The 1992 Eruptions of Crater Peak Vent, Mount Spurr Volcano, Alaska: Chronology and Summary

By John C. Eichelberger, Terry E.C. Keith, Thomas P. Miller, and Christopher J. Nye

CONTENTS

ABSTRACT

Following 39 years of inactivity, Crater Peak vent on the south flank of Mount Spurr volcano burst into eruption at 7:04 a.m. Alaska daylight time (ADT) on June 27, 1992. This and subsequent eruptions on August 18 and September 16–17 were subplinian, had a volcano explosivity index (VEI) of 3, and lasted about 4 hours. The June, August, and September eruptions released 44, 52, and 56 million m^3 (12, 14, and 15 million m^3 dense rock equivalent or DRE) of andesitic (57 weight percent SiO_2) tephra, respectively and drove tephra columns 14,000 to 15,000 m above sea level. The August eruption had the most far-reaching effects—it deposited 3 mm of ash on Anchorage, 125 km east of the volcano. Proximal pyroclastic flows accompanied the August and September eruptions. In all eruptions, lahars and debris flows descended Crater Peak's south flank, and some reached the Chakachatna River.

Real-time seismic monitoring tracked the 10-month crescendo of precursory earthquakes and allowed timely warning of the increasing unrest to State and Federal government officials, the military, air carriers, and local citizens. This monitoring was augmented with other types of observations and provided the basis for accurate eruption advisories that minimized economic losses. In particular, because of an efficient ash-cloud warning system in Alaska and new awareness of the problem of ash clouds within the aviation community, no jets were damaged. Unavoidable losses of $5 to 8 million were sustained from the August ashfall on Anchorage and the Matanuska-Susitna Valley, both of which make up the State of Alaska's center of population and economic activity. Additional but unevaluated costs were incurred from flight delays in large North American airports to the south and east as ash clouds of the August and September eruptions passed overhead.

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INTRODUCTION

The Crater Peak vent of Mount Spurr volcano, located 125 km west of Anchorage (figs. 1, 2) and last active in 1953 (Juehle and Coulter, 1955; Wilcox, 1959), erupted three times in 1992 following 10 months of heightened seismicity. The first eruption occurred on June 27, 1992, and was followed by similar events on August 18 and September 16–17, 1992. This paper provides an overview of these eruptions and the Alaska Volcano Observatory's response to them.

ACKNOWLEDGMENT

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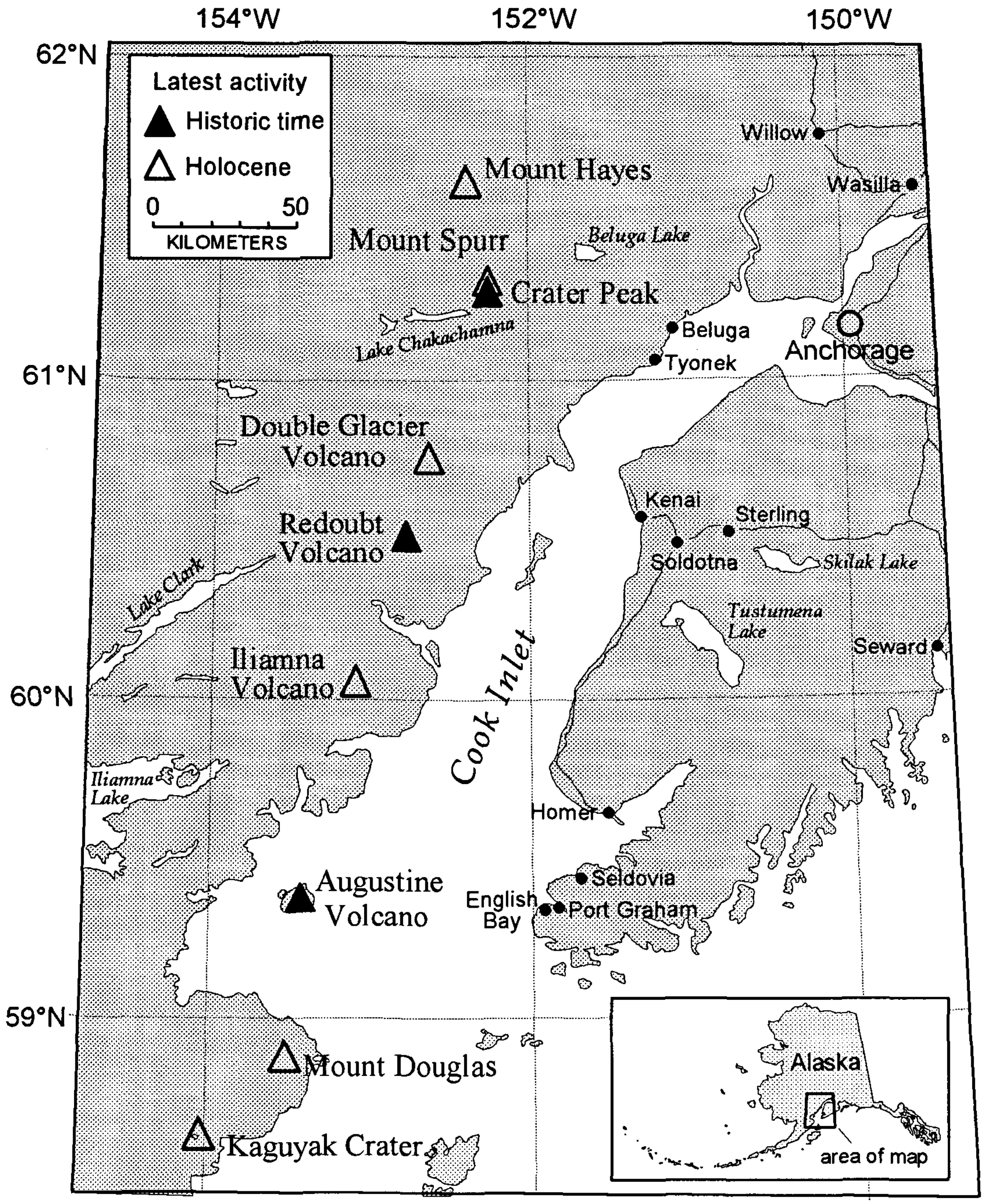

Figure 1. Index map showing volcanoes and population centers of the Cook Inlet region, Alaska.

GEOLOGIC SETTING AND HISTORY OF MOUNT SPURR VOLCANO

Mount Spurr sits 100 km above the Wadati-Benioff zone and 500 km inboard of the Aleutian Trench (Jacob and others, 1977) on a basement of mainly intrusive rocks (Nye and Turner, 1990). Its large stratovolcano edifice, built of two-pyroxene andesite (58–60 weight percent SiO_2), began to form before 255,000 yr ago (Nye and Turner, 1990). Pyroclastic rocks dominate the lower part of the volcano, and lava flows dominate the upper part. Within the past 58,000 yr but before Holocene time, the volcano collapsed southward in a manner similar to Bezymianny Volcano in Kamchatka, Russia (Gorshkov, 1959). The debris avalanche generated at Mount Spurr had a minimum runout of 25 km by 6 km and left the volcano with a horseshoe-shaped caldera rim. Collapse was followed immediately by eruption of more silicic (60–63 weight percent SiO_2) andesitic ash-flow tuffs. A large dome complex, which now forms Mount Spurr's 3,374-m summit, grew in the center of the caldera probably no later than 5,000 yr ago (Riehle, 1985). The complex consists of two-pyroxene silicic andesite, chemi-

