Seismicity and Forecasting of the 1992 Eruptions of Crater Peak Vent, Mount Spurr Volcano, Alaska: An Overview

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CONTENTS

ABSTRACT

Seismicity associated with the 1992 eruptions of the Crater Peak vent of Mount Spurr was monitored by a network of 6 to 10 seismometers within 15 km of the mountain's summit. Precursory seismicity began in August of 1991. It was marked by a conspicuous swarm of shallow volcano-tectonic (VT) earthquakes beneath Crater Peak, the first such swarm in a decade of monitoring, and by the gradual onset of seismicity between depths of 5 and 40 km, in a volume of rock that had been essentially aseismic for nearly a decade. The volcano erupted three times during 1992: on June 27, August 18, and September 16–17. The June eruption was preceded by about 14 hours of continuous tremor and a vigorous 4-hour swarm of shallow VT earthquakes. Following the June eruption, shallow seismicity decreased to normal background levels, and the August eruption occurred without any detectable precursory seismicity. A few hours of shallow seismicity preceded the September eruption, after which seismicity in the depth range of 5 to 40 km peaked. From an initial analysis of the seismic data, we suggest the 1992 eruption sequence resulted from the intrusion of magma into the mid-crust that began in mid-1991. The magma had migrated to shallower depths by early June of 1992, when the distribution of hypocenters changed and volcanic tremor began. The character of seismograms suggests the deep seismicity included a variety of source processes ranging from brittle failure of the country rock in response to injection and withdrawal of magma to the vibration of fluid-filled cracks associated with magma transport.

Close monitoring of Mount Spurr seismicity allowed the Alaska Volcano Observatory to issue public statements describing the increased activity beginning in August of 1991. Forecasts were issued prior to the June 27 and September 16–17 eruptions, and notifications were issued shortly after all three events. Two additional forecasts were issued on the basis of observed increases in seismicity that did not culminate in eruptions.

INTRODUCTION

During the summer of 1992, Crater Peak erupted three times—on June 27, August 18, and September 16–17. Each of the eruptions lasted 3.5 to 4 hours and produced large tephra plumes, which drifted downwind across large parts of Alaska (Neal and others, this volume).

Rudimentary seismic monitoring of Mount Spurr volcano began in 1971, and since 1989 the Alaska Volcano Observatory (AVO) has operated a 6- to 10-station seismic array (herein referred to as the Spurr network) centered on the volcano. The reawakening of Crater Peak was preceded by roughly 10 months of elevated earthquake activity that spanned the caldera and extended to depths of 40 km. The seismicity associated with the eruptions constitutes a complex sequence of events including shallow volcano-tectonic (VT) earthquakes, long-period (LP) events, volcanic tremor, and periods of seismic quiescence (see "Instrumentation and Data Analysis" section for definitions).

In this paper we describe the seismicity at Mount Spurr preceding and accompanying the 1992 eruption sequence. First we review the seismic instrumentation, data acquisition, and data analysis. We then briefly summarize the seismic data from the Mount Spurr area beginning in 1981 as well as develop a more detailed seismic chronology for the period between August of 1991 and December of 1992. This chronology is based primarily on earthquake hypocenter plots and helicorder records, and to a lesser degree on Real-time Seismic Amplitude Measurements (RSAM) (Endo and Murray, 1991) and Seismic Spectral Amplitude Measurements (SSAM) (Stephens and others, 1994). We offer an initial volcanological interpretation of the patterns of seismicity, and we conclude with a review of the role that seismic observations played in forecasting the 1992 eruptions.

ACKNOWLEDGMENTS

We thank John Paskievitch, Steve Estes, John Rogers, and John Benevento for keeping instrumentation and telemetry running reliably throughout the 1992 eruptions. Gail Davidson provided valuable assistance with data acquisition and computer management. The success in forecasting the Crater Peak eruptions is shared with our colleagues, most notably John Lahr, Bernard Chouet, Scott Stihler, Christopher Stephens, Guy Tytgat, and John Davies. We thank Elliot Endo and Randy White for their reviews of the manuscript and figures.

INSTRUMENTATION AND DATA ANALYSIS

Seismic monitoring on Mount Spurr volcano has a relatively long history. Station SPU was installed roughly 14 km from the summit of Mount Spurr in August of 1971 (fig. 1). The addition of stations CRP and CGL in the fall of 1981 allowed small earthquakes near Mount Spurr to be located. Station CGL was not maintained between late 1985 and early 1989, so only two stations were operating near the volcano. Following the establishment of AVO, three new stations, CKL, BGL, and NCG, were added to the seismic network in late 1989, and stations CKN and CPK were in-

