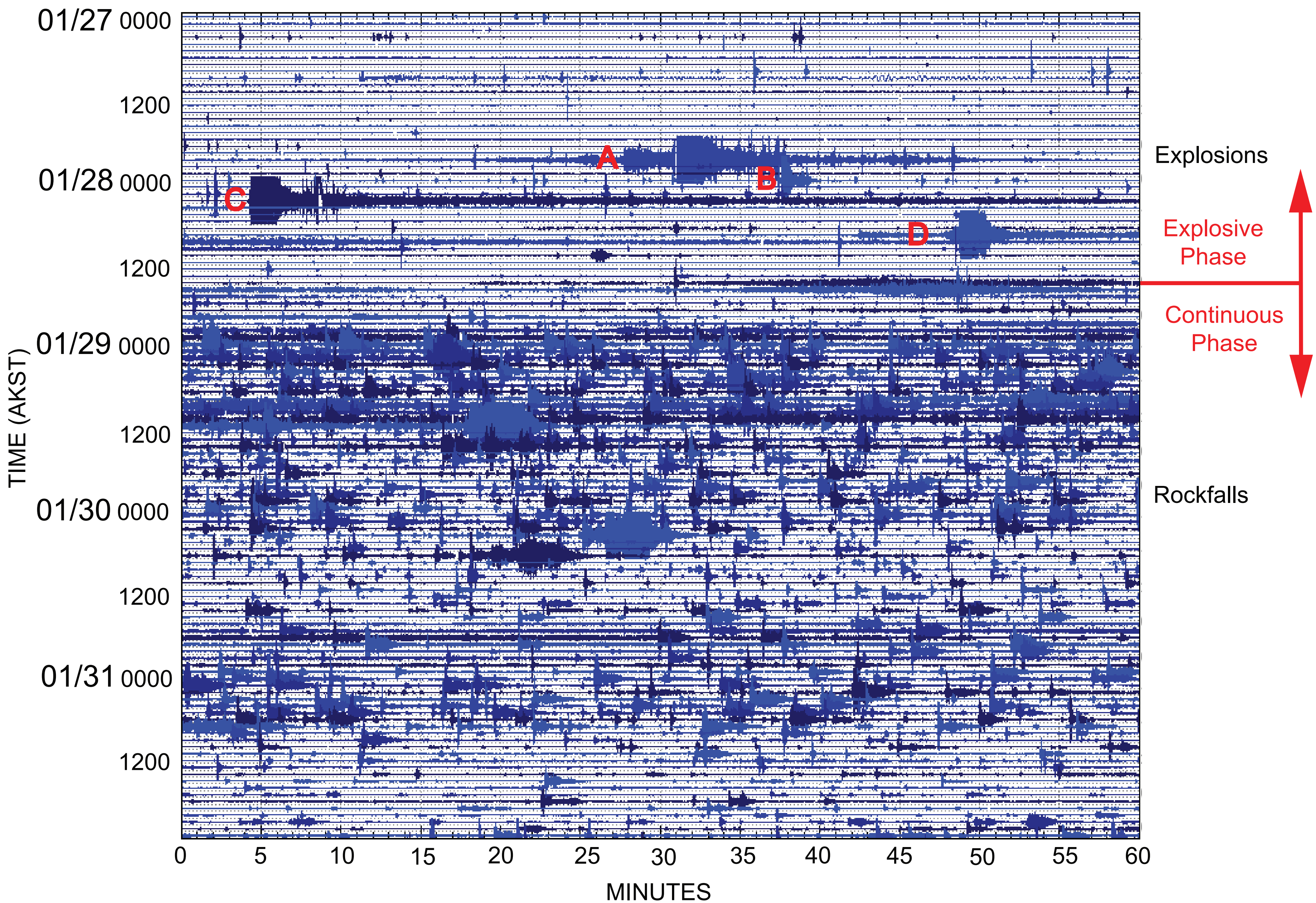


Figure 20. A 5-day velocity seismic record from station AU13 that shows the transition from the explosive to the continuous phase of the 2006 eruption. Labeled events are A, explosion at 2024 AKST on January 27; B, explosion at 2337 AKST on January 27, C, explosion at 0204 AKST on January 28; and D, explosion at 0742 on January 28, 2006.

Posteruptive Seismicity

On March 15, 2006, two earthquakes were located beneath the summit with hypocentral depths of 2.8 and 2.4 km b.m.s.l. Earthquakes with hypocenters between 2.3 and 3.75 km b.m.s.l. continued at a low rate until mid-August, by which time 18 shocks at this depth had been identified. These earthquakes had well-defined phases and a broad spectrum between 2 and 15 Hz, typical of VT earthquakes that represent a brittle failure source. To accurately locate these shocks we incorporated S-phases from the horizontal components of stations AU13, AU14, and AU15 (fig. 2*C*). Deshon and others (this volume) found that 11 of these earthquakes formed a single family suggestive of a common source, while the remaining 7 shocks had unique waveforms. These were the first earthquakes identified with hypocenters in this depth range at Augustine since December 1975. A representative waveform and a time history of these deeper earthquakes are shown in figure 22.

The seismic signals from rockfalls and the number of locatable earthquakes continued to decline throughout the summer of 2006. Small fluctuations in the rate of shallow VT earthquakes continued at Augustine throughout 2007 (figs. 3 and 4). These were generally small magnitude earthquakes that were most visible on station AUH. A pronounced increase in locatable VT earthquakes occurred between July and October, 2007 (fig. 3). Magnitudes of these earthquakes were less than 1.0 (fig. 4).