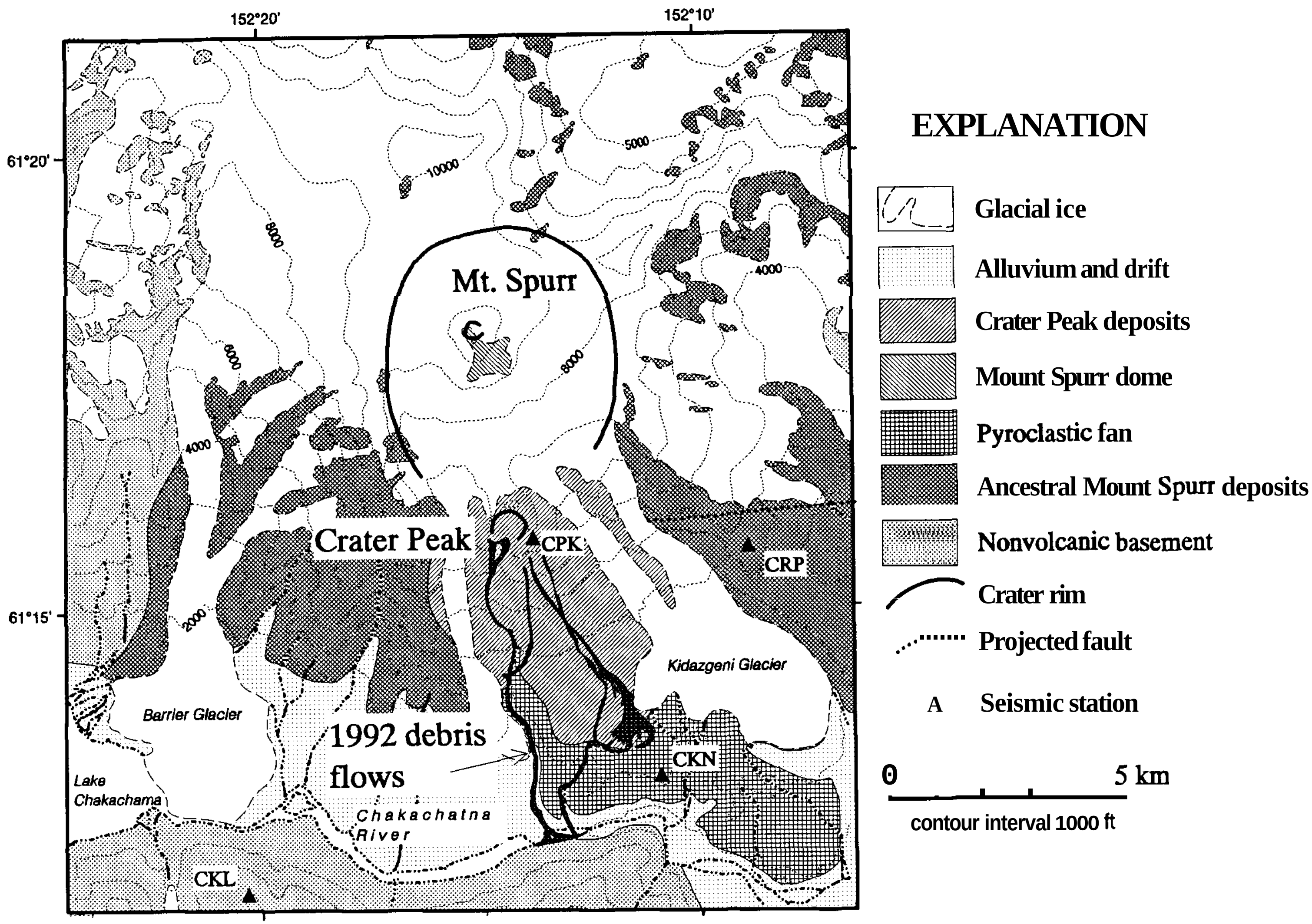

Figure 2. Generalized geologic map, of Mount Spurr area, southern Alaska.

cally similar to the ash-flow tuffs (Nye and Turner, 1990). A basaltic-andesite satellitic cone developed at the same time in the caldera breach. The present Crater Peak represents a second period of satellite cone-building at the same location; it reaches an elevation of 2,309 m, 3.5 km south of Mount Spurr's summit. Crater Peak consists of lavas and pyroclastic flows of mafic andesite (53–57 weight percent SiO_2; Nye and Turner, 1990). The 40 tephra units correlated to this vent range in age from 5,000 yr to present (Riehle, 1985). Eruption products that are apparent mixtures of Crater Peak and summit dome complex magmas indicate that the two systems were partly coeval (Nye and Turner, 1990).

Prior to 1992, the only witnessed eruption of Mount Spurr occurred on July 9, 1953. This eruption also issued from the Crater Peak vent and consisted of two main explosive pulses, followed by steam and minor ash emission. The eruption cloud rose to over 20,000 m above sea level and deposited 3 to 6 mm of andesitic (55 weight percent SiO_2) ash on Anchorage (Juehle and Coulter, 1955; Wilcox, 1959). A debris flow dammed the Chakachatna River downslope from Crater Peak, and the dam created an 8-km-long lake. The dam was overtopped and breached within a week.

ROLE OF THE ALASKA VOLCANO OBSERVATORY

The Alaska Volcano Observatory (AVO) was established in 1988, following the 1986 eruption of Augustine Volcano; the observatory conducted its first full eruption response with the Redoubt Volcano episode of 1989–90 (Miller and Chouet, 1994). AVO is a cooperative program of the U.S. Geological Survey (USGS), University of Alaska Fairbanks Geophysical Institute (UAFGI), and Alaska Division of Geological and Geophysical Surveys (ADGGS). AVO is supported by both the Department of Interior through the USGS Volcano Hazards and Geothermal Studies Program and by the State of Alaska. AVO's primary mission is to communicate timely warnings of unrest and potential eruption of Alaska's volcanoes and to investigate the fundamental processes of hazardous volcanism, with a view toward improved eruption warnings and hazard assessments.

Since World War II, Anchorage has become the population and economic center of Alaska; over half the population of the State is currently concentrated in the Anchorage area. Three of the Cook Inlet volcanoes — Augustine Volcano, Redoubt Volcano, and Mount Spurr — are frequently active. Within the past decade, their eruptions have produced ash clouds that were hazardous to aircraft as well as to the general populace. Accordingly, the Cook Inlet region presents the greatest array of volcano hazards in Alaska and is the focus of AVO's efforts.

AVO distributes updates (fig. 3) each Friday to summarize the weekly status of the monitored Cook Inlet volcanoes and any reported activity of unmonitored volcanoes on the Alaska Peninsula and Aleutian Islands. During periods of volcanic unrest and eruption crises, additional updates are issued when significant changes in activity should be made known to the public (Brantley, 1990). Updates were issued frequently to a prioritized list of well over 100 recipients during the Crater Peak eruptions. AVO at Fairbanks faxes to the local Federal Aviation Administration (FAA), the local National Weather Service (NWS), Alaska Department of Emergency Services (ADES), local military bases, Governor's and State offices, television and radio stations, and airlines. AVO at Anchorage faxes to the local FAA, the local NWS, local military bases, USGS offices, other federal agencies, television and radio stations, news wire services, and airlines. Updates are also distributed by electronic mail to the volcano information networks.

A level of concern color code was established during the Redoubt Volcano eruptions to quickly and simply convey AVO's evaluation of eruption potential and eruption severity (Brantley, 1990; Miller and Chouet, 1994). This code was modified slightly for use with the Crater Peak eruptions (fig. 4). When a volcanic crisis begins, telephone calls are made to Federal, State, and local agencies with critical public safety responsibilities to give the level of concern color code as the update is being prepared. A calldown procedure, likewise established for the Redoubt Volcano eruptions (Brantley, 1990; Miller and Chouet, 1994), was used for the Crater Peak eruptions. Responsibility for calls are shared between AVO at Anchorage and AVO at Fairbanks, so all concerned agencies are contacted within minutes.

1992 ERUPTIONS — MONITORING AND RESPONSE CHRONOLOGY

PRE-ERUPTION PERIOD

Early indication of unrest at Mount Spurr was a conspicuous swarm of volcano-tectonic (VT) earthquakes during the last half of August 1991 (table 1; Power and others, this volume). Unlike swarms that had occurred in 1982 and 1989, this one was directly under Crater Peak within a volume that had been aseismic for at least a decade (Jolly and others, 1994), and it was followed by caldera-wide seismicity. By February of 1992, seismic activity had increased to such a level that discussions of Mount Spurr's unrest were included in AVO's weekly updates. Through April

ALASKA VOLCANO OBSERVATORY

U.S. Geological Survey 4200 Universitv Drive Anchorage, AK 99508	Geophysical Institute University of Alaska Fairbanks, AK 99775	AK Division of Geological and Geophysical Surveys 794 University Ave Suite 200 Fairbanks, AK 99709

MT. SPURR UPDATE

Thursday, September 17, 1992 12:30 AM ADT

CURRENT LEVEL OF CONCERN COLOR CODE IS RED

LAST LEVEL OF CONCERN WAS YELLOW
For definitions, see update of 8/24/92

At approximately 00:04 ADT, AVO seismometers indicated a second eruption at Mt. Spurr which is ongoing at this time. An ash plume reaching an estimated altitude of at least 35,000 feet has been confirmed by NWS radar and pilot observations.

Based on forecast winds, the plume should travel in an easterly direction from Mount Spurr and could effect the Mat-Su and greater Anchorage area region with the southern edge of the fallout impacting the Anchorage area within the next two hours.

The Alaska Volcano Observatory is watching the situation closely and will remain on 24-hour staffing until futher notice.

PLEASE CONTACT AVO IF YOU HAVE ANY QWSTIONS OR COMMENTS.