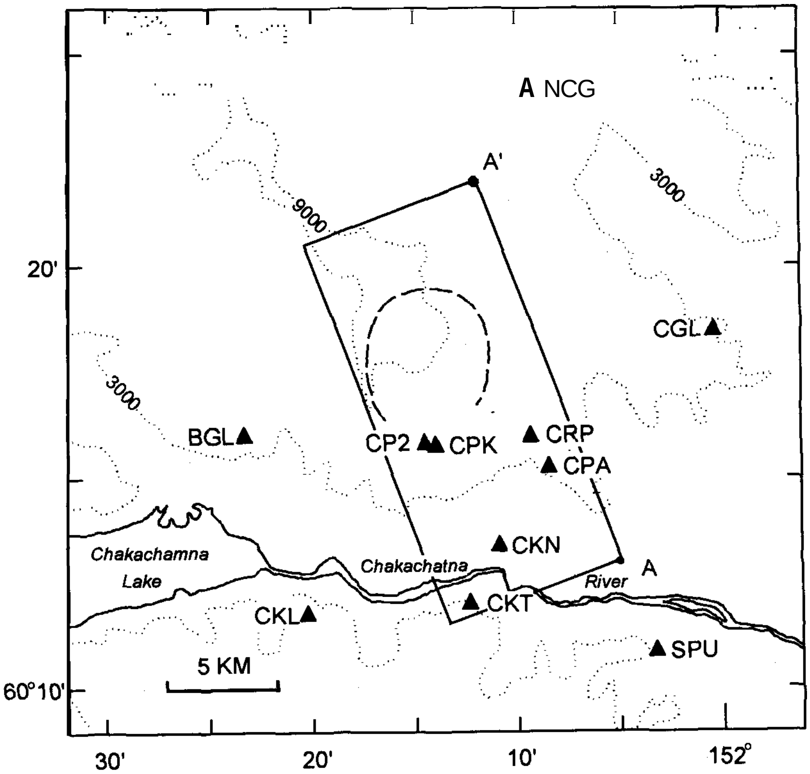


Figure 1. Seismic stations near Mount Spurr volcano, Alaska. Dotted lines represent 3,000- and 9,000- foot contours, dashed line represents approximate location of caldera rim. Box and line A-A' denote spatial extent of hypocenters shown in figure 4, and the location of projected plane for cross sections in figure 3.

stalled in the fall of 1991. Station CPK was destroyed during the June 27, 1992, eruption. A new instrument was installed at the same location on September 10, and it was subsequently destroyed during the September 16–17 eruption. Station CPK was replaced by station CP2 on October 23. Stations CKT and CPA were added to the network on September 20 and October 29, respectively, which brought the total number of stations in the seismic network to ten. All stations were short-period single-component vertical seismometers except CPA and the original CPK, each of which had horizontal components. The original CPK also had a low-gain vertical component.

Between 1981 and 1989, data from the Spurr seismic network was recorded on 16-mm photographic film. Starting in July of 1988 these data were digitally recorded on a computer system at the AVO office in Fairbanks (AVO staff, 1990). In October of 1989, we also began recording the Spurr network on a personal computer using the program MDETECT, which digitizes and records 16 channels of event-detected data (Lee and others, 1989). This acquisition system provided the primary data set used in this study. Not all the stations from the Spurr network were recorded on the personal computer system during 1990 (fig. 2) because stations monitoring the ongoing eruptions of Redoubt Volcano were given higher priority for available channels on the system (Power and others, 1994). Beginning January 1, 1991, a complete suite of Spurr stations was established on this system and the triggering parameters were held constant through February 1993. Stations in the Spurr network were also monitored by an RSAM (Endo and Murray, 1991) and an SSAM (Stephens and others, 1994) system. March and Power (1990) described the various computer systems and their networking.

Event-detected waveforms were transferred to a microcomputer and phase arrivals were determined using the program XPICK (Robinson, 1992). Hypocenters and local magnitudes were determined using the program HYPOELLIPSE (Lahr, 1989) with a flat-layered velocity model and station corrections to account for local variations in seismic-wave velocities. The model we used was developed specifically for the Mount Spurr area by Jolly and others (1994). In this model, earthquake depths are permitted to occur as much as 3.2 km above sea level: the elevation of the summit of Mount Spurr. Consequently, depths are referenced to sea level; negative depths refer to height above sea level.

In describing the various waveforms and event types at Mount Spurr volcano, we use terminology and event classifications similar to that developed by Chouet and others (1994). Lahr and others, (1994), and Power and others, (1994) during the 1989–90 eruptions of Redoubt Volcano. This classification system is based on our present understanding of the physical processes associated with various seismic sources. Volcano-tectonic earthquakes refer to sources representing purely elastic processes. Long-period events are thought to represent a more complex process in which fluids (gas and liquid phases) play an active role in the generation of seismic waves (Chouet, 1992). Volcano-tectonic and LP events represent end members of a spectrum; events combining these two characteristics are referred to as hybrid events. We do not identify hybrid events in this paper because identification of their spectral characteristics requires additional analysis, which has not yet been attempted (see Lahr and others, 1994). The seismic events associated with the forcible ejection of gas and ash from the volcano are referred to here as explosive eruptions.

SEISMIC CHRONOLOGY

OCTOBER 1981 THROUGH JULY 1991

Mount Spurr and the surrounding area has been seismically active since local monitoring began in 1981. During periods between October 1981 and August 1991 when three or more stations were operating in the Spurr network, an average of 8.5 earthquakes per month greater than magnitude (M_L) 0.0 were located within 20 km of the volcano (fig. 2). Most of this activity concentrates beneath the summit at depths shallower than 3 km. Very few shocks were located deeper than 5 km (fig. 3A). The largest located event in the Spurr area is a magnitude 3.3, which occurred on November 16, 1989, at a depth of 16.5 km about 12 km northwest of the summit. Most located events range between magnitudes -0.5 and 1.5.