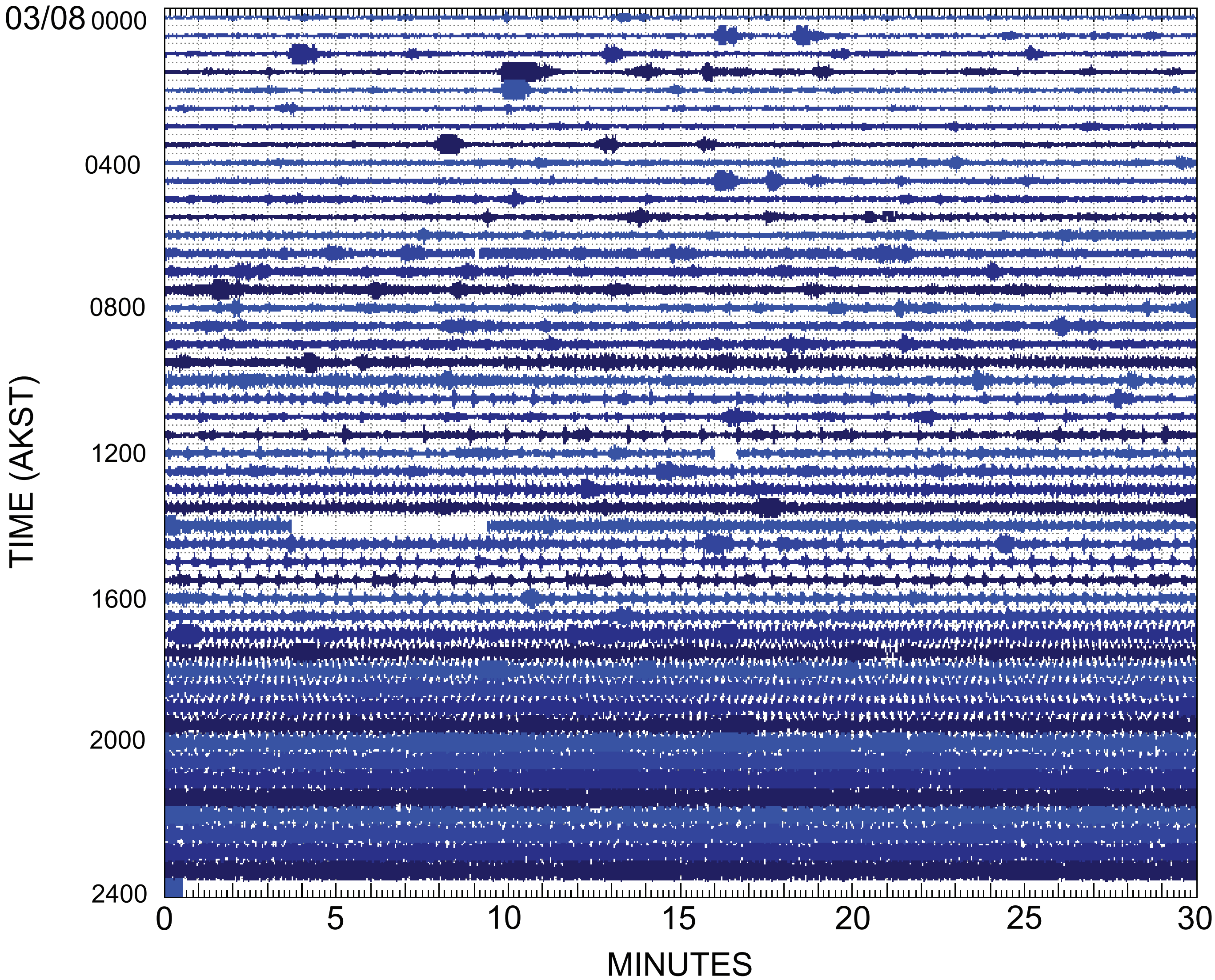
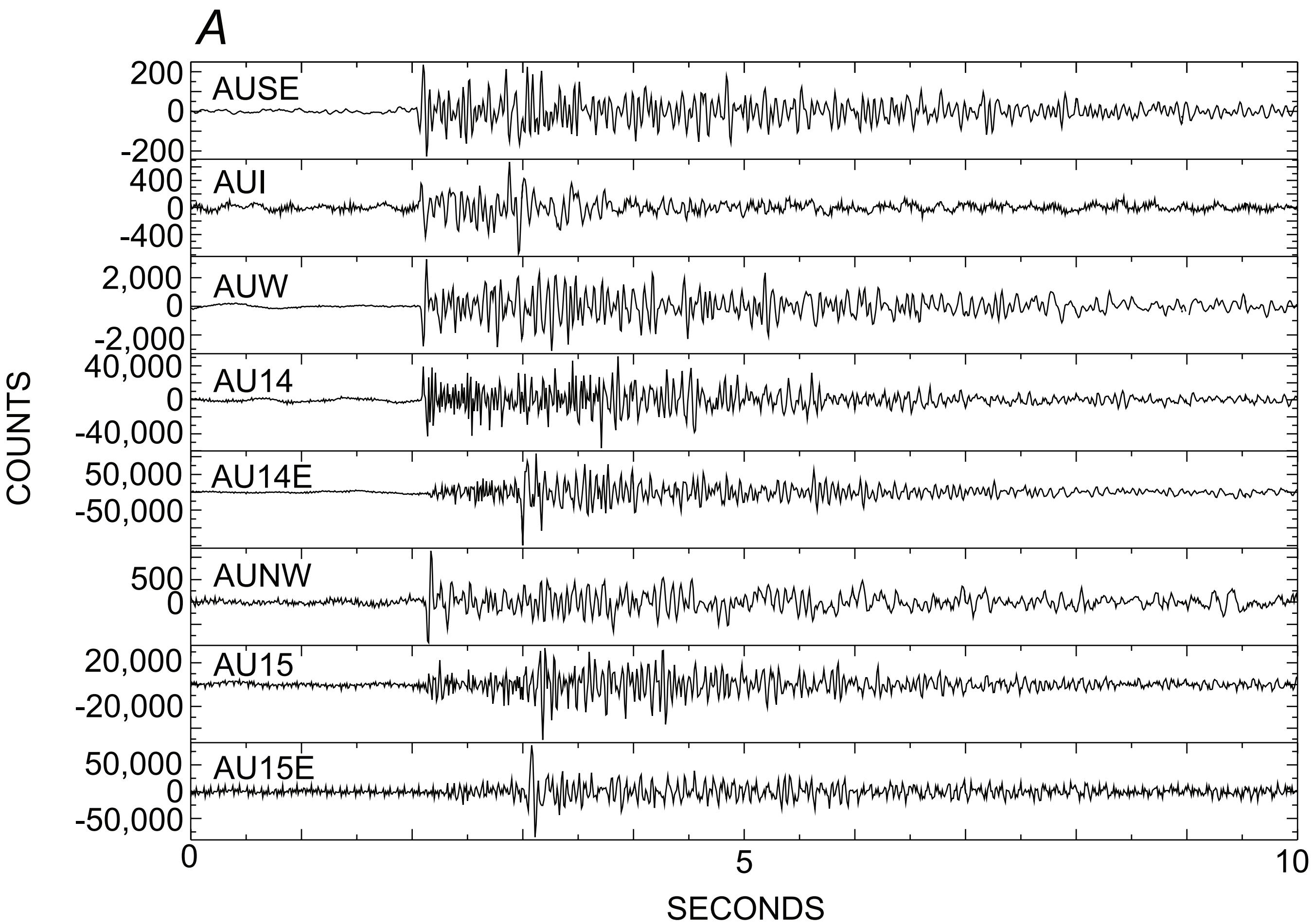


Figure 21. Velocity seismic record from station AUW on March 8 showing the onset of drumbeat earthquakes during the 2006 eruption. The rate and size of individual events changes several times until they form a nearly continuous signal at roughly 2330 AKST on March 8, 2006.