Dr. John C. Eichelberger
Geophysical Institute
University of Alaska
Fairbanks. AK 99775
(907) 474-5681
(907) 474-5618 FAX

Dr. Thomas P. Miller
4200 University Drive
U.S. Geological Survey
Anchorage, AX 99508-4667
(907) 786-7497
(907) 786-7450 FAX

Figure 3. Example of update issued by Alaska Volcano Observatory during the eruption of Mount Spurr volcano on September 17, 1992.

LEVEL OF CONCERN COLOR CODE

To more concisely describe our level of concern about possible eruptive activity at Mt. Spurr, the Alaska Volcano Observatory has developed a color-coded classification system. The definitions of the various colors have been modified slightly since the 1989-90 eruption of Redoubt Volcano. General descriptions of the type of activity associated with each of the four color codes are included below. The various colors indicating our level of concern about potential eruptive behavior are as follows:

GREEN : volcano is in its normal "dormant" state.

YELLOW: Volcano is restless.

Seismic activity is elevated. Potential for eruptive activity is increased. A plume of gas and steam may rise several thousand feet above the volcano which may contain minor amounts of ash.

ORANGE: Small ash eruption expected or confirmed. Plume(s) not likely to rise above 25,000 feet above sea level.

Seismic disturbance recorded on local seismic stations, but not recorded at more distant locations.

RED : Large ash eruptions expected or confirmed. Plume likely to rise above 25,000 feet above sea level.

Strong seismic signal recorded on all local and commonly on more distant stations.

Figure 4. Alaska Volcano Observatory's level of concern color code, as used for the 1992 eruptions of Crater Peak, Mount Spurr, Alaska. This code was distributed to government agencies, the media, airlines, and the public with the announcement of level Yellow for Mount Spurr on June 26, the day prior to the first eruption.

Table 1. Chronology of major events and Alaska Volcano Observatory notifications pertaining to the 1992 eruptions of Crater Peak vent, Mount Spurr, Alaska.

[Compiled by C.A. Neal, T. Mattox, I. Ellersieck, and T. Keith; see also Power and others and McNutt and others, this volume; Universal Time (UT) = Alaska daylight time (ADT) + 8 hours, Alaska standard time (AST) + 9 hours; * = next day in UT; altitudes are above sea level; PIREP, pilot report. Beginning and end of each eruption are in bold type.]

DATE	TIME		EVENT	COLOR CODE	EVENT DESCRIPTION OR NOTIFICATION SUMMARY ISSUED
	Local	Universal			
8/15–30/91	- -	- -	Seismicity	- -	Conspicuous swarm of shallow volcano-tectonic earthquakes beneath Crater Peak accompanied by increased seismicity in a previously aseismic zone between 10 and 40 km depth.
8/30/91	- -	- -	Update	- -	First announcement of seismic swarm of past two weeks at Mount Spurr; similar to swarms in 1982 and 1989; no further notifications of increased seismicity through end of year.
2/7/92	- -	- -	Update	- -	Increased seismicity beneath Mount Spurr volcano.
3/13/92	- -	- -	Update	- -	Began weekly reporting of increased seismicity at Mount Spurr; noted seismicity had been above background since mid-August 1991.
6/5/94	- -	- -	Seismicity		Highest number of earthquakes per day (28) recorded to date.
6/6/92	- -		Seismicity	- -	First small tremor bursts detected beneath Crater Peak.
6/8/92	- -	- -	Update	- -	Discussion of increased seismicity at Mount Spurr volcano localized beneath Crater Peak vent; highest seismicity in 10 years; possibility of a coming eruption.
6/26/92	10:30 a.m.	18:30	Update	- -	Increasing number and duration, as long as 10 minutes, of tremor bursts beneath Crater Peak; two tremor bursts of 154 and 142 minutes, respectively, on June 24 and 25.
	12:04 p.m.	20:04	Seismicity	- -	Continuous tremor began.
	3:00 p.m.	23:00	Seismicity	- -	Decision made to announce level of concern color code Yellow.
	4:30 p.m.	00:30*	Update	Yellow	Announcement of color code Yellow. Continued increase in seismicity, appearance of continuous tremor, crater lake disappeared.
6/27/92	3:00 a.m.	11:00	Seismicity	Yellow	Vigorous swarm of volcano-tectonic earthquakes began, and it included some long-period earthquakes.
	7:04 a.m.	**15:04**	**Eruption**	**Yellow**	**Eruption tremor began; poor weather precluded visual observations.**
	7:16 a.m.	15:16	Calldown	Orange	Color code Orange announced by calldown.
	7:16 a.m.	15:16	PIREP	Orange	Eruption column rose to 5,200 m.
	7:40 a.m.	15:40	PIREP	Orange	Plume rose to 5,600 m.
	8:00 a.m.	16:00	Update	Orange	Color code Orange announced by the update. Increased eruption column height; potential for ashfall north and northwest of Mount Spurr.
	8:10 a.m.	16:10	PIREP	Orange	Plume rose to 8,530 m.
	8:22 a.m.	16:22	PIREP	Orange	Plume rose to more than 8,500 m; strong sulfur smell 25 km south of Mount Spurr.
	8:50 a.m.	16:50	Eruption	Orange	Seismic station CPK on crater rim destroyed.
	9:10 a.m.	17:10	Calldown	Red	Color code Red announced
	9:10 a.m.	17:10	PIREP	Red	Plume height rose to more than 9,000 m.
	9:15 a.m.	17:15	Update	Red	Announcement of color code Red. Plume height rose to 9,100 m (from PIREPS.)
	9:35 – 10:25 a.m.	17:35– 18:25	Seismicity	Red	Tremor amplitude peaked.

Table 1. Chronology of major events and Alaska Volcano Observatory notifications pertaining to the 1992 eruptions of Crater Peak vent, Mount Spun; Alaska--Continued.

DATE	TIME Local	Universal	EVENT	COLOR CODE	EVENT DESCRIPTION OR NOTIFICATION SUMMARY ISSUED
	10:23 a.m.	18:23	Eruption	Red	Plume height reached maximum of 14,500 m, as determined from NWS radar.
	11:07 a.m.	**19:07**	**Eruption**	**Red**	**Eruption tremor ended; 24 hours of long-period events followed**
	9:00 p.m.	05:00*	Update	Red	Based on morning eruption, as well as character and elevated level of continued seismicity, color code remained at Red.
6/28/92	9:00 a.m.	17:00	Update	Yellow	Announcement of return to color code Yellow. Seismicity less than previous day but still elevated.
6/29/92	1:00 p.m.	21:00	Update	Yellow	seismicity elevated but it steadily declined.
6130192	3:30 p.m.	23:30	Update	Yellow	Seismicity elevated but it steadily declined.
7/1/92	4:00 p.m.	00:00*	Update	Yellow	Seismicity elevated but it steadily declined. Ash cloud reported over Yakutat, Juneau, and Sitka on 6/30/92.
7/3/92	3:30 p.m.	23:30	Update	Yellow	Seismicity elevated but it steadily declined. Two-page summary of eruption issued.
7/7/92	4:00 p.m.	00:00*	Update	Yellow	Continued high level of microearthquakes.
7/8/92	3:00 p.m.	23:00	Update	Green	Announcement of downgrade to color code Green. Microseismicity returned to lowest level of the past few months.
7/10–8/14/92	- -	--	Updates	Green	Return to weekly update schedule. Continued low-level seismicity and steam plumes.
8118192	3:37 p.m.	23:37	Seismicity	Green	Weak tremor and long-period events detected on proximal Mount Spurr seismic stations (post-eruption analysis).
	3:41 p.m.	23:41	Seismicity	Green	Start of 12-minute period of tremor indicated small premonitory eruption (post-eruption analysis).
	3:48 p.m.	23:48	PIREP	Green	Ash cloud rose 300 to 600 m above Crater Peak.
	4:25 p.m.	00:25*	PIREP	Green	Additional PIREPs confirmed ash plume.
	4:25 p.m.	00:25*	Calldown	Yellow	Announcement of color code Yellow; still no strong seismicity.
	4:42 p.m.	**00:42***	**Eruption**	**Yellow**	**Strong tremor began; NWS radar saw no evidence of eruption.**
	4:47 p.m.	00:47*	Calldown	Orange	Announcement of color code Orange.
	4:55 p.m.	00:55*	Eruption	Orange	Plume reached maximum height of 13,700 m, as determined from NWS C-band radar.
	4:58 p.m.	00:58*	Calldown	Red	Announcement of color code Red.
	4:58 p.m.	00:58*	Update	Red	Announcement of color code Red; PIREPS indicated plume rose to 10,700 m; warning issued that winds were toward the east and that ash could begin falling on Anchorage within several hours.
	8:10 p.m.	**04:10***	**Eruption**	**Red**	**Tremor ended.**
	8:20 p.m.	04:20*	Eruption	Red	Ash began falling in Anchorage, lasted about 4 hours.
	8:30 p.m.	04:30*	PIREP	Red	Ash-free steam rose to about 5,000 m above Crater Peak vent.
	9:30 p.m.	05:30*	Update	Orange	Announcement of color code Orange based on decreasing seismicity.
8/19/92	5:15 a.m.	13:15	Update	Orange	Decreasing but still elevated seismicity. Ash fell on the northern Kenai Peninsula, Hope, and Whittier. Ash began falling about 1:45 a.m. ADT at Valdez and Cordova.
	8:30 a.m.	16:30	Update	Yellow	Color code downgraded to Yellow. Update included three-page summary of the eruption.
	11:45 a.m.	19:45	PIREP	Yellow	Steam plume and minor amounts of ash emitted from vent.