A second concentration of epicenters lies on the north rim of the Mount Spurr caldera. Activity in this area occurred in two clusters; one is about 2 km north of the main summit cluster, and the other is roughly 3 km northeast of the main summit cluster (fig. 3A). The one northeast of the summit is the site of two small swarms of shallow earthquakes that occurred in early 1982 and in early 1989 (fig. 4A). Hypocenters could not be calculated for the 1989 swarm, because only two stations were operating at the time. On the basis of similarities in waveforms between the two swarms, however, we surmise that the 1989 swarm occurred in the same location as the 1981 swarm. A more detailed description and analysis of the seismicity during this period is given by Jolly and others (1994).

AUGUST 1991 THROUGH JUNE 27, 1992

The first sign of reawakening at Mount Spurr volcano was a small swarm of VT earthquakes be-

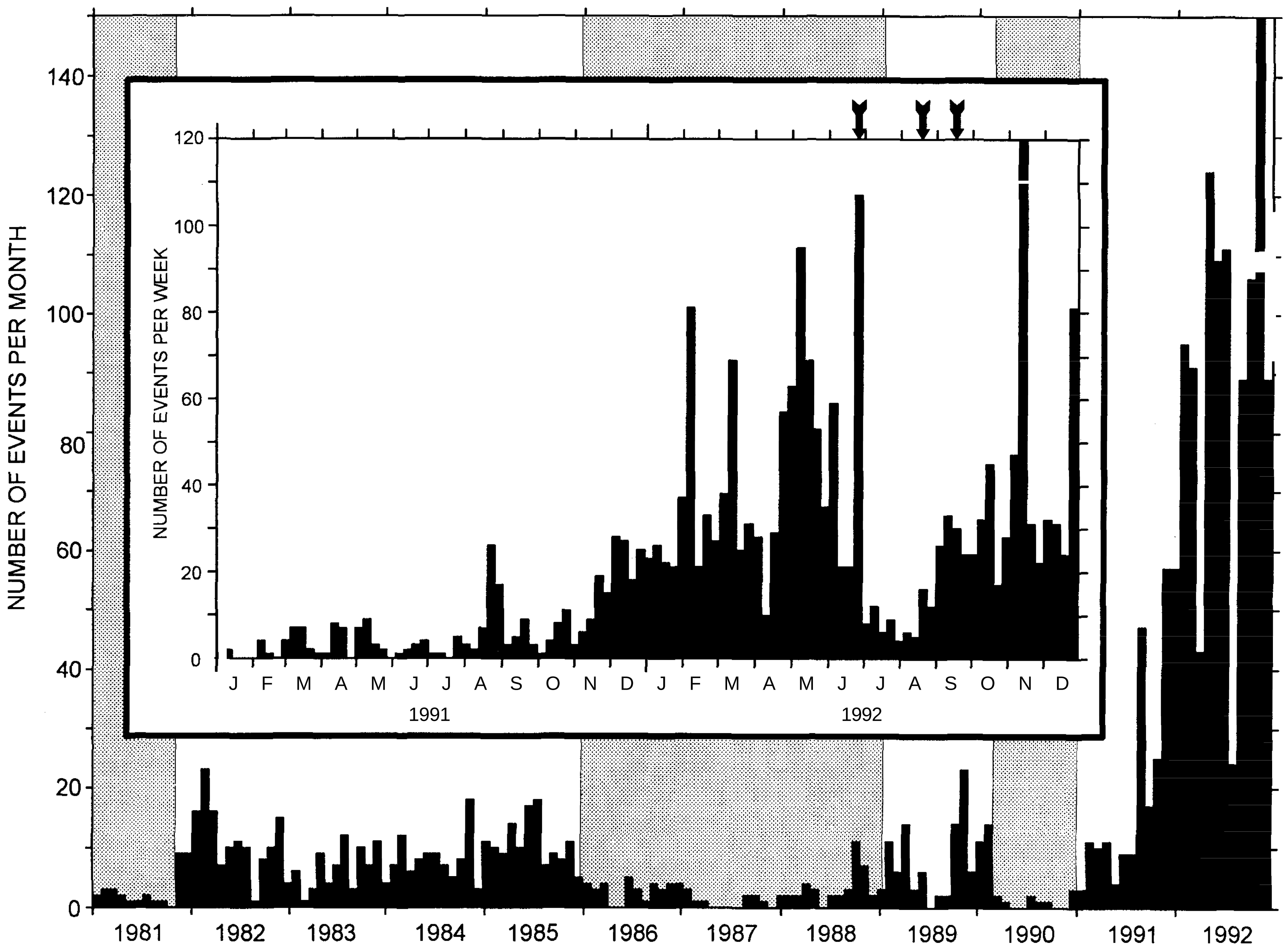


Figure 2. Histogram of monthly number of earthquakes greater than M_L 0.0 located within 20 km of the summit of Mount Spurr volcano between 1981 and 1992. Shaded pattern in 1981 and between late 1985 and early 1989 reflects periods when fewer than three stations were operating in the Spurr network. Shaded pattern in 1990 denotes a period when not all stations in the Spurr network were recorded on the computerized data-acquisition system (see text for details). Inset shows weekly number of events located regardless of magnitude during 1991 and 1992. Arrows denote approximate times of eruptions. Note peaks in activity in February, March, and May, as well as relative quiescence following the June 27 eruption. Strong peaks in June and November correspond to the swarm immediately preceding the June 27 eruption and the November 9–10 swarm.