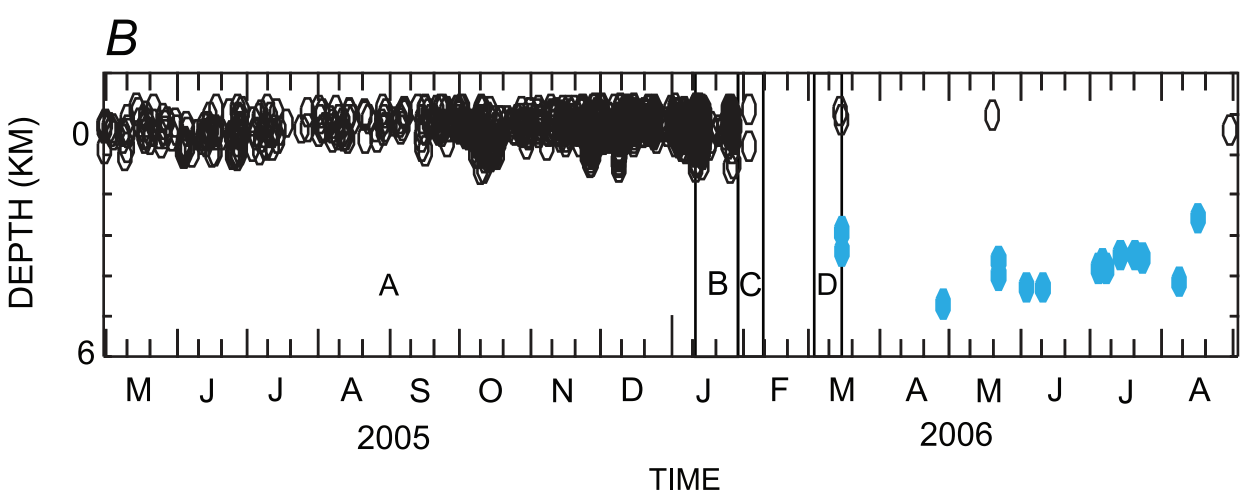


Figure 22. Representative waveform and plot of earthquake focal depth versus time, highlighting the occurrence of earthquakes between 2 and 5 km depth during the 2006 eruption sequence. *A*, Waveform of a magnitude 0.2 earthquake located at 3.55 km depth b.m.s.l. under the summit of Augustine on July 6, 2006. Individual station names are shown at left, east-west horizontal components are noted by “E” suffix. *B*, Plot of time versus focal depth showing the time history of the deeper earthquakes, noted by blue symbols, that followed the 2006 eruption. Labels A, B, C, and D note the precursory, explosive, continuous, and effusive phases of the 2006 eruption.

Discussion and Interpretation

This section relates the observed seismicity to the structure and subsurface configuration of the Augustine magmatic system and to the magmatic processes during the 1971, 1976, 1986, and 2006 eruptive sequences as well as the intervening quiescent periods. We will use the seismic patterns, waveform characteristics, and earthquake locations to infer both the geometry of the Augustine magmatic system and the evolution of the system during the three major eruptions. This discussion relies principally on the seismic record from 1970 through 2007 and secondarily on geophysical, geological, and visual observations reported by other authors.

Quiescent Periods

We think that the small shallow VT earthquakes most commonly seen at Augustine Volcano during quiescent periods, such as 1972 to 1975 and 1993 to 2004, represent small-scale adjustments within the upper portions of the volcanic edifice and summit dome complex. Deshon and others (this volume) find that only 30 to 40 percent of these earthquakes have similar waveforms, suggesting that seismicity is well distributed throughout the cone during quiescent periods. The stress regime responsible for the generation of these earthquakes is perhaps either thermal contraction of the cooling lava dome or gravitational slumping of the summit dome complex. Geodetic data from 1986 to 2000 indicate that portions of the summit dome complex can subside as much as 8 cm per year (Pauk and others, 2001). This process is relatively steady state, as evidenced by the relatively constant rate of VT earthquake activity observed between 1993 and 2004 (fig. 3).

Magmatic System Geometry

We think that the magmatic system beneath Augustine Volcano consists of a magma storage or source zone between 3.5 and 5 km b.m.s.l. that is connected by a largely aseismic conduit system to a shallower system of cracks that is centered near sea level. This shallower system roughly corresponds to the area where most earthquakes are located during the early precursory seismic sequences and may extend from as much as 0.9 km b.m.s.l. to several hundred m a.m.s.l. This shallower system of cracks is perhaps connected to the surface by a system of interconnected conduits or cracks that coalesce to a single north-south-trending dike at the volcano's summit. An idealized sketch of the inferred components of the Augustine magmatic system is shown in figure 23.

The deeper magma source area is only poorly defined seismically by the small number of earthquakes between 2 and 5 km b.m.s.l. that occurred in 1975 before the 1976 eruption (figs. 10 and 11) and following the 2006 eruption (figs. 7, 11 and 22). We speculate that the 1975 hypocenters most logically lie above the magma source zone, because they occurred before the 1976 eruption, and may reflect