Table 1. Chronology of major events and Alaska Volcano Observatory notifications pertaining to the 1992 eruptions of Crater Peak vent, Mount Spurr, Alaska—Continued.

DATE	TIME Local	TIME Universal	EVENT	COLOR CODE	EVENT DESCRIPTION OR NOTIFICATION SUMMARY ISSUED
	5:00 p.m.	01:00*	Update	Yellow	Decreasing seismicity; steam plumes and minor amounts of ash rose above Crater Peak. Update dispelled rumors of a second eruption that day.
8/20–9/3/92	- -	- -	Updates	Yellow	Issued every several days as necessary to dispel rumors of eruptions and report investigations at Mount Spurr; color code remained at Yellow: seismicitv gradually declined but remained above normal background levels.
9/4/92	3:30 p.m.	23:30	Update	Yellow	Increased long-period seismicity at depths of 20 to 40 km beneath Mount Spurr suggested that magma was again being replenished within the volcano. Update warned of possible eruption within days or weeks; color code continued at Yellow.
9/11/92	2:00 p.m.	23:00	Update	Yellow	Weekly update reported continued high level of seismicity; no additional seismicity in 20- to 40-km depth range, but eruption within days to weeks possible.
9116/92	7:30 p.m.	3:30*	Seismicity	Yellow	Weak tremor began and was accompanied by an increase in deep earthquakes.
	10:25 p.m.	6:25*	Seismicity	Yellow	Tremor amplitude increased.
	10:33 p.m.	6:33*	Calldown	Red	Announcement of color code Red.
	10:36 p.m.	**6:36***	**Eruption**	**Red**	**Tremor signified an 11-minute preliminary eruptive burst.**
	10:37 p.m.	6:37*	PIREP	Red	Ash column rose to 4,600 m.
	10:45 p.m.	6:45*	Update	Red	Announcement of color code Red: eruption began at 10:36 p.m. ADT and NWS wind data showed that the ash cloud would move easterly with fallout expected over the Matanuska-Susitna Valley region and perhaps as far south as Anchorage.
	11:11 p.m.	7:11*	PIREP	Red	Glow observed over Crater Peak.
9/17/92	**12:03 a.m.**	**8:03**	**Eruption**	**Red**	**Seismicity indicated start of main eruption.**
	12:08 a.m.	8:08	Eruption	Red	Telemetry lost from seismic station CPK on Crater Peak rim.
	12:30 a.m.	8:30	Update	Red	Plume rose to 10,700 m, reported by PIREPS and NWS radar. Warning issued that southern edge of plume could produce ashfall on Anchorage.
	12:48 a.m.	8:48	Eruption	Red	Plume rose to 12,200 m, as determined from NWS radar.
	12:50 a.m.	8:50	Eruption	Red	Beginning of intense incandescence, as recorded on the slow-scan television camera at Kasilof and on the video camera at AVO in Anchorage.
	2:21 a.m.	10:21	Eruption	Red	Maximum plume height of 13,900 m measured from NWS radar.
	3:39 a.m.	**11:39**	**Eruption**	**Red**	**Tremor ended.**
	5:45 a.m.	13:45	Update	Red	Eruption ended and seismicity declined although tremor continued; NWS radar showed no plume at Crater Peak; ashfall affected the Matanuska-Susitna Valley and stayed north of Anchorage.
	4:00 p.m.	00:00*	Update	Orange	Color code downgraded to Orange due to decreased seismicity, low-level tremor continued.
9/18/92	3:00 p.m.	23:00	Update	Orange	Summary of eruption issued; color code remained at Orange because of low-level tremor.
9/19/92	4:00 p.m.	00:00*	Update	Orange	Steam plumes rose 3,000 to 6,000 m above Crater Peak; seismicity continued but declined.
9120192	4:00 p.m.	00:00*	Update	Orange	Elevated seismicity indicated the possibility of a small eruption with little warning. Therefore, color code remained at Orange.

Table 1. Chronology of major events and Alaska Volcano Observatory notifications pertaining to the 1992 eruptions of Crater Peak vent, Mount Spurr, Alaska — Continued.

DATE	TIME		EVENT	COLOR CODE	EVENT DESCRIPTION OR NOTIFICATION SUMMARY ISSUED
	Local	Universal			
9/21/92	4:00 p.m.	00:00*	Update	Orange	Elevated seismicity indicated the possibility of a small eruption with little warning. Therefore, color code remained at Orange.
9/22/92	4:00 p.m.	00:00*	Update	Orange	Elevated seismicity indicated the possibility of a small eruption with little warning. Therefore, color code remained at Orange.
9/23/92	4:00 p.m.	00:00*	Update	Orange	Elevated seismicity indicated the possibility of a small eruption with little warning. Therefore, color code remained at Orange.
9/24/92	4:00 p.m.	00:00*	Update	Yellow	Announcement of downgrade to color code Yellow. Tremor amplitude decreased and time between tremor episodes increased.
9/25/92	4:00 p.m.	00:00*	Update	Yellow	Continued low-level seismicity.
9/28/92	4:00 p.m.	00:00*	Update	Yellow	Continued low-level seismicity.
9/29/92	4:00 p.m.	00:00*	Update	Yellow	Continued low-level seismicity.
9/30/92	4:00 p.m.	00:00*	Update	Yellow	Continued low-level seismicity
10/1/92	4:00 p.m.	00:00*	Update	Yellow	Continued low-level seismicity.
	7:00 p.m.	03:00*	Seismicity	Yellow	Continuous volcanic tremor began.
	11:00 p.m.	07:00*	Update	Yellow	Weak, continuous volcanic tremor resumed under Crater Peak; increased SO_2 emission; heightened possibility of eruption during the next several days.
10/2/92	6:17 p.m.	02:17*	Calldown	Red	Announcement of color code Red based on intense seismicity.
	6:30 p.m.	02:30*	Update	Red	Announcement of color code Red: intense seismic tremor at Crater Peak; tremor amplitude comparable to levels preceding the June 27 and September 17 eruptions; large eruption seemed likely within 24 to 48 hrs.
	6:30 p.m.	02:30*	Seismicity	Red	Tremor abruptly ended.
10/3/92	4:00 p.m.	00:00*	Update	Red	Irregular tremor signified unrest of the volcano. Eruption could occur with little or no warning; color code remained at Red.
10/4/92	9:00 a.m.	17:00	Update	Red	Continued volcanic unrest indicated by banded tremor with tremor bursts that lasted I to 2 hours.
	5:00 p.m.	01:00*	Update	Yellow	Announcement of downgrade to color code Yellow. More quiet time between tremor periods; banded tremor, which often precedes eruption, continued; volcano still considered restless.
10/5/92	4:00 p.m.	00:00*	Update	Yellow	Continued banded tremor and an 18-hour period of sustained tremor.
10/6/92	4:00 p.m.	00:00*	Update	Yellow	Intermittent tremor persisted
10/7-11/6/92	- -	--	Updates	Yellow	Daily weekday reports of continued irregular levels of seismicity and occasional gas emission, as well as other observations of the volcano. Caution issued that an eruption could occur with little warning.
11/2/92	2:00 a.m.	11:00	Seismicity	Yellow	Rate of shallow volcano-tectonic earthquakes increased.
11/9/92	12:00 m.	21:00	Update	Orange	Announcement of upgrade to color code Orange based on shallow seismic swarm; eruption could occur without additional warning.
	4:00 p.m.	01:00*	Update	Orange	Increased shallow seismicity.
	9:00 p.m.	06:00*	Update	Orange	Number of seismic events was 1.5/min for 3.5 hrs; this was the most energetic seismic swarm of 1992 eruptive period.

Table 1. Chronology of major events and Alaska Volcano Observatory notifications pertaining to the 1992 eruptions of Crater Peak vent, Mount Spurr, Alaska — Continued.