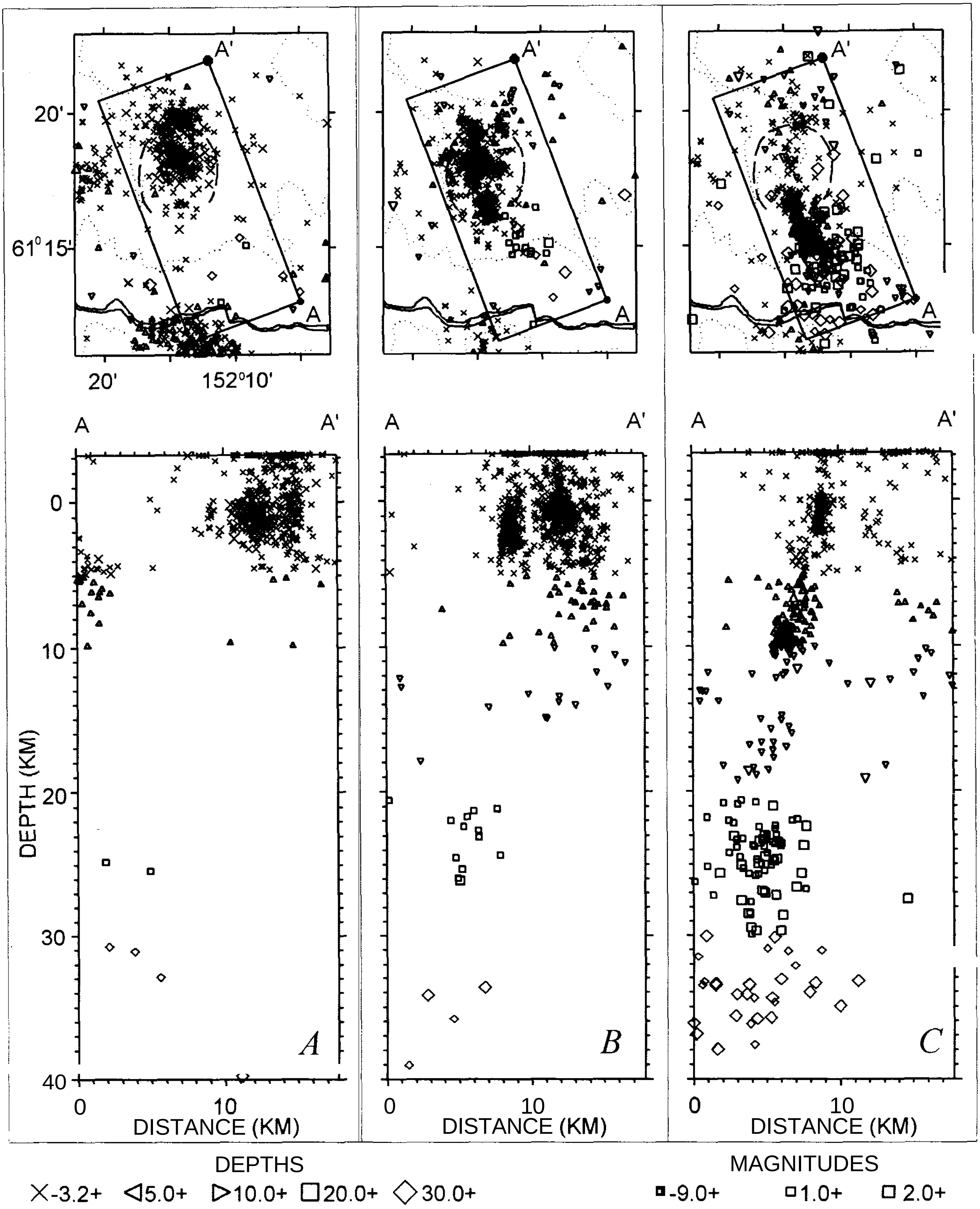


Figure 3. Epicenter maps and cross sections (A to A', figure 1) for three successive periods: A, background, October 1981 through July 1991; B, precursory, August 1991 through June 1992; and C, eruptive, July through December 31, 1992.

neath Crater Peak in August of 1991 (fig. 4B). Most of these shocks were less than ML 1.0 and ranged in depth from 1 to 4 km. This swarm marked the first sustained seismic activity observed beneath Crater Peak since earthquake hypocenters could be reliably determined in 1981 (fig. 4A).

The August activity beneath Crater Peak was followed by two months of quiescence, and then by continuous elevated activity punctuated by more intense periods of seismicity in February and May (fig. 4B).

The August 1991 Crater Peak swarm initiated an increase in shallow seismic activity, which spanned the Mount Spurr caldera. Except for the Crater Peak area, this increase was mostly confined to areas that had been historically active—the summit and the north caldera rim. The number of VT earthquakes beneath the summit of Mount Spurr began to increase in October of 1991 (fig. 4B). Activity beneath the summit then increased nearly continuously until early June of 1992. Hypocenters were generally concentrated between -1.0 and 5.0 km in depth, although several shocks were recorded as deep as 15 km (fig. 3A). The largest event during this period was a M_L 1.7 on February 18, 1992, at a depth of 0.3 km.

Activity beneath the north caldera rim was more discontinuous (fig. 4B). The first perceptible increase was a small group of earthquakes between 0 and 2 km depth in mid-December. More vigorous swarms occurred in March, April, and May of 1992. These events were concentrated near the two clusters of events from the previous decade (compare figs. 3A and 3B). The distribution of depths in the north cluster is more diffuse, generally ranging from -2.0 to 6.0 km. The largest event during this period beneath the north rim is a M_L 1.6, which occurred on May 3, 1992, at a depth of 0.3 km.