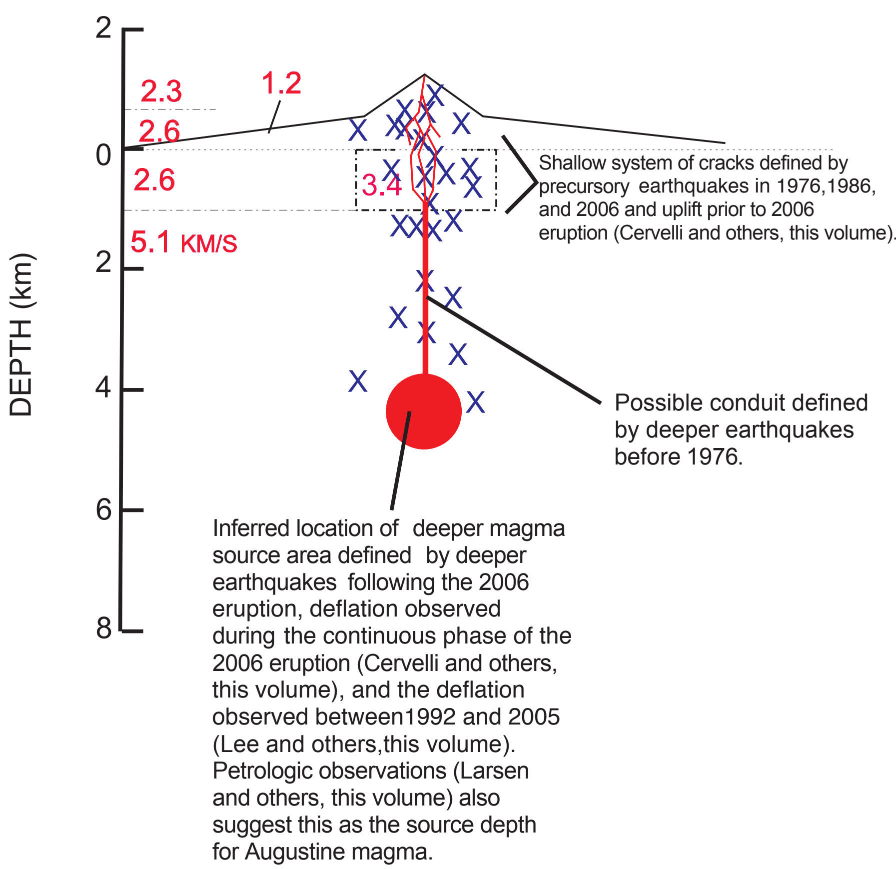


Figure 23. Inferred cross section of the Augustine Volcano magmatic system based on seismic and supporting geophysical information. Principal components of the system are a shallow system of cracks that may extend from depths of 0.9 km below sea level to a few hundred meters above sea level, a deeper magma source area at 3.5 to 5.0 km depth, and a possible conduit defined by deeper earthquake hypocenters observed in 1975 and 2006. Xs note areas of VT earthquake hypocenters. P-wave seismic velocities determined by Kienle and others (1979) are shown on the left and beneath the volcano.

the upward movement of magma and associated volatiles along a conduit system or magma pathway. The 1976 eruption was both more explosive and more voluminous than the 1986 or 2006 eruptions. Perhaps the deeper precursory earthquakes in 1975 reflect the ascent of either a greater volume of magma or a more volatile rich and consequently more explosive magma. We have no compelling explanation for the lack of earthquakes in this 2-to-5-km depth range before the 1986 and 2006 eruptions. The 2006 precursory sequence was much more closely monitored than either the 1976 or 1986 precursory phases (fig. 2) and we located many more earthquakes in 2005 and 2006 than before either the 1976 or 1986 eruptions. On the basis of the appearance of deeper earthquakes' waveforms in 1975 and 2006 (figs. 12 and 22) and the increased station coverage in 2006 (fig. 2*C*), we think the lack of observed activity in this depth range before the 1986 and 2006 eruptions is not a reflection of network aperture, station geometry, or preferential data acquisition or processing. Consequently we suggest it is most likely that earthquakes in this depth range did not occur before either the 1986 or 2006 eruption.

The deeper earthquakes at 2 to 5 km b.m.s.l. that followed the 2006 eruption most likely reflect a stress response to the removal of magma from this area (fig. 22). Earthquakes at mid to upper crustal depths are often observed to begin beneath a volcanic edifice following the onset of eruptive activity. Such a stress response has been observed at numerous volcanoes, including Mount St. Helens, Washington (Weaver and others, 1981), Redoubt Volcano, Alaska (Power and others, 1994), and Mount Pinatubo, Philippines (Mori and others, 1996). The small numbers and magnitudes of these deeper (2 to 5 km b.m.s.l.) VT earthquakes may be a reflection of a smaller change in stress or strain rate associated with the more frequently active magma system at Augustine. Additional support for this source zone comes from the synthetic-aperture radar (InSAR) measurements from 1992 through 2005 that suggest the presence of a relatively subtle inflationary source at roughly 2 to 4 km depth (Lee and others, this volume) and the deflationary pressure source at 3.5-km depth that was active during the continuous phase of the 2006 eruption (Cervelli and others, this volume). Taking these observations together, we suggest that the magma source zone might most logically lie at 3.5 to 5.0 km depth. This depth is also consistent with petrologic evidence that suggests the source zone at 4 to 6 km depth b.m.s.l. for magmas erupted in 2006 (Larsen and others, this volume). Similar earthquakes in this depth range would not have been located following the 1976 eruption, because only three stations were operating during this period (table 1). Earthquakes in this depth range could easily have been missed following the 1986 eruption, when the network was relatively sparse and the data were recorded on photographic film.

We think the shallower system of cracks likely extends from about 0.9 km b.m.s.l. to a few hundred m a.m.s.l. and is the source zone for most of the VT earthquakes located at Augustine during precursory periods (figs. 7, 10 and 11). The concentration of earthquake hypocenters at this depth range may in part be governed by changes in the density that would accompany the P-wave velocity boundaries observed at 0.9 km b.m.s.l. and sea level. These changes in P-wave velocity are thought to reflect changes from zeolitized sediments to intrusive volcanic rocks beneath the Augustine cone (Kienle and others, 1979). These changes in density and lithology may cause magma and associated volatiles to pause in this area on their rise to the surface. This area of high earthquake activity is coincident with the inflation source modeled by Cervelli and others (this volume) that was active during the 2006 precursory phase.

We find no seismic expression of the deeper inflationary source at 7 to 12 km b.m.s.l. modeled by Lee and others (this volume). The only possible seismic expression of the Augustine magmatic system at mid- to lower-crustal depths is a single magnitude (M_L) 1.5 LP event at 26-km depth that occurred on April 15, 2008 (Dixon and Stihler, 2009).