DATE	TIME Local	TIME Universal	EVENT	COLOR CODE	EVENT DESCRIPTION OR NOTIFICATION SUMMARY ISSUED
	10:07 p.m.	07:07*	Update	Red	Announcement of upgrade to color code Red. Significant increase in seismicity on all stations; large eruption seemed likely within 24 to 48 hrs.
11/10/92	3:00 p.m.	00:00*	Update	Orange	Color code downgraded to Orange. Seismicity decreased significantly since the buildup of 11/9/92.
11/11/92	3:00 p.m.	00:00*	Update	Orange	Decreased seismicity from the swarm of November 9; continued unrest could result in eruption without additional warning.
11/12/92	3:00 p.m.	00:00*	Update	Yellow	Color code downgraded to Yellow based on 2 days of relative seismic quiescence; however, volcanic unrest continued.
11/13–12/18/92	- -	--	Updates	Yellow	Daily weekday reports of continued irregular levels of seismicity and occasional gas emission, as well as other observations of the volcano, still indicated that an eruption could occur with little warning.
12/21/92	3:00 p.m.	00:00*	Update	Yellow	Color code would remain at Yellow until early January because: (1) continued high level of seismicity, and (2) eruptions and seismic crises since June eruption occurred at 55-, 30-, and 53-day intervals; and by early January, 60 days had passed since the seismic swarms on November 9–10.
12/24/92	12:00 m.	21:00	Update	Yellow	Swarm of small earthquakes occurred at depth of 8 to 12 km beneath Crater Peak during past 5 days; continued unrest indicated that the volcano was still unstable and eruption could occur with little warning.
12/28/92	3:00 p.m.	00:00*	Update	Yellow	Swarm of small earthquakes of December 20 continued through December 26, followed by increased shallow 2-hour periods of tremor-like events beneath Crater Peak on December 27; seismicity then decreased; volcano still considered unstable.
12/31/92	12:00 m.	21:00	Update	Yellow	Continued low-level seismicity including two earthquakes beneath Crater Peak and two low-amplitude tremor episodes during the previous 24 hrs. Decision made for color code to stay at Yellow.
1/4–2/26/93	- -	- -	Updates	Yellow	Return to weekly Friday reporting of low-level seismicity, steam plumes, and other observations.
3/5/93	2:00 p.m.	23:00	Update	Green	Color code downgraded to Green. Seismicity continued at a low level for a time period longer than that between the 27 June and 18 August 1992 eruptions (see 12/21/92); possibility of steam and ash explosions still existed.
3/12/93–1/14/94		--	Updates	Green	Mention of Mount Spurr seismicity and other observations in weekly updates.
1/21/94		- -	Update	Green	Announcement that level of seismicity at Mount Spurr had returned to background levels and that specific mention of Mount Spurr in weekly updates would be discontinued.

of 1992, however, updates stated that the increased seismicity was not considered precursory to eruption. The heightened seismicity continued, punctuated with stronger pulses, including a prominent pulse beneath Crater Peak in May. In an internal memorandum dated June 3, 1992, AVO scientists interpreted the seismicity as the result of increasing magmatic pressure at depth, which caused intrusion into conduits below Crater Peak and the summit dome complex and minor movement of caldera faults. The memo urged increased monitoring, as well as advising government agencies and the aviation industry to review plans for coping with an eruption. Both of these recommendations were implemented.

The number of daily locatable VT earthquakes reached 28 on June 5 and then declined to about 3 to 6 events per day. Volcanic tremor began on June 6, and an overflight on June 8 revealed upwelling in the crater lake, which had turned in color from green to gray. AVO released a special update describing the situation and stating that there would be an increase in overflights and in sensitivity of the 24-hour alarm system at the AVO Seismology Laboratory in Fairbanks, along with an added evening shift for AVO personnel. As many as 24 shallow tremor bursts per day, each burst lasting 1 to 10 minutes, were recorded at stations within 10 km of Crater Peak from June 6 to 26 (McNutt and others, this volume). A field party spent 6 hours in the crater on June 11, measured a lake temperature of 50°C and pH of 2.5, and collected water samples for chemical analysis (Keith and others, this volume). The party observed small geysers—never before seen in the crater—at the base of the north crater wall. Geysering did not coincide with seismic tremor events.

On June 17, AVO informed ADES of the evolving situation at Mount Spurr. On June 19, AVO sent briefing materials to the Governor, noting the "well above normal" activity and continuing episodes of tremor. The Anchorage Daily News published a front-page article on June 21 that described how Mount Spurr was being monitored and what the public might expect from an eruption.

JUNE 27 ERUPTION

Seismic behavior changed ominously on June 24 when a tremor episode lasted 154 minutes, followed 12 hours later by a similar episode that lasted 142 minutes. Eight additional tremor bursts occurred within the next 8 hours. The weekly update of 10:30 a.m. Alaska daylight time (ADT) on June 26 reported "well above normal" seismic activity but still cautioned that an eruption might not be imminent in view of an absence of long-period (LP) earthquakes. At about the same time, aerial observations of the crater revealed that the lake had almost completely drained and that several large rocks had impacted the resulting mud flat. At 12:04 p.m. ADT, tremor that was continuous and stronger than earlier bursts began. AVO formally issued a warning of level of concern color code Yellow at 4:30 p.m. ADT and went on 24-hour duty. At 3:00 a.m. ADT on June 27, a swarm of VT earthquakes struck at 0- to 2-km depths beneath Crater Peak; their rate soon increased to about one every 2 minutes. Three LP events accompanied this swarm. Tremor amplitude abruptly doubled at 7:04 a.m. ADT. This increase in amplitude was later interpreted to represent the onset of eruption, although weather clouds prevented visual verification. At 7:16 a.m. ADT, AVO began an emergency calldown announcing level of concern color code Orange. About the same time, telemetry was lost from the seismic station 400 m from the vent and an Alaska Airlines pilot reported that an eruption plume had risen 5,000 m above the cloud cover. AVO announced color code Red at 9:10 a.m. ADT. Tremor amplitude gradually increased, peaking between 9:35 a.m. and 10:25 a.m. ADT and registering on stations more than 100 km away. Pilots estimated the plume at mid-morning as high as 9,000 m and the NWS measured a maximum plume height of 14,500 m with C-band radar (Alaska Volcano Observatory, 1993; Rose and others, this volume). The tephra cloud moved northward and ash began falling on Denali National Park at 10:30 a.m. ADT. Debris flows swept southward down narrow drainages and entered the Chakachatna River in three places. Most debris followed the course of the 1953 lahar. At about 11:30 a.m. ADT, seismicity decreased abruptly and the eruption was over. Weather and steam obscured Crater Peak and the eruption plume track from aerial observation on the afternoon of June 27, but paths of the debris flows were visible on the lower flanks of the volcano (Meyer and Trabant, this volume).

At 9:00 a.m. ADT on June 28, the level of concern was downgraded to Yellow. Aerial observation revealed a black northward-broadening swath of tephra on snow fields and glaciers. Ash thickness was about 1 to 2 mm at Denali National Park and Manley Hot Springs, 260 and 420 km north of Crater Peak, respectively (Neal and others, this volume). This region is sparsely populated and there were no other reports of tephra there. The ash cloud continued northward to the Beaufort Sea, then it turned southeast into Canada and the coterminous United States, where it became indistinguishable from weather clouds about July 2.

The level of concern color code was downgraded to Green on July 8. This was done partly on the basis of greatly reduced seismicity and SO_2 emission, but also on the basis of analogy to the single-eruption pattern of 1953. The downgrading to color code Green proved to be premature.

AUGUST 18 ERUPTION

Following the June eruption, seismicity remained low through the first half of August. Only one shallow and two deep earthquakes were recorded between August 12 and 17. Because the closest operational seismic station at that time was 5 km from the vent, several attempts were made to reestablish a seismic station on the crater rim. These were unsuccessful because of poor weather conditions. At 3:37 p.m. ADT on August 18, a 16-minute episode of weak tremor and several LP events began, but these rather obscure events were not identified until post-eruption analysis of the data. At 3:48 p.m. ADT, a pilot reported an ash-rich plume. With confirmation of this plume at 4:25 p.m., AVO began a calldown announcing level of concern color code Yellow. The main eruption began at 4:42 p.m. ADT, when strong tremor was recorded by all Mount Spurr seismic stations. AVO began a calldown announcing color code Orange at 4:47 p.m. ADT, but repeated the calldown process 11 minutes later to raise the color code to Red. By 4:58 p.m. ADT, a subplinian column had risen through low clouds to a height of 11,000 m, and it ultimately reached nearly 14,000 m. From an aircraft only 2.5 km away, AVO staff observed and videotaped a dark roiling cloud that was periodically surrounded by lenticular shock waves. Large bombs were thrown 800 m above the vent. Small-volume pyroclastic flows of breadcrusted blocks descended the east and southeast flanks of Crater Peak; these flows formed coarse, clast-supported lobate deposits with steep-fronted margins. Other flows mixed with snow and ice high on the cone and became lahars. A late fusillade of mostly lithic ballistic projectiles, some as large as 1 m, were hurled as far as 10 km southeastward (Waitt and others, this volume). More than 170 lightning strikes were detected by the AVO lightning detection system (LDS) during the second half of the eruption (Paskievitch and others, this volume). The eruption ended at 8:10 p.m. ADT.