On June 5, 1992, the number of located earthquakes at Mount Spurr volcano reached 28, the highest number recorded in any 24-hour period. These shocks ranged in depth between -1.0 and 1.0 km and were clustered beneath Crater Peak. Coincident with this swarm, short bursts of volcanic tremor were recorded on the stations closest to Crater Peak for the first time (McNutt and others, this volume). Following the June 5 swarm, the number of locatable events declined throughout the entire caldera, most notably beneath the summit and Crater Peak (figs. 2 and 4B).

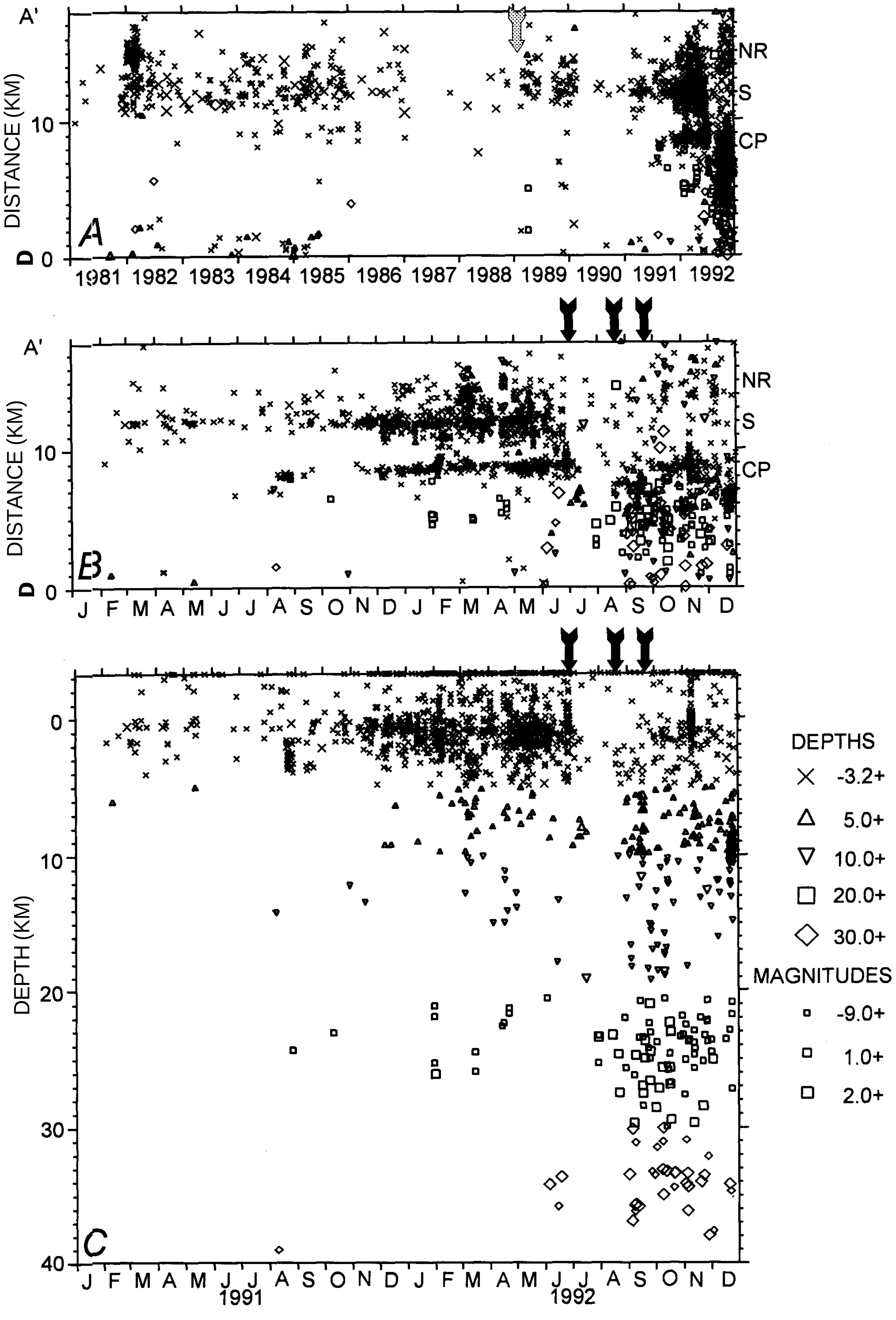
The other noticeable change in seismicity, which occurred between August of 1991 and June 27, was the onset of activity in the depth range of 10 to 40 km beneath and southeast of Crater Peak (figs. 3B, 4B). The first of these events was located in August of 1991, and more than 40 occurred before the June 1992 eruption. These events occurred in a volume that had been practically aseismic during the previous decade (compare fig. 3A and 3B). Waveforms from events at depth display a broader range of spectral characteristics that range from high-frequency earthquakes, which appear to be volcano-tectonic to low-frequency events, which have a strong long-period character. Attenuation of the seismic waves from these deep events makes their classification difficult. Those events that we feel are volcano-tectonic generally have well-defined phases and a dominant frequency between 3 and 4 Hz, whereas low-frequency events lack well-defined phases, have peak frequencies of about 2 Hz, and have extended coda. The variability in observed waveforms for two events from roughly 33 km depth is shown in figure 5. A detailed spectral analysis of all of the events below 10 km has not yet been completed.