Magmatic System Activation

Seismicity prior to the 1976, 1986, and 2006 eruptions all began within 0.5 km of sea level. We believe the onset of this seismic activity likely reflects the arrival of magmatic volatiles into the shallow system of cracks (fig. 23). The onset of seismic activity in this depth range began roughly 9 months before all three major eruptions and suggests that the processes that allow volatiles to accumulate in this area were active on a similar time scale before all three major eruptions. Confirmation of this interpretation comes from the uplift observed near sea level beneath the volcano's summit starting in July 2005 (Cervelli and others, 2006). The only seismic expression of movement of magma from greater depths are the shocks between 2 and 5 km depth below sea level that occurred between August and December 1975 (fig. 11) and between March and August 2006 (fig. 22).

As the system of cracks near sea level progressively pressurized, it likely forced some volatiles into the upper portions of the Augustine edifice. This is the process we suspect is responsible for the upward migration of hypocenters reported before the 1976 (Lalla and Kienle, 1980) and 1986 (Power, 1988) eruptions. Confirmation of this process comes from the progressive shallowing of the pressure source revealed by geodetic data between November 2005 and January 11, 2006 (fig. 17), reported by Cervelli and others (this volume). Additionally, increased fumorolic activity was reported 1 to 3 months before the 1976, 1986, and 2006 eruptions. All of these observations suggest that magmatic volatiles had moved upward through the Augustine cone in the months prior to each major eruption.

While the upward migration of earthquake hypocenters is expected, confirmed observations of this phenomenon are somewhat rare. This is perhaps more a reflection of deficiencies of volcano seismic networks, seismic velocity models, and processing methodology than an absence of physical process. The upward propagation of earthquake hypocenters has been reported at Mount Etna, Italy (Castellano and others, 1993), Mount Pinatubo (Harlow and others, 1995), Mount St. Helens (Moran and others, 2008; Thelen and others, 2008), and elsewhere. Propagating earthquake hypocenters have also often been observed associated with the intrusion of dikes in Hawaii (Klein and others, 1987). To examine this phenomenon at Augustine we use the methodology developed by Miller and others (2004) to track the progression of earthquake hypocenters driven by the migration of CO_2 in fold and thrust belts. First we smoothed our relocated hypocenter depths by calculating a 10-point running average of hypocentral depths similar to a convolution with a rectangular window or boxcar filter in the manner described by Oppenheim and Schafer (1975). We then calculated a best fit line to the relocated hypocenters of the precursory sequences of the 1976, 1986, and 2006 eruptions. The resultant data, best fit line, and linear correlation coefficient for each earthquake sequence are shown in figure 24. This analysis suggests that hypocenters moved upwards at a rate of approximately 1 km/yr before the 1976 and 1986 eruptions. A similar long-term upward progression of hypocenters was not observed during the 2006 precursory phase. This result is not unexpected, because the relocated earthquake depths in the 2006 precursory sequence began at a shallower level than in either the 1976 or 1986 precursory sequences (fig. 11). However, we do observe a short-term upward progression in hypocentral depth from 0.2 to 0.6 km a.m.s.l. between December 8 and 12, 2005 (fig. 24). A similar best-fit line for relocated hypocenters on these 4 days has a linear correlation coefficient of 0.9442 and a slope corresponding to 56 km/yr (150 m/d). Deshon and others (this volume) also found that earthquakes migrated upwards at this time on the basis of differential traveltimes measured between summit and flank stations. Geodetic data also indicate that magma and associated volatiles migrated upward between November 17, 2005, and January 10, 2006 (Cervelli and others, 2006). We note that a similar short-term upward migration in hypocenters may have occurred during the 1986 precursory phase between December 30, 1985 and January 1, 1986, when hypocenters migrated upwards from 0.2 to 0.6 km a.m.s.l. (fig. 24). The varying time scales (months and days) of these observed upward migrations suggests that separate physical processes or different conduit geometries may be responsible for generating the earthquake activity.

We did not observe any significant seismic activity under the flanks of the volcano throughout the period of this study, including the precursory sequences of the1976, 1986, or 2006 eruptions (fig. 10). Throughout the 38-year period of this study only a relatively small number of earthquakes were located under the volcano's flanks at distances of 3 to 10 km from the summit vent (fig. 7). This suggests that magma can

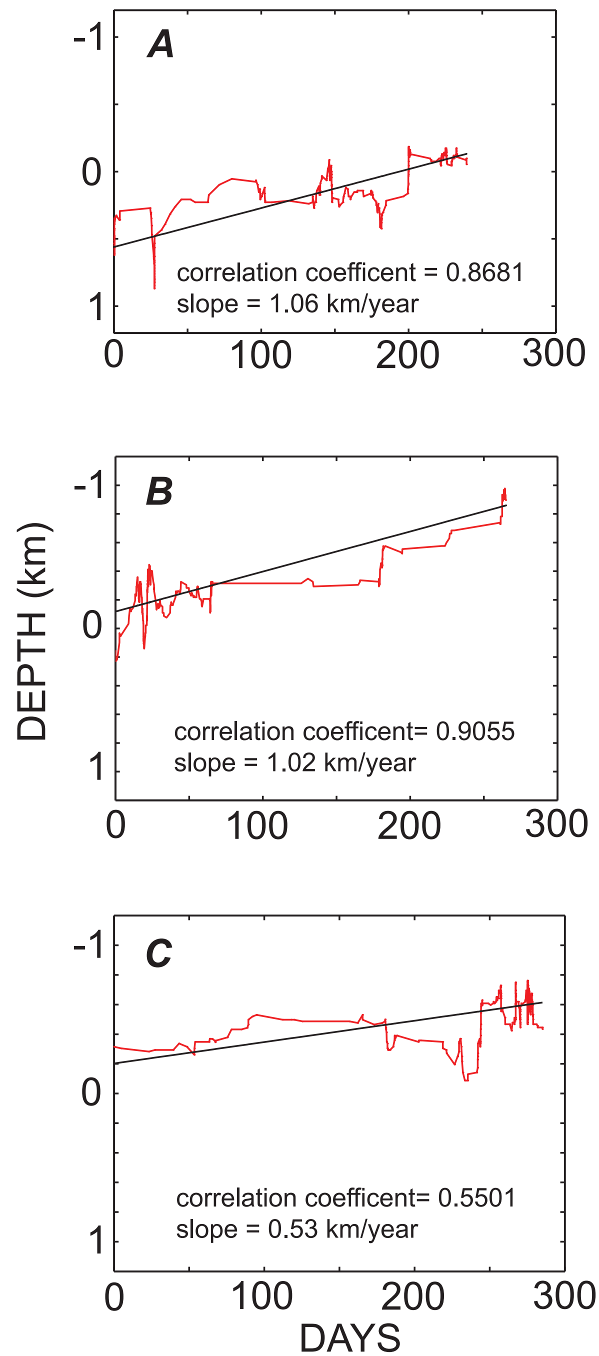


Figure 24. Smoothed hypocentral depths for relocated earthquakes (red lines) under the summit of Augustine Volcano from (*A*) May 2 to December 22, 1975, (*B*) July 4, 1985 to March 26, 1986, and (*C*) April 30, 2005 to January 11, 2006, plotted against the number of days in each sequence. These time periods correspond to the precursory seismic sequences for the 1976, 1986, and 2006 eruptions. Black lines represent least-squares fit to each set of hypocenters. Correlation coefficient and apparent rate of upward propagation of hypocentral depth are shown in each plot. The earthquake hypocenters in 2006 begin at shallower depth, and the resultant fit for the 2006 data (*C*) is poor.