Upper-level winds moved the eruption plume east-southeast directly over Anchorage, where it deposited as much as 3 mm of sand-sized ash (Neal and others, this volume). A satellite image 44 minutes after the onset of eruption shows the plume extending 80 km east from the volcano over an area of 2,000 km^2. Three hours after onset of eruption, the leading edge of the plume was 300 km southeast of Mount Spurr, and its area had grown to 21,000 km^2.

Ashfall forced the closing of Anchorage International Airport for 20 hours (N.W. Gibson, Anchorage International Airport, written commun., 1993). Air quality alerts were issued in Anchorage during the fallout period and also on the following day, as vehicle traffic stirred up ash again (R.B. Stewart, Office of Emergency Management, Municipality of Anchorage, written commun., 1993). Reworked windblown ash continued to reduce air quality until the first snow of autumn, and then it reappeared during the summer of 1993.

SEPTEMBER 16–17 ERUPTION

Following the August eruption, deep seismicity gradually increased, and by mid-September it had returned to levels comparable to mid-June. AVO teams visiting the crater on September 7 and 16 noted nothing unusual. At about 7:30 p.m. ADT on September 16, however, discrete seismic events and weak tremor were detected by the newly reinstalled crater rim station. Tremor amplitude increased at 10:25 p.m. ADT, and at 10:33 p.m. ADT, AVO declared concern color code Red and began the emergency calldown. An eruption began at 10:36 p.m. ADT that lasted 11 minutes. Incandescence was recorded on the video camera at AVO-Anchorage and on the telemetered slow-scan television camera at Kasilof, 120 km southeast of Crater Peak just south of Kenai on the Kenai Peninsula. Weak tremor through the next hour foreshadowed the main phase of eruption, which began at 12:03 a.m. ADT on September 17. Intermittent bright incandescence could be seen from Anchorage.

The September 17 eruption lasted 3.6 hours. Pyroclastic flows swept down the south-southeast and southeast flanks of Crater Peak and mixed with snow and ice to become lahars. These flows were similar in appearance to pyroclastic flows, but they were cool and water saturated hours after emplacement. Tephra fallout on the Kidazgeni Glacier generated a debris flow that temporarily dammed the Chakachatna River. Once again, a narrow ballistic field extended at least 10 km from the vent along the south margin of the tephra plume. The eruption closed with a strong swarm of about 50 VT shocks between 5 and 10 km in depth, which may reflect readjustment of the conduit after magma withdrawal.

The plume moved eastward, dusted the north edge of Anchorage and deposited about 1.5 mm of ash in Palmer, Wasilla, and nearby communities in the Matanuska-Susitna Valley north of Anchorage. Very light ashfall was reported in the town of Glenallen, 350 km east of Crater Peak.

SEISMIC SWARMS: OCTOBER 2–6, NOVEMBER 9–10, AND DECEMBER 21–27

The level of seismicity remained elevated, and several seismic crises caused concern at AVO. Tremor between 7:00 p.m. ADT on October 1 and 6:30 p.m. ADT on October 2, followed by quasiperiodic tremor over the next 72 hours, prompted AVO to announce concern color code Red twice during that period, but no eruption ensued.

At 10:07 p.m. Alaska standard time (AST) on November 9, AVO again announced concern color code Red an hour into an intense seismic swarm that lasted 3.5 hours and contained 170 detected earthquakes. These earthquakes had mixed frequency contents, occurred within a very restricted volume 1.2 km beneath the vent, and had magnitudes as large as 1.7. Again, seismicity receded without eruption. Because the duration of this swarm was similar to each of the three eruptions and its seismic energy release was the largest of the 1992 eruptive period, the swarm may be viewed as a "failed" eruption, in which magma was rapidly emplaced at shallow depth (Power and others, this volume).

A final flurry of earthquakes beneath Crater Peak on December 21 through 26 was followed by a few hours of shallow tremor-like activity on December 27. This time, AVO's advisories remained at concern color code Yellow.

At the beginning of 1993, Mount Spurr returned to a low level of seismic activity: 1 to 10 small earthquakes per day at depths of 0 to 40 km and rare periods of possible weak tremor. This background seismic "noise" fluctuated daily and seasonally (G. Tytgat and others, unpub. data). Some shallow seismic events were correlated with observed landslides, rockfalls, glacial melt runouts, and even airplanes flying over the volcano. Some seismicity may be attributed to post-eruptive readjustments of the magmatic and hydrothermal systems, and some remains unexplained. On March 5, 1993, after a time period greater than the seismic quiescence between the June 27 and August 18, 1992, eruptions had passed uneventfully, AVO lowered the level of concern color code to Green.

Vigorous white steam plumes caused false reports of eruption several times during 1993. However, volcanic gas (SO_2 and CO_2) emissions remained at or below the limit of detectability (less than 1,000 tonnes per day CO_2, less than about 4 tonnes/day SO_2; Doukas and Gerlach, this volume). New concern arose on June 29, 1993, when tremor-like seismicity appeared on records from several of the Crater Peak seismic stations. A field party was fortuitously present near Crater Peak and observed the source to be an outburst flood from Kidazgeni Glacier on the southeast slope of Mount Spurr (Nye and others, this volume).

During and following the 1992 eruptions, field investigations were carried out to map and sample the eruption products. Work in the vent area of the crater was precluded through the summer of 1993 for safety reasons. This was a lesson drawn from the sudden explosions at Galeras Volcano, Columbia, and Guagua Pichincha Volcano, Ecuador, in early 1993, that resulted in the deaths of eight volcanologists, and the September 1992 eruption of Crater Peak, which followed a period of seismic quiescence and occurred just hours after an AVO team had left the vent.

GENERAL CHARACTERISTICS OF THE ERUPTIONS

The June, August, and September 1992 eruptions produced 44, 52, and 56 million m3 of tephra (12, 14, and 15 million m^3 dense rock equivalent or DRE), respectively. In each case, juvenile tephra clasts ranged from proximal breadcrusted bombs to distal ash in a narrowly defined band of fallout extending downwind (Gardner and others, 1993; Neal and others, this volume). The vent migrated about 50 m westward from June to August to September, and so in September it was nestled against the west-northwest crater wall. Near-field ejecta from each eruption were, therefore, directed progressively more strongly to the east-southeast. Otherwise, vent geometry changed remarkably little. Distribution of pyroclastic flow deposits, ballistic showers, and lahars shows that all flanks of a volcanic cone are hazardous during subplinian activity (Miller and others, this volume; Waitt, this volume).

The eruptions were strongly magmatic in character. The dominant juvenile component of 1992 ejecta is dense to scoriaceous dark gray andesite (57 weight percent SiO_2 bulk composition) with a more silicic (60–62 weight percent SiO_2) microlite-rich matrix of brown glass (Harbin and others, this volume; Nye and others, this volume; Swanson and others, this volume). A subordinate volume of bulk-chemically identical andesite is more crystal-rich and contains clear matrix glass of rhyolitic composition (73–75 weight percent SiO_2). Trace amounts of rhyolite pumice with sparse plagioclase and quartz phenocrysts were also erupted. Pyroclastic flows of August and September contained large partially melted and greatly inflated felsic metamorphic xenoliths (Miller and others, this volume). The estimated total volume of magma for the three Crater Peak eruptions of 41 million m^3 DRE is markedly smaller than the estimated 200 million m^3 DRE (Gardner and others, 1994) released in some 20 significant eruptive events during the 1989–90 Redoubt activity.