At 12:04 p.m. ADT on June 26 continuous volcanic tremor began, which was easily visible on all stations within 14 km of the volcano (McNutt and others, this volume). At roughly 3:00 a.m. ADT on June 27, just 4 hours before eruptive activity began, a vigorous swarm of shallow VT earthquakes began. These shocks were located between -1.0 and 1.0 km in depth and ranged in magnitude between -0.6 and 1.2. The magnitudes of events increased through the duration of the swarm. To date, only three LP events have been identified in this swarm. The eruption on June 27 lasted 4 hours and 3 minutes (McNutt and others, this volume). The June 27 eruption was followed by a short-lived shallow swarm of LP events, which lasted for about 24 hours.

JUNE 27 THROUGH SEPTEMBER 17,1992

Following the June 27 eruption, the volcano entered a period of relative quiescence in which the shallow seismicity was comparable to or lower than the pre-August 1991 level (fig. 4B). In contrast, the deeper seismicity continued at a low, steady rate comparable to its August 1991 through June 1992 level. The area beneath the summit remained nearly aseismic throughout the remainder of 1992, and only low levels of activity occurred beneath the north caldera rim (figs. 3C, 4B).

Figure 4. Time-distance (*A*, B) and time-depth (C) plots for hypocenters within the box shown in figure 1. A and B are time distance plots along the line A-A' for periods 1981 through 1992 and 1991 through 1992, respectively. Shaded arrow in A shows approximate location of 1989 swarm. C, data from 1991–92. Solid arrows denote the three eruptions on June 27, August 18, and September 16–17. ➤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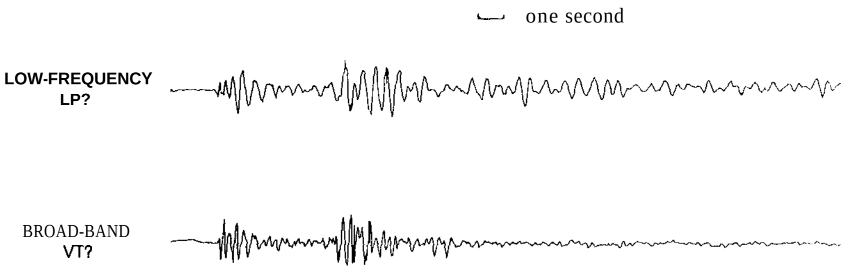

Figure 5. Comparative waveforms recorded at seismic station CGL on Mount Spurr volcano, Alaska, from two events located at a depth of approximately 33 km. These waveforms illustrate the diversity of signals observed in events at depths greater than 10 km. Note the monochromatic character and long duration of the low frequency event (upper trace). Such features are typical of long-period (LP) events.

The August 18 eruption occurred with no obvious seismic precursor at CRP, the closest station to the crater that was operating at the time. Eruptive activity on August 18 began with a small ash-laden plume at 3:37 p.m. ADT, which was accompanied by 16 minutes of weak tremor and several LP events. The main eruption began at 4:42 p.m. ADT and lasted about 3 hours and 28 minutes (McNutt and others, this volume).

Following the August 18 eruption, seismicity below depths of 2 km began to slowly increase, while that at shallower depths remained low (fig. 4*C*). Activity in the depth range of 2 to 10 km and below 20 km appears to have stabilized at a new, higher background level at about the time of the September eruption (fig. 4C). On September 16, shallow tremor, which was interspersed with small discrete events, began about 7:30 p.m. ADT. A small eruption, which lasted about 11 minutes, began at 10:36 p.m. ADT. Seismic activity remained elevated, and at 12:04 a.m. ADT on September 17 the main eruption began. The intense seismicity associated with this eruption lasted 3 hours and 36 minutes (McNutt and others, this volume). The waning phase of the eruption included a series of VT earthquakes between 2 and 11 km depth, the largest of which was a M_L 1.9.

SEPTEMBER 17 THROUGH DECEMBER 31,1992

The seismicity that followed the September 16–17 eruption differed markedly from seismicity that followed the two earlier eruptions. Strong volcanic tremor occurred for roughly 9 days on stations close to the volcano. The rate of VT earthquakes between depths of 0 and 5 km increased and remained elevated over the next 6 weeks (figs. 4*B*, 4C). The occurrence rate of shocks deeper than 10 km also increased following the September eruption.

Shallow volcanic tremor returned several times between October 2 and 7. Early on November 9 the rate of shallow VT earthquakes began to increase on the stations closest to the volcano. By 9:00 p.m. ADT the events were occurring at a rate of approximately 1.5 per minute. This activity continued for roughly 3.5 hours and comprised more than 170 shocks. The magnitude of the largest earthquake was 1.7. This was the most energetic swarm recorded at Mount Spurr associated with the 1992 eruption sequence.

Following the swarm on November 9 and 10, activity remained elevated at all depths. In early December the rate of events between depths of 20 and 40 km began to decline slowly. A swarm of small ($M_L < 1.5$) VT earthquakes occurred between December 21 and 26. These events originated between depths of 5 and 12 km, and most of the events were clustered between 8 and 10 km. Activity slowly declined through early 1993 and by late April the number of locatable earthquakes in the Mount Spurr area approached a level comparable to that observed prior to August of 1991.