move and erupt at Augustine without significantly stressing the surrounding crust. However, Fisher and others (this volume) did notice an increase in earthquake activity 25 km northeast of Augustine Island in the 6 months prior to the onset of the 2006 eruption and suggest that these earthquakes were triggered by magmatic processes at Augustine Volcano.

Eruption Initiation

The initial vent opening or onset of explosive activity appears to vary a great deal between the 1976, 1986, and 2006 eruptions. The onset of explosive activity in 1976 was extremely energetic seismically and was accompanied by a series of several hundred earthquakes on January 22 and 23, 1976 with larger magnitudes ($M_{L\max} \sim 2.75$) than any observed at Augustine between 1970 and 2007 (fig. 4). The most intense period of earthquake activity preceded the largest explosive eruptions reported by Kienle and Shaw (1977) by more than three hours (fig. 14). In contrast, explosive activity in 1986 was preceded by 3 days of increasing earthquake activity (fig. 16). The 1986 explosive sequence began with relatively small explosions that increased in size over 2 days (Power, 1988, fig. 22). Explosive activity in 2006 was immediately preceded by a 12-hour-long VT swarm (fig. 18) with a maximum magnitude of 1.6 (fig. 20), which is smaller than reported magnitudes of earthquakes that immediately preceded eruptions in 1976 or 1986 (figs. 4, 13).

The observed differences in the magnitudes and durations of earthquake swarms immediately preceding the three major eruptions suggest that the final ascent of magma and associated volatiles occurred differently in 1976, 1986, and 2006. The size of earthquakes does seem to scale roughly with the size of explosions and the amount of modification to the volcano's summit.

Drumbeat Events

The appearance of small, repetitive low- to medium-frequency seismic events or drumbeats at Augustine is very similar to seismicity often observed during effusive eruptions at Mount St. Helens (Moran and others, 2008; Thelen and others, 2008), Redoubt Volcano in Alaska (Power and others, 1994), Usu Volcano in Japan (Okada and others, 1981), Soufriere Hills Volcano in Montserrat (Rowe and others, 2004) and elsewhere. Often events with these frequency characteristics are referred to as hybrids (Lahr and others, 1994). The source mechanism of drumbeat seismicity has been the subject of vigorous research since their recent appearance at Soufriere Hills Volcano and Mount St. Helens. Proposed source models for drumbeat-style seismicity include a pressure transient in a fluid filled crack (Chouet, 1996; Waite and others, 2008), resonance of a fluid within a crack or conduit initiated by a stick-slip event within the magma (Neuberg and others, 2006), and stick-slip along the conduit magma interface (Iverson and others, 2006, Harrington and Brodsky, 2007; Iverson, 2009). It is not possible to fully characterize the source of repetitive events or drumbeats at Augustine given the observations and analysis presented here. However, the repeated occurrence of drumbeat seismicity during several eruptive events at Augustine allows us make some inferences about their source and significance.

Drumbeat-style seismicity was observed at Augustine associated with active periods of lava extrusion during both the initial dome building phase of the 1986 eruption (Power, 1988) and during the effusive phase of the 2006 eruption (fig. 21). In each case the drumbeats quickly coalesced into a continuous high-amplitude signal that persisted for roughly 8 days in both 1986 and 2006. At the end of each episode the high-amplitude signal slowly diminished until individual events could again be distinguished and then slowly faded into the normal seismic background. The initial dome building phase of the 1986 eruption had a second pulse of drumbeat seismicity that consisted only of discrete events and continued for 5 days. This second episode followed a 2 day hiatus in drumbeat activity (Power, 1988). In each of these cases of drumbeat style seismicity, the effusion of magma was actively occurring at the summit, building a lava dome.

Short episodes of drumbeat earthquakes lasting several hours were also observed briefly on January 11 and 12 during the early portions of the explosive phase of the 2006 eruption (fig. 18). These drumbeats provide some constraint on the source depth because they occur before many of the seismic stations were destroyed and we can determine their hypocentral depth relatively well. Relocated hypocenters using the 2D relocation method of Lalla and Power (this volume) suggest depths of 0.25 to 0.5 km a.m.s.l., while Deshon and others (this volume) have determined that a depth of 0.2 km a.m.s.l. or shallower for these events. The strongest sequence occurred between 2036 and 2206 AKST, and Buurman (2009) found these events to consist of a single family of events whose source migrates roughly 20 m over 1.5 hours.

The occurrence of repetitive events or drumbeats on January 11 and 12, 2006 suggests that magma may have reached the surface and a small lava dome may have begun to form as early as January 11. Unfortunately, insufficient visual observations of the summit of the volcano between January 11 and 13 do not allow us to confirm that new magma reached the surface at this time (Wessels and others, this volume). However, the strongest drumbeats begin at about 2036 AKST on January 11, which corresponds with the end of shallow deformation of the summit area. This change in deformation has been attributed to the possible onset of lava extrusion (Cervelli and others, this volume). Further, the deposits from the early explosions on January 13 contain a high percentage of dense low-silica andesite clasts, suggesting that these explosions may have partially removed new dome material (Vallance and others, this volume). The most likely explanation for these observations is that a new lava dome possibly began to form as early as late on January 11, 2006, in association with this sequence of drumbeats. Alternatively, these early drumbeats may only reflect the shallow movement of magma that may not have reached the surface.