ANALYSIS OF RESPONSE

AVO's response plan went into effect as soon as unrest was recognized at Mount Spurr in August of 1991, and it continued through post-eruptive readjustment to inactive status. For alerting a community to an imminent volcanic danger, Mount Spurr provided a favorable situation. Its Holocene deposits had been mapped and some 40 tephra layers from its 5,000-year-old Crater Peak vent had been identified (Riehle, 1985; Nye and Turner, 1990); these deposits place it among the more prolific volcanoes in the eastern Aleutian Arc. Moreover, it had erupted during historical time (Juehle and Coulter, 1955; Wilcox, 1959). In retrospect, the singularity of the 1953 eruption proved misleading for what was to come, but it did provide a useful example of Mount Spurr's behavior. Because of the relatively well documented record of activity, Mount Spurr had already been instrumented and monitored for over a decade when it reawakened. This lengthy period of monitored quiescence allowed the August 1991 seismicity to be accurately interpreted as anomalous. Mount Spurr's reawakening was gradual, and thus it permitted plans to be made and warnings to be given in a timely fashion. It was not so fast that AVO was caught off guard, nor so slow that the warnings of a future eruption could be dismissed. Care must be taken when turning observations of increasing seismicity into an appropriate warning, because not all cases of increasing seismicity, even if caused by rising magma, lead to eruption. Often, magma can solidify in the conduit without venting (Newhall and Dzurisin, 1988), as may have occurred during the seismic swarms of May, October, November, and December of 1992 (table 1). In retrospect, informing a community about the possibility of an eruption a month in advance, and issuing a serious warning a day in advance, is a useful time frame. Eruption warnings of October and November that were not fulfilled were considered by the public to be proper caution rather than mistaken judgment, coming as they did late in the episode.

Although seismic monitoring was the primary tool in AVO's response, geologic insight was necessary both for informed warnings of what was to come and for the original decision to monitor the seismic activity of Mount Spurr. A broad host of observations and techniques was used to evaluate the volcano's condition.

INTERPRETATION OF SEISMICITY

Following the establishment of AVO, seismic stations were added to the existing Mount Spurr network, making a total of 10 stations within 15 km of the summit (McNutt and others, this volume; Power and others, this volume). Seismicity that began in August 1991 eventually defined an active conduit without, unlike Redoubt Volcano, a hint of a volumetrically large storage zone. That elevated seismicity occurred throughout the volcanic massif indicates that stresses induced by magma intrusion and perhaps even magmatic vapor affected the entire Mount Spurr system. Helicorders, continuous digital data, event-triggered data, real-time seismic amplitude measurements (RSAM; Endo and Murray, 1991) and seismic spectral amplitude measurements (SSAM) were all used for analysis of the seismic information (McNutt and others, this volume).

Three types of shallow seismicity indicative of magma movement were identified: (1) tremor bursts that lasted 1 to 10 minutes, (2) continuous tremor lasting 2 hours to several days, and (3) eruption tremor (McNutt and others, this volume). Fourteen hours of continuous tremor and 4 hours of shallow VT earthquakes preceded the June eruption. However, this seismic pattern that made forecast of the June eruption possible was not repeated in subsequent events. Only 3 hours of increased seismicity preceded the September eruption; accordingly, the warning from AVO was issued just minutes ahead of the onset of eruptive activity and an hour and a half before the main pulse. Unfortunately, no detectable seismic activity foreshadowed the August eruption. Had it been possible to replace the near-vent seismic station destroyed during the June eruption, shallow precursory tremor bursts might have been recorded. However, the absence of the near-vent station does not explain the lack of locatable VT earthquakes before that eruption. Presumably, the strongest precursory signals were generated at the outset of the eruptive episode because rising magma and gases were reopening a cold, plugged conduit.

EVIDENCE FROM HYDROTHERMAL ACTIVITY AND GAS EMISSION

The sense of urgency engendered by May and June seismicity was heightened by observations of the small crater lake that had existed since the 1953 eruption. Days prior to the first eruption, lake water changed from blue-green to gray, became turbid with areas of upwelling, and finally evaporated or drained (Keith and others, this volume). A single pair of measurements, one during dormancy and the other in June, revealed a two-orders-of-magnitude increase in SO_4/Cl in the lake.

The increase in SO_4/Cl may relate to the failure of airborne SO_2 emission measurements to detect the rise of magma (Doukas and Gerlach, this volume). Airborne measurements were begun when anomalous seismicity was first detected. Not until the June eruption did the flux of SO_2 from the vent increase significantly, and SO_2 concentrations returned to low values 2 days later. SO_2 flux was also low prior to and following the August and September eruptions. Yet, the National Aeronautical and Space Administration's (NASA) Total Ozone Mapping Spectrometer (TOMS) indicated 200 ± 60, 230 ± 70, and 400 ± 120 kt of SO_2 emitted during the June, August, and September eruptions, respectively. It is likely that SO_2 released during pre-eruptive intrusion was being scrubbed and the resulting H_2S and sulfate dissolved in the hydrothermal system. Doukas and Gerlach (this volume) and Bluth and others (this volume) conclude from independent techniques that a significant amount of H_2S was emitted during the 1992 eruptions. Airborne CO_2 measurements made following the September eruption did detect substantial magmatic outgassing, which suggests that monitoring of this less water-soluble gas might have provided a more diagnostic tool than monitoring of SO_2 (Doukas and Gerlach, this volume).

VISUAL OBSERVATION OF ERUPTIONS

Visual observations, when they can be obtained, are the most direct means of assessing eruptive activity. AVO's remote, slow-scan, continuously recording television camera at Kasilof on the Kenai Peninsula was turned to view Crater Peak, 120 km away, on May 6, 1992; it provided real-time views for AVO staff in both Anchorage and Fairbanks. In addition, a video camera was set up on the roof of AVO in Anchorage and wired into the operations room. Both cameras recorded the incandescence at the crater rim during the September 16–17 eruption (Neal and others, this volume). When weather permitted, the information from these cameras was critical in responding to false eruption alarms.

Especially helpful to AVO were the pilot reports (PIREPS) of visual observations passed on by FAA and NWS. For example, although seismicity indicated that the June eruption was imminent, the ash cloud was reported by a PIREP before seismic verification could be made and while clouds prevented ground-based visual observations of the volcano. A PIREP revealed the August eruption, because there was no precursory seismicity. PIREPs also provided a valuable record of eruption column height as a function of time.

DETECTION OF VOLCANIC LIGHTNING

Once volcanic activity has been detected seismically or visually, the most important task is to establish whether ash is being emitted. This can be difficult, given weather and light conditions in Alaska. AVO has established a lightning detection system (LDS) for the Cook Inlet region; this system is based on observations that lightning is commonly associated with vigorous, ash-laden eruptive columns at volcanoes throughout the world (Hoblitt, 1994; Paskievitch and others, this volume). Detected lightning might therefore indicate significant ash emission. During the Crater Peak eruptions, this technique proved only partially successful. A ring of lightning 10 km in diameter, centered 5 km east of the vent, was detected during the August eruption, but LDS did not detect lightning during the June and September eruptions. That lightning accompanied the June and September eruptions is indicated by interruptions in signals from seismic stations (Davis and McNutt, 1993).

RADAR OBSERVATION OF ERUPTIVE COLUMNS

One technique for detection of eruptive columns is C-band radar. An experiment conducted in cooperation with NWS by Rose and others (this volume) at Kenai provided a first test with excellent results. Radar imaged the Crater Peak eruption columns regardless of weather, and it also allowed estimates of column height and mass flux to be made. A limitation of radar observation is that only coarser particles are reflective, and so neither the top of the eruptive column, nor the cloud tens of minutes after cessation of eruption, can be seen.

PROJECTION OF PLUME PATHS

During the 1980 eruptions of Mount St. Helens, graphic plots of wind direction and velocity at several altitudes, used with permission of NWS, proved useful in determining the path of eruption plumes (Miller and others, 1981). Their usefulness was demonstrated again at Mount Spurr, particularly in calculating the time for the eruption cloud of August 18 to reach Anchorage. In addition, it was immediately obvious that the June 27 eruption cloud would drift north toward sparsely populated areas and would not affect Anchorage. Winds for the September 18 eruption were flowing northeastward from the vent. A warning of possible ashfall was given to Anchorage, although the model correctly showed the ash-laden winds passing just north of the city. The model correctly predicted that ash would fall mainly on the Matanuska-Susitna Valley. Also important in tracking ash were calls from citizens informing AVO of ashfall locations and thicknesses.

TRACKING OF PLUMES BY SATELLITE

The hazards of volcanic ash emitted during eruptions extend well beyond local communities. For the first several days, a cloud from an explosive eruption is dangerous to high-flying jets (Casadevall, 1992; Casadevall and Krohn, this volume). During the Mount Spurr eruptions, advanced very high resolution radiometry (AVHRR) data were processed using a new high-resolution picture transmission (HRPT) information processing system (HIPS) at NWS for real-time tracking of volcanic clouds (Schneider and others, this volume). The August and September eruption clouds were followed for more than 80 hours and thousands of kilometers (Schneider and others, this volume). Further development of this technique may make it possible to determine particle-size distribution and particle density in volcanic clouds, so the severity of hazard they pose can be more quantitatively evaluated.

TOMS satellite images were likewise used to track the eruption clouds for as many as 7 days after formation (Bluth and others, this volume). Sulfur dioxide content of clouds from the August and September eruptions increased during their first 2 days, probably by atmospheric oxidation of H_2S. At least half the 400±120 kt of SO_2 emitted by the three eruptions reached the lower stratosphere.