DISCUSSION

VOLCANOLOGICAL INTERPRETATION

From our observations of the spatial and temporal patterns of hypocenters, waveforms of the various seismic events, and amplitude and spectral measurements, we offer some interpretations. This discussion should be viewed as preliminary, as it is based on primary observations rather than a detailed analysis of all available seismic data.

Between October 1981 and July 1991, Mount Spurr seismicity was characterized by steady-state activity beneath the summit, punctuated by two swarms under the north caldera rim. There is a marked absence of seismicity at depths greater than 5 km during this period. Jolly and others (1994) model this aseismic zone as a volume of hot buoyant rock, heated by earlier episodes of intrusion, which deformed plastically rather than elastically.

The first unusual activity identified prior to the 1992 eruptions was a shallow short-lived swarm of VT earthquakes beneath Crater Peak in August of 1991 (fig. 4B). This swarm was followed within several months by an increase in shallow activity throughout the caldera. A more subtle increase was also observed at depths greater than 10 km. Its onset may have preceded slightly the August 1991 Crater Peak swarm, but there are too few deep events to draw a definitive conclusion. We propose that most of the seismicity in the 10-month period prior to the June 27 eruption resulted from an intrusion of magma between depths of 5 and 15 km. Thus we suggest a deep origin for the initiation of the eruption sequence. The caldera-wide seismicity likely resulted from a mechanical response to deformation and stresses associated with this intrusion. We suggest that the intrusion produced strain rates that were sufficient to drive rock in the aseismic volume identified by Jolly and others (1994) from plastic to brittle behavior.

That seismicity beneath the summit declined following the June 5 swarm lends support to the mechanical model for the precursory seismicity. The June 5 swarm is coincident with the onset of volcanic tremor at Crater Peak. We suggest that magma had migrated to shallower depths by this time and had activated the shallow hydrothermal system (McNutt and others, this volume). This migration concentrated stress at Crater Peak, which resulted in the decline in activity in other areas of the caldera.

Following the June eruption, seismicity entered a 7-week period of near-quiescence comparable to or less than the level of activity observed prior to August of 1991. This quiescence suggests that stress and related deformation, as well as fluid pressures within the shallow hydrothermal system, were greatly reduced following the eruption. Activity below a depth of 10 km did not lapse into quiescence, although the overall rate of deeper events remained relatively low and did not increase until after the August 18 eruption.

That no increase in shallow seismicity preceded the August 18 eruption and that the September 16–17 eruption was preceded by only several hours of shallow activity visible on CPK suggest that the vent and shallow conduit system were left relatively unobstructed following the June eruption.

Deeper seismicity (>10 km) increased markedly following the August 18 eruption and peaked shortly after the September eruption. The waveforms of these events cover a broad spectrum ranging from VT events to rather monochromatic, low-frequency signals suggestive of LP events (fig. 5). These events might reflect the recharge and migration of magma at these depths. Alternatively, these events might result from readjustments of stress in response to the removal of magma from these depths. Both these explanations are quite plausible in view of the variety of observed waveforms. However, additional analyses are required to demonstrate that the low-frequency waveforms are related to the characteristic of the source process rather than the result of attenuation of higher frequency energy along the wave path.

The strong swarm of events on November 9 and 10 is likely related to a shallow intrusion of magma. Preliminary analysis of these events suggests they occurred at three locations a few hundred meters apart between 0.0 and -1.0 km depth (Chris Stephens, written commun.). The cluster of events in late December is perhaps related to an additional deeper intrusion at 8 to 10 km depth.

ERUPTION FORECASTING

In this section we review the role that seismological observations played in formulating eruption forecasts and the factors that influenced our interpretations at the time. The forecasting strategy used by AVO relied on the synthesis of data from a number of monitoring techniques, which include a variety of seismic methods (hypocenters, seismicity rate, RSAM, SSAM, and waveform characteristics), visual observations, measurements of gas emissions, and geochemical and petrologic analyses. In reviewing AVO's public statements concerning volcanic activity at Mount Spurr volcano, we use the terms forecast and eruption notification. A forecast describes statements issued prior to expected eruptive activity. Forecasts were relatively imprecise statements concerning the timing and nature of expected eruptive activity. Our use of the term forecast differs somewhat from that of Swanson and others (1985) because at Mount Spurr forecasts were formulated on the basis of observed changes in seismic measurements and observations of the volcano. We avoid the term prediction because statements issued for Mount Spurr contained little precise information on the timing of expected eruptive activity. Eruption notifications were purely factual statements that contained information about the onset time and size of eruptions. Eruption notifications described here belong in the category of factual statements in the terminology of Swanson and others (1985). The primary vehicle by which AVO disseminated forecasts and eruption notifications to other government agencies, industry, and the public was based on a color code system similar to that developed during the 1989–90 eruptions at Redoubt Volcano (Brantley, 1990). The color code definitions used at Redoubt were modified slightly on the afternoon of June 26 to more appropriately describe the situation and conditions at Mount Spurr.

Both the June 27 and September 16–17 eruptions were successfully forecast. Whereas no forecast was issued for the August 18 eruption, seismic confirmation allowed AVO to issue an eruption notification within minutes of the onset of both the premonitory and the main eruption. Forecasts were also issued during a period of heightened tremor on October 2 and during the November 9–10 earthquake swarm, but no subsequent eruption occurred.