During the effusive phase of the 2006 eruption, roughly 23 million m^3 of low-silica andesite (57 weight percent SiO_2) was erupted (Coombs and others, this volume). The average rate of extrusion during the 8 day period of drumbeat activity, assuming that magma effusion is restricted to periods when drumbeats are occurring, is roughly 33 m^3/s. We note that this extrusion rate exceeds the reported rates for Mount St. Helens in November 2004 through March 2005 of 4 to 5 m^3/s (Shilling and others, 2008) when drumbeat events were occurring at rates of 0.3 to 3 per minute (Moran and others, 2008). The rate of magma extrusion and drumbeat events (3 to 6 per minute) at Augustine greatly exceed the rates at Mount St. Helens, suggesting that the rate of drumbeat events may reflect the extrusion rate of magma. Unfortunately, the calculations of erupted volume at Augustine lack the temporal resolution to establish a specific relationship between magma flux and drumbeat rate and size. The drumbeats at Mount St. Helens occurred while lava was actively forming large peleean spines that were coated with fault gouge (Iverson and others, 2006). At Augustine there were no observations of notable fault gauge or spine development during the effusive phase of the 2006 eruption, suggesting that these are not required for generating drumbeat seismicity. No obvious periods of drumbeat activity were observed during the continuous phase of the 2006 eruption when magma with composition of 62.5 weight percent SiO_2 was dominant (Coombs and others, this volume). Oddly, magma erupted during the 2006 continuous phase at Augustine most closely matches the 65 weight percent SiO_2 of magma erupted at Mount St. Helens (Pallister and others, 2008) in 2004 when drumbeats were prevalent. This suggests that the occurrence of drumbeat style seismic events is not simply related to the magma's composition.

At the start of the 2006 effusive phase, drumbeats were observed to increase discontinuously in both rate and amplitude over a 16-hour period (fig. 21). At the end of the effusive phase drumbeats slowly decreased in rate and size between March 13 and 16. During most of this phase, the drumbeats formed a continuous high-amplitude signal that clipped many of the short-period stations on the island. Visual observations of the growing lava dome suggest that the high-amplitude drumbeat signal roughly corresponds to the period of maximum extrusion rate (Coombs and others, this volume; Wessels and others, this volume). These observations suggest that the rate and amplitude of drumbeats at Augustine in at least the 2006 effusive phase may correspond to the rate of magma extrusion.

It is also apparent from observations of the 2006 eruption of Augustine that lava domes can be emplaced on the summit without the occurrence of drumbeats. This was the case for the small dome observed on January 16, 2006 (Coombs and others, this volume). This dome was emplaced while stations as close as AUH (fig. 2*C*) were in operation without identifiable drumbeat seismicity. This indicates that magma of similar composition can move at shallow depths without accompanying drumbeat seismicity.

Observations of Augustine drumbeat-style seismicity suggest that its source is associated with the shallow movement of magma. The source is likely a complex process governed by a number of variables, such as the extrusion rate, ascent rate, gas content, compressibility and rigidity of magma as it moves at shallow depth. The best estimations of hypocentral depth suggest that drumbeats take place at 0.2 to 0.5 km a.m.s.l. These depths suggest that the actual source is within the Augustine cone and is not associated with a specific process related to the effusion of magma or formation of a lava dome at the volcano's summit. At Augustine the shallow movement of magma is closely associated temporally with the effusion of lava and emplacement of a lava dome at the summit of the volcano. The absence of obvious fault gauge or peleean spines at the summit of Augustine, as was observed at Mount St. Helens during drumbeat seismicity (Iverson, 2008; Moore and others, 2008) would lead us to prefer the models of Waite and others, (2008) or Neuberg and others (2006) for the source of Augustine drumbeats. At Augustine this style of seismicity is closely associated with effusion of magma at the summit.

Eruption Forecasting

In this section, we review the role that seismic observations played in formulating eruption forecasts and public warnings and the factors that influenced our interpretations during the 2006 eruption sequence, and we provide recommendations for evaluating future episodes of seismic unrest at Augustine Volcano. Neal and others (this volume) provide a detailed account of the specific warnings issued by AVO and the communication protocols used to disseminate the warnings, while Adleman and others (this volume) describe how AVO communicated with the news media and general public during the 2006 eruption. The forecasting strategy used by AVO relied on the synthesis of data from a number of different monitoring techniques, which include seismic (hypocenters, seismicity rate, RSAM, continuous spectral measurements, and waveform characteristics), visual observations, satellite observations, gas-flux measurements, and CGPS data. These observational data streams were supplemented by well-developed chronological information on the two most recent eruptions in 1976 (Johnston, 1978; Swanson and Kienle, 1985; Reeder and Lahr, 1987) and 1986 (Yount and others 1987; Power, 1988; Kienle and Swanson, 1988). The most important information for forecasting in 2006 was that the progression of unrest and eruptive events in 1976 and 1986 were strikingly similar. Both the 1976 and 1986 eruptions were preceded by roughly 9 months of slowly escalating VT earthquake activity. Each of these eruptions consisted of an initial explosive phase followed by two additional periods of eruptive activity characterized by milder explosive eruptions and effusive activity (fig. 8). Although the overall progression of seismic activity and eruptive events during the 1976 and 1986 eruptions were similar, there are notable differences that were considered in developing forecasts of the 2006 eruption. The most important differences were that the 1976 eruption was much more voluminous than the 1986 eruption, the 1976 precursory seismic sequence contained earthquakes with hypocenters in the 2 to 5 km depth range while the 1986 eruption did not, and the 1976 eruption progressed to completion much faster than the 1986 eruption (fig. 8).

The long-term AVO seismic monitoring program allowed us to identify the initial increase in VT earthquake activity and heighten our surveillance of the volcano as the shocks were occurring in the spring of 2005. Long-term seismic monitoring (fig. 3) allowed us to recognize that the initial subtle increase was significant, even though the early portions of the 2006 precursory seismicity were milder than either the 1976 or 1986 sequences (figs. 3, 4, 8). The prominent earthquake swam in October 2004 had a much shorter duration than the seismic increase in the spring of 2005.

This early identification of increased seismicity focused our attention on Augustine and allowed us to identify the uplift that began in July 2005 (Cervelli and others, 2006) at an early stage. Continued increases in both seismicity and uplift (fig. 17) provided a strong basis for the first public warning of possible renewed eruptive activity on November 29, 2005 when AVO moved the color code to yellow (Neal and others, this volume). Although some uncertainty persisted at this time about the eventuality of an eruption, the color code change positioned AVO to respond to the further escalations in unrest that were to follow shortly.