DISSEMINATION OF INFORMATION

AVO's use of updates, level of concern color code, calldown lists, and direct personal communications worked effectively to notify civil authorities and the general public of expected eruptions and resulting hazards from Mount Spurr. Intensive media coverage, based on interviews with AVO personnel by both local and national radio and television and the local newspaper, added to AVO's outreach.

AVO's color code is central to rapid communication of the level of hazard to concerned constituencies, particularly the aviation industry. As indicated in figure 4, increasing levels of concern convey both increasing likelihood of eruption and increasing potential or actual size of eruption. No simple one-dimensional scale can adequately describe an impending or ongoing event. Yet, simplicity of communication is essential during an emergency. In practice, use of the code is tempered by awareness of the consequences that communication of the concern will cause. During the 1992 Crater Peak eruptions, color was used primarily to indicate likelihood of eruption. Red meant that an eruption was imminent or ongoing; Red was used because all events were major ones with eruptive columns that reached flight levels and produced regional tephra falls.

Two occasions show the kinds of decisions that must be made in applying the code and that include factors beyond the simple criteria in the code. The volcano's behavior arguably fell within the condition "restless" beginning in August of 1991. However, uncertainty as to the significance of the early seismicity, and knowledge that premature use of warning colors would entail unnecessary fueling and routing costs for the airlines, led to deferral of use of color code Yellow. A more literally based interpretation of the code was used on August 18, 1992, when AVO downgraded the concern level from Red to Orange at the end of the eruption, but 3 hours before ash stopped falling on Anchorage. The color code was not meant to address conditions away from the volcano, so the downgrading probably did not seem an adequate portrayal of the situation to citizens of Anchorage who were just beginning to be affected by the eruption. Nevertheless, the AVO decision was appropriate to signal to the airlines and others that voluminous ash production at the vent had ceased and the end of ashfall in Anchorage could be predicted.

ECONOMIC EFFECTS OF THE 1992 ERUPTIONS

Economic losses from the Crater Peak eruptions were mainly effects of ashfall at Anchorage International Airport and associated disruption of air traffic from the August 18 eruption. Significant losses also included cleanup costs for the Municipality of Anchorage, adjacent military bases, and towns in the Matanuska-Susitna Valley. The cost of cleanup from the August 18, 1992, ashfall for Anchorage International Airport, Merrill Field, and Elmendorf Air Force Base, including cleaning buildings, runways, and aircraft on the ground, was at least $683,000 (Anchorage International Airport, unpub. report, 1993). Revenue lost from the closure of Anchorage International Airport for 20 hours is estimated at $276,000 (Casadevall and Krohn, this volume). The Municipality of Anchorage reported nearly $2 million in damage, office closures, and cleanup costs from the August eruption (Municipality of Anchorage, unpub. report, 1993). In addition, there were numerous, small-scale losses incurred by businesses and citizens from the initial ashfall and reworked volcanic ash that affected equipment such as vehicle engines, building air-circulation systems, and computers in banks, businesses, and local military installations. Economic impacts of ashfall on the upper Kenai Peninsula, Cordova, and the Matanuska-Susitna Valley have not been evaluated. AVO received calls from these areas following all three eruptions reporting school closures, poor road conditions, and health concerns. No loss of life resulted directly from the eruptions. Two heart attacks, one fatal, from shoveling ashfall were reported in Anchorage.

In contrast to the estimate of $160 million in losses from the 1989–90 Redoubt eruptions (Tuck and Huskey, 1992), total losses from Crater Peak eruptions are informally estimated to be from $5 to 8 million. This large difference arises from at least two causes. First, there were more eruptive pulses and greater eruptive volume in the Redoubt episode. Second, Redoubt losses were dominated by damage sustained by five jets (Casadevall, 1994). Damage to one of these aircraft nearly resulted in a catastrophe. The Crater Peak eruptions carried the same potential for disaster. However, increased awareness of the ash-cloud hazard within the aviation community and emplacement of an effective warning system by AVO, in concert with other agencies, resulted in minimal economic loss to air carriers.

VOLCANOLOGICAL IMPLICATIONS OF THE 1992 ERUPTIONS

The 1992 eruptions of the Crater Peak vent of Mount Spurr provide interesting insights into eastern Aleutian volcanism as well as andesitic volcanism in general. Some salient points are described below:

1. Less silicic magma composition does not necessarily mean less explosive eruptions. Silicic volcanism is often equated with explosive eruptions, and it is tempting to think of more mafic eruptions as more likely to produce lava flows. The Crater Peak eruptions were distinctly more mafic than those of either Redoubt or Augustine. Yet, these eruptions were entirely explosive, whereas a significant proportion of recent Redoubt and Augustine activity has been effusive. A rationale often applied to the case of effusive mafic eruptions is that in more fluid magma gas bubbles escape more readily and thus preclude significant buildup of pressure. However, a fluid magma can also ascend more rapidly than a viscous one. Rapid ascension of magma would prevent release of vapor from magma in the subsurface prior to eruption (Jaupart and Allegre, 1991) and could explain the explosiveness of the Crater Peak eruptions (Eichelberger, 1995).

2. Each of the three eruptions was remarkably similar in style and volume (Gardner and others, 1993; Neal and others, this volume). Quiet periods between events were of similar duration. The simplest interpretation is that the erupted magma was stored in the same way prior to each eruption. Storage at the same depth would lead to the same initial volatile conditions. One might envisage a conduit that gradually filled to the same volume prior to each event, emptied in each event, and was not physically altered during each event. In such a view, cessation of the complete eruptive episode represents decline in source region overpressure (Tait and others, 1989), and cessation of an individual eruption represents exhaustion of conduit-stored magma. Storage in a conduit extending to the base of the seismogenic zone at 40 km (Power and others, this volume) would require a conduit radius of 10 m.

3. Like Redoubt, there is evident heterogeneity in melt composition in the system (Nye and others, this volume; Swanson and others, 1994), but unlike Redoubt, there is little heterogeneity in bulk composition (Nye and others, this volume; Nye and others, 1994). This phase heterogeneity and bulk homogeneity probably represents the existence of magmatic domains that had similar origins but different pressure1 temperature histories, and that have not interacted chemically with the mid- to upper-crust (despite the presence of abundant melted felsic xenoliths), nor lingered and fractionated there. Again unlike Redoubt, melt heterogeneity increases with time through the episode (Harbin and others, this volume). Perhaps this difference relates to the clearly different styles of magma storage beneath the two volcanoes, but that relation is not clear.

4. Despite the similarities of eruptive events within the 1992 episode, the character of associated seismicity varied greatly (Power and others, this volume; McNutt and others, this volume). There was seismicity preceding and following eruption, seismic quiescence preceding and following eruption, and seismicity without eruption. Because much of the seismicity defines a near-vertical line from the active vent to 40 km in depth, there seems little doubt that the seismicity is associated with flow of magma. It must be concluded, however, that Mount Spurr's magma can also move aseismically, and that significant shallow seismically detected movement of magma can occur without eruption. There is a mirror symmetry to the pattern, that is seismicity occurred without eruption at the beginning and end of the episode and aseismic eruption occurred in the middle. This pattern is perhaps consistent with thermal waxing and waning of the shallow system. When the system was hottest, less seismogenic brittle fracturing or interaction between magma and hydrothermal fluids occurred. This symmetry, however, is not complete in terms of distribution and type of seismicity, and much early seismicity occurred far from plausible sites of intrusion. The pattern is complex. Apparently, multiple processes associated with the rise of magma generated the seismicity.

5. Although the most recent prior eruption was a good guide to the style of the 1992 events, its singularity was not. Past activity should be interpreted cautiously, especially when the data set is limited.

Interpretation of available data for the Mount Spurr volcanic system suggests the rapid migration of relatively fluid, volatile-rich magma through a narrow, deeply rooted conduit. Useful lessons have been drawn in terms of eruption prediction. For example, the importance of even weak tremor in presaging eruption and the variability of the relation between seismicity and impending eruption. However, much remains to be learned about underlying processes. The origin of seismicity accompanying magma flow is not clearly understood, nor are the mechanisms by which new magma reopens an existing conduit. Whereas petrologic inferences can be drawn about equilibrium conditions of magma storage, the chemical and physical changes that accompany magma rise and produce the large variations in eruptive behavior are poorly known. A hope for the future is that geophysical and geologic insights from active systems such as those gained from the Crater Peak eruptions will provide the basis for a better understanding of magma's ascent to the surface. Such understanding could lead to better predictive capability — that is, to predict whether magma will merely intrude or will erupt, and to predict whether eruptions are likely to be explosive or effusive.

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