The 10-month period of precursory VT earthquakes makes the June 27 eruption one of the more anticipated eruptions on record. The unusual character of the August 1991 swarm was recognized as the events were occurring. This was possible because of the long-term operation of the seismic network and the availability of the associated earthquake catalog. Between August of 1991 and June of 1992, the increasing caldera-wide seismicity was discussed in weekly AVO public information releases. On June 8 in response to the escalating seismicity, AVO issued a special public advisory, which stated that the present seismic unrest could be an early forerunner of an eruption. In response to the onset of continuous tremor on June 26, AVO issued a forecast that cited potential hazards associated with an eruption of Crater Peak. The basis for this forecast was the onset of strong continuous volcanic tremor (McNutt and others, this volume) as well as observed changes in the hydrothermal regime at Crater Peak (Eichelberger and others, this volume). While this warning did discuss the increased probability of an eruption, it did not state that an eruption was likely within the next few days. Our hesitation regarding the imminence of an eruption on the evening of June 26 largely stemmed from two factors: two strong episodes of volcanic tremor had occurred earlier on June 24 and 25 (McNutt and others, this volume), and the absence of swarms of LP events. We were perhaps overly focused on the occurrence of swarms of LP events, because of our recent experiences at Redoubt Volcano (Chouet and others, 1994, Stephens and others, 1994) and Mount Pinatubo (Harlow and others, 1991), at which strong LP swarms preceded many of the eruptions. Once the swarm of VT earthquakes began at about 3:00 a.m. ADT on June 27, we had little doubt that an eruption was close at hand. In hindsight, the strength of the tremor on June 26 differed enough from earlier episodes to justify a stronger forecast.

In contrast to late June, no unusual shallow precursory activity was observed prior to the August 18 eruption, although station CPK had not yet been repaired. The eruption ended the 7-week period of shallow seismic quiescence, which followed the June event. The eruption was not expected as the level of seismicity had declined sharply after the June eruption and remained low. Additionally, the 1953 eruption at Crater Peak consisted of a single event (Juhle and Coulter, 1955). The caldera-wide volume activated seismically prior to the June eruption raised the question of the volume of magma involved and the possibility of additional eruptive events. However, in view of the long duration of seismic quiescence following the June eruption, the timing of the August eruption was a surprise. Seismic monitoring did allow confirmation of a small premonitory eruption at 3:35 p.m. ADT, which was reported by a pilot. The occurrence of this small event prompted AVO to issue a public advisory of increased activity. When the main phase of the eruption began at 4:42 p.m. ADT, AVO issued an eruption notification within 2 minutes of its onset.

The September 16–17 eruption was preceded by 3 hours of identifiable shallow precursory activity (McNutt and others, this volume). The overall level of seismicity below a depth of 3 km had been increasing steadily since the August 18 eruption. Following the August 18 eruption, we were particularly mindful that future eruptive events might occur with little or no precursory activity. Close monitoring of the seismicity allowed identification of the precursory tremor shortly after it began and the recognition of the small premonitory eruption at 10:36 p.m. ADT. A forecast was issued at 10:45 p.m. ADT, more than an hour before the main phase of the eruption began at 12:04 a.m. ADT on September 17, and an eruption notification was issued shortly after its onset.

The two unsuccessful forecasts issued during the 1992 eruption sequence were based on an increase in tremor amplitude on October 2, and on an increase in the rate of earthquake occurrence during the November 9–10 swarm. The tremor on October 2 was similar in character to that which immediately preceded the June 27 eruption. Average tremor amplitudes increased dramatically between October 1 and 5 (McNutt and others, this volume). The swarm on November 9–10 was the most energetic observed during the eruption sequence and is likely related to the emplacement of a shallow intrusion. At the height of this swarm, earthquakes were occurring at a rate of roughly 1.5 per minute. While neither of these seismic episodes culminated in an eruption, the forecasts were justified on the basis of the continuing increases in seismicity that were larger than those observed prior to the August and September eruptions. These events serve as a reminder that not all strong increases in seismicity result in eruptions. At this time, there is no seismological basis for differentiating these sequences of events from those that resulted in eruptions.

CONCLUSIONS

Seismological observations suggest that precursory seismicity resulted from an intrusion at mid-crustal depths, perhaps 5 to 15 km. The shallow precursory seismicity that occurred throughout the Mount Spurr caldera was likely a mechanical response to the intrusion. We also observed an increase in seismicity in a previously identified aseismic volume of rock, between depths of 10 and 40 km depth (Jolly and others, 1994). The onset of this seismicity suggests the intrusion generated sufficient strain rates to induce brittle failure in a volume that had previously deformed plastically.

The June 27 eruption was preceded by 10 months of shallow VT earthquakes, several weeks of shallow volcanic tremor, and immediately by 14 hours of tremor and a 4-hour swarm of VT earthquakes between depths of -1.0 and 1.0 km. In contrast the August 18 eruption had no precursory activity visible on the stations operating at the time, and the September 16–17 eruption had only about 3.5 hours of shallow precursory activity. We conclude that the vent and the upper portions of the conduit were left largely unobstructed following the June eruption.

Seismicity between depths of 10 and 40 km exhibits a variety of waveforms ranging from VT to LP. The diversity of waveforms suggests a variety of source processes ranging from stress adjustments in the country rock caused by withdrawal or intrusion of magma, or the transport of magma. Planned analysis of individual deep events should allow us to narrow our interpretations.

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