The continued increases in seismicity rate and geodetic uplift, combined with the phreatic explosions in early to mid December, the greatly increased fumorolic activity, opening of extensional cracks on the volcano's summit, and the greatly increased gas flux (McGee and others, this volume), served only to focus more of our attention on Augustine. During this period we greatly intensified our monitoring of Augustine by adding broadband seismometers, temporary CGPS receivers, time lapse cameras, Web cams (Paskievitch and others, this volume), and a pressure sensor (Petersen and others, 2006). In hindsight much of this equipment should have been deployed on the volcano earlier in the precursory phase when snow cover would have been lighter and we could have benefited from longer daylight hours.

The energetic earthquake swarm that began late on January 10 (fig. 18) was an unequivocal sign that eruptive activity should be expected in the short term. The level-of-concern color code was raised to orange at 2105 AKST on January 10, and AVO began 24-hour monitoring in both the Anchorage and Fairbanks offices. Although it was recognized on January 10 that the 2006 swarm had a more sudden onset than the earthquake swarm that immediately preceded eruptive activity in 1986 (compare figures 15 and 17). Unfortunately no warning was issued immediately following the first explosive event at 0444 AKST on January 11. The waveform of this explosion resembles a large VT earthquake in the short-period velocity record (fig. 18), and the relatively small amount of ash generated by this explosion only produced a short radar return (Schneider and others, 2006). The waveform of the second explosion at 0512 was much less ambiguous, and the level-of-concern color code was raised to red at 0550 AKST.

Following the onset of explosive activity on January 11, careful monitoring of seismic activity, along with radar and satellite imagery, allowed AVO to issue warnings of explosive eruptions on January 13, 14, 17, 27, and 28, often within seconds of the explosion's onset (Neal and others this volume). Further warnings were issued during the later phases of the eruption, again often formulated on the basis of the similar patterns in eruption progression observed during the 1976 and 1986 eruptions. The onset of drumbeat earthquakes on March 8 was especially noteworthy, because we were immediately able to associate this seismic activity with renewed lava extrusion. AVO lowered the level-of-concern color code from orange to yellow on April 28 and from yellow to green on August 9, 2006 (Neal and others, this volume).

A significant problem during the 2006 eruption was that all telemetered seismic and CGPS instruments near the volcano's summit and on the north side of the volcano were eventually destroyed by eruptive activity. This made it impossible to reliably calculate earthquake hypocentral depths in near-real time and track deformation of the upper portions of the edifice. To some extent, station loss is unavoidable; however, if stations had been operating high on the south and east flank of the volcano in 2006 these stations would likely have survived the eruption. In future years we recommend installing telemetered stations in locations near the site of AU13 and similar higher locations on all quadrants of the volcano. Ideally these seismometers would be three-component instruments.

In evaluating future episodes of unrest at Augustine, the following observations should be considered:

1. The 1976, 1986, and 2006 eruptions were all preceded by roughly 9 months of slowly escalating earthquake activity (figs. 3, 8) and hypocentral depths were observed to migrate slowly upward before the 1976 and 1986 eruptions (fig. 24). Shorter term upward migrations were also observed before the 1986 and 2006 eruptions.

2. Each of the three major eruptions began explosively and was followed by several months of discontinuous effusive activity. Although the overall character of each major eruption was similar, they progressed to completion on different time scales. The total duration of eruptive activity from beginning to end was approximately 85, 178, and 67 days for the 1976, 1986, and 2006, eruptions respectively (fig. 8).

3. Historical reports (Davidson, 1884; Coats, 1950; Detterman, 1968; Johnston and Detterman, 1979), as well as the geologic record (Waythomas and Waitt, 1998), indicate

that past eruptions show more variability in eruptive size and duration than we have seen in 1976, 1986, and 2006.

4. Smaller eruptions similar to that seen in 1971 should also be expected, and the period of precursory activity may be shorter than what was observed in 1976, 1986, and 2006.

5. Earthquakes at 2 to 5 km depth b.m.s.l. preceded the more explosive onset of the 1976 eruption (fig. 11). Procedures should be developed to closely monitor earthquake activity in this depth range.

6. The duration and size of earthquakes over the 24 to 48 hours immediately preceding the eruption's explosive onset in 1976, 1986, and 2006 showed great variability. Such variability in the onset of explosive activity should be expected in future eruptions.

7. Drumbeat seismicity was observed during the initial dome-building phase of the 1986 eruption and during the effusive phase of the 2006 eruption, when new magma was being actively extruded at the volcano's summit. Drumbeats were also observed during several brief periods of the explosive phase of the 2006 eruption. However, drumbeats were not observed in association with active lava extrusion during the second dome-building phase of the 1986 eruption or several periods of the 2006 eruption. Drumbeats should be taken as a strong indicator that magma is moving at shallow depth within the edifice and is likely forming a lava dome at the summit.

Summary and Conclusions

This paper summarizes the primary observations of seismic activity at Augustine Volcano between 1970 and 2007. During this period, Augustine Volcano experienced one minor and three major eruptions. Judging from the spatial and temporal development of earthquake hypocenters in association with a minor eruptive event in 1971 and three major eruptions in 1976, 1986, and 2006, we suggest that the subsurface magmatic system consists of a source region between 3.5 and 5 km depth b.m.s.l., and a system of cracks near sea level where magma and magmatic volatiles pause as they ascend to the surface. The position of these cracks may be controlled by density contrasts associated with rock types that are observed in changing P-wave velocities. These two magma storage areas are perhaps connected by a system of dikes or conduits that also extend to the surface.

The last three major eruptions at Augustine were all preceded by roughly 9 months of seismic activity. Hypocenters were observed to migrate upwards before the 1976 and 1986 eruptions over the length of the precursory period. However, before the 2006 eruption hypocenters began at a shallower depth, and a longer term upward migration was not observed. Relocated earthquake hypocenters and continuous geodetic data tracked a shorter term upward progression late in the precursory phase of the 2006 eruption (Cervelli and others, 2006; Cervelli and others, this volume). Each of these eruptions also followed a similar progression from explosive to effusive activity, although the time from onset to completion of eruptive activity varied considerably. Petrologic evidence also suggests that the magma-mixing events thought to have triggered the 1976, 1986, and 2006 eruptions involved magmas of similar composition. This overall similarity suggests that the physical processes responsible for the accumulation, rise, and eruption of magma at Augustine are roughly constant or change only slowly with time. If conditions do not change, future eruptions of Augustine might be expected to follow a similar pattern.

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